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Cleaning of Woven Filter Cloths – In-Depth Analysis of Possible Concepts Utilizing Jet Cleaning in a Brewery Case Study

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Preface

Roman Werner M.Sc.

The results of the publications of this thesis were developed at the Technical University of Munich, Chair of Brewing and Beverage Technology, Research Group BioPAT and Digitalization from 2015 to 2021.

Peer-reviewed publications

The following peer-reviewed publications (shown in chronological order – in the following named thesis publication) were published in the period of this work and are related to the topic of the thesis.

The doctoral candidate is the main author of the four publications presented in this thesis and the fundamental and major part of the conceptualization, methodology, software development, validation, formal analysis, investigation, data curation and visualizations. The writing of the original drafts of the manuscripts is exclusively his product.

1. Werner, R., Geier, D., Becker, T.: The Challenge of Cleaning Woven Filter Cloth in the Beverage Industry - Wash Jets as an Appropriate Solution. Food Engineering Reviews, doi: https://doi.org/10.1007/s12393-020-09228-x.

2. Werner, R., Takacs, R., Morsch, P., Geier, D., Nirschl, H., Becker, T.: Jet Cleaning of Filter Cloths Used in Solid-Liquid Separation: a High-Speed Video Evaluation. Chemical Engineering & Technology, doi: https://doi.org/10.1002/ceat.202200468.

3. Werner, R., Schappals, L., Geier, D., Becker, T.: Pulsed forward flushes as a novel method for cleaning spent grains loaded filter cloth. International Journal of Food Science & Technology, doi: https://doi.org/10.1111/ijfs.15795.

4. Werner, R.; Hummel, A.; Geier, D.; Becker, T.: Investigations on Backflush Cleaning of Spent Grain - Contaminated Filter Cloths Using Continuous and Pulsed Jets, foods, doi: https://doi.org/10.3390/foods11121757.

Contents

Abbreviations

A	Surface
β	Mass transfer coefficient
CIP	Cleaning-in-place
$c_{S,F}$	Wave propagation velocity
$\frac{dc}{dx}$	Concentration gradient
D	Diffusion constant
δ	Boundary layer thickness
DIN	Deutsches Institut für Normung (German Institute for Standardization)
EHEDG	European Hygienic Equipment and Design Group
EoS	Equation of state
G	Degree of cleaning
g	Gravitational acceleration
H.F.	Homogeneity factor
h_i	Height/distance between actual profile and mean profile at *i*
J	Flux
l	Length of the measurement line
m	Mass
v	Kinematic viscosity
OWRK	Method according to Owens, Wendt, Rabel, and Kaelble
p_x	Pressure
PP	Polypropylene
PET	Polyethylene terephthalate
PA6.6	Polyhexamethylene Adipamide 6.6
PLN	Plain weave
PRD	Plain reverse Dutch weave
π_e	Dispersion pressure
Ra	Mean roughness of a surface
Re	Reynolds number
RFZ	Radial flow zone
RH	Research hypothesis
ρ	Density
S	Layer thickness
Sa	Mean arithmetic height value of a surface
STN	Satin weave
t	Time
τ	Wall shear stress
TWL	Twill weave
v_x	Velocity
φ	(Incidence) Angle
χ	Backflow factor
γ	Tension

Abstract

This dissertation investigates cleaning woven filter cloths in solid-liquid separation, using mash filters in breweries. In this filtration system, reusable woven filter fabrics represent the filtration’s cornerstone, separating solid spent grains from the liquid wort. Often, the cereal-based spent grains remain after filtration on the cloths and require extensive removal. However, filter structures are often complex and not designed for good cleanability, as several hygienic design guidelines proposed. Thus, there is always a serious risk of poor performance for subsequent batches and cross-contamination. Existing cleaning methods are inflexible and highly dependent on the operator’s experience, causing a rigid and unoptimized process. Current concepts are time- and fluid-consuming, resulting in economic inefficiency and poor sustainability. This thesis elaborates on these challenges through an in-depth discussion of existing knowledge and experimental cleaning investigations. The main goal is to explore efficient methods of cleaning filter cloths in solid-liquid separation, particularly in the food industry.

The literature review highlights the challenges in cleaning woven filter cloths. For instance, cloth materials have natural process limits (e.g., cleaning temperature), narrowing potential procedures, and cleaning parameters. These filter media also require careful treatment, as they can be damaged, resulting in costly and time-consuming process downtime. Further, the biophysics of adhering contamination and the fluid dynamical principles of jet cleaning are reviewed in detail. The analyses underline the potential of pulsed jets in filter cloth cleaning for food applications.

The experimental part comprises the development of residue detection, using image processing and cleaning experiments on several filter cloth types. The latter section contains the development and utilization of two different cleaning devices. The cleanability of different filter cloths is investigated on a novel developed automated cleaning device installed in a pilot mash filter. Different cleaning procedures are analyzed on a laboratory cleaning device, enabling precise residue detection and high sample throughput. Here, in particular, the process modes of forward and backflush cleaning are considered, using pulsed and continuous jets.

The thesis’s experimental results show the strong influence of several cloth parameters, e.g., weave type and mesh sizes, on its cleanability. Filter cloths can have complex surfaces, resulting in significant roughness. This aspect complicates cleaning and requires well-adjusted concepts. Discontinuous jet cleaning shows significantly better results in directly comparing the process modes. Depending on the mode and filter cloth, pulsed jets can reach up to 30% higher levels of cleanliness in the same cleaning time while using up to 50% less wash water than continuous jets. The comparison of forward and backflush cleaning reveals different advantages and disadvantages in both methods. Forward flushes have better mechanical effects on the cloth’s surface and can remove persistent contamination better in difficult-to-clean areas. In contrast, backflushes can generate more precise contamination transport away from the cloth’s surface.

The findings help to understand the requirements and mechanisms of filter cloth cleaning. They indicate ample room for economic and ecological improvements in cleaning filter presses in the food industry. For breweries, the results represent an essential step in finding new cleaning techniques for mash filters. Ultimately, the thesis conclusions contribute to a new state of the art for filter presses and breweries in particular.

Zusammenfassung

Die vorliegende Dissertation untersucht die Reinigung von gewebten Filtertüchern im Gebiet der fest-flüssig Trennung sowie der Lebensmittelindustrie. Das Fallbeispiel Maischefilter im Bereich Brauerei erzeugt eine große Praxisnähe und schnelle Umsetzbarkeit der Ergebnisse.

In Maischefiltern stellen wiederverwendbare Filtertücher den zentralen Filtermechanismus dar und ermöglichen die passgenaue Trennung fester Treber von flüssiger Bierwürze. Nach der Filtration bleiben jedoch oft viele Treberrückstände auf den Tüchern zurück, was eine aufwändige Reinigung notwendig macht. Filtertücher haben meist komplexe Oberflächenstrukturen, was speziell die Haftung von Treberresten begünstigt. Dies führt in vielen Fällen zu einer unzureichenden Reinigbarkeit der produktberührenden Oberfläche, was schon lange in vielen anderen Bereichen der modernen Lebensmittelverfahrenstechnik unzulässig ist. Die eingeschränkte Reinigungsfähigkeit kann die Leistung nachfolgender Chargen mindern und die Gefahr von Kreuzkontaminationen erheblich steigern. Momentan genutzte Reinigungskonzepte für Filterpressen sind oft unflexibel und stark anwenderbasiert, was starre und nicht optimierte Prozesse erzeugt. Die hieraus enstehenden Konsequenzen sind zeit- und reinigungsmittelintensive Prozesse, welche gleichermaßen wirtschaftlich ineffizient und wenig nachhaltig sind.

Die Dissertation greift diese offenen Fragestellungen auf und kombiniert eine detaillierte Diskussion vorhandener Literatur mit experimentellen Untersuchungen. Das übergeordnete Ziel ist die Entwicklung effizienter Methoden für die Reinigung von Filtertüchern im Bereich der fest-flüssig Trennung sowie vor allem der Lebensmittelindustrie. Die Literaturanalyse zeigt zunächst die Herausforderungen bei der Reinigung gewebter Filtertücher auf. So haben Tuchmaterialien beispielsweise Prozessgrenzen (wie maximale Reinigungstemperatur), die möglich anwendbare Verfahren und Reinigungsparameter einschränken. Filtertücher erfordern daher in vielen Fällen eine schonende Behandlung und gut abgestimmte Reinigungsprozesse. Jegliche Beschädigungen führen zu kostenintensiven sowie zeitaufwändigen Prozessausfällen und müssen daher bestmöglich verhindert werden. In der Literaturstudie werden auch die Biophysik der anhaftenden Verunreinigungen und die strömungsmechanischen Prinzipien der Düsenstrahlreinigung untersucht. Hierbei wird ein hohes Potenzial von gepulsten Strahlen bei der Reinigung von Filtertüchern für Lebensmittelanwendungen gesehen, welches detaillierte Untersuchungen erfordert.

Der zweite Teil der Arbeit behandelt die Entwicklung einer Rückstandsanalytik auf Basis von Bildverarbeitung und zugehörige Reinigungsevaluationen verschiedener Filtertücher. Die Reinigungsversuche werden mit zwei verschiedenen Reinigungsanlagen durchgeführt. Die Reinigungsfähigkeit verschiedener Filtertücher wird an einer neu entwickelten automatischen Reinigungseinheit untersucht, welche in einem Pilot-Maischefilter Anwendung findet. Die Analyse verschiedener Reinigungsverfahren wird dagegen mit einem Reinigungssystem im Labormaßstab durchgeführt. Dadurch wird eine präzise Rückstandserkennung und ein hoher Probendurchsatz ermöglicht.

Der experimentelle Schwerpunkt liegt auf der Forward- und Backflushreinigung mit gepulsten und kontinuierlichen Reinigungsstrahlen. Die Ergebnisse zeigen einen starken Einfluss verschiedener Tuchparameter auf die Reinigungsfähigkeit, welche durch den Gewebetyp und die Maschenweiten bedingt sind. Durch die komplexen Filtertuchstrukturen können hohe messbare Oberflächenrauigkeiten entstehen, welche in vielen Fällen mit der Reinigbarkeit korreliert. Dieser Aspekt erschwert die Reinigung und erfordert gut abgestimmte Konzepte. Der direkte Vergleich von diskontinuierlicher und kontinuierlicher Strahlreinigung zeigt, dass pulsierende

Strahlen bessere Reinigungsergebnisse erzeugen. Abhängig vom Prozessmodus und dem Filtertuchtyp führen gepulste Strahlen bis zu 30% höheren Reinigungsgraden im gleichen Zeitintervall und verbrauchen bis zu 50% weniger Reinigungsfluid. Der experimentelle Vergleich der Forward- und Backflushreinigung zeigt eine bessere mechanische Wirkung von direkt auf die Tuchoberfläche gerichteten Wasserstrahlen. Die Vorteile der Reinigung im Backflush liegt in einem verbesserten und präziseren Abtransport der Verunreinigungen von der Tuchoberfläche.

Die Ergebnisse dieser Dissertation erzeugen ein besseres Verständnis über die Anforderungen und Mechanismen der Filtertuchreinigung. Durch die Verwendung effizienter Verfahren zeigen die Resultate vor allem große Potenziale von ökonomischen und ökologischen Verbesserungen für die Lebensmittelindustrie auf. Insbesondere für Brauereien stellen die Ergebnisse einen wichtigen Schritt dar, um neue Reinigungstechniken für Maischefilter entwickeln zu können.

1 Introduction

One of the food industry’s core responsibilities is to deliver hygienically excellent products to its customers. For this purpose, the cleaning and disinfection of equipment and respective components are critical unit operations. While cleaning removes contamination, subsequent disinfection ensures food safety and prevents a negative influence on customer health due to remaining microorganisms [1]. It is not only the specific procedure and the chemical agents used in a cleaning concept but also the characteristics of the equipment and associated surfaces that come into contact with food [2; 3]. An essential requirement of production equipment for food applications is easy cleanability, a cleaning-compatible layout, and additional specific features [4].

Corresponding guidelines, design features, and concepts are part of *hygienic design*. This definition has been a core aspect of the modern food industry for years. Today’s standard design features in most food production equipment are, e.g., smooth surfaces, self-draining containers, and the avoidance of stream shades. The *European Hygienic Equipment and Design Group* (*EHEDG*) publishes corresponding hygienic design recommendations and certifications in Europe. In the USA, organization *3-A* is responsible for several cross-industrial guidelines concerning hygienic design [4]. With guideline 10-04, *3-A* also published a sanitary standard for filter systems using single service filter media, mainly applied in dairy [5].

However, such guidelines and rules are not yet available for reusable woven filter cloth. This type of filter medium represents the centerpiece in many filter systems due to the costs of the cloth and installation and is, thus, essential in many solid-liquid filtration processes for food products. As it always remains in the filter and is reused in large quantities, guaranteeing product safety requires regular cleaning using well-adjusted concepts. In most cases, filter cloths have complex geometries that naturally focus on filtration performance rather than easy cleanability. Current cleaning concepts for filter cloth still follow rigid and over-dimensioned techniques, wasting cleaning fluid and being too time-consuming. Thus, new solutions must be identified in times of increasingly growing environmental issues and scarcity of resources. The major challenge is maintaining or even improving the current demands on product safety while developing more resource-saving and environmentally friendly cleaning techniques. In the future, a particular emphasis will be primarily on cleaning times and water consumption.

For these reasons, new methods for woven filter cloth that provide state-of-the-art cleaning while simultaneously being economical and resource-friendly are necessary for the food sector. Regarding efficiency, the best procedure to remove contamination from filter cloth is a water jet streamed by a nozzle. Many different cleaning parameters (e.g., temperature, fluid mechanics, and agents) can be adjusted with this method. Here, the critical aspect is the adjustment of properly combined parameters, enabling high cleaning efficiency. In this context, the composition of the food or intermediate product to be filtered requires detailed consideration.

This thesis highlights the cleaning of woven filter cloth, focusing on mash filters in breweries. As cleaning techniques, forward and backflushing are compared using continuous and discontinuous (pulsatile) jets. Significantly, the last technique has already shown promising results in other applications. The brewery use case enables a food-close application and rapid transferability to industrial practice. Here, woven filter cloths facilitate the solid-liquid separation of mash, where the remaining spent grains on the cloth’s surface require separate removal.

2 State of the Art

This chapter highlights the basics of cleaning woven filter cloths. In detail, the following subchapter gives an insight into the fundamental processes of jet cleaning and the factors influencing an efficient cleaning process. The cleaning-targeted object, here the woven filter cloth, is considered how it gets contaminated by the retentate of a filtration cycle.

2.1 Filter cloths

Filter cloths are woven fabrics in a specific woven structure (see Figure 1). Exemplary industrial applications include chemical processing, water treatment, and food processing. They are commonly used to filtrate liquids, gasses, and solids [6]. Especially in food, filter cloths are used in solid-liquid separation and enable the processing of food and its stabilization. The cloth’s woven pattern allows for a reasonable flow rate and good filtration efficiency. Filter cloths are regularly constructed structures, distinguishing them from, e.g., fleeces. The cloth’s specific structure is created by a particular interweaving of warp and weft threads according to a specific weave pattern. The threads can be of different thicknesses, whether monofil (single thread) or multifil (multiple threads twisted into a bundle). This particular weave creates varying surface structures and mesh sizes and thus supports specific filtration tasks to a great extent. According to Anlauf [7], the various arrangement possibilities result in different application potentials for particle separation and mechanical stability.

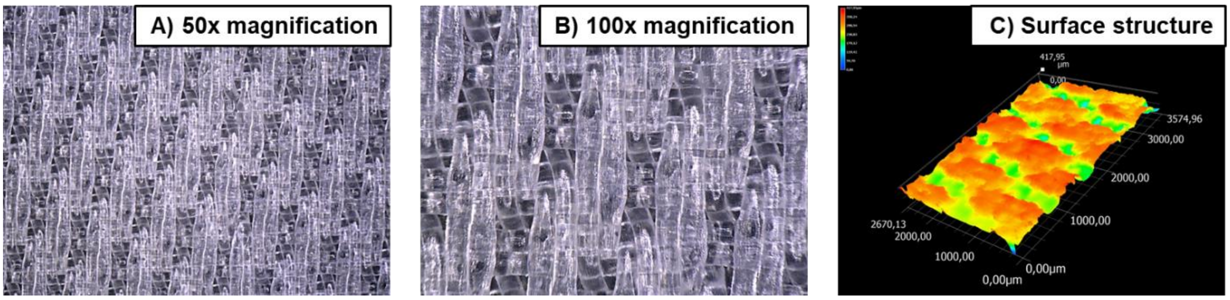


Figure 1: Exemplary 05-1001-K043 filter cloth in top view (A + B) and a measurement of the roughness profile with the VW9000 digital microscope and VH-Z20R/Z20T lens (Keyence Corporation)

2.2 Residue accumulation on filter cloths

In different filter systems like filter presses, filter cloths are the primary filter medium and enable the separation of particles (retentate) from liquids (filtrate). Filtration is one of the basic unit operations of process engineering since, in food applications, particles are often dispersed in liquids and gases. The term *particle* refers to solid particles, droplets, and microorganisms. The particles and/or the liquid can be obtained by separating both phases depending on the filtration task. The filtration of particles from liquids is also called solid-liquid separation. Its main characteristic is the formation of a surface coating or an entire filter cake on the filter medium. Most filter media follow two principles: surface and deep bed filtration, highlighted in Figure 2 in detail.

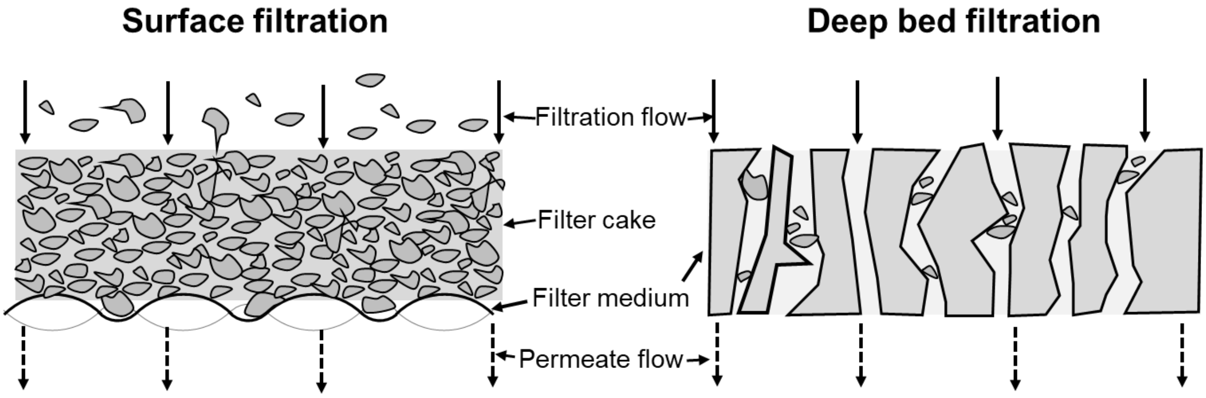


Figure 2: Schematic illustrations of surface and deep bed filtration – adapted from Hamatschek [8]

According to Hamatschek [8], in the case of surface filtration, the particle sizes are larger than the pores/meshes and cannot pass through the filter medium. The pore/mesh size must be selected according to the filtration task. The particles accumulate and form a filter cake. This cake performs the function of a sort of additional filter medium and consists of a distinct structure. Filter cakes can be beneficial for filtration performance in several operations. In deep bed filtration, the particles permeate the filter due to the size of the filter medium's filtration channels. Here, corresponding pore sizes or adhesion to the filter's material separate particles. This filtration type is used for low concentrations and minor particle suspensions.

According to Anlauf [7], deep bed filtration operations mainly employ yarn filters, resin-bound filter sheets, and bulk layers. Surface filtration, however, is achieved by using porous sinter materials, microporous membranes, wedge wire screens, and woven fabrics. Precoat layers and fleeces can work in both filtration principles.

In particular, the contamination and cleaning of woven fabrics are the experimental focus of this thesis. Consequently, the applied contamination in Chapter 5 can always be assumed to be a thin layer or cake formation, accumulating smaller particles between the individual filter meshes. A blocking of the filter can arise during filtration quickly, also called fouling. In this case, particles are deposited on the cloth and in the mesh, possibly leading to a complete filter blockage and an associated process breakdown. Whether and when such a case occurs, however, depends strongly on the filtration material, the filtration method, and respective parameters.

After filtration, the remaining filter cake must be removed to ensure the subsequent filtration is efficient. This process step is performed by mechanical separation and a cake discharge. In the latter case, the cake detaches itself from the filter cloth by gravitation. This aspect is particularly the case in filter presses, where the filter chamber is opened after filtration and the cake discharges. However, in many cases, the removal is incomplete, so extensive cleaning activities must take place.

2.3 Jet cleaning of filter cloths

At first glance, a cleaning process primarily causes work and costs, while no directly accountable profit can be expected [9]. However, a detailed analysis casts doubt on this statement since cleaning processes affect the production equipment positively and enable high product quality and safety. These aspects are critical in the food industry, so regular inspection is essential from a technical and legal perspective. Significantly, organic residues, like microorganisms, can influence a food product negatively, leading to severe poisoning in consumers. Furthermore, poorly cleaned production equipment has only reduced functionality and becomes useless due to corresponding contamination-related damage over a certain period. In conclusion, the main targets of jet cleaning, according to Wildbrett et al. [3], are:

- Achievement of a visually flawless and clean appearance
- Obtaining complete operability of equipment and its components
- Extending the service life of the equipment
- Enabling high product safety

Therefore, equipment and its components must be cleaned and disinfected frequently and uniformly. In the food industry, all remaining organic substances, such as product and raw material residues or microorganisms, and mineral deposits are defined as contamination (unwanted substances) [1; 10]. They all require a specific cleaning regime that considers their individual properties and behavior towards the surface (e.g., adhesion).

It is also essential to analyze the entire operation in any cleaning process. Significantly, the utilization of a cleaning jet requires a detailed consideration of fluid mechanics from the nozzle until the contamination's transport away from the cleaning zone. The detailed division of the jet, its impact, and drainage with all specific steps help to adjust appropriate cleaning parameters. A jet's cleaning process can be classified into the following steps.

- Step 1: Jet sprayed from the nozzle
  - Fluid dynamic consideration of a free jet
  - Determination of various parameters by free jet calculation models
  - Key parameters: jet velocity, the distance between nozzle and cloth, the potential core length
- Step 2: Impinging jet on the filter cloth surface
  - Differentiation in forward or backflush
  - Immediate impact forces with crucial initial cleaning effect
  - Subsequent formation of a cleaning flow with decreasing pressure forces
  - Key parameters: Impact velocity, incidence angle, cloth geometry
- Step 3: Cleaning effects in the impact zone
  - The breakup of the contamination
  - Release of cohesive and adhesive forces
- Step 4: Lateral flow off of cleaning stream on surface
  - Diffusion and convection effects on contamination
  - Cleaning solution enters contamination to a high degree
  - Flow on the surface causes wall shear stress
- Step 5: Contamination transport and trickle flow
  - Contamination is increasingly removed from the surface
  - Transport of contamination depends on flow conditions (turbulent flow is beneficial for cleaning)
  - Decreasing effect with growing distance from the point of impact

2.4 Parameters with specific cleaning influence

The choice of a suitable cleaning concept depends, above all, on adjusting appropriate cleaning parameters. The cleaning success for any surface highly depends on several influencing factors. According to Hofmann [2], these cleaning parameters are fluid-, contamination- or component-dependent. Tamime et al. [11] chose other descriptions by dividing the cleaning factors into the mechanical design, cleaning process, and product/process design, which are more specific to the conditions in the food industry, such as the use of cleaning-in-place systems (CIP).

In the end, however, these influencing variables are always the same, and their proper combination ensures an efficient cleaning process. The fluid-dependent parameters are critical for the final cleaning planning as they are adjustable in the cleaning fluid. These parameters are temperature, chemistry (type, concentration, water hardness), mechanics (flow rate), time, and temperature. The Sinner circle is the most common synopsis of all important cleaning parameters and the most common among practitioners [3]. The success and optimization possibilities depend on the interaction of these parameters. If one of them is increased (e.g., temperature), others can be decreased [12].

2.4.1 Cleaning time

All cleaning parameters depend on certain application times. According to Heiss et al. [9], chemical, thermal, and kinetic energies require a specific reaction time with the contamination to achieve enough chemo-physical effects to diminish the contamination. Also, mechanical cleaning components, like wash jets or pipe flows, require time to effect enough tension on the adhering contamination. The adhesion of cells, biomolecules, or other particles requires time, so their removal equally demands extended time periods [13]. Regarding the time dependency, a cleaning process has to be divided into distinct steps (e.g., swelling, diffusion), requiring different cleaning times [14]. With standard methods, determining an exact period is challenging [9].

Hauser [4] explains cleaning using fluids and flows with the mass transfer phenomenon. This process includes diffusion, convection, and dissolution of a relevant contamination load from the surface in the flow. This time-dependent mass transfer $\frac{dm}{dt}$ can be calculated with Eq. 1 [14].

$$\frac{dm}{dt} = \beta \cdot A \cdot \frac{dc}{dx} \qquad \text{Eq. 1}$$

In the equation, β describes the mass transfer coefficient, *A* the considered exchange surface, and $\frac{dc}{dx}$ the concentration gradient of the contamination between the soil layer and the cleaning stream. The entire mass transfer depends on the process length, the initial contamination quantity, and the time-dependent change of the contamination's adhesion behavior. Longer cleaning times will enable more contamination to be detached and favor the final degree of cleaning.

However, each cleaning application has a natural limit where no further effect can be observed. In food production, consistent cleaning results in small or no additional cleaning effects after a specific time interval [15]. Time is essential, as lengthy setup and cleaning intervals can lead to high costs. For this particular reason, efficient cleaning processes are needed. So, the cleaning time parameter must always be combined with the suitable composition of cleaning parameters (e.g., mechanics or temperature) to enable efficient processes.

2.4.2 Chemistry and agents

In the context of cleaning, the term chemistry sums up the use of chemical cleaning agents. Here, the type of cleaning agent and the respective concentration are decisive [11]. Most of a cleaning solution, in terms of quantity, is water, which cannot be fully classified as a cleaning agent due to its insufficient cleaning effect on certain substances (e.g., fats) [14]. For this reason, chemical substances are added to the water in specific concentrations, resulting in the cleaning solution and enabling an efficient cleaning process.

In the food industry, primarily acidic and alkaline agents are commonly utilized, strongly depending on the targeted contamination. While removing organic deposits, such as proteins or biofilms, requires an alkaline agent, mineral contamination is only removed efficiently by acidic agents [11]. Due to these different cleaning impacts, no cleaning agent can simultaneously meet all demands [3]. Commercially available cleaning agents are often available in ready-to-use mixtures and also contain other additives that provide an additional cleaning effect vis-à-vis other substances. An example is tensides, which can create emulsions from the cleaning fluid water and oily contaminants and thus make the latter removable. Another chemical component is disinfectants, used after cleaning to enable the inactivation of remaining microorganisms and hygienic conditions. In many cleaning applications, enzyme-based agents are also used to remove persistent contamination [9].

Cleaning with an agent always starts with its application to the contaminated area and subsequent soaking time. As described in 2.4.1, diffusion and convection in mass transfer are decisive factors in transporting agents into contamination and affect their relevant cleaning mechanisms. Subsequently, this effect also works vice versa for the contamination to migrate into the cleaning fluid.

Diffusion is mass transfer caused by a concentration difference between the contamination and cleaning fluid. Due to Brownian motion, particles move from a high to a low concentration c temperature-dependent in cleaning processes [2]. The diffusion can be calculated with Fick's laws. Fick's first law describes one-dimensional diffusion and is defined in Eq. 2 [16; 17].

$$J = -D\frac{dc}{dx} \qquad \text{Eq. 2}$$

The variable J defines the flux, while D is the diffusion constant, and $\frac{dc}{dx}$ represents the concentration gradient. Fick's second law in Eq. 3 extends this approach and describes the diffusion with a time-dependent and local concentration gradient [2; 17].

$$\frac{dc}{dt} = D\frac{d^2c}{dx^2} \qquad \text{Eq. 3}$$

In both Fick's laws, time t is a decisive factor, underlining the necessity of sufficient cleaning time for chemical-dominated cleaning concepts.

For state-of-the-art cleaning and subsequent disinfection, chemical products are indispensable. However, ecological and economic aspects often require re-evaluating existing cleaning processes in many applications. Additionally, chemical agents can harm the surface's material, causing damage or corrosion [9].

2.4.3 Mechanical cleaning effects

Besides the chemical factor, most cleaning concepts in food processing also depend on a particular mechanical effect [3]. In most applications, a cleaning utensil, such as brushes, or the fluid mechanical forces from an applied fluid flow enable mechanical shear stress on the contamination [9]. An essential aspect of cleaning procedures is the mechanical release of adhesive forces between the contamination and filter medium [3]. A microbiologically safe condition can never be achieved solely by mechanical cleaning but increased associated cleaning effects can lead to more optimized and resource-saving processes (e.g., of the cleaning fluid and agents). In the following, only the cleaning mechanics of a nozzle jet will be discussed, as this cleaning technique is used in the experimental section of this thesis.

In characterizing a jet's cleaning of a surface, it is essential to specify the effects that appear during its impact and as the process continues. Most fluid mechanical considerations, from the nozzle and impingement to contamination removal, are detailed in 5.2 [18]. Therefore, only a few more fundamental aspects of the pressure distribution on the surface during jet impact and trickle flow effects, which can promote the transport of contamination, are referenced.

The overall cleaning effect can be distinguished in the impact and the subsequent stream on the surface (see Figure 3). During impact, the jet applies a particular pressure to the contamination in combination with a bursting of the fouling layer due to diminishing cohesive forces. Parts of the contamination are ejected from the cloth as the jet penetrates the surface of the cloth and gradually forms a constant overflow stream.

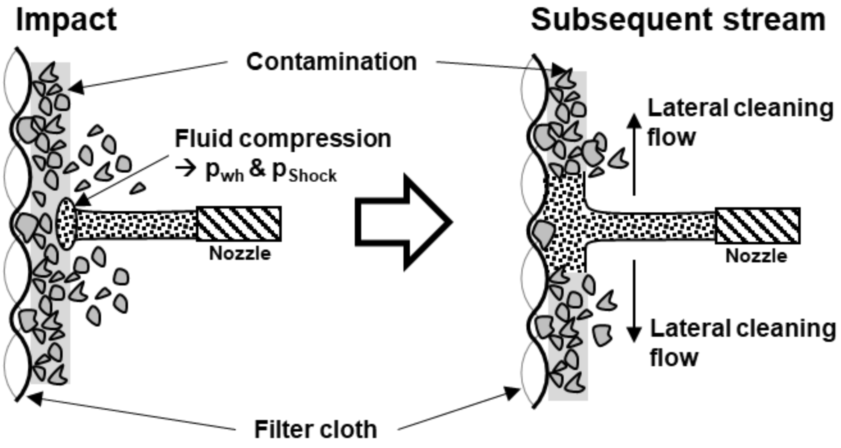


Figure 3: Schematic drawing of the jet's impact and the subsequent stream after a specific period – cloth positioned vertically (e.g., in a filter press)

According to the literature [19], the pressure distribution on the filter surface, resulting from the velocity and forces, is a critical cleaning factor. Mauermann [20] distinguished three types of pressures: water hammer, shock/impact pressure, and dynamic pressure. After the jet impact, compression of the fluids occurs, resulting in shock waves against the surface and back into the jet [21–24]. The resulting pressure between fluid and contamination is definable as the shock pressure $p_{S,\max}$ with a maximal possible value. Along the contact zone, it decreases to the water hammer pressure p_{wh} in the center [19]. This dynamic pressure change was first described by Joukowsky in 1900 [25]. According to Sigloch [26], the total water hammer originates within 1 ms after impacting the surface. After this effect, it disappears in approximately the same time frame. This consideration is crucial with regard to pulsed jets. Eq. 4 and Eq. 5 enable the Cook equation to determine the water hammer pressure p_{wh} and shock pressure $p_{S,max}$ [19; 20; 26].

$$p_{wh} = \rho \cdot c_{S,F} \cdot v_{Impact} \qquad \text{Eq. 4}$$

$$p_{S,max} = (2 \dots 3) \cdot p_{Water\_hammer} \qquad \text{Eq. 5}$$

The variable $c_{S,F}$ is the wave propagation velocity and can also be equated with the shock or acoustic wave velocity in fluids [19]. Several experiments and theoretical determinations elaborated the maximal possible pressure range 2…3 [27–33]. Parameter ρ represents the fluid's density, and v_{Impact} is the impact velocity. After the degeneration of the water hammer, the third pressure occurs. The classic dynamic pressure $p_{Dynamic}$ is quasi-static stress on the contamination and is determinable with Eq. 6 and Eq. 7 [19].

$$p_{Dynamic} = \frac{1}{2} \cdot \rho \cdot \left[v_{Impact}^2(jet) - v_{Impact}^2(wall)\right] \qquad \text{Eq. 6}$$

$$v_{Impact}(wall) = v_{Impact}(jet) \cdot \sin\varphi \qquad \text{Eq. 7}$$

Here, a differentiation in the jet $v_{Impact}(jet)$ velocity and the velocity at the wall $v_{Impact}(wall)$ is necessary. The variable φ represents the incidence angle of the jet towards the cloth surface.

After the impact, the jet flows off laterally to all sides, influenced by the position of the filter cloth. If the filter cloth is utilized in a filter press, the cloth is positioned vertically, resulting in an increased flow off in a negative *y*-direction due to gravitation. During the flow, other mechanical effects occur, such as wall shear stress τ. The resulting efficiency also highly depends on the flow condition, which has to be turbulent [14]. The turbulence leads to a statistically better contamination capacity of the cleaning flow, increased mechanical stress on the contamination, and a smaller thickness of boundary layers on the surface. Wall shear stress τ, the Reynolds number *Re*, and the determination of the boundary layer thickness δ are explained in detail in publication 1 [18] in 5.2.

The water flows off in a trickle flow at a certain distance from the impact zone. Here, turbulent flows are also required to achieve proper cleaning. However, a steady decrease in the acting fluidic effects can be observed due to fluid friction. According to Hauser [4], the velocity $v(y)$ of the trickle flow can be described by Eq. 8.

$$v(y) = \frac{g}{2 \cdot \nu}\left(y^2 - S^2\right) \qquad \text{Eq. 8}$$

The variable g represents the gravitational acceleration, ν the kinematic viscosity, $y = 0$ the velocity at the surface, and S the layer thickness (laminar flow). Further contexts of trickle flows are explained in publication 1 [18] in 5.2. Depending on the velocity $v(y)$ and the value of the *Re* number, the flow can be even or wavy.

In conclusion, mechanical cleaning is crucial in production processes. An efficient increase in corresponding components in the cleaning concept helps to decrease costly and unecological components, such as cleaning agents or extensive cleaning times. However, exaggerated mechanical influences can also damage the surface and equipment. This aspect has to be considered in filter cloth cleaning as these textiles can withstand only specific pressures.

2.4.4 Influence of temperature on cleaning

The influence of the fluid's temperature has been discussed intensively for decades. Generally, it is known that higher temperatures lead to better cleaning results. However, Wildbrett et al. [3] explain several advantages and disadvantages of increased cleaning temperatures. The benefits are decreased binding forces, reduced viscosity, faster diffusion and swelling, accelerated chemical and enzymatic reaction, better solubility and melting of fats. In contrast, the negative effects are worse protein removal due to denaturation, worse enzyme activity, and decreased lipid transportability. Additionally, the adjustment to a higher cleaning temperature is energy-consuming and costly.

Therefore, the type of contamination and the material properties are crucial in selecting the appropriate cleaning temperature, particularly with the latter, as many polymers can only withstand certain temperatures. Otherwise, they are damaged or deformed, which necessitates replacement. This aspect is essential for filter cloth cleaning, as polymers are almost exclusively used here.

2.4.5 Food-related contamination

In the food industry, all residues that remain in the process area after production are considered contamination [3]. Thus, residues of raw materials or the actual food product also become a contaminant if they remain in the equipment after production. Also, cleaning agents and disinfectants count as contamination if they remain in the equipment after cleaning [4]. According to Wildbrett et al. [3], food contamination and its constituents can be categorized in the criteria of their behavior with water:

- Soluble (salts, acids, low molecular carbohydrates)
- Swellable (proteins, high molecular carbohydrates)
- Emulsifiable (fats, lipids)
- Suspendable (particles)

In numerous areas of the food industry, contamination is a composition of all these components. This aspect creates a complex biological matrix, which requires individual cleaning. In addition, the quantity and age are also decisive contamination parameters, according to Tamime et al. [11]. Additional aging effects increase problems in cleaning processes. Hence frequent and fast cleaning after production has to be favored in every application [3]. Fryer et al. [34] have furthermore classified contamination in a prototype cleaning map to quickly estimate the cleaning effort of specific contaminants according to their properties.

Moreover, biophysical effects are another main reason influencing the degree of contamination. Various adhesive forces between the contamination and the surface complicate the contamination’s detachment [35]. Cohesive forces, on the other hand, can generate strong bonding forces between the individual contamination components, which necessitate the effects described above for the cleaning process by the cleaning solution [16]. The biophysical principles and different influencing parameters for food-related contamination are described in Section 5.2 or publication 1 [18].

2.4.6 Surface properties and hygienic design

The production equipment’s material, design, and geometry are decisive criteria in cleaning processes [11]. As mentioned above, these factors can be summarized by the term *hygienic design*. EHEDG [36] and 3-A [37] have published several guidelines, standards, and recommendations for different applications in the food industry. There are also relevant German and international standards for this industrial sector, such as DIN EN ISO 1672-2 [10]. Corresponding guidelines include avoiding stream shades or dead spaces in machines and transfer systems, e.g., pipes.

Firstly, the surface finish is crucial as a rough surface favors contamination adhesion. According to the standards DIN EN ISO 21920-2 and DIN EN ISO 25178-2 [38; 39], several methods and parameters help identify a surface’s distinct roughness. For example, the mean roughness *Ra* has been a leading parameter to characterize surface roughness for decades and can be determined using Eq. 9 [3].

$$Ra = \frac{1}{l}\int_0^l h_i \cdot dx \qquad \text{Eq. 9}$$

The parameter *Ra* describes the roughness profile on a particular measurement line. While the variable *l* describes the length of the measurement line, h_i is the distance between the actual profile and the mean profile at measurement point *i*. In different guidelines and publications, an easily cleanable surface has *Ra* values below 0.8 µm [3; 40].

However, this parameter can only partly help to identify the roughness along a specific measurement range. Thus, the mean arithmetic height value *Sa* helps extend the roughness determination to an entire surface, representing the height difference between specific measurement points and the surface's arithmetic mean. According to DIN EN ISO 25178-2 [39], Eq. 10 can determine S_a.

$$Sa = \frac{1}{A}\int\int_A h(x,y) \cdot dxdy \qquad \text{Eq. 10}$$

Here, *A* represents the regarded surface, and h is the respective height depending on the local coordinates *x* and *y*.

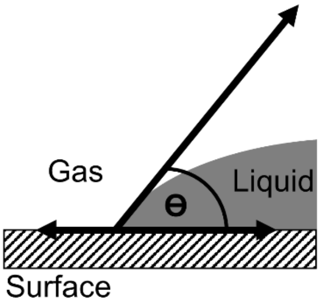


Figure 4: Determination of a contact angle Θ

Secondly, the material has a specific influence on the cleaning success. The material-dependant wettability of a surface is especially crucial to an efficient cleaning process. Wettability is the ability of a surface to be coated by a liquid and how well it will distribute and adhere to a surface. A surface with high wettability will attract a liquid, resulting in easier cleanability. This factor is highly affected by the surface chemistry (interface between liquid and surface), which several parameters can characterize. Here, an essential factor is the contact angle θ between a surface and the liquid (see Figure 4). The value of the contact angles indicates if the surface is hydrophile (small angle), hydrophobe (angle > 90°), or super hydrophobe (angle > 180°). Contact angles depend on the surface tension and are correlated by the Young equation in Eq. 11 [41; 42].

$$cos\,\theta \cdot \gamma_{LV} = \gamma_{SV} - \gamma_{SL} - \pi_e \qquad \text{Eq. 11}$$

The variable γ_{LV} is the interfacial tension between the liquid and gas phase (or saturated vapor), also known as surface tension. Parameter γ_{SL} is the interfacial tension between the surface (solid phase) and liquid. Variable γ_{SV} describes the interfacial energy between the surface and gas phase (or saturated vapor) and is also called surface free energy [43]. The parameter π_e symbolizes the equilibrium film pressure of absorbed vapor on the solid surface [42]. The surface free energy can be determined using several methods with an appropriate device, such as drop shape analysis, the Wilhelmy plate method, the Washburn method, or the top-view distance method [44]. Ultimately, based on the studies of Fowkes [42], Owens and Wendt [43], van Oss [45], Wu [46], and Li [47], there are several methods to determine the surface free energy and several other parameters based on measuring the contact angle.

The Fowkes, the OWRK, according to Owens, Wendt, Rabel, and Kaelble, and the equation of state (EoS) methods are described in more detail in the following, as they are standard methods in many measurement devices [43; 48–50]. According to Fowkes [42], the interfacial tension consists of different parts, as given in Eq. 12.

$$\gamma = \gamma^d + \gamma^n \qquad \text{Eq. 12}$$

Here, γ^d describes the dispersive portion of the force, whereas γ^n represents all non-disperse forces (e.g., hydrogen bonds or dipole-dipole interactions). It must be assumed that there is a geometric average between the individual components for the solid-liquid phase boundary. Combining Eq. 12 with the Young equation of Eq. 11, the modified Young equation in Eq. 13 is generated [43; 51].

$$\cos\theta = -1 + 2\sqrt{\gamma_S^d} \cdot \left(\frac{\sqrt{\gamma_L^d}}{\gamma_{LV}}\right) \qquad \text{Eq. 13}$$

The OWRK method also includes the influence of any polar forces. The corresponding experimental approach requires the use of two different liquids with a known dispersive and polar portion of the surface tension. The surface free energy is determinable with Eq. 13 [43; 49; 50].

$$1 + \cos\theta = 2\sqrt{\gamma_S^d} \cdot \frac{\sqrt{\gamma_L^d}}{\gamma_{LV}} + 2\sqrt{\gamma_S^p} \cdot \frac{\sqrt{\gamma_L^p}}{\gamma_{LV}} \qquad \text{Eq. 13}$$

Here, γ_L^d γ_L^p and γ_S^d γ_S^p represent the disperse and polar fractions, respectively, of surface tension γ_{LV} and surface free energy γ_{SV}. The surface free energy assesses a surface's wettability and cleanability using a particular cleaning fluid.

Another method is EoS, which was determined using several thermodynamical findings by Li et al. [47; 52], using Eq. 14.

$$\cos\theta = \gamma_{LV} + \gamma_{SV} - 2\sqrt{\gamma_{LV} \cdot \gamma_{SV}} \cdot e^{-\beta_{EOS}(\gamma_{LV}-\gamma_{SV})^2} \qquad \text{Eq. 14}$$

The variable β_{EOS} was determined empirically and has the value 0.0001247 $(m^2/mJ)^2$.

In conclusion, several research works have already investigated the cleanability of woven fabrics for specific applications [53–55]. However, the respective guidelines to improve the cleanability and hygienic design of reusable filter cloth are still missing. Such fabrics are designed to perform efficient filtration processes and not to enable easy cleanability.

2.5 Filter cloth cleaning - status quo

In industrial applications, the cleaning of filter cloths still follows unoptimized and rigid cleaning regimes. They do not go along with a demand-oriented, tailor-made process and a modern understanding of hygiene. In this context, necessary measures are the reduction of agents and energy consumption or the shortening of cleaning and setup times. When dimensioning cleaning processes, the filter cloths' requirements must be considered. Examples of existing cleaning methods are vacuum, water pressure, water jets, ultrasonic, steam, or by hand. However, the applicability highly depends on the industrial case and is limited by the filter cloth's properties.

Filter cloths are primarily manufactured from polymers. According to Heiss et al. [9], polymers are generally considered less cleanable than other technical surfaces, such as stainless steel. The reasons are less surface energy, causing worse wettability and fat removal, and rougher surfaces. Filter cloth can be damaged more easily if excessive mechanical forces or high concentrations of cleaning agents are utilized. It needs to be noted that reusable filter cloths are only manufactured for a specific life cycle. The prevailing mechanical forces during filtration and the cleaning intervals cause the cloth to wear out. It must be replaced at certain intervals, associated with considerable costs.

Another important aspect is the geometry or structure of filter cloths. Most of them have rough surfaces that disadvantage cleanability. EHEDG [40] defines a necessary roughness of Ra < 0.8 µm for good cleanability of smooth surfaces. However, also higher values are possible if the cleaning process, wash fluid rate, or other features compensate for poor surface roughness. The latter aspects must be targeted in designing an efficient cleaning procedure for filter cloths.

There has already been research on cleaning woven filter cloths. Stahl et al. [56] developed the first cleaning test for filter media. Weidemann [53] investigated backflush cleaning using filter media loaded with model contamination. In a corresponding publication [57], the *W* number as a dimensionless number was introduced, helping to describe the cleaning behavior. The first study concerning cleaning textiles in a food application was conducted by Moeller [54], where he investigated textiles for fermentation in the baking industry. For sticky doughs, he even favored textiles in contrast to smooth surfaces. Ultimately, Morsch [55] conducted the first beverage-close studies, using spent grains to evaluate the functionality of an automation concept for cleaning operations.

Overall, there is still a significant demand for further insights and research activities. Table 1 sums up the challenges compared to modern cleaning concepts.

Table 1: Overview of the status quo of filter cloth cleaning

Technical problems	Cleaning process	Digitization/Sensors	Contamination
Complex cleaning necessary	Rigid & conservative concepts	No cleaning monitoring	Complex residues of different materials
Process limits (temperature/chemistry)	Considerable lack of optimization	No cleaning sensors	Clogging of filter cloth meshes by solids
Large contaminated area	Long cleaning & downtime	No residue analysis for spent grains	Often broad particle size distributions
Different materials to be cleaned	Often extensive use of cleaning agents	Digitalization potentials unused	
Complex equipment	Often high work & personnel effort		

3 Thesis Motivation

This thesis investigates the cleaning of woven filter cloths in the food industry with the brewery-based case study of mash filters and the removal of spent grains from filter cloths. Spent grains are sticky, particle-based cereal residues and often remain after filtration on the cloths, requiring extensive effort. However, filter structures are often intricate and not according to standard hygienic design guidelines. There is constantly a serious risk of poor-performing subsequent filtrations and cross-contamination. Existing cleaning methods are rigid and highly depend on the operator’s experience, causing an uneconomic and unsustainable process. The need for novel technologies is tremendous.

There are many open questions from a scientific point of view, such as cleaning mechanisms or scientifically substantiated process recommendations. Detailed consideration and discussion of possible cleaning strategies are only possible if different disciplines are engaged. These areas are food technology (product characteristics and hygienic requirements), biophysics (contamination adhesion), process engineering (residue detection, cleaning parameters), material science (cloth material), and fluid dynamics (wash jets). It is essential to involve different cloth parameters to understand cleaning mechanisms and gain knowledge for food applications. Further research requires the combination of contamination detection, detailed consideration of cloth properties, and the selection of new ideas about efficient cleaning concepts for food applications.

Subsequently, the following research hypotheses were selected for this thesis:

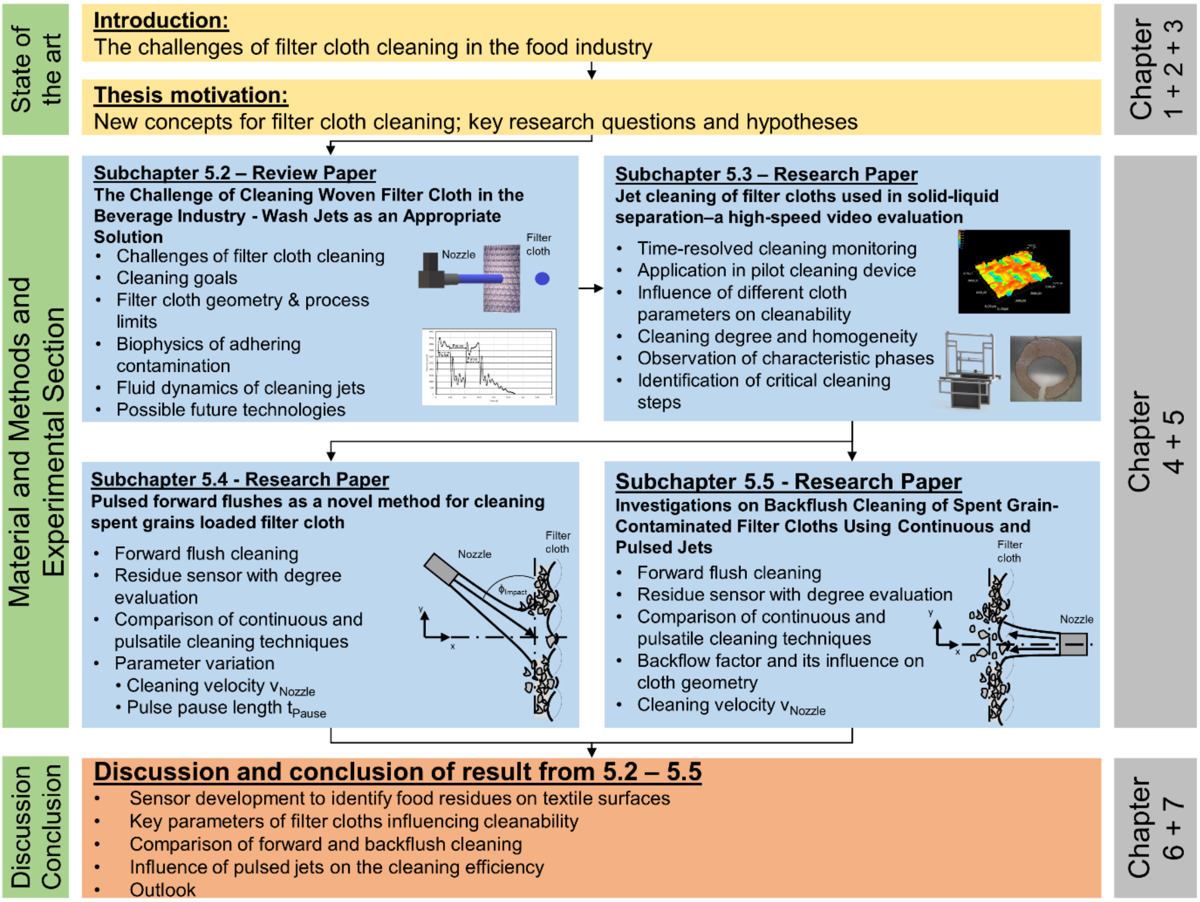
- RH 1: The precise detection of spent grains on filter cloths can be achieved with contactless image processing techniques, enabling efficient residue detection in an industrial environment.
- RH 2: The filter cloth’s structure (e.g., mesh size, weave type) significantly influences the cleaning efficiency and requires individual hygienic design concepts.
- RH 3: Backflushing and forward flushing are beneficial cleaning methods and have individual advantages, like releasing and transporting contamination.
- RH 4: Pulsatile jets enhance cloth cleaning significantly and enable ecological and economical cleaning processes in mash filters.

This thesis, which comprises a series of four publications, is intended to answer these hypotheses. The overall question with high interest for industrial application is derived from these research hypotheses and is the following:

How can filter cloth cleaning be performed efficiently for mash filters?

The systematic analysis of the given hypotheses required the conceptualization of a structured research plan. For this reason, the following main research topics were clustered in the four different publications: the development of new cleaning concepts for filter cloths in the food industry, the cleanability of filter cloths, pulsed forward flush cleaning, and pulsed backflush cleaning.

The entire concept of this thesis, with the segmentation in the different subchapters, is illustrated in Figure 5.



Introduction:
The challenges of filter cloth cleaning in the food industry

Thesis motivation:
New concepts for filter cloth cleaning; key research questions and hypotheses

Subchapter 5.2 – Review Paper
The Challenge of Cleaning Woven Filter Cloth in the Beverage Industry - Wash Jets as an Appropriate Solution

- Challenges of filter cloth cleaning
- Cleaning goals
- Filter cloth geometry & process limits
- Biophysics of adhering contamination
- Fluid dynamics of cleaning jets
- Possible future technologies

Subchapter 5.3 – Research Paper
Jet cleaning of filter cloths used in solid-liquid separation–a high-speed video evaluation

- Time-resolved cleaning monitoring
- Application in pilot cleaning device
- Influence of different cloth parameters on cleanability
- Cleaning degree and homogeneity
- Observation of characteristic phases
- Identification of critical cleaning steps

Subchapter 5.4 - Research Paper
Pulsed forward flushes as a novel method for cleaning spent grains loaded filter cloth

- Forward flush cleaning
- Residue sensor with degree evaluation
- Comparison of continuous and pulsatile cleaning techniques
- Parameter variation
  - Cleaning velocity v_{Nozzle}
  - Pulse pause length t_{Pause}

Subchapter 5.5 - Research Paper
Investigations on Backflush Cleaning of Spent Grain-Contaminated Filter Cloths Using Continuous and Pulsed Jets

- Forward flush cleaning
- Residue sensor with degree evaluation
- Comparison of continuous and pulsatile cleaning techniques
- Backflow factor and its influence on cloth geometry
- Cleaning velocity v_{Nozzle}

Discussion and conclusion of result from 5.2 – 5.5

- Sensor development to identify food residues on textile surfaces
- Key parameters of filter cloths influencing cleanability
- Comparison of forward and backflush cleaning
- Influence of pulsed jets on the cleaning efficiency
- Outlook

Figure 5: The thesis's big picture with segmentation into the individual subchapters with a specific content summary

4 Material and Methods

4.1 Experimental cleaning devices

The experiments were conducted on two different setups developed on different scales. Both were prototyped for the experimental section and automated specifically. The laboratory cleaning device was based on previous research works, like Ulmer [58], where a similar system showed promising results. This setup was used to analyze forward and backflush cleaning using continuous and pulsatile jets in detail. Further information about the setup and the cleaning evaluation can be found in research publications 3 and 4 [59; 60] in Sections 5.4 and 5.5.

In contrast, the automated cleaning device on the technical scale for a medium-sized mash filter was specifically designed for this thesis. This system was necessary to observe the cleaning mechanisms of wash jets impacting filter cloths in detail and on a bigger surface. Further technical insights, the respective automation concept, and possible image detection methods can be found in publication 2 (see 5.3) [61].

4.2 Applied filter cloth

The filter media used in this thesis were all textile fabrics based on their woven structures. Filter cloths and their specific properties are also explained in more detail in all thesis publications [18; 59–61]. In this experimental section, various filter cloths were applied to examine different properties in their impact on cleaning processes. Table 2 provides an overview of all filter cloth types employed. The filter fabrics were selected based on their applicability for mash filters or on significant differences in mesh size and thread thickness.

Table 2: Applied filter cloths and their specific properties; PP = Polypropylene; PET = Polyethylene terephthalate, PA6.6 = Polyhexamethylene adipamide 6.6; TWL = Twill weave; PLN = Plain weave; PRD = Plain reverse Dutch weave; STN = Satin weave

Manufacturer description	Material	Weave pattern	Mesh sizes [µm]	Thickness [µm]
05-1001-SK 020	PP	STN	20	500
05-1001-K 043	PP	STN	50	540
05-1001-K 70x320	PP	TWL	80 & 100	530
05-1001-K 120	PP	TWL	80 & 100	480
05-1001-K 215	PP	TWL	80 & 100	480
PP 2436 (cal.)	PP	PLN (multi)	<20	780
07-76-SK 022	PET	PRD	<20	185
07-90-SK 012	PET	PRD	<20	80
03-1001-SK 066	PA6.6	PLN	50	520
03-1010-SK 038	PA6.6	STN	20	470
03-1001-K 080	PA6.6	STN	80 & 100 µm	520

4.3 Surface roughness determination

The µsurf mobile confocal microscope (NanoFocus AG, Oberhausen, Germany) was used to determine the surface roughness. In addition to its large depth of field, it is possible to determine the surface roughness and the 3D profile of the filter cloth surface. The generated data can be evaluated with the software SensoMAP Mountain View. Filter cloths to be measured are illuminated with a confocal point sensor through a narrow aperture. This procedure illuminates only a small point-shaped area of the test surface. A detector photographs the same section with an equally large aperture in front of it. The focus of both apertures is in precisely the same place so that both coincide at the same point (lat. confocal = together). This aspect ensures that light is only reflected from the surface if it is located precisely in the focal plane of the target.

4.4 Surface tension determination

The DSA25E contact angle measuring device from KRÜSS GmbH (Hamburg, Germany) was used to measure the contact angle. The main components are a camera and a light source opposite the camera. The test liquid can be applied via microliter needles to a height-adjustable sample table. Dosing is automatic and can be preset to microliter accuracy. The filter cloth to be tested can be applied to the sample table and sampled directly. The measurement and evaluation took place in real-time with appropriate evaluation software. The software automatically recognizes the droplet and its shape based on the contrast to the measuring environment. From this, the contact angles can finally be determined. With the aid of the OWRK and the EoS method, it is possible to determine the surface tension and other parameters (OWRK can also determine the dispersive and polar fraction).

4.5 Contamination preparation

The contamination was based on spent grains. For this purpose, Pilsener malt (Mich. Weyermann® GmbH & Co. KG, Bamberg, Germany) was prepared according to the congress mashing method of MEBAK [62]. However, a hammer mill (Perten Instruments GmbH, Hamburg, Germany) was utilized for the malt milling deviating from the original method. For mash filters, hammer mills are preferred as they can generate a finer malt grist. For the malt, the standard analysis of the properties is shown in Table 3.

Table 3: Properties of an applied Pilsener malt by Weyermann® (Batch number: T253-21110025-02)

Parameter	Value
Moisture	4.4%
Extract	78.3%
Friability	89.6%
Glassy corns	1.6%
Protein content	10.3%
Soluble nitrogen	687 mg/100 g
Kolbach index	41.7%

The preparation of the congress mash was conducted in a DIMB-12 mash bath (Altmann Analytik GmbH & Co. KG, Gablingen, Germany). In this mash bath, 200 ml of demineralized water was warmed to 45°C and then mixed with 50 g of the malt grist. It was then held at a temperature of 45°C at a stirrer speed of 90 rpm for 30 min. The temperature was raised to 70°C, and 100 ml of demineralized water at the same temperature was added. For the next 60 min, the mash was constantly stirred. The congress mash was then cooled to room temperature and then brought up to 450 g with demineralized water.

This method achieved a standardized fouling matrix for filter cloths, which simulated an industrial application. This model contamination served as a uniform contaminant and can be prepared worldwide reproducibly. Its particle sizes were measured by a

Mastersizer 3000 (Malvern Instruments, Malvern, U.K.) and ranged from > 5 µm to 1,000 µm, with the most significant proportion ranging from 20 µm to 225 µm.

4.6 Contamination of the filter cloths

For the cleaning evaluation, filter cloth samples were moistened and prepared for the application of the mash with a contamination stencil. Afterward, a measured mash volume was pipetted into the stencil, resulting in a determined size and height contamination spot. The utilized filter cloth size, preparation method, necessary mash volumes, spot sizes, and post-treatment depended on the applied setup and are explained further in the respective publications in Chapter 5 [59–61].

4.7 Cleaning analysis

After its standardized contamination, the filter cloth was ready for the cleaning evaluation. For this purpose, the filter cloth sample was inserted into the corresponding cleaning system, and the respective cleaning parameters were adjusted. For the semi-online analysis in research publication 2 (5.3) [61], a VW9000 high-speed camera and a VH-Z20R/Z20T lens (Keyence Corporation, Osaka, Japan) were employed, allowing time-resolved recording of the filter cloth cleaning processes.

In research publications 3 (5.4) [59] and 4 (5.5) [60], the offline cleaning evaluation was performed via a 2000D digital microscope (Keyence Corporation V.H.X., Osaka, Japan). This microscope enabled a detailed analysis of the achieved cleaning success by giving a profound insight into deeper layers of the filter cloth via the magnification of 20. A scientific conclusion about the efficiency of the selected cleaning method was consequently achieved.

The acquired videos and images were processed via a developed algorithm (see 4.8) to determine contaminated spots on the filter cloth. This method determined different cleaning key figures, like the degree of cleaning G or the cleaning homogeneity $H.F$.

4.8 Algorithm development

The cleaning performance was analyzed with a novel algorithm based on the detection of the contrast between contamination and filter cloth. For this purpose, MATLAB (versions 2016a-2019b; The MathWorks, Inc., Natick, MA, U.S.A.) was used to identify and quantify contaminated spots on the filter cloth. The algorithm was able to process single images and videos to determine specific cleaning performance indicators, such as the degree of cleaning or homogeneity. Further details concerning the algorithm development can be found in the thesis-related publications in Chapter 5 [59–61].

5 Results – Thesis Publications

5.1 Summary of the results

This chapter highlights the summary of the peer-reviewed publications and illustrates full copies of these publications. The copies are used with the permission of the respective authors and are open-access publications of the respective journals.

Part 1 **Section 5.2**	Why can filter cloth cleaning be challenging in the beverage industry? What innovative concepts could enable efficient processes?
Title	The Challenge of Cleaning Woven Filter Cloth in the Beverage Industry - Wash Jets as an Appropriate Solution

This literature review highlights the challenging situation of cleaning beverage-related residues from filter cloths.

In the first step, the cleaning goals in the beverage industry are discussed in the context of the complex geometries of the most available filter cloths. These have, in many cases, intricate structures and rough surfaces, resulting in poor cleaning results. Furthermore, the design of a suitable cleaning concept is also limited. Cleaning parameters must often be limited to specific values as the cloths are made of polymers, withstanding only certain temperatures and agent concentrations. Secondly, the biophysics of contamination sticking to surfaces, such as filter cloths, is discussed, highlighting adhesion and cohesion. The third part of the publication discusses the fluid dynamical fundamentals of jet-cleaning woven filter cloths. Here, the different steps of a nozzle-sprayed jet, streaming over a certain distance and impinging on the cloth's surface, are reviewed in detail. The necessary parameters and the theoretical basics of optimal settings for jet cleaning are considered. This section also includes possible nozzle geometries and how they influence cloth cleaning. The last part of this publication examines potential designs for future cleaning concepts. Besides a theoretical comparison of forward and backflush cleaning, the promising concept of using pulsed jets is highlighted. This process design has been focused on in the last few years as it has already shown cleaning enhancements in other areas of the food industry.

The review's conclusion includes the most crucial cloth cleaning parameters. Here, it is implied that most of the available filter cloths contradict modern hygienic design principles. Such filter cloths are designed for high filtration processes and not for excellent cleanability. So, this paradox needs to be addressed in future research. Additionally, jet cleaning in state-of-the-art and novel technologies is concluded as the most efficient cleaning tool for filter cloth. Here, all necessary parameters are adjustable, resulting in flexible and efficient cleaning procedures. The disadvantages, like possible high water consumption, have to be countered with research studies and new concepts, such as using pulsating jets.

Authorship contributions:

The doctoral candidate planned and structured the review article. He was responsible for the literature reviews and final draft of the manuscript. The co-authors critically reviewed and edited the manuscript. All authors have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Part 2 **Section 5.3**	How does the individual filter geometry influence cleaning? What are the most influential cloth parameters on cleaning?
Title	Jet Cleaning of Filter Cloths Used in Solid-Liquid Sseparation: a High-Speed Video Evaluation

The second publication investigated the jet cleaning of spent-grain-loaded filter cloths. High-speed imaging techniques are used to analyze the cleaning progress of 11 filter cloths time-resolved. The filter cloths varied in properties, such as weave, mesh size, and material. The first two parameters, in particular, resulted in an individual filter cloth geometry for each filter type, which was also reflected in the measured roughness values (Ra and Sa). The filter cloths were contaminated with spent grains in a standardized procedure in preliminary steps and then clamped in the filter cloth device of a pilot mash filter. This device simulated the hanging of a filter cloth in a mash filter in a practice-oriented setting. An automated cleaning apparatus was used for the cleaning experiments. This device could precisely shoot a cleaning jet into the center of the created contamination spot. The high-speed camera captured the complete cleaning process in 2 s. Subsequently, the contamination state was analyzed in a time-resolved sequence, which allowed an evaluation of the cleaning efficiency and homogeneity at each stage.

From the results, critical cleaning points were derivable and categorized into the most decisive cleaning parameters. The publication concluded that there were huge influences on cleaning between different filter structures and weave types. For example, close-mesh cloths have smoother surfaces that facilitate cleaning. On the other hand, coarse structures, in combination with flow channels on the cloth's surface, can impede cleaning.

The findings allowed the cloth cleaning to be divided into three stages, each significantly influenced by the cloth's properties. The first phase represented the time during the initial impact of the jet. Here, the most intense fluid forces break up the contamination layer, creating a significant cleaning effect. Here the jet was distributed to all sides of the impact zone resulting in the radial flow zone (RFZ) and equal cleaning effect on all applied filter cloth types. In phase 2, the cleaning effects started to deviate between the cloth types caused by the filter geometry. Additionally, with the growing distance from the impact point, the cleaning effects started to decrease, caused by fluid friction and less wall shear stress on the cloth's surface. In phase 3, a constant level of cleanliness was observable, indicating no further cleaning effect.

The results help to understand procedural cleaning mechanisms in cloth cleaning and to find the principle aspects for corresponding hygienic design guidelines. The identified cloth parameter can help to select a suitable cloth that meets the performance demands during filtration and reasonable cleanability. Furthermore, these findings can support the development of new cleaning concepts.

Authorship contributions:

The doctoral candidate reviewed the corresponding literature, designed the experimental study, developed the algorithms, conducted the experiments, interpreted the acquired data, and drafted the manuscript. The co-authors critically supported the experimental study design and algorithm development and reviewed and edited the manuscript. All authors have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Part 3 **Section 5.4**	Forward flushing: What is the best concept for cleaning filter cloth using jets?
Title	Pulsed forward flushes as a novel method for cleaning spent grains loaded filter cloth

The third publication focused on the forward flush cleaning of filter cloths with parameter and method variation. To simulate real-world contamination, spent grains were utilized with the developed standard method explained in Chapter 4.5. Additionally, two cleaning methods were applied and compared directly with each other. The standard method featured a continuously flowing cleaning jet with longer process times. The second method was based on pulsed cleaning jets applied to the filter cloth in very short sequences. The cleaning experiments were performed in a laboratory setup, which provided a standardized cleaning environment and a high sample throughput. Lastly, the analysis of the cleaning success was performed with a digital microscope to detect any remaining contamination after cleaning with a high degree of accuracy.

The results showed that pulsatile forward flushing via jets is ecologically and economically advantageous. Applying short pulsed jets towards a contaminated filter cloth achieved up to 30% higher levels of cleanliness than continuous flows. Furthermore, the technique consumed up to 50% less cleaning fluid in combination with shorter cleaning times. Pulsatile jets enhanced the mechanical cleaning effect tremendously. The continuous renewal of the effecting forces and an increased wall shear stress improved the cleaning efficiency. Another crucial parameter was a longer pulse pause length which increased the level of cleanliness until a specific value. Here, the wash fluid of the previous jet could flow off, decreasing the cushioning liquid film and boundary layers on the contamination. Additionally, the first jet rewetted the contamination, and during the pulse pause, diffusion of the cleaning fluid into the contamination could occur.

The results showed the minimum cleaning settings to clean filter cloth loaded with spent grains. Moreover, the pulsatile forward flush cleaning was economically and environmentally advantageous. Thus, these results can help breweries identify new mash filter cleaning technologies.

Authorship contributions:

The doctoral candidate reviewed the corresponding literature, designed the experimental study, developed the algorithms, conducted the experiments, interpreted the acquired data, and drafted the manuscript. The co-authors critically supported the experimental study design and algorithm development and reviewed and edited the manuscript. All authors have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Part 4 **Section 5.5**	Is backflushing of filter cloth an option for efficient filter cloth cleaning in the beverage industry? Are pulsatile backflushes advantageous?
Title	Investigations on Backflush Cleaning of Spent Grain-Contaminated Filter Cloths Using Continuous and Pulsed Jets

The fourth publication investigated the backflushing of filter cloths. Here, a parameter variation in combination with pulsatile and continuous backflushes was utilized. The same laboratory setup and contamination method were used as in publication 3 in 5.4 [41]. This factor facilitated high comparability between both cleaning techniques. Two different filter cloths were employed that mainly differed in the mesh sizes and weave type.

The comparison of the two backflushing procedures for mash filters demonstrated fluid dynamical, procedural, and economic differences in cleaning. In particular, pulsed backflushes showed higher efficiency in achieving cleanliness faster with less cleaning fluid consumption. In conclusion, the pulsatile cleaning method enabled higher efficiency, improving filter cloth cleaning ecologically and economically.

In addition, the backflow factor of the two employed filter cloths was determined. This parameter is the proportion of the water that can flow through the filter cloth and reach the adhering contaminants on the other side of the cloth. The other proportion of the water flows off laterally at the cloth surface and has no cleaning effect. Larger mesh sizes allow more significant amounts of water to flow through, which thus increases the backflow factor. It can therefore be concluded that cloths with larger meshes can be back washed more efficiently.

In addition, the tests showed that a specific inflow speed is crucial for achieving a sufficient cleaning effect. Thus, a certain velocity is required for significant mechanical cleaning effects on the adhering contamination on the opposite side of the cloth. The mesh size also plays an important role here since a comparatively higher velocity is required for smaller meshes.

The results led to a better understanding of the cleaning effects of backflushes on woven filter cloth soiled with simulated real-world contamination. Respective advantages and disadvantages of backflushes were shown, and pulsed flows, particularly, were presented as a beneficial principle for future cleaning concepts.

Authorship contributions:

The doctoral candidate reviewed the corresponding literature, designed the experimental study, developed the algorithms, conducted the experiments, interpreted the acquired data, and drafted the manuscript. The co-authors critically supported the experimental study design and algorithm development and reviewed and edited the manuscript. All authors have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

5.2 Publication 1: The Challenge of Cleaning Woven Filter Cloth in the Beverage Industry - Wash Jets as an Appropriate Solution

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The Challenge of Cleaning Woven Filter Cloth in the Beverage Industry—Wash Jets as an Appropriate Solution

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Abstract
Beverage production requires many different and complex unit operations. One crucial procedural step is filtration. Typical filters are filter presses, candle filters, membrane filters, belt filters, and drum filters, which require considerable hygienic precaution and the application of appropriate cleaning concepts. In the last decades, the hygienic design has become a central design feature of equipment in the beverage and food industries. Today, also correspondent concepts regarding filter cloth increasingly come to the fore. However, filter cloth cleaning is rapidly facing limitations. Complex filter geometries originating from different gauzes and sensitive polymeric materials hinder efficient cleaning. Additionally, extensive biological residues adhering to the filter surface increase the challenge of cleaning. The goal of this paper is to outline the cleaning of woven filter cloths systematically with a particular focus on beverages and correspondent biophysical interactions between filter and residue. Based on these elemental cleaning limits of filter cloths, this paper focuses mainly on jet cleaning as one of the most appropriate cleaning methods. The flow-mechanical properties are discussed in detail since these are precisely the parameters that, on the one hand, describe the understanding of the cleaning process and, on the other hand, show how a wash jet can be adjusted precisely. In contrast to conventional cleaning techniques, such wash jets are expeditious to adapt and offer the best prerequisites to enable demand-oriented and optimized cleaning concepts. The latest research and approaches are enhancing jet efficiency and highlight their potentials for future process strategies.

Keywords Cleaning · Filter media · Filter cloth · Biophysics of adhesion · Wash jets · The beverage industry

Abbreviations

CIP	Cleaning in place
EHEDG	European Hygienic Equipment Design Group
VDMA	Verband Deutscher Maschinen- und Anlagenbau e.V.
(X)DLVO	(X) Derjaguin, Landau, Verwey, Overbeek
D-D	Disk–disk
S-D	Sphere–disk
S-S	Sphere–sphere

Variables

A	Area [m^2]
a	Particle distance [m]
α	Polarizability, A^2 s^4 kg^{-1}
d	Diameter [m]
δ	Boundary layer thickness [m]
E	Energy [J]
ε	Relative permittivity, AsV^{-1} m^{-1}
ε_0	Electric field constant, AsV^{-1} m^{-1}
$\epsilon_{\mathrm{Fluid}}$	Backflow effect [–]
F	Force [N]
f	Frequency [Hz]
G	Gibbs free/adhesion energy [J]
g	Earth acceleration [m s^{-2}]
H	Hamaker constant [J]
h	Planck's constant [J s]
$\hbar$	Lifshitz constant, J
k_B	Boltzmann constant [J K^{-1}]
κ	Debye–Hückel parameter [m^{-1}]
l	Length [m]
l_0	Equilibrium distance [m]
λ	Decay rate of polar interactions [m]
M	Mass [kg]
$\dot{m}$	Mass flow [kg s^{-1}]
Oh	von-Ohnesorge number [–]
μ	Dipole [C m]
η	Dynamic viscosity [Pa s]

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p	Pressure [Pa]
R_a	Mean roughness [μm]
Re	Reynolds number [–]
R_q	Square roughness [μm]
Φ	Porosity [–]
ρ	Density [kg m^{3}]
T	Temperature [K]
t	Time [s]
τ	Wall shear stress [kg m^{-1} s^{-2}]
ΔU	Interaction energy [J]
v	Velocity [m/s]
ϑ	Kinematic viscosity [m^{2} s^{-1}]
x	x coordinate [m]
ζ	Zeta potential [V]

Introduction

Filtration is a central unit operation in modern beverage production. In many relevant applications, filter media are the centerpiece of filtration systems. Filter systems comprise a filter medium featuring the barrier function and an apparatus keeping the filter medium in the desired position and providing mechanical functionality [130]. Filter media, e.g., woven filter cloths or membranes, regulate filtration processes via pore sizes, adhesive material properties, or other specific characteristics [145]. In the beverage industry, filter media assist in creating interstage products or the actual final products for consumption. They avoid unwanted turbidities or deposits that usually do not fit into the general consumer perception of healthy merchandise. Besides, the filtration of beverages results in longer storage life and increases beverage stability due to the removal of microorganisms and suspended solids [25].

Textile filter cloths are present in numerous forms and have applications in beverage production. Due to increasing consumer interest, product safety, and new legal requirements, the filtration industry highlights research and development of filter cloths. Since decades, polypropylene, polyethylene, polyester, or polyamide polymer filter cloths are state of the art [32, 66, 103]. Such filters increase filtration performance and system durability. However, after filtration, cohesive filter cakes require a full discharge to guarantee efficient filtration of subsequent batches. Unfortunately, this discharge is mostly incomplete, and the remaining residues need a separate removal [92, 166]. Production conditions (e.g., temperature, cake size) favor residue adhesion on the filter surface, which results in filter blinding and fouling [47]. A closer look at filter cloth cleaning reveals a big dilemma: During the filtration process, the growth of a filter cake on the filter surface is necessary to generate sufficient filtration performance and product yield. However, this desired adhesion has a detrimental effect on the cleaning process. Residue removal is only successful if the adhering forces are overcome [45, 92, 131]. It can thus be concluded that filter cloths are designed for proper filtration performance and not for optimal cleanability [156]. Nevertheless, cleanability determined by the combination of the surface properties and the contamination type is essential in order to avoid production-related spoiling of beverages.

For decades, cleaning is one of the primary endeavors in food and pharmaceutical processing plants [21, 63, 101, 106, 160]. This testimony of the literature incorporates the development of appropriate design features of the equipment. In mechanical engineering, the construction of easily cleanable surfaces and hygienic production equipment are standard features of *hygienic design*. The main goals are safe and efficient cleaning in production cycles and the avoidance of cross-contamination [114, 123, 124]. However, respective regulations or concepts for filter media are still unknown [106]. Due to involved, unpredictable beverage residues, organic and inorganic fouling decrease product safety, filtration performances, and cleaning efficiency [160]. Especially water-insoluble particle contamination adheres to filter cloth due to adhesive forces. If located in the inner filter structure, they are difficult to remove using water or cleaning agents [45, 97, 176]. These reasons postulate the use of reliable cleaning concepts. Requirements for a suitable cleanability have to be as high as the requirements for the process itself [167].

Consequently, it is necessary to extend efforts in cleaning research and development. In the beverage industry, water cleaning (rinsing or mixed with cleaning agents), which is common in cleaning tanks or pipe systems, removes residues efficiently by wash jets [52, 160]. Indeed in the future, it is inevitable to highlight water jets for cleaning of filter cloth increasingly. Exemplary wash jet systems already carry out cleaning tasks in filter presses or belt filters. Parameters like nozzle geometry or operating pressure ensure adjustable and sufficient cleaning efficiency [101]. There is, however, still a significant deficiency in the concept design, processing knowledge, and ecological and economic optimization, which have to be surveyed by corresponding research efforts.

The focus of this review article is the cleaning of filter cloth with wash jets applied in the production of beverages. An overview of filter cloth and design features shows its potentials and limitations in cleaning processes. A review of the biophysical properties delivers insight into interactions between beverage contaminants and filter cloths and how they have to be exceeded by a wash jet. Finally, the application of wash jets for the cleaning of filter media is part of a discussion. The detailed jet analysis includes the fluid mechanical principles while leaving the nozzle, impacting on the filter surface and removing residues.

Goals and Importance Regarding Cleanability

Careless treatment and incorrect processing of beverages cause diseases or negatively influence health. During production, beverages can easily absorb contaminants, microorganisms, or other particles, which are unfit for consumption, unhealthy, or even toxic. In the production chain, industrial equipment needs cleaning concepts that agree to the highest possible hygienic standards [78, 122, 147, 178]. The significance of cleaning processes also becomes apparent in the number of guidelines and configuration proposals for hygienic design in the food-producing industry. According to the literature [45, 47, 177], the goals of sufficient cleanability are as follows:

- Removal of deposits (constant equipment performance)
- Clearance of beverage arrears (prevention of microorganism growth)
- Fulfillment of consumer requirements (healthy and safe products)
- Achievement of secure production cycles (avoidance of cross-contamination)
- Extension of equipment life and long-term maintenance of value

In separation processes, filter media are in direct contact with the product, which requires an increased awareness when designing cleaning concepts. Spoiled filter media need sufficient and exact adjusted cleaning concepts, which reliably remove residues and provide clean conditions for subsequent product cycles. The specific objectives of filter cleaning are as follows:

- Sufficient cake discharge
- Successful removal of residues and fouling
- Gentle treatment of filter media (extended lifetime)
- Using less concentrated chemicals (economic and ecologic advantages)
- Short cleaning time (avoidance of extended downtime)

Filtration processes in the beverage industry stabilize final products or convert pre-stages [13]. After filtration, many substances remain as residues on the filter cloth. Soil is categorizable according to physical, chemical, or microbiological criteria [173, 177]. Beverages consist of different ingredients like proteins, carbohydrates, or fats, which form a complex biological contamination matrix [151]. Furthermore, specific fundamental removal mechanisms complicate cleaning. Table 1 characterizes different residue types, their occurrence, and cleaning as an unpredictable bottleneck in modern beverage processing.

Woven Filter Cloth—a Hard-to-Clean Surface

Filter cloths consisting of plastic polymers (e.g., polypropylene and nylon) represent the most significant market share among filter fabrics, which underlines their economic relevance [103, 130]. The main utilizations are solid–liquid separation processes like cake filtration and surface filtration, which are common in the beverage industry [5, 13]. Concerning beverages, exact and sparing filtration is inevitable to separate solids from liquids while keeping valuable or value-adding substances in the product. Filter cloths are insertable into different filter systems and thus guarantee flexibility and precise selectivity (see Table 2). Aperture sizes or pore sizes—resulting from thread thickness, weave, and construction—have to be product- and residue-specific. Due to these reasons, filter cloths create complex and hard-to-clean geometries with high surface roughness.

Filter Cake Formation and Fouling on Filter Media

Filter cakes (retentate) grow over time and are the most used mechanism for filtration [66]. In general, the classification of cake filtration is possible in two categories: cross-flow filtration describes a tangential product approach flow toward filter media by keeping filter cake thickness constant in a defined size [28, 167]. In contrast, dead-end filtration is more static: retentate particles cluster on filter surface while filter cakes expand [39]. Large retentate fragments generate permeable cakes where fluids have many passing possibilities. However, smaller particles result in more dense, filter performance-reducing cakes. In the beverage industry, production operators often add filter aids (e.g., diatomaceous earth or perlite) if the product to be filtered is not capable of satisfactory separating processes [13].

During beverage filtration, the fouling of filter media always occurs due to retentate or product contamination [86]. Process performances (flux) will decrease with time, and grave pore blinding is caused [17, 96, 167]. Although this problem is more severe in membranes, it also plays an essential role in filter cloths due to production limitations. Consequently, after almost every filtration process, sufficient cake discharges have to take place to ensure proper filtration performances in subsequent product cycles and process cost reduction [66]. Cake discharge occurs by gravity (e.g., filter press) or mechanically using cutting or vibration-based equipment [173]. However, large amounts of residues remain on filter cloths due to the moisture of solid–liquid operations [66]. In this context, water jets are the ideal cleaning option for combining mechanical cleaning effects with chemical additives.

Filter Materials

Besides the filterability, cloth material also determines the cleanability [130]. Leipert and Nirschl [92] showed that polymer filter cloth showed no differences in cleanability. Since polymers basically have similar material features and thus

Table 1 Exemplary beverage residues on filter media

Residue type	Subtypes	Category	Exemplary appearance and importance	Cleanability	Cleaning challenge	Key removal mechanism	Cleaning concept					References
							Mech./ jet	Acid	Alkaline	Enzymatic	Temperature	
Organic	Carbohydrates • Low molecular (lm) • High molecular (hm)	Water-soluble: lm Swellable: hm	• Unmalted barley in breweries • Alternative cereal use in beverages • The main component in plants, • Serve as raw material	lm: + hm: −	• High molecular starch very difficult to clean • Formation of gel on filter media (e.g., starch, glucans) due to viscosity • Gelatinous soil cushion mechanical effects • High temperatures favor caramelization	• Decrease in viscosity by increased temperature • Split of polysaccharides	+/−	0	0	+	+/−	[120], [99], [62], [45], [104], [73], [173], [72], [87]
	Microorganism • Yeast • Bacteria • Molds	Particle behavior	• Breweries • Wineries • Juices	−	• Formation of firmly adhering biofilms • Biofilms soil new locations continuously • Ability to neutralize (chlorine) agents • High resistance to common cleaning agents • Microorganism (e.g., *E. coli*) on fruit skins	• Chemicals indispensable • Mechanical cleaning needed for transportation • Disinfection after biofilm release	+	0	+	+	+	[99], [112], [41], [116], [173], [4], [36], [17]
	Lipids/wax • Fat/triglycerides • Fatty acids/oils • Phospholipids • sphingolipids	Emulsive, water-insoluble, alkali-soluble	• Component of biomembranes • Metabolism of plants and microorganism • Appearance in many beverage raw materials	−	• Avoidance of heating processes due to fat polymerization • Cleaning agents and enzymes or substantial mechanical cleaning necessary	• Saponification (alkaline hydrolysis) to increase water solubility • Melting of fat by increased temperatures	−	0	+	+	+	[30], [99], [177], [173]
	Proteins • Peptides • Amino acids	Swellable, alkali-soluble, slightly acid-soluble	• Beer (fermentation, foam, turbidity) • Juice (unwanted turbidity)	−	• Spontaneous and nonspecific adhesion • Protein denaturation favors surface adhesion • Wettability as decisive surface characteristic • Hydrophobic filter cloth binds protein firmer • Complex filter surfaces are hard to clean	• Swelling necessary • Proteolysis (via enzymes or alkaline agents) • Avoidance of strongly increased temperatures	0	0	+	+	−	[30], [59], [48], [29], [79], [10], [181], [99], [46], [182], [127], [160], [117], [34], [77], [115], [173], [81]

Table 1 (continued)

Residue type	Subtypes	Category	Exemplary appearance and importance	Cleanability	Cleaning challenge	Key removal mechanism	Cleaning concept					References
							Mech./ jet	Acid	Alkaline	Enzymatic	Temperature	
					• The main factor regarding filter media (due to disulfide binding)							
Inorganic	• Minerals • Salts • Metals • Cleaning agents	Water- and acid-soluble	• Wine (tartrate crystals) • Scale (boiler/beer /milk/wine) • Alkaline deposits (agents) • Beer (calcium oxalate) • Metal/glass grit, dust, and rust	+	• Considered to be easily cleanable • Interaction with other components (especially organic) decreases cleanability	Utilization of sufficient mechanical cleaning and chemical agent concentration	0	+	−	−	0	[30], [99], [41], [157], [40], [173], [36]
Organic/ inorganic	(Large) solid components	Particular contamination	• Beer (spent grain) • Wine (grape remains) • Juice (pomace) • Fibers	−	• Cleanability depends on particle size/shape and the location on/in the filter medium • Moistened condition: more easily cleanable • Dry condition: cleanability decreases rapidly	• Decrease of adhesion by wetting soil and surface • Penetration of soil by cleaning fluid	+	+	+	−	+	[30], [33], [99], [173], [36]

Note: + = good, 0 = neutral, - = bad

Table 2 Applications of filter cloths in the beverage industry

Application	Filter system	Task	Reference
Water treatment	Drum filter, (vacuum) belt filter	Separation of solids	[82]
Wine	Filter press	Decrease of must turbidity	[40]
		Clarification of polyphenols and polysaccharides	[86]
Beer (pre-stage mash)	Filter press, rotating disk filter	Separate beer wort from spent grain	[112]
Syrups and brines	Filter press	Removal of unwanted particles; sugarcane juice production	[13], [86]
Fruit and vegetable juices	Belt filter, filter press, filter centrifuge	Detachment of suspended and colloidal particles	[167], [68]
		Removal of polyvinylpolypyrrolidone- or bentonite-treated product	[151], [184]
		Separation in pulp and (microorganism-free) clarified juice	[28]
Product recuperation via yeast separation (beer, wine)	Filter centrifuge, filter press	Removal of yeast cells (defined size)	[7]

interface properties, the cleaning dependency between different materials is negligible. However, the cloth material requires careful considerations regarding chemical and physical resistivity and sensitivity. In separation processes, different pressures, temperature levels, or other special conditions occur. Although they are not as extreme as in the chemical industry, filter materials have to resist environmental conditions well enough to guarantee acceptable lifetimes [5]. This fact is also crucial for the cleaning and regeneration of filter cloth by using increased process parameters and high-concentrated cleaning agents. By the current state of scientific knowledge, the application range of cleaning is limited in the beverage industry. Because of high hygiene standards and microbiological safety, the use of chemical cleaning agents is, in most cases, inevitable [160]. Nevertheless, the various kinds of polymeric filter cloth are sensitive at certain processing or cleaning conditions due to specific material properties. Also, national or international laws, e.g., FDA regulations, have to be considered when choosing the material. Polymer fabrics require sufficient declaration of conformity as indirect food additives, and also corresponding threads have to agree with equivalent legislation [5]. An additional coating of yarns or complete filter fabrics also has to comply with legal requirements as well [130]. Table 3 gives an overview of the properties of different filter media materials (filter cloth in particular and also membranes). The average values of the specific material properties given in Table 3 originate from the scientific literature and the online database CAMPUS (*Computer-Aided Material Preselection by Uniform Standards*).

In most cases, these values depend on the manufacturer (here with the example of the RIWETA 4.2 online database), which can lead to individual deviations in the properties of commercially available polymers. The selection and the applicability of the material depend on the process, product, performance, and desired cleaning behavior. Regarding cleaning, the most certain characteristics are mechanical and chemical factors due to their strong influence on the filter lifetime. Additionally, a high dependency between material and cleanability regarding surface properties like free surface energy is expected [20, 21, 71, 101, 102].

In the beverage industry, most common chemical cleaning agents are strongly alkaline or acidic, which are potentially abrasive to synthetic yarns [160, 167]. Novel agents, including oxidizers or enzymes, increase cleaning and disinfection efficiency. However, they are difficult to handle (enzymes) or considered to be the most dangerous agent type (oxidants). Generally, chemicals have to be used in exact concentrations to guarantee sufficient cleaning and to ensure that no contamination remains. Considering the problematic cleanability of filter cloths, incorrectly concentrated agents reduce the stability and lifetime of a filter due to abrasive effects and resulting yarn impairment. These unwanted aspects result in more frequent cloth changes, more extended system downtime, and higher process costs. Regarding physical stress, abrasion is caused by temperature gradients, filtration pressures, mechanical cleaning, or the product to be filtered. If there are particles with sharp edges, the filter cloths have to be designed robustly and stiffly [66].

The challenge of choosing the right material becomes apparent regarding the two most common filter polymers (see Table 3). According to Horrocks and Anand [66], polypropylene is the most widely used thread material in solid–liquid separations due to its high acidic and alkaline resistance. However, this polymer is susceptible to oxidizing agents and has low physical resistance to mechanical stress (e.g., high temperatures). In contrast, polyamide offers high abrasion resistance but has weaker chemical resistance. In conclusion, there is a considerable need for better adjustable cleaning mechanisms, e.g., via wash jets, to extend the lifetime of filter cloths.

Mesh Types

Since humans started to weave yarns into textiles, a variety of different weaves found their way into everyday life. Many of

Table 3 Overview of different materials used for filter media

Material	Abbreviation	Chemical cleaning agent resistance			Maximal working temperature [°C]	(Physical) abrasion resistance	Absorbency for water (% wt)	Additional remarks	References Generally referenced by the CAMPUS online database [27] and with additional references below
		Acid	Alkali	Oxidant					
Polyvinylidene fluoride	PVDF	+++	+++	+	120–160	+++	0.1–1.0	High hydrophobicity inhibits filtration	[130]; [135]; [180]; [91]; [81]
Polyethersulfone	PES	++	++	−	190	++	0.7–2.1	Prone to fouling	[134], [55], [185], [139–143]
Polyamide 6.6	PA6.6	−	++	−	105–120	+++	6.5–8.3	Common material for filter cloth	[130], [14], [66]
Polyamide 12	PA12	−	++	−	105–120	+++	6.5–8.3	High physical resistance	[130], [66]
Polypropylene	PP	+++	+++	−	120	+	0.01–0.1	Common material for filter cloth	[130], [66]
Polyamide 6	PA6	−	0	−	105–120	+++	6.5–8.3	Low resistance to chemical cleaning agents	[130], [139–143]
Polyethylene terephthalate	PET	+	−	0	100	++	0.2–0.5	Poor to chemical cleaning agents; stable to beverage ingredients	[14], [139–143]
Polyethylene • High density (hd) • Low density (ld)	PE	+++	+++	−	65–74 (ld); 93–110 (hd)	0	0.01	Most utilized polymer material	[130], [66]
Polybutylene terephthalate	PBT	+	0	0	100	++	0.25–0.5	Similar properties as PET	[66], [139–143]
Polyether ether ketone	PEEK	+	+	0	220	++	0.3–0.5	High-temperature tolerance	[66], [6]
Polyamide 11	PA11	−	++	−	100	+++	6.5–8.3	High physical resistance	[66]
Polytetrafluoroethylene	PTFE	+++	+++	++	240	0	< 0.1	High resistance to soiling and cleaning agents; poor physical resistance	[66], [6], [139–143]
Polyvinylidene chloride	PVDC	+++	++	++	75	+	n/a	Agrees with FDA in packaging materials; less commonly used for beverage filtration	[66]
Polyphenylene sulfide	PPS	++	+++	0	190	+	0.5	Less beverage relevance; brittle	[66], [180], [6]
Polyvinyl chloride	PVC	+++	+++	0	75	++	Little	Less relevant for beverages due to plasticizers	[66]
Cotton	−	−	+	0	90–93	n/a	16–22	Historic filter material; no relevant use today	[130], [66]

Note: +++ = very good, ++ = good, + = adequate, 0 = average, − = bad

these developed web types are also suitable for filter fabrics [66, 103]. In the production of textile filters, different threads are interweaved and form distinctive filter structures. Each filter cloth is unique due to different thread diameters,

Table 4 Influence of the yarn type on the cleanability behavior of the filter fabric

Type	Lowest cake moisture after filtration	Cake discharge	(Physical) abrasion resistance	Cleanability (via wash jets)	References
Monofil	+++	+++	+	+++	[66], [6]
Multifil	++	++	++	++	
Staple	+	+	+++	+	

Note: +++ = very good, ++ = good, + = adequate

materials, and mesh types that worsen the cleaning predictability [99, 130].

In the beverage industry, woven filters mainly consist of single monofil (one single thread) or multifil threads (composed of several threads) in single or multilayer filters. The advantages of multifil threads are enhanced safety and improved lifetime by hindering thread breakage [130]. In terms of cleanability, the thread choice is vital due to the moistening behavior of filter cakes or abrasion resistance. Table 4 illustrates the influence of the thread on the cleanability of a whole mesh.

Filter cloths are used singly in combination with a second cloth layer or interlinked with porous membranes. Combinations of several filter cloths are defined as composite fabrics and are used to adjust a different filterability [130]. This publication does not consider needle felts or fleeces due to their subordinated role in beverage production.

The smallest particle size to be filtered determines the choice of the mesh, the pore size of which depends on the construction and thread thickness [5, 6, 66]. The weave type forms distinct geometric structures by particular arrangements of chaining and weft threads. While chaining threads extend in the web direction, weft threads are perpendicular to this direction and enlace the longitudinal warp threads [138]. General filter cloth properties (e.g., thread diameter, porosity, or pore velocity) are central to determine the cleaning efficiency of different filters [173]. Especially porosity seems to be a possible factor in comparing the cleanability of various filters. With this parameter, it is possible to determine the flow rates of cleaning jets on or in filter media. According to the literature [136, 173], the filter porosity Φ is calculated according to Eq. 1.

$$\Phi = \frac{V_{\text{total}} - V_{\text{yarn}}}{V_{\text{total}}} \quad (1)$$

V_{total} is the whole volume of the mesh, while V_{yarn} represents the volume of weft and chaining threads. Commonly used weave types in industrial textiles are plain, twill, and satin weaves (see Fig. 1) [130]. There are many areas, stream shadows, and dead spots that are decreasing cleanability. Accurately fitting particles located in these hard-to-clean areas are difficult to remove [97].

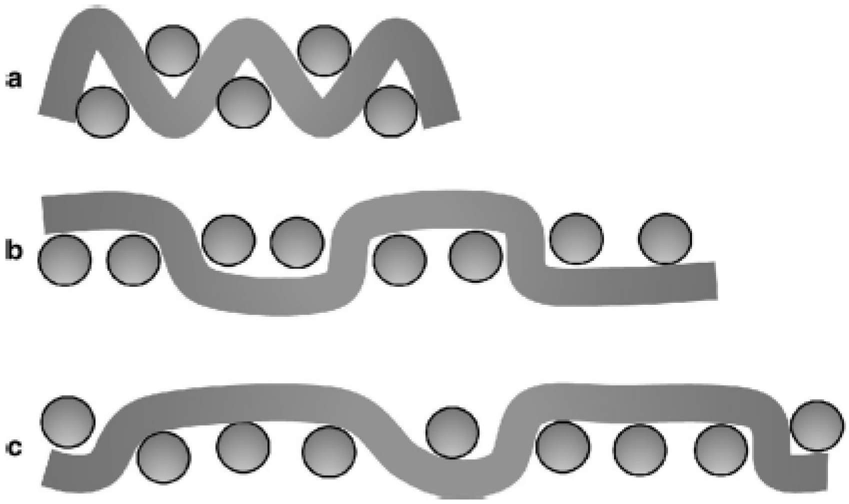
According to Purchas and Sutherland [130], the twill weave mainly has more significant gaps in the meshes, which results from the inhomogeneously woven threads. This construction enhances the float in separation processes and creates deeper layers, which are easier to reach for wash jets. The utilization of satin weaved cloths even enhances the floating effect. Here, structures are increasingly irregular, which results in very smooth surfaces. This filter evenness reduces the likelihood of firmly adhering particles in deeper meshes and care for better cake discharges with fewer residues [66]. Thus, on the one hand, minor residue disposition is favoring cleaning processes. On the other hand, hard-to-clean zones are more comfortable to reach using wash jets, improving effectivity. Table 5 illustrates the common weave types of industrial textiles.

After weaving, almost every cloth undergoes an after-treatment. This conditioning is necessary for stability, surface enhancement, and permeability modification of the filter fabric [57]. Such treatments improve the filtration process but also increase the cleanability of filter media. Calendering of filter cloth enhances the cake discharge and thus favors cleaning [5]. Additionally, calendering can regulate permeability, which supports backwashing methods [66]. For calendering, the filter cloth runs through heated mills that smooth the surface [6]. Supernatant parts of yarns can hinder sufficient cake discharge and can thus influence cleaning efficiency. Singeing removes protruding parts by contact with gas flames or hot metal boards [66].

The Roughness of Filter Cloths

Following the literature [26, 74], surface roughness has significant adhesion influence on biological residues located on surfaces. Due to their complex structures, the transformation of *hygienic design* concepts to filter media is difficult, which requires reliable cleaning methods. The topography of filters strongly affects the adhesion of biomolecules [42, 111]. Therefore, surface geometry and adhering contamination are central to the strength of adhesive forces [76, 122, 175]. Binding points of adhering particles depend on the roughness profile. Particles located between two threads cause more than one contact point with the filter. Regarding filter cloths, we must differentiate between thread roughness and whole meshes. For textile filters, it is possible to describe the aperture with the same roughness analysis tools as standard surfaces. Here, the values of the mean roughness R_a and the square roughness R_q are decisive. Moeller [106] developed more

Fig. 1 Commonly used weaved types of filter cloths: **a** plain weave, **b** twill weave, **c** Satin weave



precise methods to characterize the filter cloth roughness. Particle residues that fit in the roughness profile are difficult to remove due to several contact points (see Fig. 2).

Biophysics of Particle Detachment

Particles or other colloids adhere to surfaces due to interatomic or intermolecular adhesive forces [101]. According to Weigl [175], these types of forces are essential in many processes like agglomeration, crushing, or transportation of solids. Regarding cleaning operations, these interactions and similar effects are the critical aspects in removing contamination from surfaces, e.g., cleaning filter cloths by water flows. Such wash jets (F_{Jet}) have to overcome any binding mechanisms (F_{Adhesion}) and release contamination from filter cloths [92, 122, 175].

$$F_{\mathrm{Jet}} > F_{\mathrm{Adhesion}} \tag{2}$$

The definition of F_{Jet} is given in the "Fluid Mechanical Principle of Wash Jets" section and of F_{Adhesion} in the "Adhesive Forces" section. As already mentioned above, successful removal requires detachment work. Regarding the common physical approach in Eq. 3, the adhesive forces are linkable to the detachment work W.

$$W = \int_0^a F(x)\,\mathrm{d}x \tag{3}$$

The range [0:a] distinguishes the particles on the surface (= 0) and the particles at a certain distance from the surface (= a). The acting work leads to a change in energy balance. Thus, the energy of the detachment has to outstrip the adhesion energy. While the detachment energies include the jet properties (e.g., kinetic energy), the interaction energy consists mostly of the adhesion and repulsion. Several models (e.g., DLVO or XDLVO) determine the interdependency of these effects.

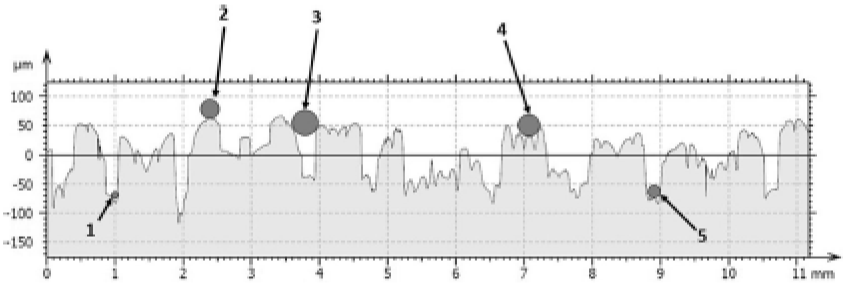
Furthermore, the particle has to be moved to a particular distance a_x so that adhesive forces do not affect anymore (see also Fig. 3). Regarding the impact forces of a water jet, the impact area is a decisive aspect. Here, the acting hydrodynamic jet force and the impact surface must cohere with effecting pressure distributions on the filter surface. The resulting pressures are responsible for the area-specific cleaning effect and generate the necessary mechanical impulses on the contamination as well as the wall shear stress (see "Impinging Jet—Forces on the Residues on the Filter Cloth" section). Palabiyik et al. [125] also concluded rheology as necessary for a proper cleaning design. With a certain particle distance, the prevention of force recovery and complete deportation of unwanted residues by using liquid films after the impact are desirable to guarantee sufficient cleaning efficiency [47, 183]. Different publications researched the cleaning kinetics of jets [50, 178].

Nevertheless, the type of application and soil are decisive as cleaning optimization often fails due to unknown adhesion mechanisms or detachment kinetics. To ensure sufficient cleaning, many companies in the beverage industry use exaggerated cleaning concepts. The following section gives an

Table 5 Exemplary types of gauze construction for filter cloths

Type name	Abbreviation	Cake discharge	References
Plain (reverse Dutch)	PRD	+	[173], [66], [6]
Twill	TWL	++	
Satin	STN	+++	

Note: +++ = very good, ++ = good, + = adequate



	Particle 1	Particle 2	Particle 3	Particle 4	Particle 5
Radius r [mm]	1.0	3.0	4.0	3.5	4.0
Contact points [-]	2	1	2	3	4

Fig. 2 Exemplary roughness profile of a filter cloth with exemplary particles of different sizes; mean roughness $R_a = 18.8$ µm, square roughness $R_q = 22.4$ µm; measurement of the roughness occurred via a confocal laser scanning microscope; the illustration is the authors' own creation

overview of acting adhesive forces, how they work, and how several models can determine their interaction.

Adhesive Forces

Purchas and Sutherland [130] have stated that adhesion is a central filtration characteristic depending on the application field. Its mechanism belongs to attractive intermolecular forces like van der Waals or electrostatic forces [69, 101]. Once such forces arise, they are the critical aspect of cleaning. Concerning cleaning with nozzle, impinging jets have to affect the filter surface with a minimum of energy to release existing attractive forces [122]. Besides adhesion, cohesion—binding forces between the residue particles—is also central to obtaining appropriate cleaning degrees [47, 106, 175].

Three range-dependent groups classify adhesive forces. The first group includes long-range forces, which act in the contact zone and beyond due to greater strength and more extended ranges. Exemplary forces are van der Waals forces and electrostatic forces. Short-range forces belong to the second group and define chemical bond forces and hydrogen bonds (e.g., Lewis acid–base interactions). The third group contains forces, which arise by reactions of the boundary layer, e.g., colloids interacting with the surface [40, 84]. Here, particles possess nonspecific and specific adhesive attitudes

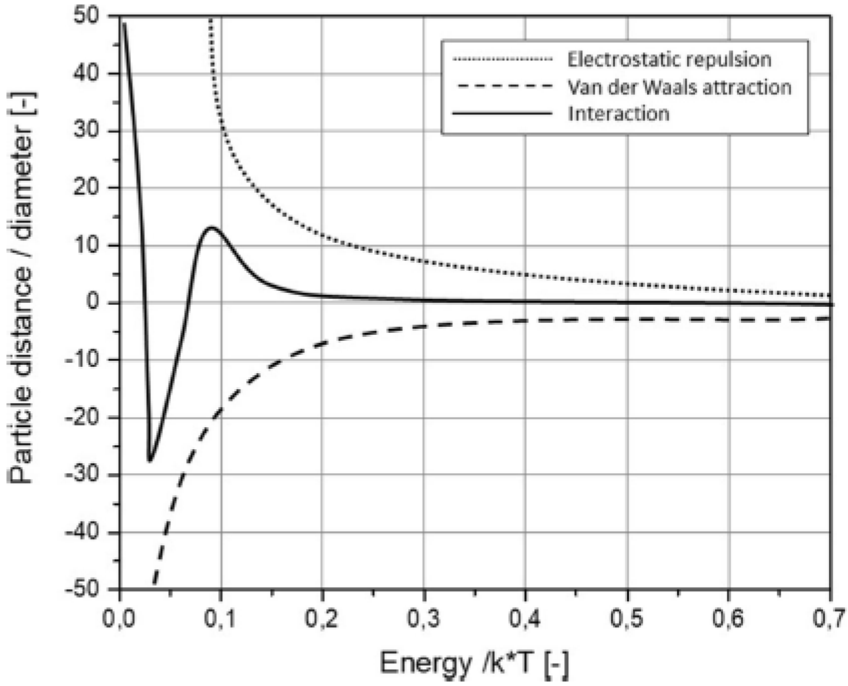


Fig. 3 Interactions between a suspended particle and the surface (overlap of adhesive van der Waal attraction and repellent electrostatic potential)—illustration is an the authors' own creation and was adapted from Adair et al. [1] and Koglin [80]

toward the filter structure. Nonspecific adhesive forces arise from a combination of physiochemical influences.

In contrast, the specific interaction between particles, e.g., microorganisms, and filter surfaces depend on stereochemical interactions between corresponding substances on the surface, e.g., adhesion [108]. Besides the named adhesive influences, there are other influences like capillary forces, capillary condensation, solid bridges, and form closure [106, 148]. However, they are negligible in fluid systems [158], such as the solid–fluid filtration of beverages. The following subchapters illustrate the three most relevant adhesive forces.

Lifshitz–van der Waals Interactions

Central components of particle adhesion are Lifshitz–van der Waals interactions, which are boundary layer forces. The categorization of these interactions is in Keesom (interactions of permanent dipoles), Debeye (magnetic induction interactions of permanent dipoles), and London forces (dispersion forces without permanent dipoles) [69, 85]. Although these forces arise inside solids, they are mainly acting outside of them. They make solids cling to a surface or other particles due to dipole interactions [98, 108]. Atoms consist of an atomic nucleus surrounded by electrons in the nuclear shell. According to Heisenberg's uncertainty principle, which states that there is no specific location of the electrons around the atomic nucleus, atoms are fluctuant dipoles [60, 69]. This fluctuating charge distribution is responsible for the Lifshitz–van der Waals forces due to dipole charge-related attraction. The adhesive strength depends on the material, particle diameter, and surrounding medium [175]. Moriarty et al. [108] define Lifshitz–van der Waals forces as the apolar energy component of adhesion.

According to the literature [171, 172, 175], there are different approaches to determine this force. The microscopic theory by Hamaker [56] describes interactions between single atoms and molecules, which are additive and not influencing mutually. Differentiation between different compound geometries due to various adhesion forms of contamination on filters helps to understand the adhesion determination. Here, the models of a disk to another disk (D-D), a sphere to a disk (S-D), or a sphere to another sphere (S-S) are commonly used to describe adhesive forces. Considering the Lifshitz–van der Waal interactions F_{Hamaker}, three different models (Eqs. 4–6) are deployed [56, 85, 131].

- Disk–disk model (D-D):

$$F_{\text{D-D}}^{\text{Hamaker}}(a) = \frac{H}{12\pi \times a^3} \tag{4}$$

- Sphere–disk model (S-D):

$$F_{\text{S-D}}^{\text{Hamaker}}(a) = \frac{H \times d}{12 \times a^2} \tag{5}$$

- Sphere–sphere model (S-S):

$$F_{\text{S-S}}^{\text{Hamaker}}(a) = \frac{H \times d_1 \times d_2}{12a^2 \times (d_1 + d_2)} \tag{6}$$

The variable H represents the Hamaker constant, while d_n is the sphere diameter and a the particle distance. Regarding particular contamination on the filter surface, the S-D and the S-S models are most relevant. The second proposed theory—the macroscopic theory by Lifshitz—does not include the atomic structure. Furthermore, measurable properties like the dielectric constant are incorporated. The polarization of atoms is additionally influenced by neighboring atoms, which is neglected by Hamaker's microscopic theory [24]. Lifshitz includes such effects in his approach, which is measurable with Eq. 7 (S-D model) [94].

$$F_{Lifshitz} = \frac{\hbar\bar{\varpi} \cdot d}{16\pi a^2} \tag{7}$$

Here, the factor $\hbar\varpi$ represents the Lifshitz constant, d is the diameter of the spherical particle, and a the particle distance. The two theories are combinable via Eq. 8 [84, 171].

$$\hbar\bar{\varpi} = \frac{4}{3}\pi \mathrm{H} \tag{8}$$

Other geometries are determinable by knowing this correlation. According to Rumpf [144], considering smooth spheres with sizes below 100 µm, the electrostatic or hydrogen bonds are negligible in contrast to Lifshitz–van der Waals forces. The surface roughness influences the strength significantly and decreases the Lifshitz–van der Waal interactions at specific roughness radii. Filter cloths possess a more complex and rough surface, which reduces the meaningfulness of the two theories above. However, they are the basis of further and more precise models, which include defined surface roughness [132, 133].

Electrostatic Force—Attraction and Repulsion

Electrostatic forces (EL), which arise between two charged surfaces, are essential regarding the adhesion or repulsion of contaminants [106, 108, 175]. Most liquid-solved particles have a charge, which results in an electric double layer due to the dissociation of functional groups [98]. Depending on the pH of the surrounding fluid, particles are positively or negatively charged [113, 175]. Consequently, the charge decides whether particles cling to a surface or repel. Around the particle, there is an accumulation of oppositely charged ions forming a diffuse layer, which makes the particle appear to be neutral [58]. For small distances between particle and surface, electrostatic forces of electrical conductors are determinable using Eqs. 9–11 [98, 175].

- Disk–disk model (D-D):

$$F_{\mathrm{D\text{–}D}}^{\mathrm{EL}}(a) = -\frac{1}{2\pi} \times \varepsilon \times \varepsilon_0 \times \zeta_1 \times \zeta_2 \times \ln\left(1 + e^{-\kappa a}\right) \tag{9}$$

- Sphere–disk model (S-D):

$$F_{\mathrm{S\text{–}D}}^{\mathrm{EL}}(a) = -\varepsilon \times \varepsilon_0 \times \kappa \times \frac{1}{2} \times d \times \zeta_1 \times \zeta_2 \times \ln\left(1 + e^{-\kappa a}\right) \tag{10}$$

- Sphere–sphere model (S-S):

$$F_{\mathrm{S\text{–}S}}^{\mathrm{EL}} = -\varepsilon \times \varepsilon_0 \times \kappa \times \frac{\frac{1}{2}(d_1 \times d_2)}{d_1 + d_2} \times \zeta_1 \times \zeta_2 \times \ln\left(1 + e^{-\kappa a}\right) \tag{11}$$

The variable ε_0 designates the electric field constant, ε the relative permittivity of the medium between the adhering components, ζ_i the equivalent zeta potential of sphere/disk i, κ the Debye–Hückel parameter, d the diameter of the spherical particle, and a the adhesion distance. In nature, the majority of particles and surfaces have a negative charge. Therefore, most electrostatic interactions are repulsive [108]. Formerly considerations yielded electrostatic forces as less critical than Lifshitz–van der Waals forces. For decades, scientific approaches regard electrostatic forces as central in describing and understanding particle adhesion due to natural surface roughness [144].

Lewis Acid–Base Interactions

Lewis acid–base forces (*LAB*) describe attractive interactions of hydrophobicity and repulsion via hydration around surfaces [108]. These interactions are dominated by hydrogen bonds, which are even up to two times stronger than Lifshitz–van der Waal forces [75]. Hydrogen bonds require donors, which are atoms bond to other atoms (e.g., oxygen, nitrogen), and acceptors, which are additional oxygen, nitrogen, or fluorine atoms [85]. Adhesion arises due to the interaction of a charged hydrogen acceptor and an electronegative receptor. In solid–fluid filtration processes, this effect is central because water is both a hydrogen donor and a hydrogen acceptor [168]. The result is strong hydrogen bonds and firmly adhering colloids on the surface. Equations 12–14 show the geometry-related definitions [85].

- Disk–disk model (D-D):

$$F_{\mathrm{D\text{–}D}}^{\mathrm{LAB}}(a) = -\frac{1}{\lambda} \times \Delta G^{\mathrm{LAB}} \times e^{\frac{l_0 - a}{\lambda}} \tag{12}$$

- Sphere–disk model (*S-D*):

$$F_{\mathrm{S\text{–}D}}^{\mathrm{LAB}}(a) = -\pi \times d \times \Delta G^{\mathrm{LAB}} \times e^{\frac{l_0 - a}{\lambda}} \tag{13}$$

- Sphere–sphere model (*S-S*):

$$F_{\mathrm{S\text{–}S}}^{\mathrm{LAB}}(a) = -\frac{\pi \times d_1 \times d_2}{d_1 + d_2} \times \Delta G^{\mathrm{LAB}} \times e^{\frac{l_0 - a}{\lambda}} \tag{14}$$

The variable d defines the equivalent diameter, ΔG is the adhesion energy, l_0 depicts the equilibrium balance between the considered adhesion partners, a is the adhesion distance, and λ is the decay rate of polar interactions.

Models of Residue Adhesion

Several theories are commonly used for modeling and determining colloid adhesion [76]. However, following Moriarty et al. [108], their suitability has to be discussed critically because they are not entirely appropriate in most cases. The majority of the models require surfaces to be as smooth as possible without any measurable topography. Furthermore, the product to be filtered has to be isotropic and should be of consistent composition. Both requirements are here hard to achieve due to rough filter topographies and complex beverage compositions. Following van Oss [168], further interactions (e.g., Lewis acid–base) are acting in biological systems, which reduce the adhesion prediction via DLVO and thermodynamic theory. However, both approaches have been used for particles (e.g., macromolecules, microorganisms) for years and are still state of the art. In addition to the thermodynamic and the DLVO theory, the XDLVO theory that also includes additional interactions (see Table 6) shows an extended approach.

Thermodynamic Theory

This theory describes adhesion by changing the Gibbs free energy of particles. This shift happens when the particles start to adhere to the filter surface. Moriarty et al. [108] assume that the distance between filter and particle is zero. Consequently, it is the total change of free energy which defines total available energy in closed systems. More accurate determinations require the incorporation of Lewis acid–base interactions and Lifshitz–van der Waal forces. Furthermore, this approach assumes reversible adhesive properties. Following the literature [108, 109], adhesion energy is defined by Eq. 15.

$$\Delta G_{\mathrm{Adhesion}} = \Delta G_{\mathrm{Lifshitz\text{–}vdW}} + \Delta G_{\mathrm{Lewis\text{–}acid\text{–}base}} \tag{15}$$

Here, $\Delta G_{\mathrm{Adhesion}}$ is the Gibbs free energy shift of adhesion, $\Delta G_{\mathrm{Lifshitz\text{–}vdW}}$ is the Gibbs free energy change of acting

Lifshitz–van der Waals interactions, and $\Delta G_{\text{Lewis-acid-base}}$ includes Lewis acid–base forces. Adhesion takes place when the result of Eq. 15 is negative due to a more stable condition by decreasing the free energy.

DLVO Theory—the Combination of the Adhesive Forces

The most famous approach of the interaction of Lifshitz–van der Waal and electrostatic forces is the DLVO theory (named after Derjaguin, Landau, Verwey, and Overbeek), which defines interactions between the two forces [35, 170]. Depending on the distance between particle and surface, these forces influence each other and describe either residue adhesion or repulsion.

Considering Fig. 3, van der Waal forces act over small distances, while electrostatic forces affect considerable distances. For reaching adhesion, it is crucial to overcome energy barriers. DLVO is defined by Eq. 16 [108].

$$E_{\text{DLVO}} = E_{\text{Lifshitz-vdW}} + E_{\text{Electrostatic}} \tag{16}$$

E_{DLVO} is the total energy of the adhesion, and $E_{\text{Lifshitz-vdW}}$ and $E_{\text{Electrostatic}}$ are the proportionate Lifshitz–van der Waals forces and electrostatic interactions, respectively. The most accurate results are determinable when the electrostatic forces are dominant.

This theory is suitable for describing bacterial adhesion [9, 12, 23]. However, other critical potential influences (e.g., steric forces) are not included [181]. The neglect of direct surficial impacts to bind or repel electrons limits the applicability (especially with particles of biological origin) [85].

XDLVO Theory

In contrast to the DLVO theory, the extended DLVO theory model (XDLVO) incorporates the influence of polar forces [168, 169]. Following the literature [12, 108, 126, 186], it is the most advanced theory because it combines aspects of thermodynamic and DLVO theory resulting in a more accurate adhesion prediction. There are numerous publications, which favor this theory, especially for microorganism adhesion [9, 12, 76]. Equation 17 defines a simple way to calculate adhesion energy via the XDLVO theory [108].

$$E_{\text{XDLVO}} = E_{\text{Lifshitz-vdW}} + E_{\text{Electrostatic}} + E_{\text{Lewis-acid-base}} \tag{17}$$

E_{XDLVO} describes the total energy of adhesion, while $E_{\text{Lifshitz-vdW}}$, $E_{\text{Electrostatic}}$, and $E_{\text{Lewis-acid-base}}$ are Lifshitz–van der Waals forces, electrostatic interactions, and Lewis acid–base forces, respectively [179]. The XDLVO theory is distance-dependent, too.

Jet Cleaning—an Appropriate Solution for Filter Cloths

The issue of insufficient cake discharges and the removal of remaining residues on the filter cloth have existed for decades. Many studies have shown suitable as well as improper techniques. Brush cleaning devices remove residues mechanically but can irreversibly damage the surface [99, 106]. Scraper blades also remove several residues by scratching on the filter surface [53]. Following Horrocks and Anand [66], they are jointly responsible for the abrasion of the filter cloth. The use of chemical agents—especially in the beverage industry—offers increased cleaning efficiency in addition to high microbiological safety. Agent utilization possibly damages filter cloths, however. The most commonly applied cleaning medium in the food industry is water, which adjusts agent concentration or acts as an autonomous mechanical cleaning tool [99].

Regarding the technique, jets are streamed mostly via nozzles onto soiled surfaces. In the beverage industry, this technology operates in many cleaning processes, e.g., cleaning in place (CIP) of tanks and pipe systems [52, 54, 99, 125, 160]. The cleaning of woven filter cloths includes the utilization of wash jets, too. Cleaning effects are impact forces and result in pressure distributions on the filter surface, which have to overcome the adhesive forces between the contamination and the filter cloth. The removability of residues using wash jets depends on four effects: direct residue deformation, stress wave creation and transfer, lateral outflow jetting, and hydraulic permeation in the soil layer [15, 54, 110]. Another advantage of wash jets is the adjustability of mechanical properties, e.g., nozzle geometry, pressure, fluid velocity, or incidence angle. This technique also combines the mechanical effect (kinetic energy) with the absorption of residues and their transport away from the contamination zone.

Agent-free cleaning is still not recommended, but cleaning with fewer agents and increased mechanical energy has

Table 6 Interactions and illustration of relevant adhesive forces and models

Force	Distance [nm]	Strength [kJ]	Model	References
Lifshitz–van der Waals	0.3–0.4	< 2	Thermodynamic theory, DLVO theory, XDLVO theory	[150], [12], [149], [95], [108]
Electrostatic	Depends on media		DLVO theory, XDLVO theory	
Lewis acid–base	0.2–0.3	12–16	Thermodynamic theory, XDLVO theory	

become popular due to economic and ecological advantages. Besides, less cleaning agents or pure water cleaning decreases the risk of chemical soiling of beverages [114]. The easily adjustable combination of wash jets with specific temperature levels or adjusted pH values will have a positive synergetic effect on cleaning [129]. Therefore, wash jet techniques offer a demand-oriented setup for careful cleaning of filter cloths at a sufficient degree of cleaning. This section outlines the fluid mechanical properties and determination possibilities of wash jets and highlights their increased cleaning efficiency.

Fluid Mechanical Principle of Wash Jets

Following Fryer et al. [47], the understanding of fluid mechanical residue removal and its different realization possibilities are vital aspects for future research and developments for cleaning optimization. These aspects are also valid for wash jets, which have the potential to shorten cleaning time while reducing costs and sparing the environment. A nozzle always is in the responsibility of generating a cleaning jet. Here, static, static–dynamical, and dynamical systems are commercially available [52]. Following Mauermann [101] regarding cleaning processes, four different nozzle geometries are distinguishable:

- Flat jet nozzle
- Full/round jet nozzle
- Full cone nozzle
- Hollow cone nozzle

The nozzle geometry influences the acting forces and the corresponding area to be cleaned of the cloth (see Fig. 4). Out of this, the resulting pressure distribution and cleaning effect are derivable.

Cleaning jets released by nozzles are divisible into three distinct parts in terms of mechanical properties. The first part illustrates the nozzle leaving jet and its streaming into space (free jet). By impacting on filter surfaces, flow profiles change entirely due to complex filter geometries. The wash jet converts from a free jet (part one) to an impinging jet (part two). At the initial contact with the surface, wash jets distribute in different directions, which are almost parallel to the wall. The third part defines the behavior of absorbing contamination in the fluid. The absorption is an essential removal mechanism of the existing transportation streams and the flow-off of the impact area. Cleaning standards state that devoid of soil transportation by streams or jets cleaning processes would be insufficient [99]. Furthermore, the jet will also run partly through the filter mesh due to the distinct filter cloth porosity. Backflush cleaning uses this effect as an individual cleaning principle (see "The Process Design of Filter Cloth Cleaning with Jets" section).

Although all three fluid mechanical parts form one single jet, they are determinable independently. Tani and Komatsu [163] recognized that surfaces are not effecting on free jets about two jet diameters away from the surface, which is assumed to be the transition from free to impinging jet. In further research, Gauntner et al. [49] confirm the link of both parts by the definition of impinging jets having the same properties and behavior as free jets until the impact.

In every cleaning concept of wash jets, detailed knowledge about laminar or turbulent stream conditions is fundamental [52, 166]. The Reynolds number *Re* serves as a significant dimensionless quantity (Eq. 18) [137].

$$\mathrm{Re} = \frac{v_a \times d_x}{\vartheta} = \frac{\text{Inertforce}}{\text{Friction force}} \tag{18}$$

The variable v_a illustrates the average velocity, d_x the characteristic diameter (e.g., particle diameter), and ϑ the kinematic viscosity. *Re* classifies pipe or channel streams in three stream areas: laminar area ($Re \leq 2300$), transition area ($2300 \leq Re \leq 10^4$), and turbulent region ($Re \geq 10^4$) [146, 157].

Free Jet—Between the Nozzle and the Impact Zone

Regarding surrounding conditions, a differentiation in one-phase and two-phase jets is necessary. One-phase jets—submerged jets—describe fluids that stream into a space filled with the same fluid. In general, wash jets, which are pure water or water mixed with cleaning agents in most cases, belong to the second group—the two-phase streams [64]. Here, jets exit a nozzle and impact on filter surfaces in an air-filled space.

The surrounding fluid profoundly influences many properties of free jets. Regarding classic free jets, the fluid streams into free space without any wall limitation. In the mist area between the streaming liquid and the surrounding medium, there are different velocities causing shear forces. Additionally, the different density and surface tension at the boundary layer of the two phases create turbulences, friction, and gas entrainment. The result is a jet break-up and an increasing jet decay in the axial direction. The appearance of this phenomenon and where it occurs highly depends on the nozzle geometry and operating pressure. Although this approach skips the direct jet impact on a wall to be cleaned, it is necessary to characterize the free jet properties, e.g., velocity gradients. Figure 5 illustrates the free jet while leaving a nozzle and streaming into space.

The literature [49, 105, 121, 161, 162] shows several models to determine a two-phase free jet. Especially the core length and the velocity reduction in the axial x-direction are part of these approaches. In this publication, the free jet determinations by Gauntner et al. and Hrycak et al. are focused [49,

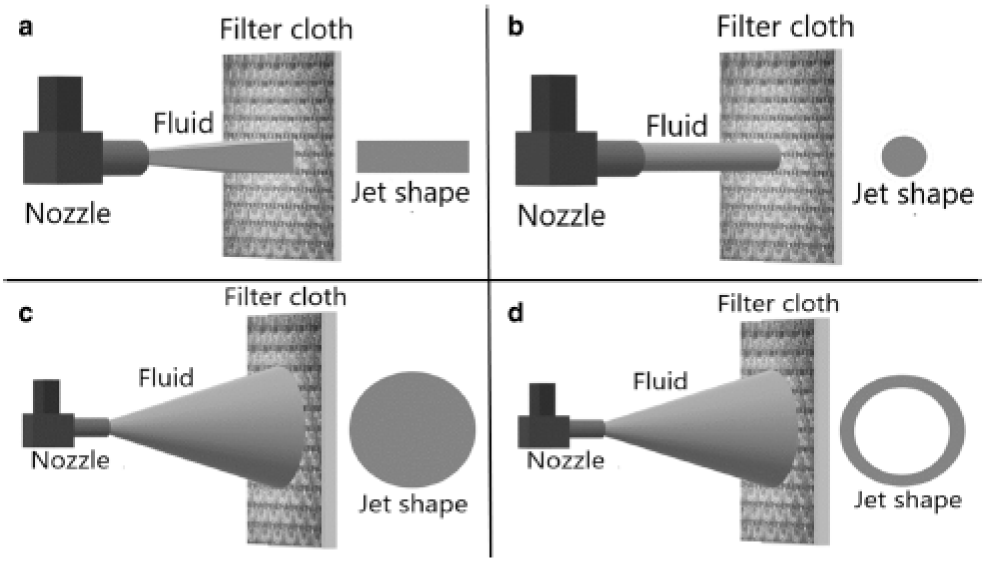


Fig. 4 Different nozzle geometries and the resulting impact area on the filter cloth: **a** flat jet nozzle, **b** full/round jet nozzle, **c** full cone nozzle, and **d** hollow cone nozzle; illustration is the authors' own creation and was inspired by Mauermann [101]

67] as it is the original method to determine a water jet in air-filled space. According to this approach, a classification of the flow profile of a jet into three distinct areas is necessary. Knowledge about these areas is essential to determine velocity and pressure conditions at specific stream points. These parameters are crucial for calculating the removal energy of the impinging jet.

Initial and Core Area—the Coherent Jet This area describes the flow of a jet from the nozzle and its dynamical establishment. It lasts from the nozzle to the apex of the potential core, which is the central part of the fluid. In the core area, velocity and several other parameters in the flow profile remain constant until the apex. By gaining distance from the nozzle, the core is decreasing due to the entrainment of the surrounding fluid. Mixing layers originate between the potential core and the surrounding fluid due to primary and secondary mass and momentum transfer effects (e.g., Kelvin–Helmholtz instabilities) [54]. This mixture of both fluids can be observed by a jet breaking up into droplets.

For complete descriptions of these two areas, the potential core length or nominal potential core length is decisive. According to the literature [49, 100], the core length depends on initial conditions and is four to six nozzle diameter long. However, core lengths are strongly dependent on the Reynolds number. In laminar streams, the range is proportional to the Reynolds number, while turbulent conditions are independent [67]. This aspect possibly results in enhanced and optimizable cleaning conditions. Velocities within the potential core depend on the nozzle diameter. Mass conservation (mass M to time t) and continuity act between the nozzle $\dot{m}_{\mathrm{Nozzle}}$ and connected pipe $\dot{m}_{\mathrm{Pipe}}$ (Eq. 19) [11].

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \dot{m}_{\mathrm{Pipe}} - \dot{m}_{\mathrm{Nozzle}} \tag{19}$$

Subsequently, the integral form is obtained (Eq. 20).

$$\int_0^t \rho \times A_{\mathrm{Nozzle}} \times v_{\mathrm{Nozzle}} \mathrm{d}t = \int_0^t \rho \times A_{\mathrm{Pipe}} \times v_{\mathrm{Pipe}} \mathrm{d}t \tag{20}$$

By knowing v_{Nozzle}, nozzle area A_{Nozzle}, sectional pipe area A_{Pipe}, and regarding water as wash fluid with constant density ρ over time, v_{Nozzle} (velocity of the potential core at the centerline) is determinable with Eq. 21.

$$v_{\mathrm{Nozzle}} = \frac{A_{\mathrm{Pipe}} \times v_{\mathrm{Pipe}}}{A_{\mathrm{Nozzle}}} \tag{21}$$

Further, the relationship between v_{Nozzle} and nozzle diameter d_{Nozzle} is according to Eq. 22 (regarding round nozzles connected to pipes).

$$v_{\mathrm{Nozzle}} = \frac{d^2_{\mathrm{Pipe}} \times v_{\mathrm{Pipe}}}{d^2_{\mathrm{Nozzle}}} \tag{22}$$

Main Area—the Droplet Jet This central part of the free jet describes conditions after the potential core end. The jet

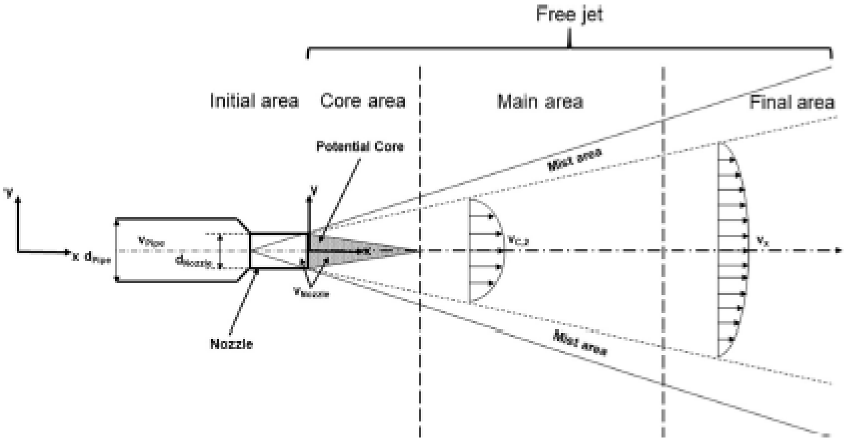


Fig. 5 The path of a wash jet from the nozzle into the free space (free jet); variables: v_{Pipe} = fluid velocity in the supply pipe; v_{Nozzle} = fluid velocity after the nozzle; $v_{\mathrm{C,2}}$ = centerline velocity in the x-direction; v_x = velocity at coordinate x; d_{Pipe} = pipe diameter; d_{Nozzle} = nozzle diameter; the illustration is the authors' own creation and was adapted from Sigloch [153]

becomes broader and results in droplets due to the increased entrainment of the surrounding fluid and the already mentioned reasons. By momentum preservation, jet velocity decreases, which is describable by Gaussian curves [65]. The centerline velocity $v_{\mathrm{C,2}}$ of area 2 is determinable via Eq. 23 [67].

$$v_{\mathrm{C,2}} = \frac{v_{\mathrm{Nozzle}} \times l_{\mathrm{Core}} \times d_{\mathrm{Nozzle}}}{x} \tag{23}$$

Here, variable x defines the specific x-position, while l_{Core} is the dimensionless potential core length. The mixture of jet and surrounding fluid results in larger droplets. The droplet size increases by gaining distance from the nozzle. The region nearest to the radial x-axis is named the water droplet zone, according to Guha et al. [54], while mixing zones of both phases are called mist areas due to the small droplet size.

Final Area—Atomized Jet The third and final area of a free jet is named the diffused droplet region [54]. Here, wash jets disintegrate fully and atomize into small droplets with negligible velocities. If distances between the nozzle and filter surface are too vast, the impact zone is in the diffused droplet region. As a result of this, contamination on filters is merely moistened but not cleaned away. The design of a cleaning concept has to consider a nozzle position close to the filter surface. The transition from the droplet jet to the atomized jet is determinable with the von-Ohnesorge number (Oh), Re, and the von-Ohnesorge diagram [119].

Optimally, distances between nozzles and filter surfaces should be within the potential core or, at the least, the first part of area 2. On the one hand, the technical requirements do not always permit such close nozzle installations. On the other hand, too short distances between nozzle and surface end in jet rebounds, which result in flow blocks [54].

Impinging Jet—Forces on the Residues on the Filter Cloth

The impinging jet definition is a stream or a droplet that collides against a wall. After the collision, the jet is decelerated and deflected, while the kinetic energy resulting from the jet velocity is discharged to the filter cloth. The forces that are derivable from the energy result in a particular pressure distribution that creates impulses as well as wall shear stress on the filter cloth. The combination of different hydraulic effects finally cares for the cleaning effect. The changeover from the free jet observation to the impinging part is within a short distance from the surface. Leach et al. [90] showed that by using surface cutting water jets, fluid pressure became equal to the pressure of the surrounding fluid in distances of $1.3 \cdot d_{\mathrm{Nozzle}}$ (nozzle diameter) from the impact point due to less shear stress. In newer studies, Guha et al. [54] determined distances up to $1.68 \cdot d_{\mathrm{Nozzle}}$. However, this parameter is strongly dependent on nozzle and fluid properties. The impingement of a jet can be categorized in different areas, as shown in Fig. 6.

Area of Impingement Before the collision, the jet has an absolute velocity (see free jet calculation) and kinetic energy. Here, forces result in effecting the contamination on the surface. The wall shear stress τ dominates direct mechanical effects on filter cloths (see Eq. 24), which has a cleaning impact due to the inner friction of real fluids [30, 46, 70].

$$\tau = \frac{F}{A} \tag{24}$$

F is the effecting force, while A is the corresponding area. However, it is necessary to consider that it is not the actual force that is responsible for cleaning in the impact area. Instead, the resulting occurrence of pressures and their distribution on the cloth gives the cleaning effect [105]. By collision with the filter cloth, the jet fluids are compressed, which results in pressures affecting the surface in a time interval < 1 ms [101]. At the boundary layer to the soiled filter cloth, shock waves act equally to the surface and against the jet direction [2, 3, 153]. The resulting pressure distribution undergoes a reduction in the inner part of the contact zone to the normal water hammer pressure. After a particular streaming time, the jet stabilizes, and a dynamic pressure effect on the filter cloth acts. For this quasistatic effect, a coherent jet with a specific flowing time is necessary.

Radial Flow Area—the Lateral Drainage of the Cleaning Fluid After impacting on the filter cloth, the liquid is drained off around the impingement area almost symmetrically. Impacting jets are slowed down in the axial direction and accelerated in the radial direction in the eddy area. At the impact point, the fluid velocity is even zero [65]. Therefore, the radial flow is also responsible for detachment of soil, which can even reach higher speeds than the jet velocity [105]. Wilson et al. [178] also defined this area as a radial flow zone (RFZ). Knowledge about the distribution (backflow) of jets after impacting on filter surfaces is essential due to cleaning efficiency and sufficient transport of product residues away from filter cloths. Siekmann and Thamsen [152] define the backflow effect $\epsilon_{\mathrm{Fluid}}$ with Eq. 25. Figure 6 shows the distribution of the jet and the resulting mass transfers.

$$\epsilon_{\mathrm{Fluid}} = \frac{\dot{m}_2}{\dot{m}_1} \tag{25}$$

The variable $\epsilon_{\mathrm{Fluid}}$ is the backflow coefficient, $\dot{m}_1$ is the mass flow of the fluid after the nozzle, and $\dot{m}_2$ is the mass flow of the deflected jet. Regarding a distributed stream in two directions, the following context is valid (Eqs. 26–27).

$$\dot{m}_3 = \dot{m}_1 \times \varepsilon_{\mathrm{Fluid}} \tag{26}$$

$$\dot{m}_2 = \dot{m}_1 \times (1 - \varepsilon_{\mathrm{Fluid}}) \tag{27}$$

Here, $\dot{m}_3$ is the second deflected jet after the impact. As can be seen, backflow is irrespective of jet velocity. Here, the most influencing factor is the incidence angle. If increased, fluids will stream in almost equal parts in both directions. It is concludable that angled jet incidents toward the filter surface are an essential parameter and always require incorporation in cleaning concept planning.

Transition Area Direct after the impingement and within the radial flow zone, Wilson et al. describe the formation of a thin liquid layer [178]. This boundary layer is observable from the filter cloth until the layer between the liquid and the surrounding gas phase (e.g., air). Within this small layer, the stream along the filter cloth is laminar. After a certain distance, the distinctive film jump takes place where an arching of the liquid changes the flow properties to turbulent. The reason for this effect is derivable from the balanced outward momentum before the jump, which is caused by the surface tension between the two phases [16].

Regarding a full/hollow cone or a round jet nozzle, this jump is a circular ring around the impingement area. Concerning filter cloths, this jump depends on the turbulence condition and the type of fixing of the filter cloth in the filter apparatus. If the cloth is not tensioned enough, the softness reduces this effect, as the jet may press the cloth too much. Concluding, the boundary layer thickness δ is a decisive parameter for determining the velocity decreasing effect and friction in this layer [46]. The thickness can be determined by Eq. 28 for laminar and turbulent conditions [83].

$$\begin{aligned} \delta_{\mathrm{laminar}}(x) &= \frac{4.9 \times x}{\sqrt{\mathrm{Re}_x}} \\ \delta_{\mathrm{turbulent}}(x) &= \frac{0.37 \times x}{\mathrm{Re}_x^{0.2}} \end{aligned} \tag{28}$$

Determination of Acting Forces Impinging jets are difficult to predict and calculate due to existing turbulences and different flow profiles. Impulse, pressure, wall, and other forces, which are acting directly on impact areas, are discoverable via the momentum conservation principle. Entering and leaving impulse streams in self-contained fluid spaces are balanced in every coordination direction. A possible approach to determine forces of a jet impacting on a surface is findable in the literature [37, 61, 118, 153]. Firstly, the impulse equation serves as a point of origin (Eq. 29).

$$\rho A c^2 + \sum F = 0 \tag{29}$$

With the impulse equation, different fluid mechanical influences become clear for Newtonian fluids (e.g., wash water in jets). The differential form is the base of the determination (Eq. 30).

$$\rho\left(\frac{\mathrm{d}v_j}{\mathrm{d}t} + v_i \frac{\mathrm{d}v_j}{\mathrm{d}x_i}\right) = -\frac{\mathrm{d}p}{\mathrm{d}x_j} - \frac{\mathrm{d}\tau_{ij}}{\mathrm{d}x_i} + \rho g_j \tag{30}$$

The variable p presents the pressure, t is the time, and g is the gravity acceleration constant. Integration over a control volume and addition of continuity equation results in Eq. 31.

$$\begin{aligned} \int_{V_C} \frac{d\rho v_j}{dt} \mathrm{d}V + \int_{A_C} \rho v_i v_j \mathrm{d}A_i = -\int_{A_C} p \mathrm{d}A_j - \int_{A_C} \tau_{ij} \mathrm{d}A_i \\ + \int_{V_C} \rho g_j \mathrm{d}V + \sum F_j \end{aligned} \tag{31}$$

The impulse equation was transferred and simplified in the Euler equation for fluid mechanical models (Eq. 32) [11, 31, 89]. Here, neglect of liquid friction, as well as viscosity, and consideration of elastic fluids within the stream are necessary.

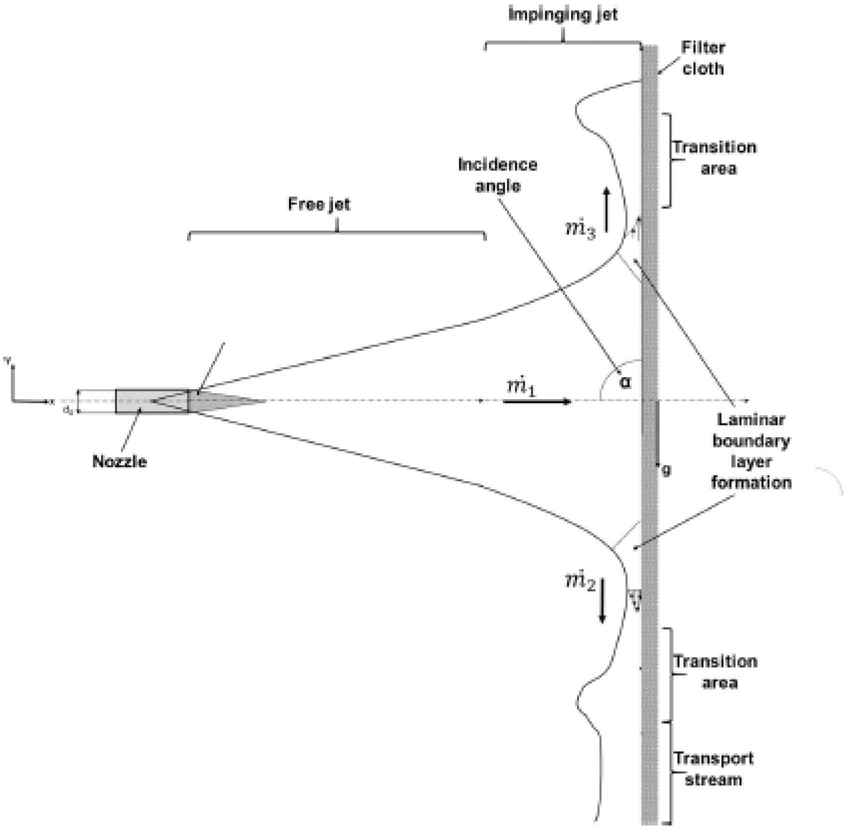


Fig. 6 Vertical impinging ($\alpha = 90°$) and transport jet with corresponding jet areas (example: filter cloth in a vertical, most common position like in filter presses). $\dot{m}_1$ = entire mass flow impacting on the surface; $\dot{m}_2$ = portion of the mass flow in the negative y-direction; $\dot{m}_3$ = portion of the mass flow in the positive y-direction; g = acceleration of gravity constant; the illustration is the authors' own creation and was adapted from Siekmann and Thamsen [152], Wilson et al. [178], and Bhagat and Wilson [16]

$$\rho\left(\frac{\mathrm{d}v_j}{\mathrm{d}t}+v_i\frac{\mathrm{d}v_j}{\mathrm{d}x_i}\right)=-\frac{\mathrm{d}p}{\mathrm{d}x_j}+\rho g_j \tag{32}$$

The further advanced Navier–Stokes equation (Eq. 33) respects viscosity [146, 159].

$$\rho\left(\frac{\mathrm{d}v_j}{\mathrm{d}t}+v_i\frac{\mathrm{d}v_j}{\mathrm{d}x_i}\right)=-\frac{\mathrm{d}p}{\mathrm{d}x_j}+\mu\frac{\mathrm{d}^2v_j}{\mathrm{d}x_i^2}+\rho g_j \tag{33}$$

In general, the assumption is necessary that high fluid pressures result in high jet velocities, which will favor the cleaning effect. However, attention has to be paid to the damaging effect of high pressures toward filter cloths. Furthermore, forceful impacts also benefit aerosol distribution and the unwanted re-soiling of filter cloths [157]. According to the literature [41], minimum pressure has to range between 3 and 5 bar, while jet speed has to be 3 to 4 m/s.

Transport Stream—Removing Detached Residues

Cleaning processes are ineffective without complete removal of the contamination. Therefore, it is necessary to observe the liquid film that runs off. Concerning the stream condition, turbulent flows favor cleaning due to a considerable soil retention capacity and increased wall shear stress [166]. Due to inconsistent axial velocity and resulting transverse flows, the fluids, which absorbed already a soil quantity, are mixed in the turbulent stream [128]. Particular forms of the impulse equation also conduct the determination of transport streams. Creeping flows describe streams with small Reynolds numbers, where viscosity forces are more influential than acceleration forces. The Navier–Stokes equation serves as the origin of the approach to determine the velocity of certain areas in the flow profile of a transport stream [118]. Equation 34 is applicable when observing laminar film flows on even surfaces [154].

$$\frac{\Delta p}{L}=\mu\frac{d^2v_1}{\mathrm{d}x_2^2}+\rho g_1 \tag{34}$$

In contrast, boundary layer flows are valid for streams with high Reynolds numbers. For careful considerations, accurate measurements, in addition to numerical methods, have to be performed.

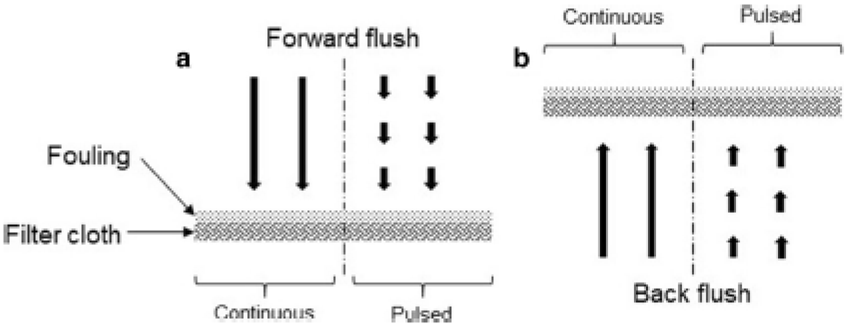


Fig. 7 Concepts for cleaning filter media with wash jets. **a** Forward flush cleaning. **b** Backflush cleaning. The illustration is the authors' own creation

The Process Design of Filter Cloth Cleaning with Jets

The literature concludes that cleaning fluid velocity is one of the most important parameters [78, 160]. For cleaning of technical surfaces consisting of stainless steel or other metals, the range of jet velocity should be between 80 and 200 m/s [54]. However, this speed is often too high for interweaved sensitive textiles like filter cloths. Furthermore, filter fabrics are stretched by impacting jets that additionally increase pressure and stress on the material and weave. The design of the cleaning process also is vital in choosing the right cleaning concept. Here, continuous jet cleaning via forward flush or backflush is state of the art. Alternative ideas, e.g., pulsatile jets, have been developed in the last years.

The big difference between forward flush and backflush is the jet direction to the filter (see Fig. 7). While forward flushes are contacting contamination directly, backflushes reach residues on filter cloths after crossing the whole filter cloth. Therefore, forward flushes unfold their full pressure completely onto adhering residues, while backflushes reach the contaminated areas with modified energy and even avoid contamination in stream shadows. On the other hand, forward techniques press residues deeper into the filter cloth, while backwashing provides full transport—if reachable—away from the filter. The selection of the right cleaning concept in terms of the suitability depends strongly on the filter type, weave, construction, material, and product.

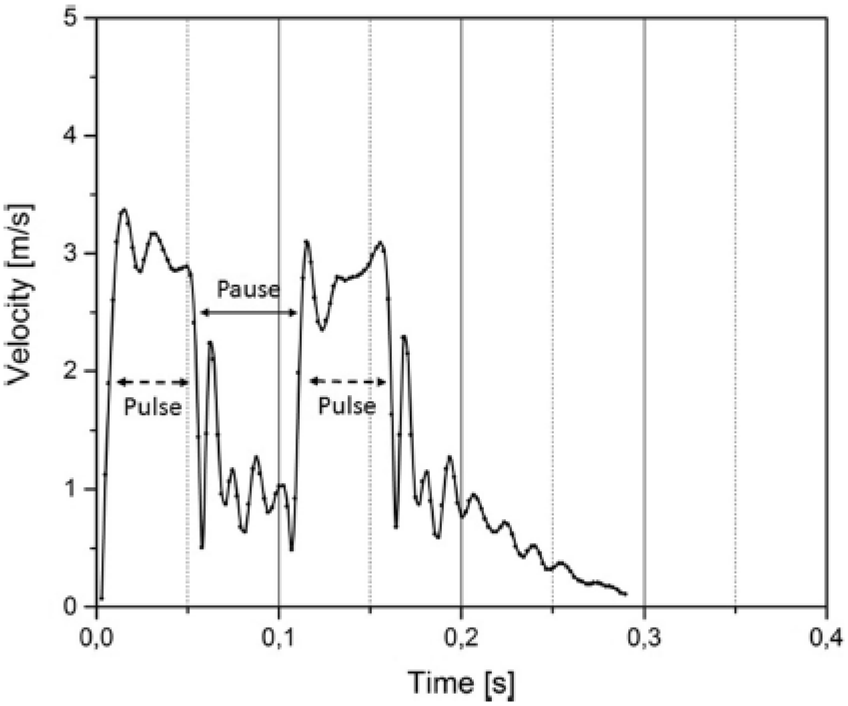


Fig. 8 Illustration of the fluid velocity of a jet with two pulses and one pause; the illustration is the authors' own creation

Fig. 9 Influencing factors for filter media cleaning; the illustration is the authors' own creation

General:
- Temperature
- Chemistry/detergent
- Cleaning time
- Mechanical effects
- Soil composition
- Surface

Filter media parameter:
- Material
- Construction
- Finish
- Product composition
- Detergent
- Costs (systems, detergents, life span of cloths)
- Technical requirements

Wash jet:
- Velocity
- Process type (pulsatile, continuous)
- Incidence angle
- Fluid pressure
- Nozzle geometry
- Nozzle distance
- Surrounding fluid
- Back-/Forward flush

Detergent cleaning:
- Type and amount of soil
- Detergent type
- Concentration
- Surface properties
- Surface Material
- Economy and costs
- Ecologic aspects

Continuous Wash Jet

A simple way to use wash jets for filter cloth cleaning is to stream them continuously onto the surface or to backflush them. As a result of this, jets are focused on the area to be cleaned. They have direct contact with residues, which results in immediate force effects (conservation of the momentum). Although many different applications are using continuous wash jets in various cleaning units, there is only a little research concerning filter cloth cleaning. Initial investigations in cleaning filter media were performed by Stahl et al. [155] in observing particle-loaded filter media. Furthermore, they calculated stream and wall shear stress distributions of woven filter media and identified low wall shear stressed areas. Weidemann [173] observed the cleaning kinetics of different filter cloths using model contaminations. The results showed a high dependency on cleaning velocity, filter roughness, and weave type. Ulmer [166] developed a cleaning model for filter media, where a layer with versatile particles originated after residue detachment resulting in equilibrium concentrations. Mass transport between equilibrium layers and fluid streams ensures contamination transport away from the surfaces. However, the thickness of the equilibrium layers depends on fluid velocity.

Pulsatile Wash Jet

Pulsatile jets depict non-continuous streams on filter media. With this, the cleaning jet divides into several jet intervals that subdivide into pulse length and pulse pause (Fig. 8). Pulsatile cleaning has been investigated for many different applications in the beverage and food industries [22, 38, 43, 46, 51]. The advantages of this concept were verified in cleaning elbows and straight pipes [8, 18, 19, 44]. Trials using pulsatile cleaning for filter media were conducted with bag filters and dust removal [66, 88, 97, 164, 165].

Generally, cleaning efficiency increases by using higher stream velocities due to higher wall shear stress. However, in most cases, an increase in cleaning speed is only reasonable using pulsatile applications (e.g., fluid consumption, too strong continuous impulses). Due to the desired reduction of liquid mass, initial investigations in cleaning filter media with pulsatile jets via backflush were performed by Weidemann et al. [93, 173, 174]. The cleaning results showed 1.5 higher cleaning degrees compared to continuous wash jets. Werner et al. [176] extended the investigations on forward flush cleaning. They showed the suitability of pulsatile jets in comparison to backwashing or continuous cleaning by removing yeast cells from filter cloths. The advantages of this promising concept are the reduction of cleaning fluid and higher cleaning degrees.

The increased cleaning performance is related to higher wall shear stress by pulsating wash jets and waviness onto the surface, which also decreases boundary layers [8]. The effect of acting shock waves and water hammer pressures within the first microsecond of the jet impingement can also be used by pulsed jet cleaning more efficiently [153]. Another effect is fluid drainage between two jets and the joint removal of cushioning liquid layers on filter surfaces. Subsequent jets can unfold their pressure on contamination due to direct contact fully. Furthermore, pulsatile jet cleaning also enhances the cleanability of difficult-to-clean areas [44]. From an ecological and economic point of view, as well as regarding cleaning efficiency, pulsatile jet cleaning is the most promising method for filter fabrics. Cleaning in both directions offers appropriate cleaning results, even if direct contact of the wash jet with residues is preferable due to higher affecting forces.

Conclusion

This paper outlined the cleaning challenges of woven filter cloths in detail. Besides the cleaning limitation due to the material properties of cloths (e.g., temperatures, cleaning agents, and sanitizers), the complexity of the filter structures hinders cleaning. Designed for efficient filtration processes, the rough topographies of filter cloth contradict any regulations and design features in terms of *hygienic design*. Furthermore, involved beverage residues that adhere heterogeneously on filter cloth increase this problematic situation. For a sufficient cleaning efficiency, the cleaning mechanism has to overcome the adhesive forces between the soil and surface. This paper showed here the relevant biophysical interactions in order to show the necessities of a sufficient cleaning concept. Finally, water jet cleaning highlights as the cleaning method with the most significant and most optimizable cleaning effect.

The main advantage is the easy adjustability and flexibility of new products. Wash jets are categorizable into three different areas: free jet, impinging jet, and the transport stream of residues. Here, the distance between the nozzle and filter surface and nozzle geometries are critical aspects for the determination of optimal cleaning concepts.

Regarding the fluid mechanical properties, stream velocity and the resulting wall shear stress on the residues are central. The integration of these aspects into the design of the cleaning process is crucial. Neglect of chemical agents is not possible due to high hygienic standards. However, economic and ecological aims negate a further increase in chemicals or temperature in future research. Here, the mechanical effects of wash jets need to be in focus. Previous studies confirmed pulsed jets as a promising method and advantageous for filter cloth.

The aim of complete cake discharges and a fully automated filtration process is the focus of research for decades. The goals of efficient cleaning concepts are short filter downtimes, prevention of cross-contamination, high product safety, and economic and ecologic aspects (e.g., cleaning agent reduction). Besides, filter cloths require considerately and function-retaining treatment to ensure long service life. Jet cleaning can be a milestone that may reach these goals in combination with adequate sensor techniques and demand-oriented cleaning [107]. For finding the right procedure, Fig. 9 illustrates possible ways for filter cloth cleaning.

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Compliance with ethical standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

1. Adair JH, Suvaci E, Sindel J (2001) Surface Colloid Chem:1–10. https://doi.org/10.1016/B0-08-043152-6/01622-3
2. Aganin A, Guseva T (2019) Numerical simulation of liquid mass collision with a wall. Progress Comput Fluid Dyn 19(5):293. https://doi.org/10.1504/PCFD.2019.102058
3. Aganin A, Guseva T (2020) Liquid jet impact on a wet wall. European Journal of Mechanics - B/Fluids 79:141–150. https://doi.org/10.1016/j.euromechflu.2019.09.001
4. Anand S, Singh D, Avadhanula M, Marka S (2014) Development and control of bacterial biofilms on dairy processing membranes. Compr Rev Food Sci Food Saf 13(1):18–33. https://doi.org/10.1111/1541-4337.12048

5. Anlauf H (2007) Filtermedien zur Kuchenfiltration – Schnittstelle zwischen Suspension und Apparat. Chemie Ingenieur Technik 79(11):1821–1831. https://doi.org/10.1002/cite.200700093
6. Anlauf H (2019) Wet cake filtration. Fundamentals, equipment, strategies. Wiley-VCH, Weinheim
7. Annemüller G, Manger H-J, Lietz P (2011) The yeast in the brewery. Management - pure yeast cultures - propagation, 1. Ed. VLB manuals. VLB, Berlin
8. Augustin W, Fuchs T, Föste H, Schöler M, Majschak J-P, Scholl S (2010) Pulsed flow for enhanced cleaning in food processing. Food Bioprod Process 88(4):384–391. https://doi.org/10.1016/j.fbp.2010.08.007
9. Azeredo J, Visser J, Oliveira R (1999) Exopolymers in bacterial adhesion. Interpretation in terms of DLVO and XDLVO theories. Colloids Surf B: Biointerfaces 14(1-4):141–148. https://doi.org/10.1016/S0927-7765(99)00031-4
10. Back W (ed) (2008) Ausgewählte Kapitel der Brauereitechnologie, 2nd edn. Nürnberg, Fachverlag Hans Carl
11. Batchelor GK, Batchelor GK (2000) An introduction to fluid dynamics, 2nd edn. Cambridge University Press, Cambridge
12. Bayoudh S, Othmane A, Mora L, Ben Ouada H (2009) Assessing bacterial adhesion using DLVO and XDLVO theories and the jet impingement technique. Colloids and Surfaces. B, Biointerfaces 73(1):1–9. https://doi.org/10.1016/j.colsurfb.2009.04.030
13. Berk Z (ed) (2013) Food process engineering and technology, 2nd edn. Amsterdam, Academic
14. Bessada R, Silva G, Paiva MC, Machado AV (2011) Functionalization of PET and PA6.6 woven fabrics. Appl Surf Sci 257(18):7944–7951. https://doi.org/10.1016/j.apsusc.2011.04.002
15. Beutin EF (1975) Flüssigkeitsschlag, Grundlagen der Beanspruchung und ihre technische Nutzanwendung. Dissertation, Technical University of Hannover
16. Bhagat RK, Wilson DI (2016) Flow in the thin film created by a coherent turbulent water jet impinging on a vertical wall. Chem Eng Sci 152:606–623. https://doi.org/10.1016/j.ces.2016.06.011
17. Biswas P, Bandyopadhyaya R (2017) Biofouling prevention using silver nanoparticle impregnated polyethersulfone (PES) membrane: E. coli cell-killing in a continuous cross-flow membrane module. J Colloid Interface Sci 491:13–26. https://doi.org/10.1016/j.jcis.2016.11.060
18. Blel W, Le Gentil-Lelièvre C, Bénézech T, Legrand J, Legentilhomme P (2009a) Application of turbulent pulsating flows to the bacterial removal during a cleaning in place procedure. Part 1. Experimental analysis of wall shear stress in a cylindrical pipe. J Food Eng 90(4):422–432. https://doi.org/10.1016/j.jfoodeng.2008.07.008
19. Blel W, Legentilhomme P, Bénézech T, Legrand J, Le Gentil-Lelièvre C (2009b) Application of turbulent pulsating flows to the bacterial removal during a cleaning in place procedure. Part 2. Effects on cleaning efficiency. J Food Eng 90(4):433–440. https://doi.org/10.1016/j.jfoodeng.2008.07.019
20. Bobe U (2008) Die Reinigbarkeit technischer Oberflächen im immergierten System. Dissertation, Technische Universität München
21. Bobe U, Hofmann J, Sommer K, Beck U, Reiners G (2007) Adhesion – where cleaning starts. Trends Food Sci Technol 18:S36–S39. https://doi.org/10.1016/j.tifs.2006.10.019
22. Bode K, Hooper RJ, Paterson WR, Ian Wilson D, Augustin W, Scholl S (2007) Pulsed flow cleaning of whey protein fouling layers. Heat Transfer Eng 28(3):202–209. https://doi.org/10.1080/01457630601064611
23. Boks NP, Kaper HJ, Norde W, van der Mei HC, Busscher HJ (2009) Mobile and immobile adhesion of staphylococcal strains to hydrophilic and hydrophobic surfaces. J Colloid Interface Sci 331(1):60–64. https://doi.org/10.1016/j.jcis.2008.11.025
24. Bowen WR, Jenner F (1995) The calculation of dispersion forces for engineering applications. Adv Colloid Interf Sci 56:201–243. https://doi.org/10.1016/0001-8686(94)00233-3
25. Brennan JG (2012) Food processing handbook, 2nd edn. Wiley-VCH, Weinheim
26. Brunette DM (2001) Principles of cell behavior on titanium surfaces and their application to implanted devices. Titanium in Medicine. Engineering Materials.:485–512. https://doi.org/10.1007/978-3-642-56486-4_15
27. CAMPUS - Computer Aided Material Preselection by Uniform Standards (2020) Material information system for the plastics industry. https://www.campusplastics.com. Accessed 07 Mar 2020
28. Cassano A, Conidi C, Drioli E (2013) Membrane processing. Dairy and beverage applications, Wiley-Blackwell, Chichester
29. Chan R, Chen V (2001) The effects of electrolyte concentration and pH on protein aggregation and deposition. Critical flux and constant flux membrane filtration. J Membr Sci 185(2):177–192. https://doi.org/10.1016/S0376-7388(00)00645-1
30. Cheow CS, Jackson AT (1982) Circulation cleaning of a plate heat exchanger fouled by tomato juice. Int J Food Sci Technol 17(4):431–440. https://doi.org/10.1111/j.1365-2621.1982.tb00198.x
31. Chorin AJ, Marsden JE (2000) A mathematical introduction to fluid mechanics, vol 4, 3rd edn. Springer, New York
32. Colmenares JC, Kuna E, Jakubiak S, Michalski J, Kurzydłowski K (2015) Polypropylene nonwoven filter with nanosized ZnO rods: promising hybrid photocatalyst for water purification. Appl Catal B Environ 170-171:273–282. https://doi.org/10.1016/j.apcatb.2015.01.031
33. Cox MF (1986) Surfactants for hard-surface cleaning: mechanisms of solid soil removal. J Am Oil Chem Soc 63(4):559–565. https://doi.org/10.1007/BF02645756
34. Davey KR, Chandrakash S, O'Neill BK (2015) A Friday 13th failure assessment of clean-in-place removal of whey protein deposits from metal surfaces with auto-set cleaning times. Chem Eng Sci 126:106–115. https://doi.org/10.1016/j.ces.2014.12.013
35. Derjaguin B, Landau L (1993) Theory of the stability of strongly charged lyophobic sols and of the adhesion of strongly charged particles in solutions of electrolytes. Prog Surf Sci 43(1-4):30–59. https://doi.org/10.1016/0079-6816(93)90013-L
36. Drioli E, Giorno L (eds) (2016) Encyclopedia of membranes. Springer, Berlin
37. Durst F (2006) Grundlagen der Strömungsmechanik. Eine Einführung in die Theorie der Strömung von Fluiden. Springer, Berlin
38. Edwards M, Wilkinson W (1971) Review of potential applications of pulsating flow in pipes. Trans Inst Chem Eng 49(2):85–94
39. Ehlers S (1961) The selection of filter fabrics re-examined. Ind Eng Chem 53(7):552–556. https://doi.org/10.1021/ie50619a024
40. El Rayess Y, Albasi C, Bacchin P, Taillandier P, Raynal J, Mietton-Peuchot M, Devatine A (2011) Cross-flow microfiltration applied to oenology: a review. J Membr Sci 382(1-2):1–19. https://doi.org/10.1016/j.memsci.2011.08.008
41. Esslinger HM (2009) Handbook of brewing. Processes, technology, markets. Wiley-VCH, Weinheim
42. Filali L, Brahmi Y, Sib JD, Bouhekka A, Benlakehal D, Bouizem Y, Kebab A, Chahed L (2016) The effect of amorphous silicon surface hydrogenation on morphology, wettability and its implication on the adsorption of proteins. Appl Surf Sci 384:107–115. https://doi.org/10.1016/j.apsusc.2016.05.013
43. Förster M, Augustin W, Bohnet M (1999) Influence of the adhesion force crystal/heat exchanger surface on fouling mitigation. Chem Eng Process Process Intensif 38(4-6):449–461. https://doi.org/10.1016/S0255-2701(99)00042-2
44. Föste H, Wesche M, Kücke M, Augustin W, Scholl S, Helbig M, Majschak J-P (2014) Pulsierende Strömung. Ressourceneffiziente

Cleaning-in-Place-Reinigung. Chemie Ingenieur Technik (CIT plus) 17(12):50–52

45. Fryer PJ, Asteriadou K (2009) A prototype cleaning map: a classification of industrial cleaning processes. Trends Food Sci Technol 20(20):255–262. https://doi.org/10.1016/j.tifs.2009.03.006
46. Fryer PJ, Christian GK, Liu W (2006) How hygiene happens: physics and chemistry of cleaning. Int J Dairy Technol 59(2):76–84. https://doi.org/10.1111/j.1471-0307.2006.00249.x
47. Fryer PJ, Robbins PT, Asteriadou K (2011) Current knowledge in hygienic design. Can we minimize fouling and speed cleaning? Proc Food Sci 1:1753–1760. https://doi.org/10.1016/j.profoo.2011.09.258
48. Gan Q, Field RW, Bird MR, England R, Howell JA, McKechnie MT, O'Shaughnessy CL (1997) Beer clarification by cross-flow microfiltration: fouling mechanisms and flux enhancement. Chem Eng Res Des 75(1):3–8. https://doi.org/10.1205/026387697523327
49. Gauntner JW, Livingood JNB, Hrycak P (1970) Survey of literature on flow characteristics of a single turbulent jet impinging on a flat plate. Technical report (NASA-TN-D-5652, E-5203). https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19700009658.pdf. Accessed 17 May 2020
50. Gerhards C, Schramm M, Schmid A (2019) Use of the Weibull distribution function for describing cleaning kinetics of high pressure water jets in food industry. J Food Eng 253:21–26. https://doi.org/10.1016/j.jfoodeng.2019.02.011
51. Gillham CR, Fryer PJ, Hasting APM, Wilson DI (2000) Enhanced cleaning of whey protein soils using pulsed flows. J Food Eng 46(3):199–209. https://doi.org/10.1016/S0260-8774(00)00083-2
52. Goode KR, Asteriadou K, Robbins PT, Fryer PJ (2013) Fouling and cleaning studies in the food and beverage industry classified by cleaning type. Compr Rev Food Sci Food Saf 12(2):121–143. https://doi.org/10.1111/1541-4337.12000
53. Groysman A (ed) (2017) Corrosion problems and solutions in oil refining and petrochemical industry, 1, Ed., vol, vol 32. Springer, Cham
54. Guha A, Barron RM, Balachandar R (2011) An experimental and numerical study of water jet cleaning process. J Mater Process Technol 211(4):610–618. https://doi.org/10.1016/j.jmatprotec.2010.11.017
55. Guo J, Sotto A, Martin A, Kim J (2017) Preparation and characterization of polyethersulfone mixed matrix membranes embedded with Ti- or Zr-incorporated SBA-15 materials. J Ind Eng Chem 45:257–265. https://doi.org/10.1016/j.jiec.2016.09.033
56. Hamaker HC (1937) The London—van der Waals attraction between spherical particles. Physica 4(10):1058–1072. https://doi.org/10.1016/S0031-8914(37)80203-7
57. Hardman E (1994) Some aspects of the design of filter fabrics for use in solid/liquid separation processes. Filtr Sep 31(8):813–806. https://doi.org/10.1016/0015-1882(94)80539-3
58. Hauser G (2008) Hygienische Produktionstechnologie. Wiley-VCH, Weinheim
59. Haynes CA, Norde W (1994) Globular proteins at solid/liquid interfaces. Colloids Surf B: Biointerfaces 2(6):517–566. https://doi.org/10.1016/0927-7765(94)80066-9
60. Heisenberg W (1927) Ueber den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik. Z Phys 43(3-4):172–198. https://doi.org/10.1007/BF01397280
61. Herwig H (2008) Strömungsmechanik. Einführung in die Physik von technischen Strömungen, 1st edn. Vieweg+Teubner, Wiesbaden
62. Hmidet N, El-Hadj Ali N, Haddar A, Kanoun S, Alya S-K, Nasri M (2009) Alkaline proteases and thermostable α-amylase co-produced by Bacillus licheniformis NH1. Characterization and potential application as detergent additive. Biochem Eng J 47(1-3):71–79. https://doi.org/10.1016/j.bej.2009.07.005
63. Hoffmann W, Reuter H (1984) Zirkulationsreinigen (CIP) von geraden Rohren in Abhängigkeit von der Oberflächenrauheit und anderen Einflußfaktoren. Chemie Ingenieur Technik 56(4):328–329. https://doi.org/10.1002/cite.330560419
64. Hofmann HA (2005) Wärmeübergang beim pulsierenden Prallstrahl. Dissertation, Universität Karlsruhe (TH)
65. Hofmann HM, Kaiser R, Kind M, Martin H (2007) Calculations of steady and pulsating impinging jets—an assessment of 13 widely used turbulence models. Numerical Heat Transfer, Part B: Fundamentals 51(6):565–583. https://doi.org/10.1080/10407790701227328
66. Horrocks AR, Anand S (2016) Handbook of technical textiles. Volume 1: technical textile processes, 2. Ed. Woodhead, Duxford
67. Hrycak P, Lee DT, Gauntner JW, Livingood J. N. B. (1970) Experimental flow characteristics of a single turbulent jet impinging on a flat plate. Technical report (NASA-TN-D-5690, E-5239). https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19700011262.pdf. Accessed 17 May 2020
68. Ibarz A, Garza S, Pagán J (2008) Nonenzymatic browning of selected fruit juices affected by D-galacturonic acid. Int J Food Sci Technol 43(5):908–914. https://doi.org/10.1111/j.1365-2621.2007.01541.x
69. Israelachvili JN (ed) (2011) Intermolecular and surface forces, 3rd edn. Burlington, Academic
70. Jensen B, Friis A (2005) Predicting the cleanability of mix-proof valves by use of wall shear stress. J Food Process Eng 28(2):89–106. https://doi.org/10.1111/j.1745-4530.2005.00370.x
71. Jullien C, Bénézech T, Carpentier B, Lebret V, Faille C (2003) Identification of surface characteristics relevant to the hygienic status of stainless steel for the food industry. J Food Eng 56(1):77–87. https://doi.org/10.1016/S0260-8774(02)00150-4
72. Jurado E, Herrera-Márquez O, Plaza-Quevedo A, Vicaria JM (2015) Interaction between non-ionic surfactants and silica micro/nanoparticles. Influence on the cleaning of dried starch on steel surfaces. J Ind Eng Chem 21:1383–1388. https://doi.org/10.1016/j.jiec.2014.06.011
73. Jurado-Alameda E, Herrera-Márquez O, Martinez-Gallegos JF, Vicaria JM (2015) Starch-soiled stainless steel cleaning using surfactants and α-amylase. J Food Eng 160:56–64. https://doi.org/10.1016/j.jfoodeng.2015.03.024
74. Kasemo B (2002) Biological surface science. Surf Sci 500(1-3):656–677. https://doi.org/10.1016/S0039-6028(01)01809-X
75. Katsikogianni M, Missirlis YF (2004) Concise review of mechanisms of bacterial adhesion to biomaterials and of techniques used in estimating bacteria-material interactions. Eur Cells Mater 8(8):37–57. https://doi.org/10.22203/eCM.v008a05
76. Katsikogianni MG, Missirlis YF (2010) Interactions of bacteria with specific biomaterial surface chemistries under flow conditions. Acta Biomater 6(3):1107–1118. https://doi.org/10.1016/j.actbio.2009.08.006
77. Khaldi M, Blanpain-Avet P, Guérin R, Ronse G, Bouvier L, André C, Bornaz S, Croguennec T, Jeantet R, Delaplace G (2015) Effect of calcium content and flow regime on whey protein fouling and cleaning in a plate heat exchanger. J Food Eng 147:68–78. https://doi.org/10.1016/j.jfoodeng.2014.09.020
78. Khalid NI, Aziz NA, Nuraini AA, Taip FS, Anuar MS (2014) Alkaline cleaning-in-place of pink guava puree fouling deposit using lab-scale cleaning test rig. Agriculture and Agricultural Science Procedia 2:280–288. https://doi.org/10.1016/j.aaspro.2014.11.040
79. Kidoaki S, Matsuda T (2002) Mechanistic aspects of protein/material interactions probed by atomic force microscopy. Colloids Surf B: Biointerfaces 23(2-3):153–163. https://doi.org/10.1016/S0927-7765(01)00232-6

80. Koglin B (1974) Systematik der Dispergiermittel. Chemie Ing Techn 46(17):720–726. https://doi.org/10.1002/cite.330461704
81. Koh E, Lee YT (2017) Antimicrobial activity and fouling resistance of a polyvinylidene fluoride (PVDF) hollow-fiber membrane. J Ind Eng Chem 47:260–271. https://doi.org/10.1016/j.jiec.2016.11.042
82. Kotsanopoulos KV, Arvanitoyannis IS (2015) Membrane processing technology in the food industry: food processing, wastewater treatment, and effects on physical, microbiological, organoleptic, and nutritional properties of foods. Crit Rev Food Sci Nutr 55(9):1147–1175. https://doi.org/10.1080/10408398.2012.685992
83. Kraume M (2012) Transportvorgänge in der Verfahrenstechnik. Grundlagen und apparative Umsetzungen, 2. Ed. Springer-Verlag, Berlin, Heidelberg
84. Krupp H (1967) Particle adhesion: theory and experiment. Adv Colloid Interf Sci 1(2):111–239
85. Kühnl W (2011) Kolloidale Wechselwirkungen zwischen Proteinen im Zusammenspiel mit fluid-dynamischen Kräften an der Grenzfläche von Filtrationsmembranen. Gezeigt am Beispiel der Fraktionierung von Milchproteinen mittels Mikrofiltration. Dissertation Technische Universität München. VDI-Verlag, Düsseldorf
86. Kumar R, Ismail AF (2015) Fouling control on microfiltration/ultrafiltration membranes: effects of morphology, hydrophilicity, and charge. J Appl Polym Sci 132(21). https://doi.org/10.1002/app.42042
87. Kupetz M, Aumer J, Harms D, Zarnkow M, Sacher B, Becker T (2017) High-throughput β-glucan analyses and their relationship with beer filterability. Eur Food Res Technol 243(2):341–351. https://doi.org/10.1007/s00217-016-2748-3
88. Kurtz O, Meyer J, Kasper G (2016) Influence of filter operating parameters on fine dust emissions from pulse-cleaned filter bags. Chem Eng Technol 39(3):435–443. https://doi.org/10.1002/ceat.201500340
89. Landau LD, Lifsic EM (1991) Hydrodynamik, 5th edn. Akademie, Berlin
90. Leach SJ, Walker GL, Smith AV, Farmer IW, Taylor G (1966) Some aspects of rock cutting by high speed water jets [and discussion]. Philos Trans R Soc A Math Phys Eng Sci 260(1110):295–310. https://doi.org/10.1098/rsta.1966.0051
91. Lee JS, Seo JA, Lee HH, Jeong SK, Park HS, Min BR (2017) Simple method for preparing thin film composite polyamide nanofiltration membrane based on hydrophobic polyvinylidene fluoride support membrane. Thin Solid Films 624:136–143. https://doi.org/10.1016/j.tsf.2017.01.031
92. Leipert C, Nirschl H (2011) Untersuchung der Reinigungsfähigkeit von Filtergeweben aus Polymeren. Filtrieren und Separieren 25(5):270–277
93. Leipert C, Nirschl H (2012) Untersuchungen zum Reinigungsverhalten von Filtermedien mithilfe pulsatorischer Strömung. Chemie Ingenieur Technik 84(8):1285. https://doi.org/10.1002/cite.201250370
94. Lifshitz EM, Hamermesh M (1956) The theory of molecular attractive forces between solids. Soviet Phys 2(1):73–83. https://doi.org/10.1016/B978-0-08-036364-6.50031-4
95. Lin T, Shen B, Chen W, Zhang X (2014) Interaction mechanisms associated with organic colloid fouling of ultrafiltration membrane in a drinking water treatment system. Desalination 332(1):100–108. https://doi.org/10.1016/j.desal.2013.11.001
96. Liu W, Fryer PJ, Zhang Z, Zhao Q, Liu Y (2006) Identification of cohesive and adhesive effects in the cleaning of food fouling deposits. Innovative Food Sci Emerg Technol 7(4):263–269. https://doi.org/10.1016/j.ifset.2006.02.006
97. Löffler F, Dietrich H, Flatt W (eds) (1988) Dust collection with bag filters and envelope filters. Vieweg+Teubner, Wiesbaden
98. Luckert K(E) (2004) Handbuch der mechanischen Fest-Flüssig-Trennung, 1st edn. Essen, Vulkan-Verlag
99. Marriott NG, Schilling W, Gravani RB (eds) (2018) Principles of food sanitation, 6th edn. New York, Springer
100. Martin H (1977) Heat and mass transfer between impinging gas jets and solid surfaces. Adv Heat Tran 13:1–60. https://doi.org/10.1016/S0065-2717(08)70221-1
101. Mauermann M (2012) Methode zur Analyse von Reinigungsprozessen in nicht immergierten Systemen der Lebensmittelindustrie. Dissertation, Technische Universität Dresden
102. Mauermann M, Eschenhagen U, Bley T, Majschak J-P (2009) Surface modifications – application potential for the reduction of cleaning costs in the food processing industry. Trends Food Sci Technol 20:S9–S15. https://doi.org/10.1016/j.tifs.2009.01.020
103. Miao M, Xin JH (2017) Engineering of high-performance textiles, 1st edn. Woodhead, Duxford
104. Middlewood PG, Carson JK (2012) Extraction of amaranth starch from an aqueous medium using microfiltration. Membrane fouling and cleaning. J Membr Sci 411-412:22–29. https://doi.org/10.1016/j.memsci.2012.04.008
105. Milchers W (2001) Abtrag von Polymeren mit dem reinen Wasserstrahl. Dissertation Universität Hannover. Bericht aus dem Institut für Werkstoffkunde, Universität Hannover, vol 639. VDI-Verl., Düsseldorf
106. Moeller R-S (2018) Haftkräfte, Alterung und Überwachung funktionaler Oberflächen - Gärtücher im Gebrauch. Dissertation, Karlsruhe Institute of Technology
107. Moeller R-S, Nirschl H (2018) Optical dirt detection for a demand-controlled cleaning of woven filter cloth. Sep Purif Technol 207:336–343. https://doi.org/10.1016/j.seppur.2018.06.058
108. Moriarty TF, Poulsson AHC, Rochford ETJ, Richards RG (2015) Bacterial adhesion and biomaterial surfaces. Comprehensive Biomater 4:75–100. https://doi.org/10.1016/B978-0-08-055294-1.00007-6
109. Morra M, Cassinelli C (1998) Bacterial adhesion to polymer surfaces. A critical review of surface thermodynamic approaches. J Biomater Sci Polym Ed 9(1):55–74. https://doi.org/10.1163/156856297X00263
110. Mulugeta E, Geyer M (2005) Characterising the washing processes of vegetables and potatoes. Biosyst Eng 91(4):441–453. https://doi.org/10.1016/j.biosystemseng.2005.05.009
111. Nakamura M, Hori N, Ando H, Namba S, Toyama T, Nishimiya N, Yamashita K (2016) Surface free energy predominates in cell adhesion to hydroxyapatite through wettability. Mater Sci Eng C Mater Biol Appl 62:283–292. https://doi.org/10.1016/j.msec.2016.01.037
112. Narziß L, Back W (2008) Abriss der Bierbrauerei, 7th edn. Wiley-VCH, Weinheim
113. Nassauer J, Kessler HG (1985) Einfluß elektrostatischer Vorgänge auf die Reinigung von Oberflächen. Chemie Ingenieur Technik 57(3):235–236. https://doi.org/10.1002/cite.330570309
114. Nerín C, Aznar M, Carrizo D (2016) Food contamination during food process. Trends Food Sci Technol 48:63–68. https://doi.org/10.1016/j.tifs.2015.12.004
115. Neugrodda C, Gastl M, Becker T (2015) Comparison of foam analysis methods and the impact of beer components on foam stability. J Am Soc Brew Chem 73(2):170–178. https://doi.org/10.1094/ASBCJ-2015-0129-01a
116. Nguyen T, Roddick FA, Fan L (2012) Biofouling of water treatment membranes: a review of the underlying causes, monitoring techniques and control measures. Membranes 2(4):804–840. https://doi.org/10.3390/membranes2040804
117. Noh H, Vogler EA (2006) Volumetric interpretation of protein adsorption: mass and energy balance for albumin adsorption to

particulate adsorbents with incrementally increasing hydrophilicity. Biomaterials 27(34):5801–5812. https://doi.org/10.1016/j.biomaterials.2006.08.005

118. Oertel H, Böhle M, Reviol T (2015) Strömungsmechanik. Für Ingenieure und Naturwissenschaftler, 7th edn. Springer, Wiesbaden
119. Ohnesorge WV (1936) Die Bildung von Tropfen an Düsen und die Auflösung flüssiger Strahlen. J Appl Math Mech 16(6):355–358. https://doi.org/10.1002/zamm.19360160611
120. Olsen HS, Falholt P (1998) The role of enzymes in modern detergency. J Surfactant Deterg 1(4):555–567. https://doi.org/10.1007/s11743-998-0058-7
121. Or CM, Lam KM, Liu P (2011) Potential core lengths of round jets in stagnant and moving environments. J Hydro Environ Res 5(2):81–91. https://doi.org/10.1016/j.jher.2011.01.002
122. Otto C, Zahn S, Hauschild M, Babick F, Rohm H (2016) Comparative cleaning tests with modified protein and starch residues. J Food Eng 178:145–150. https://doi.org/10.1016/j.jfoodeng.2016.01.015
123. Otto C, Zahn S, Plenker J, Rohm H (2014) Application of a flow cell for the comparative investigation of the cleaning behavior of starch and protein. J Food Eng 131:1–6. https://doi.org/10.1016/j.jfoodeng.2014.01.008
124. Otto C, Zahn S, Rost F, Zahn P, Jaros D, Rohm H (2011) Physical methods for cleaning and disinfection of surfaces. Food Eng Rev 3(3-4):171–188. https://doi.org/10.1007/s12393-011-9038-4
125. Palabiyik I, Yilmaz MT, Fryer PJ, Robbins PT, Toker OS (2015) Minimising the environmental footprint of industrial-scaled cleaning processes by optimisation of a novel clean-in-place system protocol. J Clean Prod 108:1009–1018. https://doi.org/10.1016/j.jclepro.2015.07.114
126. Park J-A, Kim S-B (2015) DLVO and XDLVO calculations for bacteriophage MS2 adhesion to iron oxide particles. J Contam Hydrol 181:131–140. https://doi.org/10.1016/j.jconhyd.2015.01.005
127. Petrus H, Li H, Chen V, Norazman N (2008) Enzymatic cleaning of ultrafiltration membranes fouled by protein mixture solutions. J Membr Sci 325(2):783–792. https://doi.org/10.1016/j.memsci.2008.09.004
128. Pope SB (2015) Turbulent flows, 2nd edn. Cambridge University Press, Cambridge
129. Prieto NE, Lilienthal W, Tortorici PL (1996) Correlation between spray cleaning detergency and dynamic surface tension of nonionic surfactants. J Am Oil Chem Soc 73(1):9–13. https://doi.org/10.1007/BF02523441
130. Purchas DB, Sutherland K (2002) Handbook of filter media, 2nd edn. Elsevier Science, Oxford
131. Quadt T, Schmidt E (2012) Untersuchungen zur Haftkraftberechnung bei der Partikelablösung in der Querstromfiltration. Filtrieren und Separieren 26(3):175–181
132. Rabinovich YI, Adler JJ, Ata A, Singh RK, Moudgil BM (2000a) Adhesion between nanoscale rough surfaces: I. Role of asperity geometry. J Colloid Interface Sci 232(1):10–16. https://doi.org/10.1006/jcis.2000.7167
133. Rabinovich YI, Adler JJ, Ata A, Singh RK, Moudgil BM (2000b) Adhesion between nanoscale rough surfaces: II. Measurement and comparison with theory. J Colloid Interface Sci 232(1):17–24. https://doi.org/10.1006/jcis.2000.7168
134. Rahimpour A, Madaeni SS (2010) Improvement of performance and surface properties of nano-porous polyethersulfone (PES) membrane using hydrophilic monomers as additives in the casting solution. J Membr Sci 360(1-2):371–379. https://doi.org/10.1016/j.memsci.2010.05.036
135. Ravereau J, Fabre A, Brehant A, Bonnard R, Sollogoub C, Verdu J (2016) Ageing of polyvinylidene fluoride hollow fiber membranes in sodium hypochlorite solutions. J Membr Sci 505:174–184. https://doi.org/10.1016/j.memsci.2015.12.063
136. Reh A, Plank B, Kastner J, Gröller E, Heinzl C (2012) Porosity maps - interactive exploration and visual analysis of porosity in carbon fiber reinforced polymers. Computer Graphics Forum 31(3):1185–1194. https://doi.org/10.1111/j.1467-8659.2012.03111.x
137. Reynolds O (1883) An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels. Philos Trans R Soc Lond 174(224-226):84–99. https://doi.org/10.1098/rstl.1883.0029
138. Rieger H, Piesche M (2013) CFD-Simulation zur Berechnung der durch Gewebestrukturen induzierten Strömungsfelder mithilfe der Immersed-boundary-Methode. Chemie Ingenieur Technik 85(12):1921–1927. https://doi.org/10.1002/cite.201300001
139. RIWETA 4.2 (2020a) Polyamid 6 (PA6). http://www.kern.de/de/technisches-datenblatt/polyamid-pa-6?n=1102_1. Accessed 16 May 2020
140. RIWETA 4.2 (2020b) Polybutylenterephthalat (PBT). http://www.kern.de/de/technisches-datenblatt/polybutylenterephthalat-pbt?n=1311_1. Accessed 16 May 2020
141. RIWETA 4.2 (2020c) Polyethersulfon (PES). http://www.kern.de/cgi-bin/riweta.cgi?lng=1&nr=2441. Accessed 16 May 2020
142. RIWETA 4.2 (2020d) Polyethylentherephtalat (PET). http://www.kern.de/de/technisches-datenblatt/polyethylenterephthalat-pet?n=1301_1. Accessed 16 May 2020
143. RIWETA 4.2 (2020e) Polytetrafluorethylen (PTFE). http://www.kern.de/de/technisches-datenblatt/polytetrafluorethylen-ptfe?n=1601_1. Accessed 16 May 2020
144. Rumpf H (1974) Die Wissenschaft des Agglomerierens. Chemie Ingenieur Technik 46(1):1–46. https://doi.org/10.1002/cite.330460102
145. Rushton A, Ward AS, Holdich RG (1999) Solid-liquid filtration and separation technology. Wiley-VCH, Weinheim
146. Schlichting H, Krause E (2006) Grenzschicht-Theorie, 0th edn. Springer, Berlin
147. Schmidt RH, Rodrick GE (2003) Food safety handbook. Wiley, Hoboken, N.J.
148. Schubert H (1982) Kapillarität in porösen Feststoffsystemen. Springer, Berlin
149. Schwegmann H, Ruppert J, Frimmel FH (2013) Influence of the pH-value on the photocatalytic disinfection of bacteria with TiO2 - explanation by DLVO and XDLVO theory. Water Res 47(4):1503–1511. https://doi.org/10.1016/j.watres.2012.11.030
150. Sharma PK, Hanumantha Rao K (2003) Adhesion of Paenibacillus polymyxa on chalcopyrite and pyrite: surface thermodynamics and extended DLVO theory. Colloids Surf B: Biointerfaces 29(1):21–38. https://doi.org/10.1016/S0927-7765(02)00180-7
151. Siebert KJ, Lynn PY (1997) Haze-active protein and polyphenols in apple juice assessed by turbidimetry. J Food Sci 62(1):79–84. https://doi.org/10.1111/j.1365-2621.1997.tb04372.x
152. Siekmann HE, Thamsen PU (2009) Strömungslehre für den Maschinenbau. In: Technik und Beispiele, 2nd edn. Springer, Berlin
153. Sigloch H (2017) Technische Fluidmechanik, 0th edn. Springer, Berlin
154. Spurk JH, Aksel N (2010) Strömungslehre. Einführung in die Theorie der Strömungen, 8th edn. Springer, Berlin
155. Stahl S, Leipert C, Nirschl H (2013) The cleanability of particle loaded woven filter media in solid–liquid separation. Sep Purif Technol 110:196–201. https://doi.org/10.1016/j.seppur.2013.02.003
156. Stahl S, Siggelkow S, Nirschl H (2007) A microbiological test method to determine the cleanability of filter media in solid-

liquid-separation applications. Eng Life Sci 7(2):136–142. https://doi.org/10.1002/elsc.200620183
157. Stanga M (ed) (2010) Sanitation, Cleaning and disinfection in the food industry, 1st edn. Weinheim, Ed. Wiley-VCH
158. Stieß M (ed) (2009) Mechanische Verfahrenstechnik - Partikeltechnologie 1, 3rd edn. Berlin, Springer
159. Stokes GG (1845) On the theories of internal friction of fluids in motion. Transactions of the Cambridge Philosophical Society (8): 287–305
160. Tamime AY (ed) (2008) Cleaning-in place: dairy, food and beverage operations, 3rd edn. Oxford, Wiley-Blackwell
161. Tang G, Chen Y, Silaen AK, Krotov Y, Riley MF, Zhou CQ (2019a) Investigation on coherent jet potential core length in an electric arc furnace. Steel Research International 90(4): Publication: 1800381 1-9. Doi: https://doi.org/10.1002/srin.201800381
162. Tang G, Chen Y, Silaen AK, Wang T, Zhou CQ (2019b) Investigation of supersonic oxygen jet potential core length at various ambient temperatures. JOM 71(2):633–643. https://doi.org/10.1007/s11837-018-3244-y
163. Tani I, Komatsu Y (1966) Impingement of a round jet on a flat surface. Proceedings of the Eleventh International Congress of Applied Mechanics:672–676. https://doi.org/10.1007/978-3-662-29364-5_88
164. Templin BR, Leith D (1988) Effect of operating conditions on pressure drop in a pulse-jet cleaned fabric filter. Plant/Operations Progress 7(4):215–222. https://doi.org/10.1002/prsb.720070404
165. Tien C (2012) Principles of filtration, 1st edn. Elsevier, Boston
166. Ulmer MU (2014) Analyse der Reinigung von Sieb- und Filtergeweben im Querstrom mit Hilfe der Gesetze des Stoffübergangs. Dissertation, Technische Universität München
167. Valentas KJ (1997) Handbook of food engineering practice. CRC, Boca Raton
168. van Oss CJ (ed) (2006) Interfacial forces in aqueous media, 2nd edn. Boca Raton, CRC
169. van Oss CJ (2007) Development and applications of the interfacial tension between water and organic or biological surfaces. Colloids Surf B: Biointerfaces 54(1):2–9. https://doi.org/10.1016/j.colsurfb.2006.05.024
170. Verwey EJW, Overbeek JTG (1947) Theory of the stability of lyophobic colloids. J Phys Colloid Chem 51(3):631–636. https://doi.org/10.1021/j150453a001
171. Visser J (1972) On Hamaker constants. A comparison between Hamaker constants and Lifshitz-van der Waals constants. Adv Colloid Interf Sci 3(4):331–363. https://doi.org/10.1016/0001-8686(72)85001-2
172. Visser J (1989) Van der Waals and other cohesive forces affecting powder fluidization. Powder Technol 58(1):1–10. https://doi.org/10.1016/0032-5910(89)80001-4
173. Weidemann C (2014) Reinigungsfähigkeit mithilfe kontinuierlicher und pulsierender Strömung. Dissertation, Karlsruhe Institute of Technology
174. Weidemann C, Vogt S, Nirschl H (2014) Cleaning of filter media by pulsed flow – establishment of dimensionless operation numbers describing the cleaning result. J Food Eng 132:29–38. https://doi.org/10.1016/j.jfoodeng.2014.02.005
175. Weigl B (2003) Trennkräfte zwichen Mikroorganismen, Partikeln und Oberflächen. Dissertation, Technische Universität München
176. Werner R, Bollwein B, Petersen R, Tippmann J, Becker T (2016) Pulsatile jet cleaning of filter cloths contaminated with yeast cells. Chem Eng Technol. https://doi.org/10.1002/ceat.201600049
177. Wildbrett G (ed) (2006) Reinigung und Desinfektion in der Lebensmittelindustrie, 2nd edn. Hamburg, Behr
178. Wilson DI, Le BL, Dao HDA, Lai KY, Morison KR, Davidson JF (2012) Surface flow and drainage films created by horizontal impinging liquid jets. Chem Eng Sci 68(1):449–460. https://doi.org/10.1016/j.ces.2011.10.003
179. Wu W, Giese RF, van Oss CJ (1999) Stability versus flocculation of particle suspensions in water—correlation with the extended DLVO approach for aqueous systems, compared with classical DLVO theory. Colloids Surf B: Biointerfaces 14(1-4):47–55. https://doi.org/10.1016/S0927-7765(99)00023-5
180. Xing J, Ni Q-Q, Deng B, Liu Q (2016) Morphology and properties of polyphenylene sulfide (PPS)/polyvinylidene fluoride (PVDF) polymer alloys by melt blending. Compos Sci Technol 134:184–190. https://doi.org/10.1016/j.compscitech.2016.08.020
181. Xu L-C, Logan BE (2005) Interaction forces between colloids and protein-coated surfaces measured using an atomic force microscope. Environ Sci Technol 39(10):3592–3600. https://doi.org/10.1021/es048377i
182. Xu L-C, Siedlecki CA (2007) Effects of surface wettability and contact time on protein adhesion to biomaterial surfaces. Biomaterials 28(22):3273–3283. https://doi.org/10.1016/j.biomaterials.2007.03.032
183. Yang J, Bhagat RK, Fernandes RR, Nordkvist M, Gernaey KV, Krühne U, Wilson DI (2019) Cleaning of toothpaste from vessel walls by impinging liquid jets and their falling films: quantitative modelling of soaking effects. Chem Eng Sci 208:115148. https://doi.org/10.1016/j.ces.2019.08.006
184. Yousaf MS, Yusof S, Bin Abdul Manap MY, Abd-Aziz S (2010) Storage stability of clarified banana juice fortified with inulin and oligofructose. J Food Process Preserv 34:599–610. https://doi.org/10.1111/j.1745-4549.2009.00419.x
185. Zhang X, Wang H, Liu Z, Zhu Y, Wu S, Wang C, Zhu Y (2017) Fabrication of durable fluorine-free superhydrophobic polyethersulfone (PES) composite coating enhanced by assembled MMT-SiO2 nanoparticles. Appl Surf Sci 396:1580–1588. https://doi.org/10.1016/j.apsusc.2016.11.217
186. Zuki FM (2012) The use of XDLVO theory in the prediction of adhesion of Pseudomonas putida to mineral surfaces. Dissertation, University of Sheffield

5.3 Publication 2: Jet Cleaning of Filter Cloths Used in Solid-Liquid Separation: A High-Speed Video Evaluation

Chemical Engineering & Technology

Research Article

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Jet Cleaning of Filter Cloths Used in Solid-Liquid Separation: A High-Speed Video Evaluation

Cleaning avoids cross-contamination and sustains production safety and efficiency. While there have been discoveries for technical surfaces, data on activities for filter cloth are still in the early stages. In the food industry, there is a lack of knowledge and innovative ideas on how to clean cloths efficiently. This study combined high-speed recordings with cleaning experiments. Cleaning of eleven filters was captured, enabling time-resolved analysis of the cleaning degree, the cleaning homogeneity, and insights into the mechanisms. The findings divide cloth cleaning into three phases, each significantly influenced by the properties of the cloth. Exemplarily, close-mesh cloths have smoother surfaces that facilitate cleaning. Coarse structures with flow channels on the cloth surface can complicate cleaning.

Supporting Information available online

Keywords: Cleaning control, Filter cloth cleaning, Filter press, High-speed video analysis, Nozzle cleaning

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1 Introduction

Cleaning is one of the most crucial unit operations in the food industry. As defined by the German DIN 10516 [1], cleaning removes all (visible) contamination from any surface when using a suitable cleaning utensil. Cleaning success is well known to be dependent on the temperature, the chemical agents, mechanical effects, and the time [2]. Furthermore, publications in recent years have demonstrated that the targeted contamination and the surface characteristics have a high cleaning impact, as well [3]. Cleanability in this context refers to how easily a surface can be cleared of adhering contamination in terms of time, fluid consumption, and the thoroughness of the cleaning.

Increasing cleaning efficiency is essential for economic and ecological reasons [2, 4, 5]. While cleaning vessels, equipment, and technical surfaces were researched extensively, other items, such as filter media, have received little attention. Exemplary media are woven filter cloths applied in filter systems, e.g., presses. These fabrics enable solid-fluid separation in food production, e.g., mash filtration in breweries. They form the barrier that keeps the retentate in place while allowing the filtrate to pass through. Filter cloths are textiles with warp and weft threads interwoven to distinct weave patterns [6]. The threads vary in diameter and can be monofil (one single thread) or multifil (various threads twisted into one). These cloth characteristics determine the resulting mesh sizes. Such cloth parameters can be summed up to the term filter geometry, which represents the complexity of the cloth and influences the its cleanability.

According to the European Hygienic Engineering & Design Group (EHEDG) [7], the roughness of a surface plays a vital role in its cleanability. Although Mauermann et al. [8] identified more influence of the surface energy and less of rougher stainless-steel surfaces, a more significant roughness influence can be assumed for cloths due to an excessively complex surface. Especially here, a significant backlog demand in cleaning exists. While the actual filtration processes are well understood, the regeneration of filters still adheres to rigid and exaggerated concepts. Although there are partly automated concepts, most of the cleaning depends on the operator's experience and never considers the degree of contamination present. Thus, exaggerated cleaning is used to achieve a safe status at the cost of economic and ecological aspects. There is a lack of optimization and necessary approaches for enabling innovative, fully automated, demand-oriented, or digitalized methods. Finally, the corresponding manufacturing recommendations for hygienic design can still be improved [9].

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Previous studies looked at the particle-based cleanability of filter cloths and cleaning efficiency test procedures [10–12]. Necessary cleaning parameters of wash jet cleaning for model and food-related contaminations were studied by Morsch et al. [13, 14]. Other publications focused on alternative cleaning procedures like pulsatile jet cleaning [15–18]. These publications paved the way for a first understanding and optimization of cloth cleaning and the development of new concepts. However, a thorough examination of the critical cleaning mechanisms and the influence of different cloth properties is lacking, although being especially crucial in food applications. For instance, in previous studies, only the status before and after the cleaning procedure was observed, which leaves out the critical steps of a wash jet affecting the cloth. Most notably, the effect of the filter cloth geometry on the actual food-related contamination necessitates extensive research. Morsch [19] already assumed the influence of the filter geometry and showed worse cleaning results using coarse mesh sizes.

This paper examines the time-resolved cleaning of various filter cloths with optical methods. For this purpose, a high-speed (HS) camera monitored the impact of a wash jet on a filter cloth and its cleaning effect. The cleaning efficiency and homogeneity could be deduced from these time-resolved videos. Several filter cloth types were tested, with differences in weave type, thread diameters, mesh sizes, and material. This cloth selection allowed a more thorough examination of the direct cleaning impact of common cloth properties. As model contamination, brewer's spent grains (BSG) were used to simulate a highly practice-close case study that is a frequent problem in breweries. The findings yielded important conclusions about different cleaning phases and the effect of the cloth on its cleanability.

2 Material and Methods

2.1 Filter Cloth Types

Eleven different cloth types were selected for the experiments, varying in weave type, material, and mesh size (for the properties, see Tab. 1). The cloth manufacturers were Sefar AG (Thal, Switzerland) and Otto Markert & Sohn GmbH (Neumünster, Germany). This selection emphasized the individual impact on cleanability and covered a wide range of cloth types in this application field. Fig. 1 shows top views of the samples with the

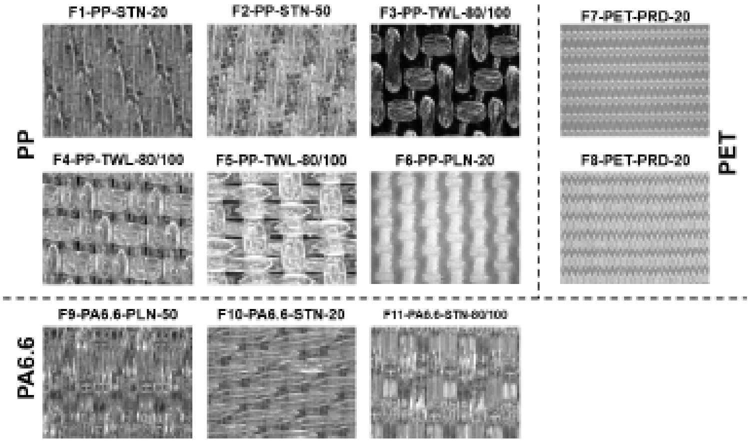

Figure 1. Top-view images of the filter cloth samples with their respective designations (magnification 20×), clustered according to the material.

Table 1. Filter cloth samples with specific properties and manufacturer description.[a)]

Type	Type (mfr.)[a)]	Thread material	Weave pattern	Mesh sizes (mfr.)[a)] [µm]	Thickness (mfr.)[a)] [µm]	R_a [µm]	S_a [µm]
F1-PP-STN-20	05-1001-SK 020	PP	STN	20	500	4.2	16.9
F2-PP-STN-50	05-1001-K 043	PP	STN	50	540	6.3	27.6
F3-PP-TWL-80/100	05-1001-K 70×320	PP	TWL	80, 100	530	3.5	13.6
F4-PP-TWL-80/100	05-1001-K 120	PP	TWL	80, 100	480	8.5	15.1
F5-PP-TWL-80/100	05-1001-K 215	PP	TWL	80, 100	480	5.8	15.6
F6-PP-PLN-20	PP 2436 (calendared)	PP	PLN (multifilament)	< 20	780	33.8	68.2
F7-PET-PRD-022	07-76-SK 022	PET	PRD	< 20	185	13.5	20.1
F8-PET-PRD-012	07-90-SK 012	PET	PRD	< 20	80	6.5	6.9
F9-PA6.6-PLN-50	03-1001-SK 066	PA6.6	PLN	50	520	6.6	21.1
F10-PA6.6-STN-20	03-1010-SK 038	PA6.6	STN	20	470	5.6	19.1
F11-PA6.6-STN-80/100	03-1001-K 080	PA6.6	STN	80, 100	520	12.3	30.2

[a)] Information source: technical data sheet of the respective manufacturer.

surface geometry captured by a digital microscope (VHX-200D; Keyence Corporation, Osaka, Japan) with a magnification factor of 20×.

The woven cloths could be categorized into three clusters according to their material: polypropylene (PP), polyethylene terephthalate (PET), and polyhexamethylene adipamide (PA6.6). The mesh sizes ranged from <20 to 100µm. The weave patterns of the samples were either plain (PLN), satin (STN), or twill (TWL). In addition, samples with a plain reverse Dutch (PRD) weave were used. This weave structure differed from the standard PLN in that the warp and weft thread diameters were different. The surface roughness was measured using a surf mobile confocal microscope (NanoFocus AG, Oberhausen, Germany) in accordance with ISO 4287 [20] and ISO 25178 [21]. The mean roughness index R_a[1] and the mean arithmetic height value S_a were selected to define the individual line and surface roughness [21]. While R_a described the roughness profile on a particular measurement line, S_a extended the measurements and specified the entire surface. The value of S_a represented the height difference between each two points and the surface arithmetic mean.

2.2 HS Camera System and Video Acquisition

The camera VW9000 and the objective VH-Z20R/Z20T (Keyence Corporation, Osaka, Japan) were used for monitoring the cleaning process. The system recorded HS videos at 500 frames per second for 2.0 s, with an exposure time of 1/1000 s. The resulting videos provided high-quality slow-motion videos that allowed tracing of the entire cleaning. Each video could be divided into single images to show the cleaning in greater detail and for further data evaluation. Any further advantages and disadvantages of the system are discussed in the Supporting Information (SI).

2.3 Cleaning Setup

The experimental studies were conducted in a cleaning device developed for the pilot filter press Meura 2001 (MEURA, Péruwelz, Belgium) in the Research Brewery Weihenstephan (Fig. 2). In this case, a traverse system allowed for an automated approach of the cleaning nozzle to the filter, resulting in a demand-oriented cleaning procedure. The applied cleaning nozzle was the full/round jet nozzle 544.360.30.CA.00.1

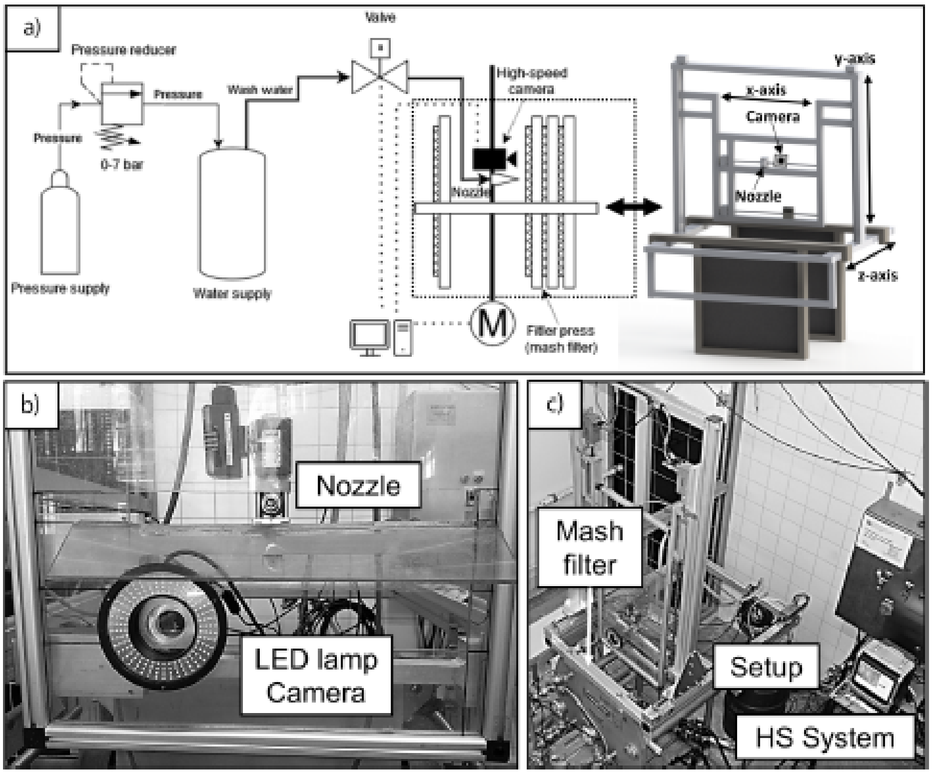

Figure 2. Experimental setup. (A) Process flow chart and computer-aided design (CAD) drawing of the setup. (B) Opto-mechanical cleaning unit. (C) Setup overview with the HS system and the mash filter.

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[1] List of symbols at the end of the paper.

(Lechler GmbH, Metzingen, Germany), using a pressure of 3×10^5 Pa. More details about the setup automation and the nozzle can be found in the SI.

In most experiments, the cleaning time was 2.0 s, which was long enough to see the full impact of an impacting jet on the cloth surface. According to Siekmann et al. [22] and Sigloch [23], the main effect of the cleaning occurs within the first 1.5 s, which is why the selected time frame enabled sufficient observation of the different cleaning phases. In all experiments, the distance between the cleaning nozzle and the cloth surface was 35 mm (z-axis). This value originated from previous publications of Morsch et al. [13, 14], where this distance demonstrated high suitability.

2.4 Preparation of the Contamination

For the model contamination, the industrial example brewery was selected. Thus, a practical method was necessary to produce a standardized BSG composition. According to the literature [24, 25], BSG is a complex mixture of proteins, carbohydrates, water-insoluble components (husks), and other partially sticky substances. These variables provided a good starting point for a model contaminant with adhesive and cohesive binding forces.

The preparation of this BSG-based model contamination followed the congress mash method according to MEBAK (Mitteleuropäische Brautechnische Analysenkommission) (see the SI) [26]. This practical procedure allowed the creation of a standardized fouling matrix to analyze cleaning effects in the experimental runs. The particle size distribution q3 of the malt particles in the mash was measured with a Mastersizer 3000 (Malvern Instruments, Malvern, UK) and ranged from >5 to 1000 µm, with the most significant proportion in the range of 20–225 µm. Regarding the mesh sizes (Tab. 1), these particle sizes could be retained by the cloths to deposit in the mesh apertures.

2.5 Soiling of Filter Cloths

The respective filter cloth with a total size of 297 mm × 210 mm was clamped in a frame to simulate cloth tightening similar to that in a filter plate. Then, an acrylic glass pattern with six round holes (7 cm in diameter) was placed on the clamped cloth, generating reproducible contamination spots. Finally, 20 mL of the prepared congress mash was poured homogeneously into each pattern hole. Afterward, a specific sedimentation time of 1.5 h at 20 °C was used to allow particles to penetrate the meshes, form adhesive forces to the surface, create cohesive forces and achieve a filter cake with defined moisture. The contaminated filter cloth had been placed in the cleaning apparatus and was ready for the experimental trials. The cloths were positioned vertically to simulate the condition of nozzle cleaning in a filter press.

3 Results and Discussion

3.1 Video Evaluation and Cleaning Analysis

The automated cleaning device approached each prepared contamination spot and fired a precise jet. This procedure produced a distinct cleaning effect dependent on the properties of the cloth. All other parameters, like the nozzle, the cleaning fluid, and the contamination, were kept constant.

In every case, the HS camera system captured a full video and could thus monitor the cleaning. As a result of these slow-motion videos, an analysis method was developed to identify the cleaning progress time dependently. The videos were cut into frames, resulting in single images in BMP format. Finally, only the tenth image in chronological order was used for analysis to reduce the complexity of the measurement results. Thus, a specific image processing algorithm was used to perform the final residue analysis on each image.

The acquired images were analyzed by a batch evaluation algorithm programmed using MATLAB 2019b by MathWorks® (Natick, MA, USA). The code was based on a threshold analysis and the contrast between the contamination and the filter cloth. The advantage of this method was its quick analysis combined with high precision. Any information about the detection procedure and the developed algorithm can be found in the SI. The analysis results were used to determine the cleaning degree G and the cleaning homogeneity HF of each cloth. Fig. 3 depicts the residue analysis by listing the required steps and exemplary recordings.

The parameter used to determine the cleanability was the cleaning degree G. It represented the area cleaned by the impacting jet. The cleaning degree was computed by

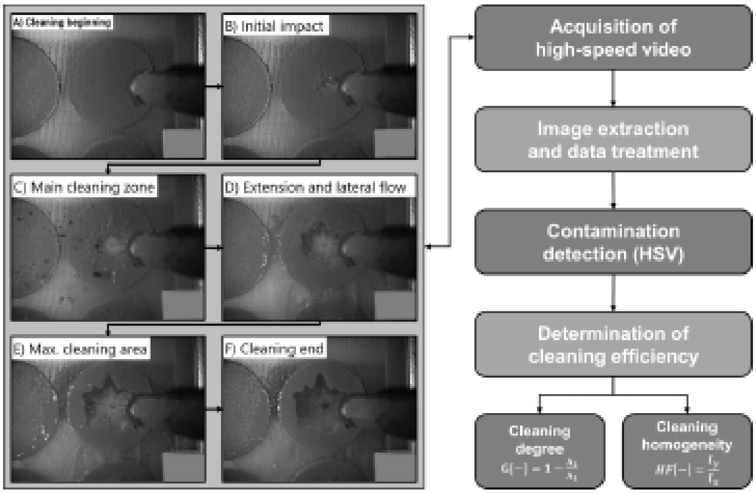

Figure 3. Schematic illustration of the image-processing procedure and determined parameters evaluating the cleaning efficiency.

comparing the contamination load in pixels before cleaning, A_1, and after cleaning, A_2 (Eq. (1)).

$$G[-] = 1 - \frac{A_2}{A_1} \tag{1}$$

A value of 0 means no cleaning effect was observed, while 1 designated the complete residue removal.

However, G only showed the total effect on the surface without specifying any locally resolved cleaning effects. During the initial experimental runs, it became clear that each filter cloth displayed a distinct form of the cleaned surface. As a result, a location-based and appropriate cleaning pattern calculation method became necessary. For this purpose, the homogeneity factor *HF* as a second characteristic was introduced, illustrated in Eq. (2).

$$HF[-] = \frac{l_y}{l_x} \tag{2}$$

A process engineering approach to evaluate characteristic particle forms was adapted for the determination of *HF*. Here, the most extended length of the cleaned surface in y- (l_y) and x-direction (l_x) was measured with MATLAB by MathWorks® (USA) – the division of y to x results in *HF*. A value of 1 indicates that the cleaning effect acted homogeneously in a circular cleaning shape. Any deviation denotes a heterogeneous cleaning effect.

Fig. 4 shows the procedure for the determination of l_y and l_x and the decision criteria. The selection of l_n was based on the most extended range within the respective quadrant of the x-y coordinate system.

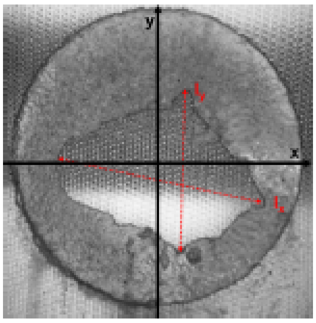

Figure 4. Exemplary cleaned filter cloth with geometric decision criteria for l_y and l_x.

3.2 Cleanability of the Selected Filter Cloth as a Function of the Cleaning Time

Fig. 5 illustrates the time-resolved cleaning degrees of the filter cloths. Since Leipert et al. [10] found only a minor material influence, the results were clustered material-dependently into three subfigures. Following Mauermann [27], cleaning time-resolved monitoring is crucial for analyzing occurring effects and efficiency.

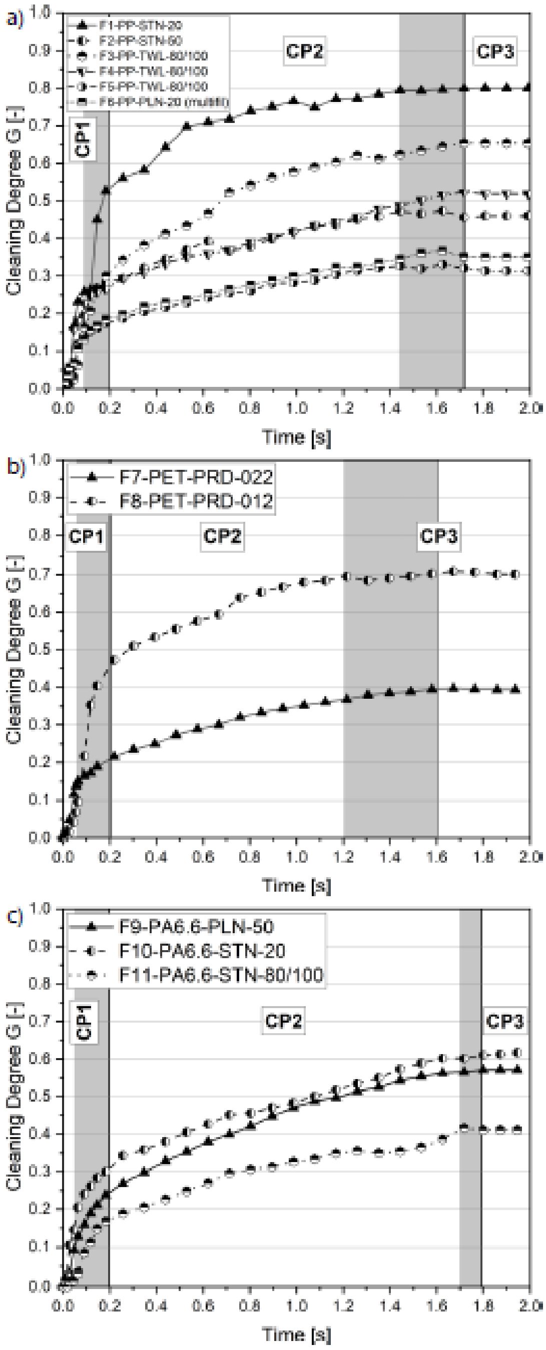

Figure 5. Gradual development of the cleaning degree G of 11 filter cloths, grouped according to the material. Cloths manufactured of (A) PP, (B) PET, (C) PA6.6. CP = cleaning phase (individual sections are qualitatively visualized using a gray-colored area). Other constant cleaning parameters: v = 11.44 m s^{-1}, $p = 3 \times 10^5$ Pa, $x_{\text{Nozzle\_Surface}}$ = 35 mm, T = 22 °C, n = 6. The confidence intervals (α = 0.05) ranged from 0.05 to 0.10 and are not shown in the graph for readability.

The results showed increasing cleaning degrees over time. In most cases, the curves followed different cleaning efficiencies, resulting in different final cleaning degrees *G*. However, in no case did the filter cloths reach a *G* value of 1.0. This can be attributed to the fact that the contaminated area was selected as oversized. This size was used in all experiments as the specific area to be cleaned was the decisive criterion. So, it was unimportant whether the specific cleaning concept also cleaned the entire experimental surface. Therefore, this overdimensioning even turned out to be an advantage, as it enabled a high degree of comparability between the different cleaning experiments. As a result, different cleaning effects could occur within the same material cluster, implying that a material influence could not be demonstrated. This aspect was remarkable as the material specifically influences the cleaning surfaces. Here, the surface energy or wettability (e.g., determination via contact angles) is essential to consider [8]. However, concerning filter cloths, the complex structured surfaces seem to have more influence on the cleanability.

Initially, the contamination was homogeneous in each spot, and the effecting cleaning parameters were kept constant. As a result, the cleaning success had to depend on the filter structure, such as different weaves, meshes, and thread sizes. Individual properties (Tab. 1) revealed higher *G* in cleaning cloths with smaller mesh sizes, indicating better cleanability. Significantly, this aspect was represented by F1-PP-STN-20, F8-PET-PRD-012, and F10-PA6.6-STN-20, which showed the best cleanability while having the smallest meshes. The coarser meshes almost always resulted in the lowest cleaning degree. This observation could be combined with the findings of the roughness profiles in Tab. 1. For instance, all filters with the best cleanability also have minor R_a and, in parts, S_a values.

Furthermore, the weave type, as an additional central parameter, had an effect that was directly related to the mesh size and thread diameter. When the mesh sizes were small, PLN and STN weaves favored cleanability. The weave pattern explained this observation where the PLN and STN weaves show more homogeneous structures than TWL. These parameters were also part of other research findings in which smooth surfaces showed an appropriate hygienic design. Consequently, a significant influence of the filter geometry on the cleanability could be concluded.

The multiple yarn, which resulted in poor cleanability, was an exception to these findings. The previous conclusion could be underlined as the filter cloth F6-PP-PLN-20 showed the highest R_a and S_a values due to the increased roughness. This yarn bunch is also thicker, resulting in deeper valleys between the threads. At first glance, this conclusion contradicts the findings of Morsch et al. [13], who found multifil weaves more easily cleanable. However, these results were based on cleaning in a small area; so, a detailed observation of the cleaning phases was still required. The entire contamination was located in the impact area where most of the forces of the initial jet could have an effect (Fig. 6C).

The overall cleaning progress resulted in distinct phases that allowed for cloth-specific cleaning classification. The respective end times are illustrated in the SI. Cleaning phase 1 could be observed at the beginning, where the central cleaning zone formed. All cleaning curves show the same cleaning progress, with the zone (impact area) expanding to a cloth-specific maximum. This zone was visible in the related videos as white flow zones on the cloth in the jet impact area. Wilson et al. [28] demonstrated that this area could be equalized to the radial flow zone (RFZ) for flat solid surfaces (Fig. 6). Initially, shock waves and, later, lateral flows acted on the surrounding area, and the jet generated enough pressure to clean all filter cloths uniformly. The impacting fluids underwent dynamic compression, decelerating until almost zero velocity [23, 27]. This impact force caused a shock wave (also water hammer) against the fluid jet and into the contamination, which created the initial strong cleaning effect by bursting the top layer. Arising forces overcame the cohesive forces within the contamination and also adhesive forces of the contamination towards the cloth surface in the impact area. Subsequently, the jet could penetrate the contamination down to the filter cloth, forming the RFZ. Flows streamed laterally to all sides from the point of impact, which removed the surrounding contamination and resulted in phase 2.

In phase 2, the cleaning degrees diverged significantly in most cases. Here, fluid friction and reduced wall shear stress along the surface reduce cleaning. Because of the cohesive and robust interaction effect of the filter cake, the removal was further downgraded. Any cleaning flow influence required sufficient pressure and wall shear stress along the surface to

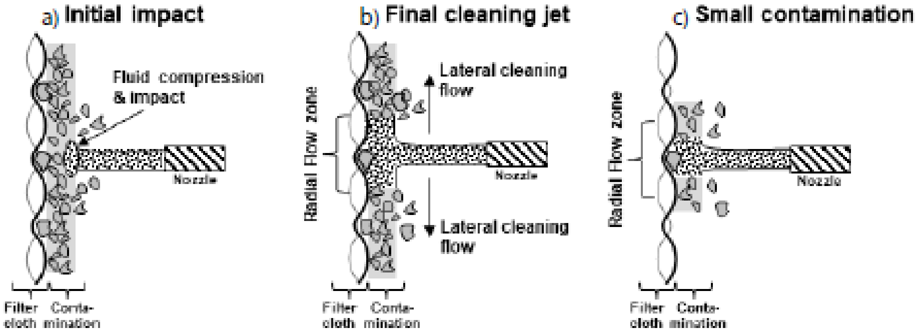

Figure 6. Schematic illustration of the jet (A) at initial impact, (B) in its final shape, and (C) at a small contaminated area.

overcome the acting adhesive forces. However, the cleaning effect differed between the filter cloth types in phase 2. It had to be concluded that the different cleanability had to depend on the filter geometry as well. After approximately 1.4–1.6 s (PP, PET) and 1.8 s (PA6.6), the cleaning progress followed an asymptotic trend, turning into constant *G* values. Here, the final cleaning phase 3 was reached, and no further cleaning took place. The highest pressure forces were observed in the impact area of the wash jet during cleaning phase 1, accomplishing cleaning with the highest reliability and performance here.

3.3 Cleaning Homogeneity at Selected Cleaning Times

So far, a significant influence of the filter geometry on the cleanability of a cloth has been determined. Significantly, the combination of mesh sizes and weave type, as well as the resulting roughness profile, could be identified as essential. The previous results, however, did not determine the location-specific cleaning effects. Another study [17] discovered an impact in areas other than the RFZ. However, it was unclear how uniformly the cleaning effect decreased away from the RFZ. For these reasons, the *HF* homogeneity factor was created. This parameter was monitored for all applied filters in equal material clusters. Fig. 7 displays the time-resolved results of the experimental investigations.

The results of *HF* represented the homogeneity of the cleaning effect. Values near *HF* = 1 demonstrated a circular cleaning effect in the range, indicating a homogeneous cleaning. Respective values above 1 and higher displayed a more considerable cleaning effect in the *y*-direction, while a score below 1 and lower represented more cleaning influence in the *x*-coordinate. It can be hypothesized that the lateral flow direction of the impinging jet is associated with a particular deflection potential of the filter cloth.

First, in all diagrams, equal curves could be observed. During cleaning phase 1, all filter cloths showed values of *HF* around 1, which evidenced a very homogeneous cleaning effect. The corresponding cloth areas only covered a small portion of the contaminated area. In cleaning phase 2, a split between several cloths could be noticed. *HF* remained constant until cleaning phase 3 was reached. This observation demonstrated that the wash water distribution on the cloth is consistent. The contamination outside the RFZ was constantly removed, depending on the cloth parameters. However, the weave type had to be taken into account, particularly in terms of filter geometry. Because of the homogeneous cloth structure, the PLN with monofil threads was cleaned homogeneously. It was followed by STN, which produced reliable homogeneity in almost all cases. More heterogeneous results were observed when a TWL or a PRD weave was applied. This was due to the typical weave structures of the woven cloths, as illustrated in Fig. 8. The structures and resulting geometries of these weave patterns could be assumed to create flow. The fluid-dynamical obstacles resulted in an inhomogeneously cleaned area that only improved drainage in specific directions. In addition to the adhesive and cohesive forces, the contamination that adhered to the deeper cloth

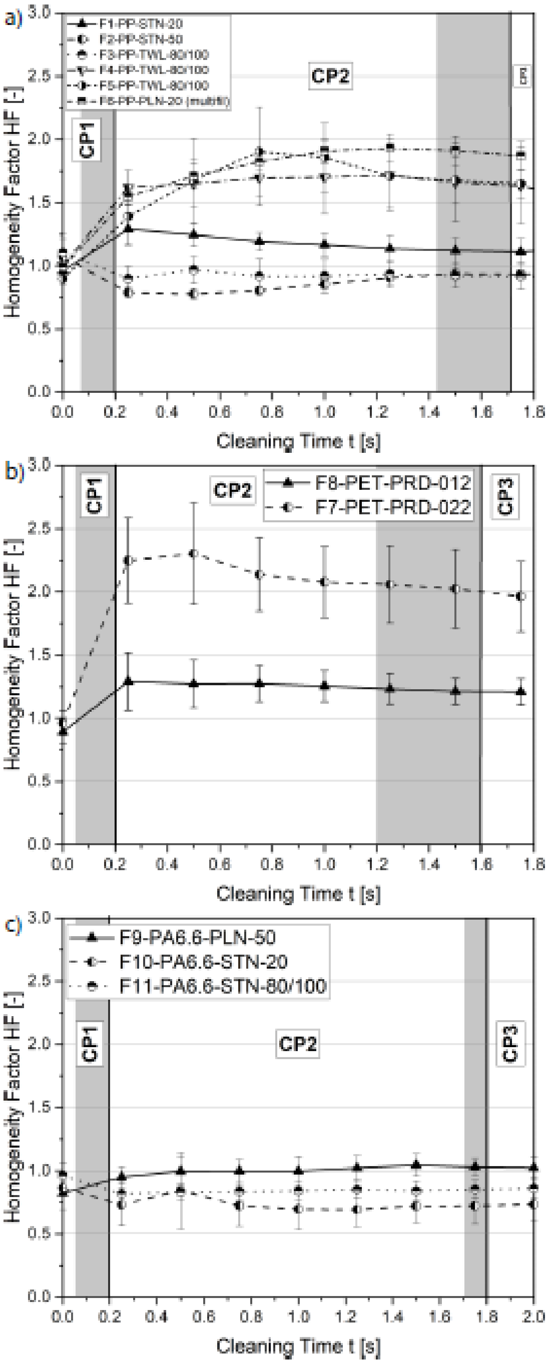

Figure 7. Homogeneity factors depending on the cleaning time. Values close to *HF* = 1 designate homogeneous cleaning areas; any deviations indicate heterogeneous cleaning. Cloths manufactured of (A) PP, (B) PET, (C) PA6.6. Other constant cleaning parameters: $v = 11.44\,\mathrm{m\,s^{-1}}$, $p = 3\times10^5$ Pa, $x_{Nozzle\_Surface} = 35$ mm, $T = 22$ °C, $n = 6$.

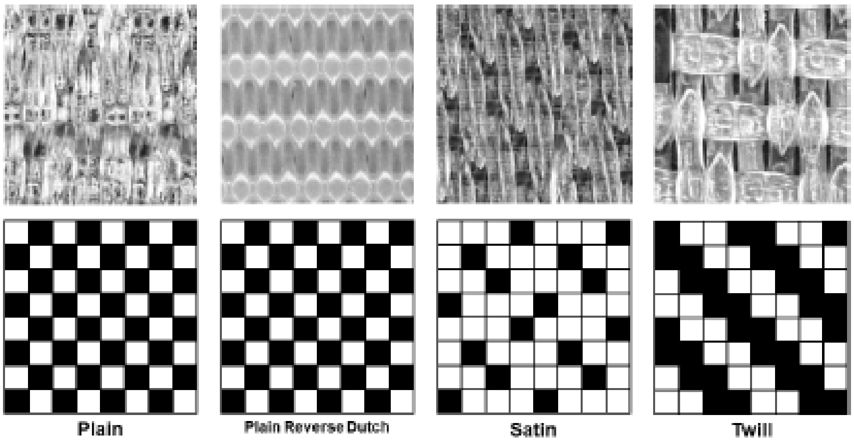

Figure 8. Weave types of the applied woven filters with schematic weave patterns to identify the flow stream. Black squares represent peaks and white squares represent the weave valleys. Illustration inspired by Purchas [29] and Anlauf [6].

layers required additional jet force to be transported out of the cloth weave valleys. Here, it is more efficient for particles and the wash stream to follow the weave-specific flow channel, resulting in a higher deviation of *HF*. During the stream away from the RFZ, the fluid friction increased, resulting in declined *G* and *HF*.

Additionally, two additional exceptions required detailed analysis. First, it had to be discussed why F3-PP-TWL-80/100 resulted in a considerably better and more homogeneous cleanability than the other TWL fabrics. This cloth type, like the others, had similar properties. However, the mesh distribution and permeability were different, resulting in a more open surface finish and destructured TWL.

Second, F7-PET-PRD-022 and F8-PET-PRD-012 differed significantly in their cleanability, although PRD was applied in both cases. The solution could be found in the filter thickness. Both types were the thinnest applied types, while F8-PET-PRD-012 was even 57 % thinner. This aspect resulted in pressing of the thin cloth at the initial impact, explaining more heterogeneous cleaning and poor cleaning results, as shown in Fig. 6B. All other cloths were thicker, giving them a more resistant stiffness. So, thin filters require extra care.

4 Conclusion

The influence of the woven cloth properties on their cleanability was investigated in this experimental study using jets. HS videos were recorded with an HS camera, allowing for precise and time-resolved cleaning analysis. The results were applied using BSG, which continues to cause complex cleaning procedures in breweries.

First, the cleaning videos showed that the cleaning of filter cloths could be distinguished into three cleaning phases. Cleaning phase 1 represented the impact area, where the most intense fluid forces allowed consistent contamination removal. The properties of the filter cloth had less effect on the cleanability here. In contrast, due to friction and decreased wall shear stress, phase 2 demonstrated decreased cleaning efficiency that was highly dependent on the woven filter type. These findings were essential as this phase comprised the longest cleaning part and the most extensive surface range. The last phase 3, illustrated a status quo where the maximum effect was reached, and no further cleaning took place.

Second, the influence of the filter geometry and its respective components on the cleanability could be detailed. The cleaning degree *G* and the homogeneity factor *HF* were used to illustrate the influencing effects primarily in cleaning phase 2. The results revealed a dependence on the filter roughness, as indicated by R_a and S_a. However, the roughness was caused primarily by the mesh sizes in combination with the weave type, which is why these factors required careful consideration. As a result, according to common hygienic design principles, rough surfaces of filter cloths will always result in complicated cleaning. In future research, these findings can be further detailed with a study concerning wettability and the surface energy of the cloth.

The presented research results help find the requirements for cleaning concepts for woven filter cloths. The weave types and mesh sizes were the most important criteria for effective and uniform cleaning. Furthermore, the findings can help to develop hygienic design guidelines. The image-based residue detection and the developed cleaning setup are suitable for improving filter presses. Automated and digitalized cleaning, in particular, can potentially be critical elements in this field [30].

Supporting Information

Supporting Information for this article can be found under DOI: https://doi.org/10.1002/ceat.202200468.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Symbols used

A_n	[m^2]	surface
G	[–]	cleaning degree
HF	[–]	cleaning homogeneity factor
l_n	[m]	length
R_a	[µm]	mean roughness index
S_a	[µm]	mean arithmetic height value

Abbreviations

BSG	brewer's spent grains
HS	high-speed
PA6.6	polyhexamethylene adipamide
PET	polyethylene terephthalate
PLN	plain
PP	polypropylene
PRD	plain reverse Dutch
RFZ	radial flow zone
STN	satin
TWL	twill

References

[1] DIN 10516, *Lebensmittelhygiene – Reinigung und Desinfektion*, Beuth, Berlin **2020**.

[2] G. Wildbrett, *Reinigung und Desinfektion in der Lebensmittelindustrie*, 2nd ed., Behr, Hamburg **2006**.

[3] J. Hofman, Stoffübergang bei der Reinigung als Qualifizierungsmethode der Reinigbarkeit, *Ph.D. Thesis*, Technical University of Munich, Freising-Weihenstephan **2007**.

[4] H. Stoye, H. Köhler, M. Mauermann, J.-P. Majschak, *Chem. Ing. Tech.* **2014**, *86 (5)*, 707–713. DOI: https://doi.org/10.1002/cite.201300047

[5] H. Köhler, H. Stoye, M. Mauermann, T. Weyrauch, J.-P. Majschak, *Food Bioprod. Process.* **2015**, *93*, 327–332. DOI: https://doi.org/10.1016/j.fbp.2014.09.010

[6] H. Anlauf, *Wet Cake Filtration: Fundamentals, Equipment, and Strategies*, 1st ed., Wiley-VCH, Weinheim **2019**.

[7] *DOC 8: Hygienic Design Principles*, 3rd ed., European Hygienic Engineering & Design Group, Frankfurt **2018**.

[8] M. Mauermann, J.-P. Majschak, T. Bley, C. Bellmann, A. Calvimontes, A. Caspari, *Chem. Ing. Tech.* **2012**, *84 (9)*, 1568–1574. DOI: https://doi.org/10.1002/cite.201100232

[9] R.-S. Möller, Haftkräfte, Alterung und Überwachung funktionaler Oberflächen – Gärtücher im Gebrauch, *Ph.D. Thesis*, Karlsruhe Institute of Technology **2018**.

[10] C. Leipert, H. Nirschl, *Filtr. Sep.* **2011**, *25 (5)*, 270–277.

[11] S. Stahl, S. Siggelkow, H. Nirschl, *Eng. Life Sci.* **2007**, *7 (2)*, 136–142. DOI: https://doi.org/10.1002/elsc.200620183

[12] S. Stahl, C. Leipert, H. Nirschl, *Sep. Purif. Technol.* **2013**, *110*, 196–201. DOI: https://doi.org/10.1016/j.seppur.2013.02.003

[13] P. Morsch, J. Kühn, R. Werner, H. Anlauf, D. U. Geier, T. Becker, H. Nirschl, *Chem. Eng. Sci.* **2020**, *226*, 115889. DOI: https://doi.org/10.1016/j.ces.2020.115889

[14] P. Morsch, A. Arnold, H. Schulze, R. Werner, H. Anlauf, D. U. Geier, T. Becker, H. Nirschl, *Sep. Purif. Technol.* **2021**, *256*, 117793. DOI: https://doi.org/ 10.1016/j.seppur.2020.117793

[15] C. Weidemann, Reinigungsfähigkeit mithilfe kontinuierlicher und pulsierender Strömung, *Ph.D. Thesis*, Karlsruhe Institute of Technology **2014**.

[16] C. Weidemann, S. Vogt, H. Nirschl, *J. Food Eng.* **2014**, *132*, 29–38. DOI: https://doi.org/10.1016/j.jfoodeng.2014.02.005

[17] R. Werner, B. Bollwein, R. Petersen, J. Tippmann, T. Becker, *Chem. Eng. Technol.* **2017**, *40 (3)*, 450–458. DOI: https://doi.org/10.1002/ceat.201600049

[18] C. Leipert, H. Nirschl, *Chem. Ing. Tech.* **2012**, *84 (8)*, 1285. DOI: https://doi.org/10.1002/cite.201250370

[19] P. Morsch, Detachment of fine-grained thin particle layers from filter media, *Ph.D. Thesis*, Karlsruhe Institute of Technology **2021**.

[20] DIN EN ISO 4287, *Geometrical Product Specifications (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters*, Beuth, Berlin **2010**.

[21] DIN EN ISO 25178-2, *Geometrical Product Specifications (GPS) – Surface texture: Areal – Part 2: Terms, definitions and surface texture parameters*, Beuth, Berlin **2020**.

[22] H. E. Siekmann, P. U. Thamsen, *Strömungslehre für den Maschinenbau: Technik und Beispiele*, 2nd ed., Springer, Berlin **2009**.

[23] H. Sigloch, *Technische Fluidmechanik*, 10th ed., Springer, Berlin **2017**.

[24] M. Santos, J. Jiménez, B. Bartolomé, C. Gómez-Cordovés, M. Del Nozal, *Food Chem.* **2003**, *80 (1)*, 17–21. DOI: https://doi.org/10.1016/S0308-8146(02)00229-7

[25] J. Steiner, S. Procopio, T. Becker, *Eur. Food Res. Technol.* **2015**, *241 (3)*, 303–315. DOI: https://doi.org/10.1007/s00217-015-2461-7

[26] *MEBAK brautechnische Analysenmethoden – Rohstoffe. Rohfrucht, Gerste, Malz, Hopfen und Hopfenprodukte: Methodensammlung der Mitteleuropäischen Brautechnischen Analysenkommission* (Ed: F. Jacob), Selbstverlag der MEBAK, Freising-Weihenstephan **2016**.

[27] M. Mauermann, Reinigbarkeit von Oberflächen in der Lebensmittelindustrie durch Flüssigkeitsstrahlen, *Ph.D. Thesis*, Technische Universität Dresden **2012**.

[28] D. I. Wilson, B. L. Le, H. Dao, K. Y. Lai, K. R. Morison, J. F. Davidson, *Chem. Eng. Sci.* **2012**, *68 (1)*, 449–460. DOI: https://doi.org/10.1016/j.ces.2011.10.003

[29] D. B. Purchas, K. Sutherland, *Handbook of Filter Media*, 2nd ed., Elsevier, Oxford **2002**.

[30] M. Windisch, V. Seifert, M. Mauermann, *Adhaes. – Kleben Dichten* **2018**, *62 (11)*, 26–29. DOI: https://doi.org/10.1007/s35145-018-0076-4

5.4 Publication 3: Pulsed forward flushes as a novel method for cleaning spent grains loaded filter cloth

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Original article

Pulsed forward flushes as a novel method for cleaning spent grains-loaded filter cloth

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Summary This paper presents a novel method to remove spent grains efficiently from filter cloths via pulsed forward flushes. In breweries, mash filters separate liquid wort from solid spent grains, a by-product. These mash filters use woven fabrics made from synthetic materials as filter media. However, rough filter surfaces often hinder the cleaning process. Concerning modern hygienic design principles, filter cloths are only designed for efficient filtration performances, in which cleanability is not considered. Hence, in combination with strongly adhesive spent grains, brewers often reject mash filters. The paper illustrates an experimental parameter variation and a comparison of pulsed with continuous cleaning in respect to their cleaning performance. The results showed that the proposed method is suitable, reaching up to 30% higher cleaning degrees than conventional methods. Furthermore, the technique required up to 50% fewer cleaning fluids and shorter cleaning times, indicating economic and ecological advantages.

Keywords cleaning sensory, filter cloth cleaning, forward flush, mash filter cleaning, pulsed cleaning, spent grains removal, wash jet.

Introduction

The simple cleanability of production equipment and reliable cleaning concepts are essential parts of modern engineering in the beverage, food, and pharmaceutical industry (Hauser, 2012). In this context, cleaning procedures are fundamental unit operations, requiring specific adaption to the application field. Besides external energies (temperature, time, chemistry and mechanics), the cleaning concept's efficiency depends on the contamination type and the surface to be cleaned (Valentas *et al*., 1997; Wildbrett, 2006; Hofmann, 2007). As multiple residues types occur in most applications, filtration systems require custom-fit cleaning concepts.

Filtration is also an elementary unit operation in the brewing industry. In the brewhouse, mash filters efficiently separate solid spent grains from liquid lauter wort. The spent grains are by-products and are no longer necessary for the subsequent process (Mussatto *et al*., 2006; Narziß & Back, 2009). However, mash filters are currently retrogressive in terms of existing cleaning concepts. After the filtration, operators open the plate packs, and the spent grains cake is discharged from the filter cloth. However, in most cases, this step is performed incompletely. Accordingly, the remaining spent grains adhering to the filter cloth reduce the performance of subsequent filtration cycles, carry the risk of cross-contamination and result in poor hygiene. Currently, the brewing industry uses rigid filter cloth washing systems, mechanical scraping systems, and above all, manual removal processes. Usually, the breweries use these concepts with pure water to remove adhering spent grains between two filtration cycles. Chemical agents are applied less frequently and typically take place weekly (Narziß & Back, 2009). However, these outdated concepts have never been optimised, causing high costs due to long set-up times and more intense regular cleaning intervals. Therefore, despite its significant advantages during filtration, the mash filter has been less attractive for many breweries.

Following the literature (Santos *et al*., 2003; Aliyu & Bala, 2011; Steiner *et al*., 2015), spent grains consist of a complex composition of proteins, carbohydrates, and many more substances. Some of these are strongly adhesive and can complicate any cleaning process. Moreover, common polymers are the primary raw material of filter cloths, limiting the operating temperature and chemical concentration in the cleaning process (Purchas & Sutherland, 2002). Additionally, extensive mechanical pressure can harm the cloth's lifespan. As a result, filter cloths often do not achieve the lifetime that the manufacturer guarantees. Thus, it

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is vital to optimise cleaning concepts for mash filters. This backlog also occurs in other industries, where new techniques can perform similar enhancements.

Employing pulsed wash jets in cleaning procedures is state of the art in many areas of the food and pharmaceutical industries, like in cleaning tanks or heat exchangers (Gillham *et al*., 2000; Christian & Fryer, 2006; Augustin *et al*., 2010). With this method, a pulsed cleaning jet with a defined pulse length and pulse pause (pulse frequency) removes product remains from surfaces. The pulsing improves the cleaning efficiency compared with continuously performed wash jets through additional mechanical effects like increased wall shear stress (Bode *et al*., 2007; Blel *et al*., 2009b; Föste *et al*., 2013). Local velocity profiles can have a significant cleaning effect, attributed to the periodic renewal of the boundary layers between the cleaning stream and targeted surface (Blel & Le Gentil-Lelièvre *et al*., 2009). The pulsed washing water flows off the surface in a pulse pause, which reduces the laminar boundary layer on the filter surface. The following pulse can thus discharge its total kinetic energy onto the contamination.

The present work shows the application of pulsed cleaning to filter cloths soiled with spent grains as natural food-related contamination. Due to the complex cloth structures and firmly adhering spent grains, the framework conditions are challenging, making detailed investigations necessary. Previous studies on pulsed forward flushes have been carried out exclusively on model contamination, neglecting the actual needs (Stahl *et al*., 2007; Weidemann *et al*., 2014; Werner *et al*., 2017). In this context, Weidemann *et al*., (2014) also established the dimensionless number *W*, describing the cleaning influence of fluid dynamics, the pulse frequency, filter geometry and particle size. The *W* number can also help up-scaling small-scale experiments to a technical scale. First experimental trials focussed on spent grains-loaded cloths were recently published by Morsch *et al*., (2020), (2021).

In this study, the primary experimental investigations are based on two filter cloth types that differ in construction and geometry. A parameter variation of jet velocity, incident flow angle, pulse/pause length and a comparison with a continuous wash jet cleaning highlighted the promising approach of this method. A digital microscope and a specially developed analysis algorithm enabled the assessment of the cleaning degree. This detector allowed contact-less identification of spent grains on the cloth and in the open meshes that mainly contributed to cleaning problems. Finally, the novel developed method created an optimised, economically more efficient, and resource-saving cleaning method for woven filter cloths. The use of spent grains, which have a complex matrix, allows the concept transfer to many other residues.

Material and methods

Filter cloth samples

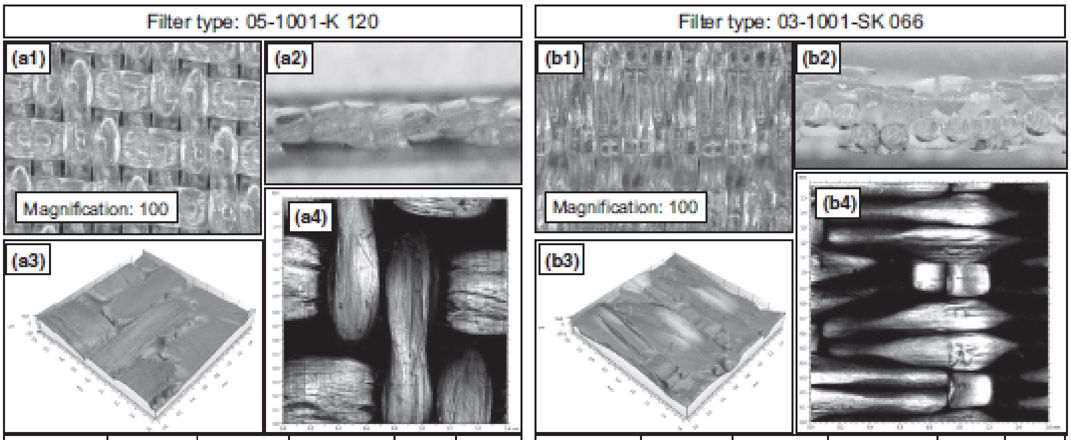
The experimental investigations were carried out on two different Sefar filter cloths (Sefar Holding AG, Thal, Switzerland), illustrated in Fig. 1. These monofil cloths possessed different materials, construction, and mesh sizes. Thus, transferring pulsed cleaning and the presented residue analysis to a broader application area is possible. The selected cloths are mainly used in chamber or membrane filter presses, which represent the basic filtration structure of a mash filter. The filter cloth *03-1001-SK 066* consisted of polyamide (nylon) and fine aperture in a plain reverse dutch weave. In contrast, the filter cloth *05-1001-K 120* was made of polypropylene and had huger mesh sizes in a twill weave. Notably, the application of these filter types is frequent in beer mash separation.

The digital microscope VHX-200D (Keyence Corporation, Osaka, Japan) and the confocal microscope µsurf (Nanofocus AG, Oberhausen, Germany) captured high-qualitative images for detailed characterisation of the filter cloths and analysed their surface profile. In detail, the confocal microscope could measure the broadly used line roughness parameters R_a and R_q according to DIN EN ISO 4287 (DIN, 2010). R_a characterises the arithmetic mean of the profile's height deviations from the base line, while R_q extends this approach to the quadratic mean. Here, 05-1001-K 120 disposed of a rougher surface than 03-1001-SK 066. Additionally, the manufacturing of both cloth types included a calendaring process that flattened the threads on the top layer.

In advance, the filter cloths were cut into rectangular samples with a length of 4.4 cm and a width of 1.4 cm for the experimental studies. The pieces were insertable into object slides made of acrylic glass that fitted accurately in the stream channel of the measuring cell. Additionally, the object slides could be positioned in an enclosure under the digital microscope. This enclosure enabled the exact positioning to guarantee always the same image section and area of interest.

Preparation of spent grains contamination

The next step was developing a reproducible contamination method based on the use case mash filtration in a brewery. Using Pilsener malt, the applied spent grains contamination originated from beer mash, obtained according to the MEBAK congress mash method (Jacob, 2016). The applied malt possessed standard specifications and originated from the batch Q250 001060-02 Weyermann® GmbH (Bamberg, Germany). The malt was milled by a hammer mill Laboratory Mill 3100 (Perten, Hamburg, Germany) to a fine grist.



Mesh Size [µm]	Material	Weave	Thickness [µm]	R_a [µm]	R_q [µm]
80 & 100	PP	Twill	480	8.49	11.07

Mesh Size [µm]	Material	Weave	Thickness [µm]	R_a [µm]	R_q [µm]
50	PA6.6	Plain	520	6.55	8.43

Figure 1 Illustration of the used filter samples with corresponding properties; A = 05-1001-K 120; B = 03-1001-SK 066; (1) Top-view image (digital microscope); (2) Side-view image (digital microscope); (3) Top-view image (confocal microscope); and (4) Side-view image (confocal microscope); Additional designations: K = calendered; SK = special calendered; PP = Polypropylen; PA6.6 = polyhexamethylene adipamide 6.6.

Compared with the MEBAK method, this mill type was an adaption as the standard procedure with more coarse grist was exclusively designed for lauter tun mash.

The preparation of the congress mash started with mixing a grist amount of 50 g with a volume of 200 mL demineralised water at a temperature of 45 °C. Constant stirring (90 rpm) avoided clumps that could negatively influence the mashing and result in inhomogenous contamination. The mash was kept at 45 °C for 30 min and afterwards increased to 70 °C. A volume of 100 mL demineralised water (at 70 °C) was added and held for 60 min. Ultimately, the mash was cooled to 20 °C, and demineralised water was added to a total weight of 450 g. In this case, the use of demineralised water was an essential factor, as cleaning processes can be strongly influenced by different water compositions (e.g. degree of hardness).

Filter cloth contamination

The mash now served as the contamination matrix for the spoiling of the filter cloth. In the first step, the trimmed filter cloth samples were moistened with demineralised water for 30 min to accelerate filtration and adhesive forces. Secondly, a circular aluminium pattern was placed on the sample's centre to generate a reproducible contamination spot. A well pre-mixed amount of 20 µL mash was pipetted into the template, resulting in a circular contamination area with a diameter of 10.0 mm and a height of ca. 2.6 mm. After a filtration and sedimentation time of 240 min at 20 °C, the contaminated filter cloth sample was ready for the experimental runs. This time frame simulated the standard duration of industrial filtration processes, plate package opening, cake discharges and set-up times. The particles had enough time to penetrate the wet meshes and generate adhesive forces to the cloth's surface. The spent grains-loaded surfaces with a defined moist represented reproducible contamination spots. Spent grains are problematic and complex contamination due to different material classes and particle size distributions. The q3-distribution for the applied mash ranged from >5 to <1000 µm, while the most significant proportion was from 20 to 225 µm.

The entire method of spent grains preparation until contamination of the filter cloths is illustrated in Fig. 2.

Cleaning set-up

The equipment used for the cleaning experiments was a self-developed measuring cell with a defined streaming channel. Figure 3 shows the entire set-up as a schematic drawing.

After being photographed, the contaminated filter cloth sample was inserted into the measuring cell's flow channel. The uncleaned sample's taken image helped later evaluate the respective cleaning degree. The geometry of the nozzle was cylindrical with a

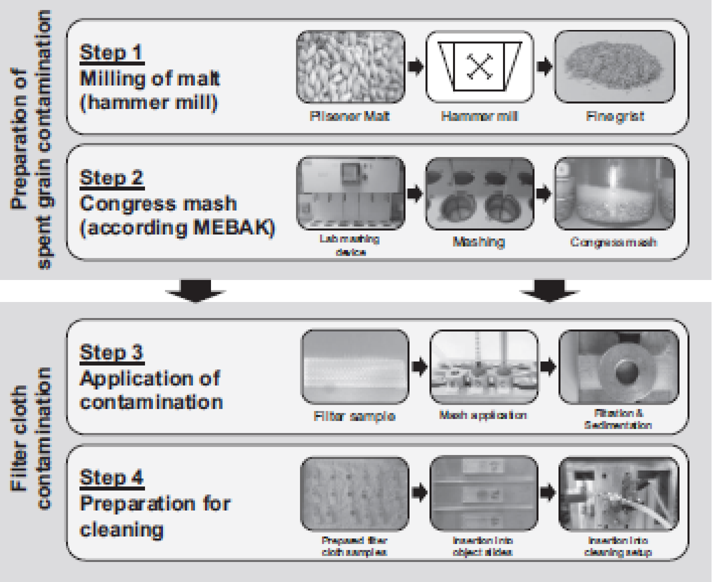


Figure 2 Overview of the developed contamination method—segregated in the different steps from the spent grains preparation until the contamination of the filter cloth sample (figure illustrates subchapters 2.2 and 2.3).

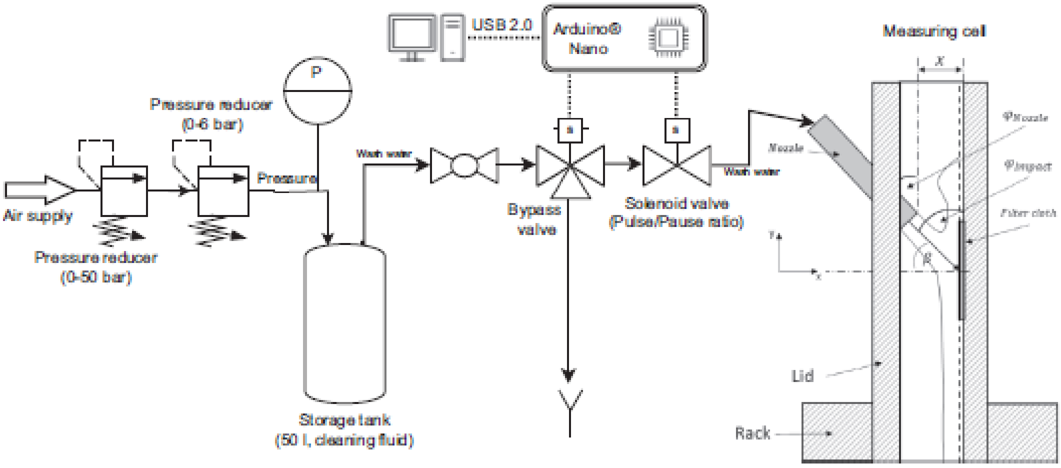


Figure 3 Schematic P&ID drawing of the experimental set-up and an illustration of the corresponding flow conditions in the measuring cell.

diameter d_{Nozzle} of 2 mm, representing a close practical design. Similar nozzle designs are commonly used in spot-jet cleaning of various industrial processes. An Arduino® NANO (Arduino®, Boston, USA) microcontroller regulated a solenoid valve for pulse-pause-control. The developed algorithm triggered the cleaning nozzle's opening time with an accuracy of 10 ms and enabled defined pulse lengths and pauses.

The cleaning nozzle was adjustable with two different nozzle angles (70°, 43°) between water flow direction and surface (see Fig. 3). According to the literature (Kate *et al.*, 2007), the possible deviation between the nozzle angle φ_{Nozzle} and the incidence flow angle φ_{Impact} had to be considered. However, any deviation was neglectable due to the small distance of 2 mm between the nozzle outlet and cloth surface.

Subsequently, the correlation in Equation 1 could be assumed.

$$\varphi_{\text{Nozzle}} = \varphi_{\text{Impact}} \tag{1}$$

The nozzle received cleaning fluid (demineralised water) from a 50 L container, refilled before each measurement cycle. The cleaning fluid was transported constantly from this container to the nozzle using a static pressure between 0.5 and 6 bar. Before each measurement, a pressure presetting was necessary to enable the precise target velocity v_{Nozzle}. The velocity adjustment was performed with a gravimetrical determination of the mass transfer through the nozzle. Here, the released water amount during a nozzle opening time of 10 s was collected in a vessel and weighed with the scale PCB 2500-2 (KERN & Sohn GmbH, Balingen-Frommern, Germany). The measured water volume $\dot{m}$ in 10 s, helped determine the target velocity using Equation 2.

$$v_{\text{Nozzle}} = \frac{\dot{m}}{A_{\text{Nozzle}} * \rho_{\text{Fluid}}} \tag{2}$$

Here, ρ_{Fluid} was the fluid's density, while A_{Nozzle} represented the nozzle outlet surface. As the ambient temperature was kept constant at 20 °C, $\rho_{\text{Fluid}} = 998.2$ kg m^{-3} could be assumed for all velocity determinations. Thus, six different cleaning velocities v_{Nozzle} from 1.5 to 4 ms^{-1} were adjustable in total.

First experiments showed less reproducible results due to a necessary liquid's pre-acceleration in the hose before the nozzle. This problem was resolved by installing a bypass valve upstream of the cleaning nozzle. Here, a constant flow circulated and was deflected into the nozzle by activating the solenoid valve. So, a stream with the constant target velocity resulted.

The overall set-up created a flow channel inside the cell, which allowed defined conditions for draining spent grains, cleaning fluids and standardised contamination removal. Thus, any inhomogenous stream profiles such as isosceles triangular or the typical fish form could be prevented (Kate *et al.*, 2007). During cleaning, the cell remained in a vertical position. Consequently, the cleaning fluid loaded with spent grains could drain problem-free after hitting the contamination area. This set-up design was based on industrial scale mash filters and thus had high practical relevance. The selection of the pulse frequency f_{Pulse} with pulse length t_{Pulse} and pulse pause t_{Pause} was according to Equations 3.1 and 3.2.

$$t_{\text{Pause}} = t_{\text{Pulse}} = 100\,\text{ms} \tag{3.1}$$

$$f_{\text{Pulse}} = \frac{1}{t_{\text{Pause}} + t_{\text{Pulse}}} = 5\,\text{Hz} \tag{3.2}$$

This chosen pulse frequency has already been proven in previous studies (Werner *et al.*, 2017).

After cleaning, images of each filter sample were again taken and used to evaluate the cleaning influences. The digital microscope VHX-200D (Keyence Corporation, Osaka, Japan) was used with a 20-fold magnification factor to record the acquired contamination in detail. The microscope system took images of the surface before and after cleaning with a 2180 × 1478 px resolution.

Results and discussion

Residue analysis

Foremost, it was necessary to develop a reliable image analysis tool to identify remaining residues. Here, the choice was made for an image-analytical method with a before-after comparison, which could assess cleaning results individually.

An own developed image analysis algorithm in Matlab® (MathWorks Corporation, Natick, USA) evaluated the images batch-wise. After automatically determining the area of interest, a particular image conversion into the HSV colour space uncovered the contaminated spots. Besides a colour evaluation with the value H, this colour space also enabled the colour saturation (S) and the light value (V). The HSV colour space decision was based upon the variably adjustable light value. In practice, different ambient lights can often influence the quality of the image sensor. However, in these experiments, the light colour and intensity stayed constant. After the HSV image transformation, the algorithm fixed the saturation and brightness values. The provision enabled contamination detection and converted the overall picture into a binary image (see Fig. 4).

The algorithm analysed the white areas quantitatively, calculated the number of pixels, and determined the contaminated area in pixel. Thus, the contaminated areas by spent grains before cleaning A_1 and after cleaning A_2 were ascertainable. Using Equation 4, the degree of cleaning G was determinable, characteristic of the cleaning process's efficiency.

$$G[-] = 1 - \frac{A_2}{A_1} \tag{4}$$

A disadvantage of this method was the exclusive detectability of visible contamination on the surface. However, the filter cloth primarily consisted of flat structures with defined meshes (see side view in Fig. 1). Here, hidden areas were not possible as small particles just went through the cloth, while larger ones remained adhering on the surface or within the meshes with visibility from the top. So with the help of the digital microscope, even tiny particles in the deeper layer of the meshes were detectable. Another critical factor was a proper contrast between cloth and spent

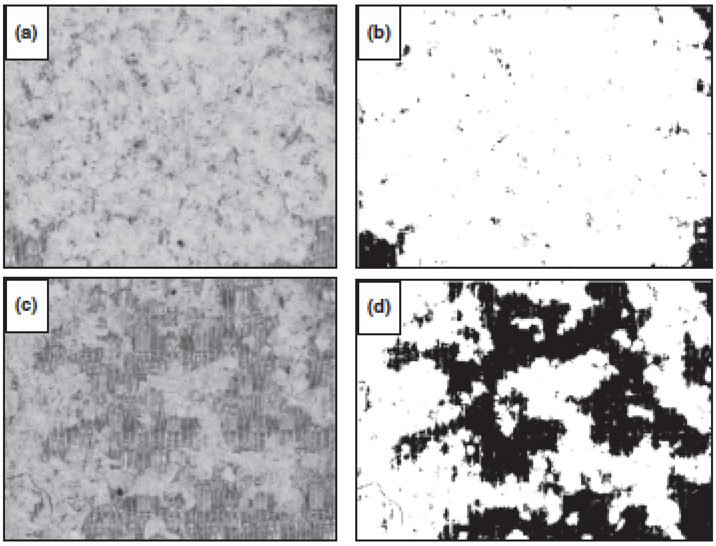


Figure 4 Exemplary images of the thoroughly contaminated and the cleaned filter surface. (a) Original image before cleaning, (b) Binary image before cleaning, (c) Original image after cleaning, and (d) Binary image after cleaning.

grains, which was crucial in identifying contamination quickly and precisely. Certainly, the method's significant advantage was the contact-less detection method that did not influence the consistency or texture of the contamination spot.

Comparison of pulsed to continuous jet and influence of nozzle angle

When using nozzle systems for filter cloth cleaning, mainly continuous procedures are applied to date. Therefore, pulsed cleaning had to prove itself specifically towards this method. Fig. 5 compares continuous and pulsed jet cleaning with the two applied filter cloths and incidence angles of 43° and 70°.

Considering the results (Fig. 5 subfigures a–d), an increase in the cleaning degrees by applying higher pulses numbers or jet lengths was observable. Deficient and partly constant cleaning degrees were visible at low pulse numbers or jet lengths. An abrupt increase until almost G = 1.0 occurred by reaching a particular value. The change over from low G values to high ones can be named es the transition zone (TZ). It was, in all experiments, the most thrilling part of the curve due to the possibility to adjust the minimal necessary process time. TZ occurred in pulsed cleaning between 4 and 64 pulses and continuous cleaning between 0.4 and 128 s. Additionally, larger error bars were seen in TZ, which can refer to more inconstant cleaning procedures due to probable laminar boundary layers. In comparing both diagrams, filter cloth *05-1001-K 120* showed increased cleanability due to higher cleaning degrees and the same adjusted pulse number or jet length. The subfigures c and d in Fig. 5, using an incidence angle of 70°, depicted similar curves. The comparison of both applied angles showed a difference visible at filter cloth 05-1001-K 120, where the 70° angle increased the cleaning degree.

Here, theoretical forces described the more powerful impulse generated by a non-flat dipping angle. However, this observation was not valid regarding *03-1001-SK 066,* where no difference between both angles was detectable. The results showed that the angle had a subordinate significance caused by the rougher filter geometry (see Fig. 1). Generally, flat dipping angles resulted in better cleaning effects at more uneven surfaces due to enhanced transport away from the contaminated area. Additionally, the flatter jet incidence favoured the contamination transportation at this filter type. The respective weave resulted in more extended flow channels that allowed better drainage of the washing water. Regarding the thread repetition, *05-1101-K 120* showed the same weaving repetition on shorter distances, which led to smoother surfaces.

Following Fig. 5, there were significant differences between the continuous and pulsed cleaning procedures. Generally, the pulsed jet method resulted in faster cleaning degrees while using fewer cleaning fluids. In TZ, up to 30% higher cleaning degrees by using only 50% of the water amount simultaneously were possible (compare Fig. 5-a value mark 48 pulses/ 4.8 s). Although in most cases, the average of G in TZ ranged between 10% and 20%.

These results illustrated a promising method for more efficient filter cloth cleaning from an economic and ecological perspective. The reasons were the

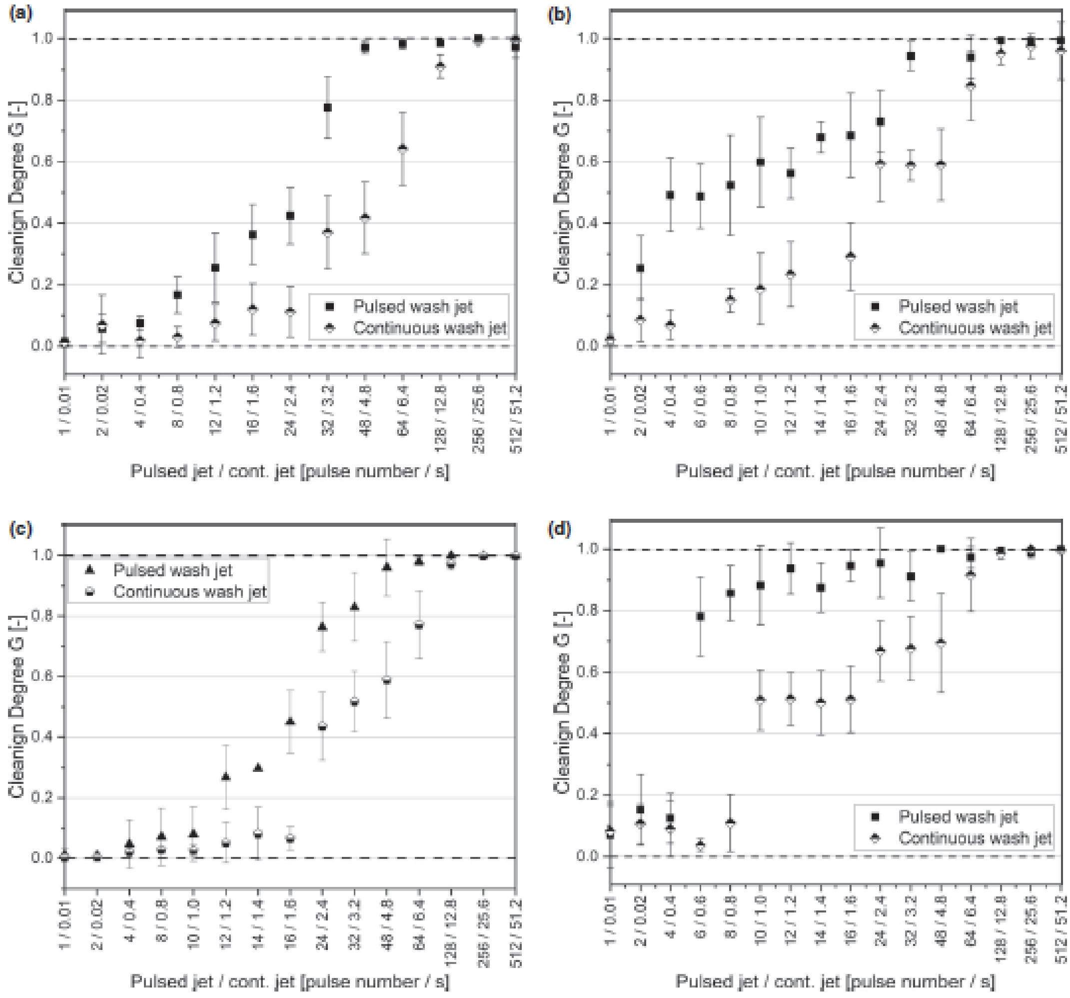


Figure 5 Comparison of continuous cloth washing and the use of pulsed jets for v_{Impact} = 3 m/s; $n > 6$; a: Filter cloth 03-1001-SK 066, φ_{Impact} = 43 °; b: Filter cloth 05-1001-K 120, φ_{Impact} = 43 °; c: Filter cloth 03-1001-SK 066, φ_{Impact} = 70 °; and d: Filter cloth 05-1001-K 120, φ_{Impact} = 70 °, confidence intervals with α = 0.05.

increased mechanical component of the impulse due to more significant wall shear stress and increased waviness on the filter surface (Augustin *et al.*, 2010). Notably, higher waviness reduced the thickness of the laminar boundary layer. Due to the filter cloth's vertical position, the liquid sprayed on the filter surface in the previous jet had time to drain during pulse pauses. Any cushioning effect by an occurring liquid layer due to the jet could be minimised or even eliminated.

So, first, the subsequent jet could almost entirely affect its kinetic energy on the adhering contaminant, protected by the laminar boundary layer with a liquid shield. Second, the thickness of the laminar boundary layer was additionally reducible due to the drainage. The ongoing renewal of the boundary layer resulted in local velocity gradients, contributing to the increase of the wall shear stress.

Jet velocity and incidence angle of wash jet

The understanding of the appearing forces is essential to adjust the most appropriate cleaning setting.

However, the force approach only partly leads to an entire jet cleaning model. Following the literature (Momber, 1993; Milchers, 2001), the pressure distribution on the filter surface, resulting from the velocity and forces, is the more decisive cleaning factor.

Thus, the cleaning velocity had to be optimised for pulsed forward flush cleaning of filter cloths. The cleaning operator always has to balance enough performance and efficiency concerning the nozzle velocity. Higher cleaning velocities induce increased impulses on the filter that potentially damage the weaving. Furthermore, additional cleaning fluid streams on the cloth and increased cleaning efforts are necessary. Thus, from an economic and ecologic perspective, the proper equilibrium of the parameters has to be found. Figure 6 shows the results of using six different velocities ranging from 1.5 to 4 ms^{-1} to clean both filter samples. With $n_{Pulse} = 16$, a pulse number in the TZ of the results in Fig. 5, it became possible to selectively differentiate between the applied velocities.

The results showed a constant increase in the cleaning degree using higher cleaning velocities concerning filter types and incidence angles. The comparison of both applied angles showed a considerable difference. Here, the applied 43° angle results depicted a slight difference in the cleaning degree. However, the difference was insignificant; this indicated a better cleaning result using a more angled jet.

Regarding angle 70°, on the one hand, the difference was more significant, and on the other hand, the better-applied angle changed. Here, an angle of 70° resulted in a significantly higher cleaning degree. Regarding the results of both filter types, the results indicated a big difference in the cleanability. Additionally, *05-1001-K 120* is more cleanable from spent grains contamination than *03-1001-SK 066*.

Weidemann *et al.*, (2013) conducted similar investigations with model contamination. Here, an increase in the cleaning velocity significantly influenced the cleaning degree. It was also detectable that the filter type required an appropriate angle selection, attributing to the filter structure and material. Following the literature (European Hygienic Engineering & Design Group, 2018), it is evident that smoother surfaces are better cleanable. Also, Weidemann *et al.*, (2013) found a correlation between filter surface roughness and cleanability. Compared with the results in Figs 1 and 6, filter *05-1001-K 120* had higher surface roughness values for R_a and R_q and was more cleanable than *03-1001-SK 066*. On the first view, this result seemed to be contradictory. The twill-weave texture was the decisive factor, resulting in a smoother and bigger surface on filter 05-1001-K 120 (see Fig. 1).

In contrast, *03-1001-SK 066* had a plain weave consisting of more interweaved threads and created more complex furrowed surface structures. Regarding the q3-distribution, the most substantial proportion of the spent grains contamination were particle sizes of 100–1000 µm. These particles could not permeate through the cloth and locate in the deeper mesh areas (mesh size of 80 & 100 µm). However, smaller particles, which did not penetrate the filter, contaminated deeper layers and blocked the meshes.

Concluding, the filter structure is one of the decisive cleaning parameters. All properties require detailed consideration because negligence hinders cleaning optimisation (e.g. just regarding surface roughness parameters). The literature underlines this observation, where

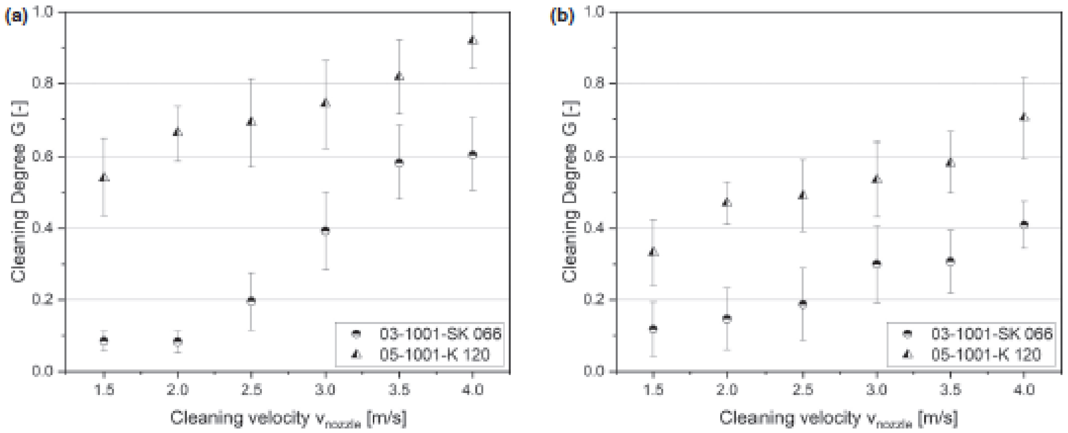


Figure 6 Variation of cleaning velocity v_{Impact} with a nozzle angle φ_{Nozzle} of a: 70°; and b: 43°; $f_{Pulse} = 5$ Hz; $n \geq 6$, confidence intervals with $\alpha = 0.05$.

smooth technical surfaces always required attention in cleaning planning (Wildbrett, 2006; Hofmann, 2007; Tamime, 2008).

Pause and pulse length variation

In previous studies, an increase in the pulse length resulted in lower cleaning degrees due to the rapid formation of boundary layers on the contaminated surface (Weidemann *et al.*, 2014). These layers decreased the influence of the acting forces, and the jet represented a continuous cleaning flow. However, the cleaning effect of longer pulse pauses required detailed investigations. Figure 7 illustrates the correlation between the cleaning degree and different pulse pauses.

The results showed an increase in the cleaning degree while using longer pulse pauses. Additionally, the significant difference in the cleaning degree of both filter types was again recognisable. The applied contamination consisted of spent grains, which mostly involved organic substances. According to the method described in 2.3, the contamination rested for a certain period to allow small particles to penetrate the pores and form a filter cake. This process resulted in specific drying processes and thus an increased caking of the contamination. Therefore, the advantage of longer pulse pauses was also the enhanced rewetting of the filter cake. This rewetting resulted in swelling processes of the contamination, which facilitated the detachment.

Additionally, the pulse pause was decisive for sufficient drainage of cleaning water streamed on the previous jet's filter cloth. The difference in the cleaning degrees of both filter cloths depended on the cloth structure. The finer meshes with simultaneous uneven geometry of *03-1001-SK 066* retained small particles better. First, the rewetting of contamination in larger meshes was more comfortable due to the fluid's enhanced lateral accessibility. Besides, small particles had plenty of possible contact points to the filter where higher adhesive forces affect.

Secondly, the structure of 05-1001-K 120 improved the cleanability. Also, the material properties are worth a closer look. Although Leipert & Nirschl, (2012) showed material independence in filter cloth cleaning, the wetting behaviour may differ. Here, minor differences could result in varied rewetting and fluid absorption of the contamination from the surrounding filter area.

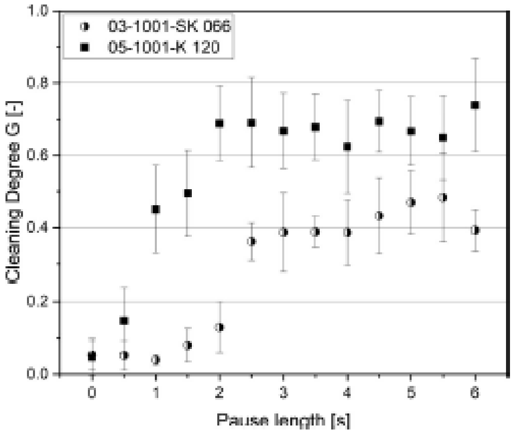


Figure 7 Influence of the pause length on the cleaning degree G, $\varphi_{Impact} = 70°$; $n_{Pulses} = 2$; $n_{Trials} \geq 6$, confidence intervals with $\alpha = 0.05$.

Conclusion

This paper performed the jet cleaning of filter cloth with continuous and pulsed jets. The experimental investigations found that the filter cloth's cleanability significantly depended on the geometry, such as mesh sizes and weave type. Furthermore, a residue analysis concept was developed, which can also be applied in industrial processes.

The experimental parameter variation confirmed that the cloth cleanability also depended on the adjusted nozzle velocity and the jet's incidence angle under certain circumstances. Regarding the velocity, an increase will cause a higher cleaning degree. However, increased velocities can also lead to higher cleaning fluid consumption and possible damage to the filter cloth. In consideration of the incidence angle, flatter angles showed less efficiency for the impact force. However, it was not concludable that more vertical angles enhance the cleaning. Due to the mentioned geometry influence, also flatter angles contributed to the cleaning success as the contamination transport away was more efficient.

In selecting the proper cleaning procedure, pulsed forward flushes were advantageous. They resulted in similar cleaning degrees in a shorter time, reducing the cleaning agent consumption. Additionally, they could be readily adjusted and offer a promising cleaning possibility, which results in economic and ecological benefits.

The presented conclusions showed minimal settings applicable to clean spent grains-loaded filter cloth. These necessary parameters will help breweries find the most appropriate and efficient cleaning adjustments. Due to applying a standard industry-scale nozzle, the findings help to realise efficient cleaning concepts with pulsed jets in a mash filter. The next step can be constructing a cleaning device on a technical scale for direct application in a brewery. Looking at Industry 4.0, the results are also usable for developing demand-oriented cleaning concepts that can pave the way to better automated cleaning.

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Conflicts of interest

The authors declare that there is no conflict of interest.

Author contribution

Roman Alejandro Werner: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Funding acquisition (equal); Investigation (lead); Methodology (lead); Project administration (equal); Resources (lead); Software (lead); Supervision (equal); Validation (lead); Visualization (equal); Writing – original draft (lead); Writing – review & editing (equal). **Lukas Schappals:** Data curation (supporting); Formal analysis (supporting); Investigation (supporting); Methodology (supporting); Software (supporting); Validation (supporting); Writing – review & editing (supporting). **Dominik Ulrich Geier:** Conceptualization (supporting); Funding acquisition (equal); Investigation (supporting); Methodology (supporting); Project administration (supporting); Software (supporting); Supervision (equal); Validation (supporting); Visualization (supporting); Writing – original draft (supporting); Writing – review & editing (equal). **Thomas Becker:** Conceptualization (equal); Funding acquisition (equal); Project administration (equal); Supervision (lead); Writing – original draft (supporting); Writing – review & editing (equal).

Peer review

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Aliyu, S. & Bala, M. (2011) Brewer's spent grain: A review of its potentials and applications. *African Journal of Biotechnology*, **10**, 324–331. Available from: https://doi.org/10.5897/AJBx10.006.

Augustin, W., Fuchs, T., Föste, H. (2010) Pulsed flow for enhanced cleaning in food processing. *Food and Bioproducts Processing*, **88**, 384–391. Available from: https://doi.org/10.1016/j.fbp.2010.08.007.

Blel, W., Le Gentil-Lelièvre, C., Bénézech, T., Legrand, J. & Legentilhomme, P. (2009a) Application of turbulent pulsating flows to the bacterial removal during a cleaning in place procedure. Part 1: Experimental analysis of wall shear stress in a cylindrical pipe. *Journal of Food Engineering*, **90**, 422–432. Available from: https://doi.org/10.1016/j.jfoodeng.2008.07.008.

Blel, W., Legentilhomme, P., Bénézech, T., Legrand, J. & Le Gentil-Lelièvre, C. (2009b) Application of turbulent pulsating flows to the bacterial removal during a cleaning in place procedure. Part 2: Effects on cleaning efficiency. *Journal of Food Engineering*, **90**, 433–440. Available from: https://doi.org/10.1016/j.jfoodeng.2008.07.019.

Bode, K., Hooper, R.J., Paterson, W.R., Ian Wilson, D., Augustin, W. & Scholl, S. (2007) Pulsed flow cleaning of whey protein fouling layers. *Heat Transfer Engineering*, **28**, 202–209. Available from: https://doi.org/10.1080/01457630601064611.

Christian, G.K. & Fryer, P.J. (2006) The effect of pulsing cleaning chemicals on the cleaning of whey protein deposits. *Food and Bioproducts Processing*, **84**, 320–328. Available from: https://doi.org/10.1205/fbp06039.

Deutsches Institut für Normung e. V. (2010). *DIN EN ISO 4287: Geometrische Produktspezifikation (GPS) – Oberflächenbeschaffenheit: Tastschnittverfahren – Benennungen, Definitionen und Kenngrößen der Oberflächenbeschaffenheit*. Berlin: Beuth Verlag.

European Hygienic Engineering & Design Group. (2018). DOC8 – Hygienic Design Principles, 3rd Edition. Available from: https://ehedg.co.uk/guidelines/ Accessed 20 February 2022.

Föste, H., Schöler, M., Majschak, J.-P., Augustin, W. & Scholl, S. (2013) Modeling and validation of the mechanism of pulsed flow cleaning. *Heat Transfer Engineering*, **34**(8-9), 753–760. Available from: https://doi.org/10.1080/01457632.2012.741499.

Gillham, C., Fryer, P., Hasting, A. & Wilson, D. (2000) Enhanced cleaning of whey protein soils using pulsed flows. *Journal of Food Engineering*, **46**, 199–209. Available from: https://doi.org/10.1016/S0260-8774(00)00083-2.

Hauser, G. (ed.). (2012). *Hygienegerechte Apparate und Anlagen*. Hoboken: John Wiley & Sons.

Hofmann, J. (2007). Stoffübergang bei der Reinigung als Qualifizierungsmethode der Reinigbarkeit. Dissertation, Weihenstephan, Technische Universität München.

Jacob, F. (ed.). (2016). MEBAK brautechnische Analysenmethoden - Rohstoffe. Rohfrucht, Gerste, Malz, Hopfen und Hopfenprodukte: Methodensammlung der Mitteleuropäischen Brautechnischen Analysenkommission. Mitteleuropäische Brautechnische Analysenkommission. Freising-Weihenstephan: Selbstverlag der MEBAK.

Kate, R.P., Das, P.K. & Chakraborty, S. (2007) Hydraulic jumps due to oblique impingement of circular liquid jets on a flat horizontal surface. *Journal of Fluid Mechanics*, **573**, 247–263. Available from: https://doi.org/10.1017/S0022112006003818.

Leipert, C. & Nirschl, H. (2012) Untersuchungen zum Reinigungsverhalten von Filtermedien mithilfe pulsatorischer Strömung. *Chemie Ingenieur Technik*, **84**, 1285. Available from: https://doi.org/10.1002/cite.201250370.

Milchers, W. (2001). *Abtrag von Polymeren mit dem reinen Wasserstrahl*. Düsseldorf: VDI-Verl.

Momber, A. (1993). *Handbuch Druckwasserstrahl-Technik*. Düsseldorf: Beton-Verl.

Morsch, P., Arnold, A., Schulze, H. *et al.* (2021) In-situ cleaning process of chamber filter presses with sensor-controlled and demand-oriented automation. *Separation and Purification Technology*, **256**, 117793. Available from: https:/doi.org/10.1016/j.seppur.2020.117793.

Morsch, P., Kühn, J., Werner, R. *et al.* (2020) Influence of the filter cloth and nozzles type on the in-situ cleaning procedure of filter presses. *Chemical Engineering Science*, **226**, 115889. Available from: https://doi.org/10.1016/j.ces.2020.115889.

Mussatto, S.I., Dragone, G. & Roberto, I.C. (Eds.) (2006) Brewers' spent grain: generation, characteristics and potential applications. *Journal of Cereal Science*, **43**, 1–14.

Narziß, L. & Back, W. (2009) *Die Technologie der Würzebereitung*, 8th ed. Weinheim: WILEY-VCH.

Purchas, D.B. & Sutherland, K. (eds.). (2002). *Handbook of filter media*, 2nd ed. Oxford: Elsevier Advanced Technology.

Santos, M., Jiménez, J., Bartolomé, B., Gómez-Cordovés, C. & Del Nozal, M. (2003) Variability of brewer's spent grain within a brewery. *Food Chemistry*, **80**, 17–21. Available from: https://doi.org/10.1016/S0308-8146(02)00229-7.

Stahl, S., Siggelkow, S. & Nirschl, H. (2007) A microbiological test method to determine the cleanability of filter media in solid-liquid-separation applications. *Engineering in Life Sciences*, **7**, 136–142. Available from: https://doi.org/10.1002/elsc.200620183.

Steiner, J., Procopio, S. & Becker, T. (2015) Brewer's spent grain: Source of value-added polysaccharides for the food industry in reference to the health claims. *European Food Research and Technology*, **241**, 303–315. Available from: https://doi.org/10.1007/s00217-015-2461-7.

Tamime, A.Y. (ed.). (2008). *Cleaning-in place: Dairy, Food and Beverage Operations*, 3rd ed. Oxford, UK, Ames, Iowa: Blackwell Pub.

Valentas, K., Paul Singh, R. & Rotstein, E. (eds.). (1997). *Handbook of Food Engineering Practice*. Boca Raton, New York: CRC Press.

Weidemann, C., Stahl, S. & Nirschl, H. (2013) Development of a qualitative test method for the cleanability of polymer woven filter media. *Food and Bioproducts Processing*, **91**, 515–524. Available from: https://doi.org/10.1016/j.fbp.2013.05.005.

Weidemann, C., Vogt, S. & Nirschl, H. (2014) Cleaning of filter media by pulsed flow – Establishment of dimensionless operation numbers describing the cleaning result. *Journal of Food Engineering*, **132**, 29–38. Available from: https://doi.org/10.1016/j.jfoodeng.2014.02.005.

Werner, R., Bollwein, B., Petersen, R., Tippmann, J. & Becker, T. (2017) Pulsed jet cleaning of filter cloths contaminated with yeast cells. *Chemical Engineering & Technology*, **40**, 450–458. Available from: https://doi.org/10.1002/ceat.201600049.

Wildbrett, G. (ed.). (2006). *Reinigung und Desinfektion in der Lebensmittelindustrie*, 2nd ed. Hamburg: Behr.

5.5 Publication 4: Investigations on Backflush Cleaning of Spent-Grain-Contaminated Filter Cloths Using Continuous and Pulsed Jets

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Investigations on Backflush Cleaning of Spent Grain-Contaminated Filter Cloths Using Continuous and Pulsed Jets

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Abstract: This study investigated the continuous and pulsed backflush cleaning of woven fabrics that act as filter media in the food and beverage industry. Especially in breweries, they are commonly used in mash filters to separate solid spent grains from liquid wort. After filtration, the removal of such cereal residues via self-discharge is necessary. However, this filter cake discharge is typically incomplete, and various spots remain contaminated. In addition to the reduced filter performance of subsequent batches, cross-contamination risk increases significantly. A reproducible contamination method focusing on the use case of a mash filter was developed for this study. Additionally, a residue analysis based on microscopical image processing helped to assess cleaning efficiency. The experimental part compared two backflushing procedures for mash filters and demonstrated fluid dynamical, procedural, and economic differences in cleaning. Specifically, pulsed jets show higher efficiency in reaching cleanliness faster, with fewer cleaning agents and less time. According to the experimental results, the fluid flow conditions depended highly on cloth geometry and mesh sizes. Larger mesh sizes significantly favored the cloth's cleanability as a larger backflush volume can reach contamination. With these results, cloth cleaning can be improved, enabling the realization of demand-oriented cleaning concepts.

Keywords: cleaning; filter media; filter cloth; backflush cleaning; pulsed wash jets; spent grains

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1. Introduction

Filter cloths are textiles widely used in many solid–liquid filtration processes. Mono-or multifil yarns as chaining and shoot threads form a particular fabric's weave pattern and create different surface topographies [1]. The term filter geometry can be derived from a specific filter structure, significantly influenced by mesh sizes and weave type. During filtration, different apertures represent the selectivity of particle sizes [2]. In addition, the surface properties of materials should be considered, as these can influence the selective binding of certain substance classes on filter cloth [3]. The materials used are mostly polymers such as polypropylene or polyamide. Threads of various thicknesses are produced by technical extruders from polymer raw materials. In addition to different mesh sizes, interwoven threads have hilly structures that form flow channels of different depths and facilitate particle adhesion points. This intricate geometry facilitates filtration processes and provides various application possibilities [4]. However, the complexity and material limits (e.g., temperature and pH value) can be detrimental to the filter surface during the cleaning process [5]. The structures of commercially available filters contradict the common hygienic design principles. To date, no corresponding guidelines for filter cloths have been published by corresponding organizations or associations [6].

Filter cloths have a wide range of applications in the beverage, food, and pharmaceutical industries. In breweries, mash filters, which are chamber or membrane filter presses, use filter cloths to separate solid spent grains from the liquid wort. This segregation can also be performed using lauter tuns with a slotted plate as filter support and spent grain as the actual filter medium. The plate is usually located close to the tun's bottom and facilitates dead-end filtration. Unfortunately, the lauter tun's flexibility is limited due to long filter times as the entire mash volume has to be separated using one single tun. Here, mash filter systems are often preferred because they are typically more flexible in batch quantities and cereal variety (e.g., unmalted barley or corn) than other systems [7]. Such filter presses consist of several frames covered with large-scale filter cloths, forming filter plates. The compression of various plates leads to multiple filter chambers in the system [8]. After filtration, the release and pulling apart of these plates produce a cake discharge of spent grains from the filter cloth. However, this cake release is typically incomplete, as spent grain-contaminated spots remain on the cloth and in its meshes.

After a certain batch amount, extensive cleaning must be performed to ensure sufficient spent grain removal and high product safety. In particular, the residues in the meshes create a problem during cleaning. A lack of optimization is evident in the brewing industry, as cleaning is commonly performed manually or only with rigid cleaning systems. Due to increased ecological and economic awareness over the last decades, the beverage and food industries (especially breweries) have also highlighted the necessity to enhance cleaning concepts. Modern cleaning research has recognized the high potential in more optimized mechanical cleaning concepts and simultaneous chemical agent reduction [5,9–12].

One promising cleaning method for mash filter systems can be backflush cleaning, which has already enhanced the cleaning of membranes in dairy or wastewater treatment. Here, this technique pushes water from the filtrate side through the filter medium. Concerning cloths, the aim is to realize sufficient mechanical forces in adjusting flow rates to release adhesive forces between spent grains and the filter cloth at the feed side. In addition, the backwashing must ensure that the residues in the mesh can be reached. This may be an advantage compared with forward flushing as backflushes can reach small particles that blind the filter meshes more efficiently and enable direct dirt transport away from the filter cloth. However, many aspects are still unknown and require comprehensive research. Objects for investigation are the flow loss due to pressure drops and a possible cleaning effect decrease during the cloth passthrough. Here, a loss of mechanical effects can occur that needs to be compensated.

Weidemann et al. [13] and Leipert and Nirschl [14] conducted the first studies on pulsed backflushing filter cloths using model particles. Other publications generally proved the suitability of discontinuous streams in cleaning concepts results [15,16]. Focusing on pulsed cleaning in an industrial context, previous publications [10,13,17–24] have shown promising results using this cleaning method in beverage and food applications such as pipes or heat exchangers. In dust filters and gas filtration, pulsed cleaning is already state of the art [25–28]. In these studies, the pulsed mode significantly increased the mechanical component of the cleaning concept.

The first studies on cleaning spent grains loaded filter cloth with forward flushes were conducted by Morsch et al. [11,12,29] and Werner et al. [30]. Their conclusions were a promising starting point for investigating the industry applications of pulsed backflushes and breaking down decisive mechanisms in filter cloth cleaning. An in-depth scientific analysis was necessary as different disciplines need to be combined, such as biophysics (heterogenous contamination), fluid dynamics (backflush), material science (filter cloth), and process engineering (cleaning and process design). In the end, in brewery practice, the technical realization of this cleaning concept can be achieved either by nozzles arranged on the back of the plate or by direct backwashing of the filter cloth with pumps.

This study aimed to use pulsed jets to enhance the mechanical cleaning effects of backflushing filter cloth. Two different filter cloths with different mesh sizes and weave types formed the centerpiece of the investigations. An industrial-close use case was selected, focusing on spent grains-loaded filter cloths that appear in mash filters in a brewery. For this purpose, a tailor-made contamination method was developed to assess cleaning procedures reproducibly. This was combined with a novel residue analysis by microscopical image processing. The experimental results illustrated the most influential cloth cleaning parameters on backflushing and determined the most suitable cleaning design between continuous and pulsed backflushing. The latter used pulsed streams with a defined ratio of jet lengths to pauses, increasing mechanical cleaning effects. In addition, using water as the only cleaning agent significantly reduced the amount of aggressive chemicals possible. The increase in mechanical parameters may also decrease other factors such as temperature and time. This change in the cleaning method can preserve cloth materials, extend the filter lifetime, and reduce costs.

2. Materials and Methods

2.1. Filter Cloths

The experimental investigations used two different types of filter cloths. Both were manufactured by Sefar AG (Heiden, Switzerland), and their names are 05-1001-K 120 (here: F1-TWL-80/100) and 03-1010-SK 038 (here: F2-STN-20). The annotation F1 represented filter type 1 with a twill weave (TWL) and mesh sizes of 80 and 100 µm. On the other hand, filter type 2 was designated as F2 and had a satin weave (STN) and mesh sizes of 20 µm. They are both commonly used in different filtration applications and mash filters, in particular. Table 1 illustrates the different filter properties and design features. The main differences between the two filter cloths were the material, the weave type, and the mesh size.

Table 1. Applied filter cloth types with their distinct properties and designations.

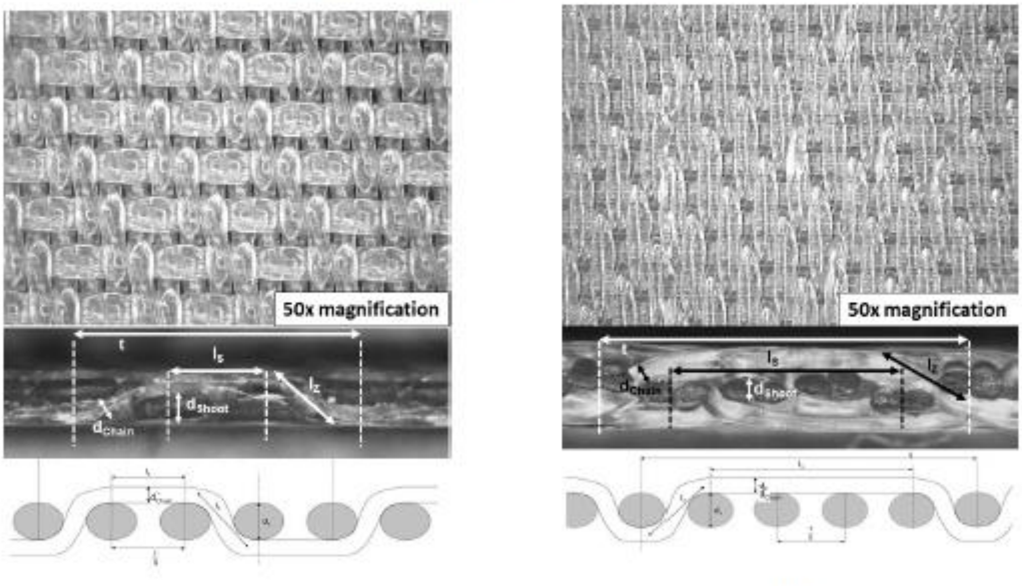
Designation	Manufacturer's Designation	Mesh Sizes [µm]	Material	Weave Type	Thickness [µm]	Finish
F1-TWL-80/100	05-1001-K 120	80 & 100	Polypropylene	TWL	480	Calendared
F2-STN-20	03-1010-SK 038	20	Polyamide 6.6	STN	470	Special calendared

K = calendared. SK = special calendared. TWL = twill weave. STN = satin weave.

A detailed consideration of the fluid dynamics of backflushing led to the assumption that the mesh sizes will significantly influence cleaning efficiency. Here, F1-TWL-80/100 had mesh four times larger than that of F2-STN-20, whereas the thicknesses of both cloths were similar. Additionally, the filter cloths had calendared surfaces, as the fabric surface had been smoothed by rolling through heated rollers. Figure 1 shows both filter types, with images taken using the digital microscope Keyence Corporation VHX 2000D (Osaka, Japan). For this purpose, the filter cloth was positioned directly under the microscope lens for frontal and side imaging. The objective was used with a magnification factor of 50 to display a sufficient degree of detail. For the subsequent contamination process, the filters were cut into rectangular samples with a length of 4.4 cm and a width of 1.4 cm. This size enabled a suitable contamination area that was able to be cleaned in the cleaning device and examined by the digital microscope VHX 2000D.

2.2. Contamination Preparation

In this study, the mash filter in a brewery served as an industry-related case study that required a corresponding contamination type based on spent grains. Thus, a standardized mash using the brewer's MEBAK R-206.00.002 [31] congress mashing method provided a suitable contamination suspension. However, a slight adaption of the method was necessary. In the developed procedure, the cross-hammer mill PerkinElmer, Inc. LM 3100 (Hamburg, Germany) was used for crushing the malt instead of a roller mill. In general, hammer mills are the preferred type of mill in breweries to grind malt for mash filter applications. The malt used was a Pilsener Malt of the malthouse Malzfabrik Mich. Weyermann GmbH & Co. KG® (Bamberg, Germany), the most commonly used malt type in Germany. The resulting spent grains of this malt contained a wide variety of non-cellulosic polysaccharides, proteins, cellulose, lignin, lipids, and ash that produced problematic sticky or insoluble contamination on filter cloths [32,33]. The particle size distribution q3 ranged from >5 µm to <1000 µm, where the most significant proportion was from 20 µm to 225 µm. For this reason, applying simple and homogenous model contamination (e.g., particles) to assess industrial cleaning processes has to be regarded critically.



(**a**) (**b**)

Figure 1. Microscopic image as top and side view and schematic drawing of the filter cloths: (**a**) F1-TWL-80/100; (**b**) F2-STN-20; *t* = length to the repetition on the chain/shoot thread; $d_{Chain/Shoot}$ = diameter of chain/shoot thread; l_S = length straight-thread section; l_Z = length slanted-thread section.

Moreover, the husks of the barley malt were interesting for contaminating filter cloths. Husks are insoluble parts of the barley shell that a hammer mill crushes into small particles. Once these husk parts get stuck in filter meshes, they are difficult to remove by standard cleaning methods (e.g., chemicals or surface rinsing).

The congress mash procedure started with mixing 50 g of malt grist and 200 mL of demineralized water, preheated to 45 °C. The mixing was carried out with care and under constant stirring at 90 rpm to avoid clumping. This stirring speed was kept constant by all following steps. Subsequently, the mash was held at a temperature of 45 °C for 30 min and then heated up to 70 °C. After reaching this temperature level, another 100 mL of demineralized water (70 °C) was added and mashed for another 60 min. In a final step, the mash was cooled to 20 °C and weighed up to 450 g with demineralized water (see Figure 2A).

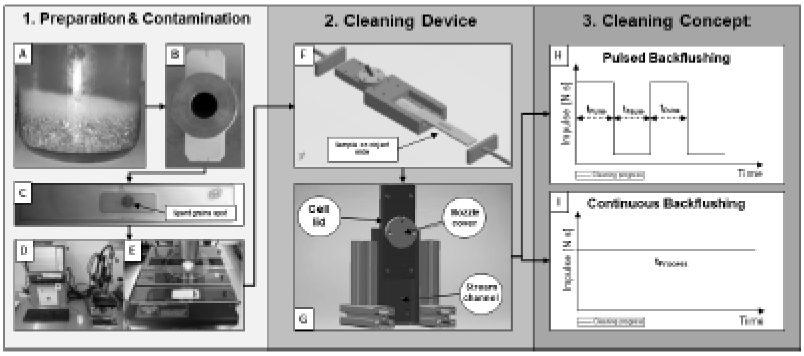


Figure 2. Illustration of the complete experimental procedure. (**A**) Prepared congress mash. (**B**) Aluminum stencil on cloth sample. (**C**) Cloth sample in the object slide. (**D**) Digital microscope device. (**E**) Object slide under microscope lens, identifying contamination. (**F**) Insertion of object slide into cleaning device. (**G**) Final vertical positioning of the cleaning device. (**H**,**I**) Applied cleaning concept. This illustration concludes Sections 2.2–2.4.

2.3. *Contamination Application*

Before the contamination suspension could finally be applied, an aluminum ring with an inner diameter of 10 mm was placed on each filter cloth sample (see Figure 2B). This stencil specified the dimensions of the circular contamination and thus enabled a standardized spent grains spot for the cleaning experiments. After prewetting the cloth samples, a mash volume of 200 µL was pipetted in this stencil to generate the contamination spot. Subsequently, the filter cloths were left to rest for 4 h at 20 °C, corresponding to an average filtration time with subsequent processing and set-up time in industrial practice. After this defined adhesion time, the aluminum circle was removed, leading to a reproducible standardized contamination spot with the same cake surface (diameter 10.0 mm) and thickness (approx. 2.6 mm).

Thus, the reproducible contamination spots provided an ideal starting point for the cleaning experiments. Due to the consistently equal mash volume, the contaminated cloth areas coincided in size and height and showed similar cleaning behavior. The reproducibility was mainly achieved by the standardized contamination procedure, same-time intervals, and equal particle size distribution. In particular, the applied hammer mill proved to be a significant advantage. In this grinding apparatus, the malt grains were milled into small particle sizes, which in this case contributed to a more homogeneous contamination appearance.

2.4. *Cleaning Device and Cleaning Processes*

The contaminated filter cloth sample was inserted into a holed microscope slide, and an image of the contaminated status quo was acquired (see Figure 2C–E). This procedure was necessary to assess the cleaning degree in a later step. Subsequently, the cloth sample in the object slide was placed directly in the cleaning apparatus (see Figure 2F). The sample was inserted with the filtrate side towards the cleaning nozzle, which ultimately allowed the cloth to be backwashed.

The experimental cleaning setup had a defined stream channel positioned vertically to simulate real-world conditions in an industrial mash filter system (see Figure 2G). This arrangement enabled industry-like conditions to be reflected in a filter press. Above the filter cloth, a cell lid with an inserted cylindrical nozzle was mounted. The nozzle streamed vertically (incidence angle = 90°) on the filtrate side of the filter cloth sample on the microscope slide, backflushing the filter cloth. The nozzle had a pipe connected to a solenoid valve, where cleaning streams with defined time lengths could be adjusted by an Arduino© NANO microcontroller of Arduino LLC (Boston, MA, USA). The adjustable parameters on the cleaning device can be taken from Table 2. The experimental cleaning setup enabled the generation of pulsed jets with variable pulse lengths and pauses as well as standard continuous cleaning. As the mechanical cleaning effect of backflush cleaning was the focus, demineralized water was used as the only cleaning agent in all experiments.

Table 2. Cleaning parameters and the corresponding ranges applicable in the cleaning setup.

Cleaning Parameter	Range	Unit
Jet velocity	1.5–4.0	m/s
Number of pulses	1–1000	-
Minimum pulse length	15	ms
Standard pulse–pause ratio	100/100	ms/ms

The wash water was directly transportable from a storage tank to the cleaning device by applying pressure to the tank. Hence, the velocity of the fluid was directly affected by the pressure level. The connected solenoid valve was connected to an upstream 3-way system. By closing the valve, the water circulated in and out of the tank. When the valve was open, water shot into the nozzle. This jet pre-acceleration was necessary to achieve a constant and adjustable speed. Before every measurement, it was necessary to determine the jet velocity. Key parameters included the mass of the emitted water m_{Fluid} and the corresponding time length t_{open}. Equation 1 theoretically calculated the desired impact velocity by weighing the emitted fluid mass.

$$v_{Nozzle} = \frac{m_{Fluid}}{t_{open} \times A_{Nozzle} \times \rho_{Fluid}} \tag{1}$$

Here, the amount of water m_{Fluid} (measured gravimetrically) escaping from the nozzle at the surface A_{Nozzle} (1.57×10^{-3} m^3) equaled the velocity v_{Nozzle}. For an exact calculation, the water density ρ_{Fluid} (1.0 g·cm^{-3} at 20 °C) and a defined nozzle-opening time of 10 s were required. The cleaning temperature was 20 °C and kept constant in the test laboratory.

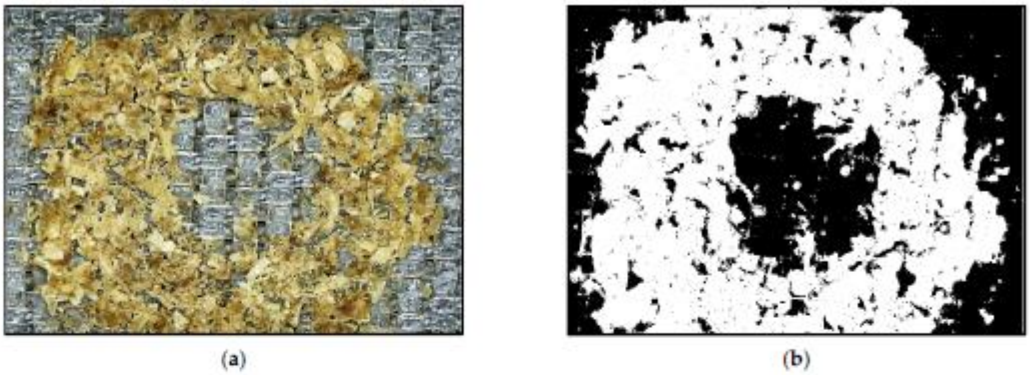
3. Results and Discussion

3.1. Residue Analysis

A suitable detection method for the residues was the critical element in assessing the cleaning degree of the corresponding cleaning experiment. For this purpose, the digital microscope VHX 2000D was used to capture images of the filter cloths. The microscope camera (18 MP) took images of the contaminated and cleaned filter cloths with a 20× magnification. An image analysis algorithm coded in MATLAB 2019b of The MathWorks®, Inc. (Natick, MA, USA) processed and analyzed both pictures (see Figure 3). For the image processing, the color space HSV was used.

The algorithm generated a cut picture and converted it into hue (H), saturation (S), and value color space (V) (see Figure 3b). The determination of the contaminated areas depended on the desired color spectrum in H and the exclusion of white and gray tones by setting the saturation scale. For this type of residue analysis, there had to be sufficient color contrast between the filter cloth and contamination spots. The light conditions were adapted to the measurement environment in the lab. The proper adjustment implied the balanced illumination of the image while avoiding reflections on the contamination in case of overlighting.

Furthermore, the lighting settings had to be consistent to achieve highly reproducible measurements. In the case of spent grain-loaded filter cloths, the color values of contamination spots were brownish, ocher, and yellowish, allowing sufficient detectability on white filter cloths. The precisely adjustable illumination of the samples was achieved with the aid of a high-power LED lamp installed in the Keyence microscope.



(a) (b)

Figure 3. Original image of the cleaned filter sample (**a**) and its binarized image (**b**). The white spots represent the remaining contamination after cleaning, whereas the black areas show the cleaned or contaminated surface. The picture also illustrates the area where the jet streamed through the filter cloth (the black spot in the middle of (**b**)).

Subsequently, the resulting binary image's contaminated areas (white) were computed. By identifying the contaminated areas before cleaning A_1 and after cleaning A_2, the cleaning degree G was determined with Equation (2)

$$G\,[-] = 1 - \frac{A_2}{A_1} \tag{2}$$

The cleaning degree reflected the amount of contamination removed from the respective cleaning process. Thus, the efficiency of cleaning methods depended on the cleaning degree.

3.2. Determination of the Backflow Factor

Before conducting the parameter variation and comparing the different cleaning concepts, it was necessary to consider the resulting cleaning effect in detail. For this reason, it was necessary to identify the relevant backflush volumes that can percolate the filter cloth. Ultimately, this specific volume generated the cleaning effect.

Here, the novel introduced backflow factor ζ_{BF} could represented the backflush's volume (the portion of the total amount of water used) that could flow through the dense filter meshes. The other portion was deflected on the cloth and flowed off laterally on the filtrate side due to back pressures at thread bridges. ζ_{BF} was the guiding parameter for the amount of water passing through the filter. For this purpose, the filter sample was mounted on a microscope slide and placed in front of the nozzle. A seal ensured the complete separation between the top and bottom parts of the slide. Afterward, a jet with mass m_{Fluid} was streamed onto the filter cloth. The amount of water $m_{Fluid\_Filtered}$ that passed through the filter cloth was drained into a small container. The amount of fluid passing through the filter was measured gravimetrically and helped determine ζ_{BF} with Equation (3).

$$\zeta_{BF} = \frac{m_{Fluid\_Filtered}}{m_{Fluid}} \tag{3}$$

Figure 4 shows the results of ζ_{BF} for both filter cloth types using six different stream velocities with an inflow time of 10 s.

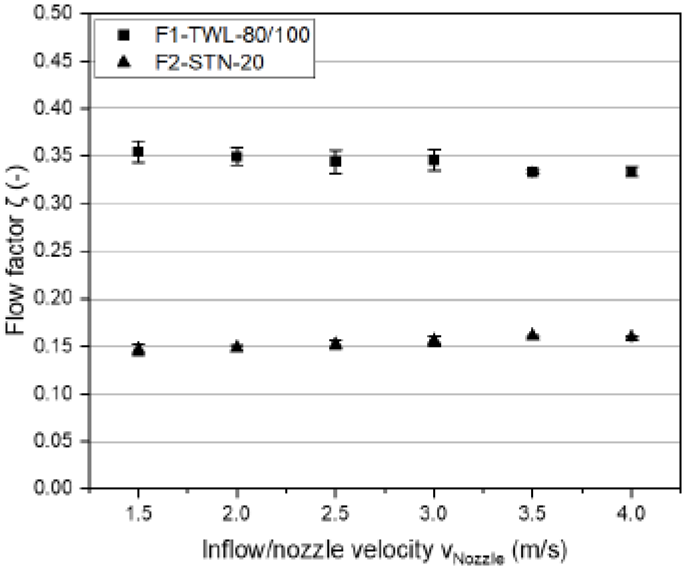


Figure 4. Backflow factor ζ_{BF} of a defined water volume streaming through filter cloths. Confidence intervals with $\alpha = 0.05$.

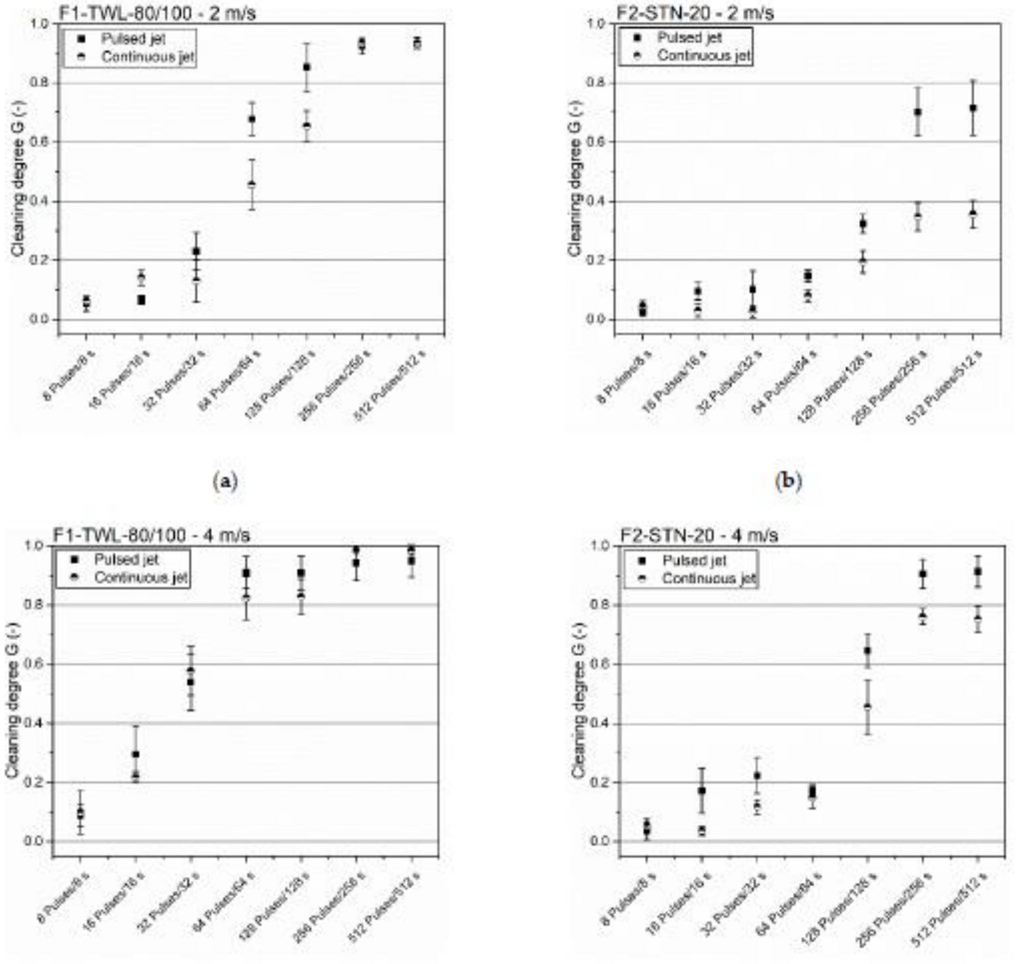
Regarding F1-TWL-80/100, the results depicted a slightly decreasing ζ_{BF} by increasing the inflow velocity v_{Nozzle}. This was in contrast to the observation regarding F2-STN-20, where a slight increase was visible. On the one hand, v_{Nozzle} significantly influenced wash-water consumption, increasing with higher velocities. On the other hand, the difference was insignificant, which derived the assumption that v_{Nozzle} had no increasing influence on ζ_{BF} when only short cleaning streams were used. This observation may result from the free passage surface, which allowed only a certain amount of backflush to pass in a particular time interval. The passage surface depended on the mesh sizes, weave type, and thread thickness.

However, there were significant differences in a direct comparison of both filter types. For F1-TWL-80/100, twice as much wash water shot through the filter cloth. This result depended on mesh sizes, which in F1-TWL-80/100 were four times bigger. For F2-STN-20, there was a larger filter surface, resulting in back pressures and increased dynamic pressures. Overall, the measured values of F2-STN-20 were only approximately half those of F1-TWL-80/100.

3.3. *Comparison of Pulsed and Continuous Backflush Cleaning*

Jet cleaning can be applied either as a standard continuous or the novel pulsed cleaning process. Recently, the pulsed procedure has been increasingly considered for filter cloths [10,13,14,17,30]. Figure 5 compares the continuous and pulsed backflushing techniques using the velocities 2 m/s and 4 m/s for cleaning both filter cloths.

Significant differences were observable in the results regarding a low velocity of 2 m/s. Pulsed jets resulted in significantly higher cleaning degrees when compared to the two cleaning methods. Notably, the transition zone from 32 pulses/32 s to 256 pulses/265 s showed these efficiency differences. In summary, the pulsation operating mode had a high ecological and economic potential, as comparable degrees of cleaning could be achieved in a shorter time with considerably less cleaning fluid than the continuous operation. Regarding the applied cleaning velocities, a difference between 2 and 4 m/s became apparent, which is highlighted more in Section 3.4.



(a) (b)

(c) (d)

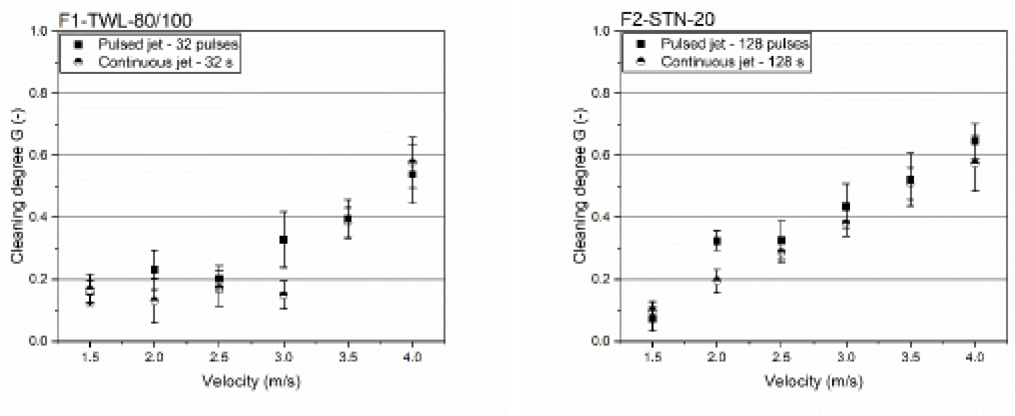
Figure 5. Comparison of pulsed and continuous cleaning with two different cleaning velocities. Settings for pulsed cleaning: $t_{Pulse} = t_{Pause} = 0.1$ s in a logarithmic interval [8:265]. Continuous cleaning settings: unpaused in a logarithmic interval [8:256] s. (**a**) F1-TWL-80/100 and 2 m/s. (**b**) F2-STN-20 and 2 m/s. (**c**) F1-TWL-80/100 and 4 m/s. (**d**) F2-STN-20 and 4 m/s. $n \geq 5$. Confidence intervals with $\alpha = 0.05$.

The comparison of both filter cloths also showed efficiency differences. The better cleanability of F1-TWL-80/100 confirmed the above-stated assumptions. Fewer pulses or small cleaning lengths did not lead to appropriate cleaning degrees, resulting in poor removal effects. The appropriate adjustment was in the mentioned transition zone and had significantly higher pulse numbers and washing lengths depending on the filter geometry. Pulsed cleaning had more advantages when selecting the most suitable process design. Augustin et al. [18] also saw a higher efficiency of pulsed cleaning, resulting in higher wall shear stress and waviness on the applied technical surfaces, favoring contamination detachment.

Furthermore, in this experimental setup, the filter cloth was positioned vertically. Respective pulse pauses allowed improved drainage of the wash water and simultaneous contamination removal from the cleaning zone. A reduction of the liquid layer thickness also occurred, which could have cushioned contamination from previous jets.

3.4. Influence of Cleaning Velocity

The previous results indicated an influence of the stream velocity v_{Nozzle} on the cleaning degree. Other studies [21,34–36] also followed that the dirt-removing wall shear stress depended on the applied flow velocity. A closer look at the transition zone needed to be taken regarding the velocity influence: for F1-TWL-80/100, the transition area was 32 pulses/32 s, whereas it was 128 pulses/128 s for F2-STN-20. As adjusted velocities, a range from 1.5 to 4.0 m/s was chosen as these are standard cleaning settings in the beverage and food industry [37,38]. Figure 6 shows the influence of these average velocities on the cleaning degree of both filter cloths.



(**a**) (**b**)

Figure 6. Velocity variation of v_{Nozzle} regarding the transition area of pulsed and continuous cleaning. (**a**) Pulsed wash jet with 32 pulses and continuous wash jet with a length of 32 s at F1-TWL-80/100. (**b**) Pulsed wash jets with a quantity of 128 pulses and continuous wash jet with a length of 128 s at F2-STN-20. $t_{Pulse} = t_{Pause} = 0.1$ s. $n \geq 5$. Confidence intervals with $\alpha = 0.05$.

The results depicted in all subfigures showed increased cleaning degrees using higher velocities v_{Nozzle}. The comparison of both cleaning designs showed pulsed jets reaching similar cleaning degrees earlier. From the velocity curves in each diagram, the cleaning degree remained constant at a small value until a particular velocity was applied. Afterward, a linear increase in the cleaning degree could be assumed.

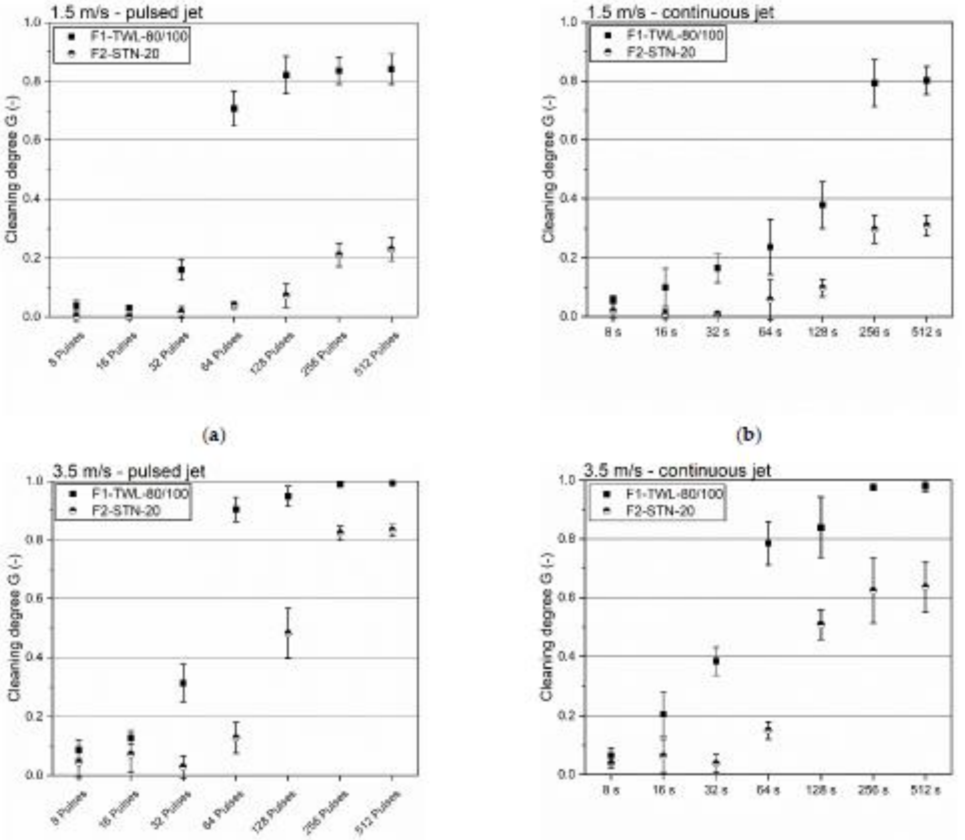
Of high interest was the velocity at which the degree of cleaning increased significantly. At this point, the cleaning efficiency could be related to the turbulence degree. Efficient cleaning procedures are facilitated by turbulent flows, increasing the wall shear stress, reducing the boundary layer, and absorbing more contamination [37]. In particular, the results of F1-TWL-80/100 showed a significant cleaning effect with adjusting inflow velocities of 2.5 to 3.0 m/s. It could be assumed that a turbulent backflush at the contaminated filter side only occurred with these higher velocities at the inflow side.

Thus, adjusting a higher v_{Nozzle} is necessary to reach enough mechanical effect and turbulences of the backflush, favoring the cleaning process. Regarding continuous cleaning (32 s) of F1-TWL-80/100, this issue became apparent at 3.5 m/s. Concerning the pulsed method, the transition point is visible at 3.0 m/s. In addition, F2-STN-20 showed similar observations. Here, a four-times longer cleaning length and pulse number were necessary to reach the corresponding transition point. Comparing continuous and pulsed backflushing, the point of interest was 2.0 m/s. Here, the pulsed jet achieved 1.5 times higher cleaning degrees.

In conclusion, the adjusted velocity v_{Nozzle} of backflushing was crucial to reaching acceptable cleaning efficiency. Remarkably, the same cleaning effects on the filtrate side could not necessarily be assumed when setting a turbulent cleaning jet on the feed side. However, pulsed cleaning jets could help achieve a better cleaning result, even with lower backflush velocities. Firstly, pulsed cleaning can compensate arising losses in the cleaning effect and reduction of turbulent conditions. Secondly, there was a significant ecological and economic potential in using pulsed backflushes, as cleaning time and fluid consumption in particular could be reduced.

3.5. Comparison of Both Filter Types

In the last step, both filter cloths were compared to illustrate the differences in their cleanability. For this purpose, two different velocities were used to examine the influence of filter geometry. The first velocity was the lowest at 1.5 m/s, where all mechanical effects were minimal, helping to understand the different cleanabilities. The second cleaning speed was at a change to the turbulent condition of 3.5 m/s. All results are shown in Figure 7.



(a) (b)

(c) (d)

Figure 7. Comparison of both filter cloths using pulsed and continuous cleaning. (**a**) Pulsed cleaning at an inflow velocity of 1.5 m/s. (**b**) Continuous cleaning at an inflow velocity of 1.5 m/s. (**c**) Pulsed cleaning at an inflow velocity of 3.5 m/s. (**d**) Continuous cleaning at an inflow velocity of 3.5 m/s. $n \geq 5$. Confidence intervals with $\alpha = 0.05$.

A difference between both filters was visible in all diagrams. The abrupt increase in the degree of cleaning above a certain speed was again observable. In addition, the transition zone became obvious between 16 pulses/16 s to 128 pulses/128 s. After the contamination application, spent grain cake discharges penetrated the meshes due to the filtration effect and dried partly. The jets rewetted the contamination in these first cleaning steps, reducing adhesion towards the cloth surface.

Regarding the geometry, F1-TWL-80/100 was a twill weave, whereas F2-STN-20 was a satin weave. According to Table 1, F1-TWL-80/100 had a simpler geometry and bigger mesh sizes that facilitated backflush cleaning. The difference in mesh sizes had a decisive influence on the cleaning performance. Larger mesh sizes allowed much larger quantities of washing water to pass through. This larger volume of wash water was thus able to remove more significant amounts of contamination and ultimately transport it away from the contamination zone. In addition, an influence on the backflush's velocity could also be observed here, which was reduced to a minor degree in the case of large-mesh cloths.

4. Conclusions

This study presented filter cloth backflushing for industrial-close contamination removal—in this case, spent grains in a brewery. Therefore, continuous and pulsed jets were applied and compared. The observations help to clarify backflush cleaning and oversee critical aspects of finding the proper cleaning procedure. The method showed satisfactory reproducibility for industry-related food contamination based on spent grains, which was confirmed by the determined confidence intervals. The results also show significant differences when comparing the different cleaning concepts and critical cleaning parameters.

Firstly, pulsed backflushing could be presented as a promising cleaning concept for filter cloths and mash filters in particular. The increased mechanical cleaning effect could enhance and optimize the cleaning process significantly. Pulsed backflushes were advantageous in economic and ecological aspects as they cleaned more effectively, achieving similar cleaning degrees faster, with a reduced amount of wash water and less cleaning time. However, at this point, it needs to be clarified that chemical agents will always be necessary to guarantee hygienic and microbiological-uncritical conditions.

Secondly, the mesh size and respective backflow factor ζ_{BF} influenced cleanability, as larger meshes allowed more cleaning fluid to pass the filter cloth. The weave type concerning mesh sizes was decisive in a filter cloth's cleanability in this context. Other parameters such as materials or calendaring seemed to be less important. In addition, the latter has to be critically discussed as it can, even more, reduce mesh sizes by cloth flattening. Conclusively, filter geometry—derived from weave type and mesh sizes—is the decisive parameter in designing the appropriate backflushing concept. More fine meshes and complex geometries require higher inflow velocities to achieve a sufficient cleaning effect.

Ultimately, the cleaning velocity was the third vital aspect in finding the proper cleaning concepts. Higher inflow velocities resulted in higher cleaning degrees, although their speed seemed to be reduced after passing through the filter cloth. Thus, adjusting a sufficient nozzle velocity v_{Nozzle} was crucial to ensure sufficient cleaning effects after the passage. Before selecting the respective cleaning parameters, a cloth-specific transition zone from low to high cleaning degrees had to be identified. However, higher velocities also lead to higher impulses, damaging the cloth and demanding more cleaning liquid.

In summary, it can be asserted that pulsed cleaning jets are preferable for mash filter cleaning. Depending on the cloth design, applying 64 pulses in a quick sequence (clocking 100 ms) and an incident flow velocity of at least 3.0 m/s can yield good cleaning results. In addition, a more apertured cloth favored cleaning with backflushes. However, this depends on the application field and the required filtration properties. Since relatively large particles are separated during mash filtration, cloths with larger mesh sizes can be used well here.

For the food industry—especially breweries—pulsed backflush cleaning is a promising technology to optimize filter cloth cleaning in mash filters. In addition, the knowledge gained can optimize filter press cleaning in particular. The results of this study can also pave the way from rigid, operator-based cleaning procedures to demand-oriented, digitalized concepts that enable modern cleaning in terms of Industry 4.0. For a final transfer of the results into industrial application, the backflushing has to be technically realized on a large-scale. Here, direct backflushing of the entire filter cloth surface with a pump system is conceivable. It is also possible to place nozzles in the filter plate behind the filter cloth. If appropriately arranged, they enable the targeted generation of backflushes with an efficient cleaning effect. The choice of the proper technique always depends on the design of the filter press, the manufacturer, and the prevailing local requirements. For an efficient cleaning process, the cloth geometry applied should, in all cases, be taken into consideration in the preliminary stages. This requirement largely which basic cleaning parameters must be used.

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References

1. Horrocks, A.R.; Anand, S.C. *Handbook of Technical Textiles: Volume 1: Technical Textile Processes*, 2nd ed.; Woodhead Publishing: Amsterdam, The Netherlands, 2016; ISBN 978-1-78242-458-1.
2. Rushton, A.; Ward, A.S.; Holdich, R.G. *Solid-Liquid Filtration and Separation Technology*, 2nd ed.; Wiley-VCH: Weinheim, Germany; New York, NY, USA, 1996; ISBN 9783527614974.
3. Mauermann, M.; Eschenhagen, U.; Bley, T.; Majschak, J.-P. Surface modifications—Application potential for the reduction of cleaning costs in the food processing industry. *Trends Food Sci. Technol.* **2009**, *20*, S9–S15. [CrossRef]
4. Tarleton, E.S.; Wakeman, R.J. *Solid/Liquid Separation: Equipment Selection and Process Design*, 1st ed.; Butterworth-Heinemann: Amsterdam, The Netherlands, 2006; ISBN 9780080467177.
5. Stahl, S.; Siggelkow, S.; Nirschl, H. A Microbiological Test Method to Determine the Cleanability of Filter Media in Solid-Liquid-Separation Applications. *Eng. Life Sci.* **2007**, *7*, 136–142. [CrossRef]
6. Moeller, R.-S. Haftkräfte, Alterung und Überwachung funktionaler Oberflächen—Gärtücher im Gebrauch. Ph.D. Dissertation, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, 2018.
7. Narziß, L.; Back, W.; Gastl, M.; Zarnkow, M. *Abriss der Bierbrauerei*, 8th ed.; Wiley-VCH: Weinheim, Germany, 2017; ISBN 9783527340361.
8. Spellman, F.R. *Handbook of Water and Wastewater Treatment Plant Operations*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2013; ISBN 978-1420075304.
9. Deponte, H.; Tonda, A.; Gottschalk, N.; Bouvier, L.; Delaplace, G.; Augustin, W.; Scholl, S. Two complementary methods for the computational modeling of cleaning processes in food industry. *Comput. Chem. Eng.* **2020**, *135*, 106733. [CrossRef]
10. Werner, R.; Bollwein, B.; Petersen, R.; Tippmann, J.; Becker, T. Pulsatile Jet Cleaning of Filter Cloths Contaminated with Yeast Cells. *Chem. Eng. Technol.* **2017**, *40*, 450–458. [CrossRef]
11. Morsch, P.; Arnold, A.; Schulze, H.; Werner, R.; Anlauf, H.; Geier, D.U.; Becker, T.; Nirschl, H. In-situ cleaning process of chamber filter presses with sensor-controlled and demand-oriented automation. *Sep. Purif. Technol.* **2021**, *256*, 117793. [CrossRef]
12. Morsch, P.; Kühn, J.; Werner, R.; Anlauf, H.; Geier, D.U.; Becker, T.; Nirschl, H. Influence of the filter cloth and nozzles type on the in-situ cleaning procedure of filter presses. *Chem. Eng. Sci.* **2020**, *226*, 115889. [CrossRef]
13. Weidemann, C.; Vogt, S.; Nirschl, H. Cleaning of filter media by pulsed flow—Establishment of dimensionless operation numbers describing the cleaning result. *J. Food Eng.* **2014**, *132*, 29–38. [CrossRef]
14. Leipert, C.; Nirschl, H. Untersuchungen zum Reinigungsverhalten von Filtermedien mithilfe pulsatorischer Strömung. *Chem. Ing. Tech.* **2012**, *84*, 1285. [CrossRef]
15. Fuchs, E.; Helbig, M.; Pfister, M.; Majschak, J.-P. Erhöhung der Reinigungseffizienz bei der Cleaning-in-Place-Reinigung durch diskontinuierliche Flüssigkeitsstrahlen. *Chem. Ing. Tech.* **2017**, *89*, 1072–1082. [CrossRef]

16. Stoye, H.; Köhler, H.; Mauermann, I.M.; Majschak, D.-I.J.-P. Untersuchungen zur Steigerung der Reinigungseffizienz durch pulsierende Spritzreinigung. *Chem. Ing. Tech.* **2014**, *86*, 707–713. [CrossRef]
17. Weidemann, C. *Reinigungsfähigkeit von Filtermedien Mithilfe Kontinuierlicher und Pulsierender Strömung*; KIT Scientific Publishing: Karlsruhe, Germany, 2015; ISBN 978-3-7315-0322-4.
18. Augustin, W.; Fuchs, T.; Föste, H.; Schöler, M.; Majschak, J.-P.; Scholl, S. Pulsed flow for enhanced cleaning in food processing. *Food Bioprod. Process.* **2010**, *88*, 384–391. [CrossRef]
19. Blel, W.; Le Gentil-Lelièvre, C.; Bénézech, T.; Legrand, J.; Legentilhomme, P. Application of turbulent pulsating flows to the bacterial removal during a cleaning in place procedure. Part 1: Experimental analysis of wall shear stress in a cylindrical pipe. *J. Food Eng.* **2009**, *90*, 422–432. [CrossRef]
20. Blel, W.; Legentilhomme, P.; Bénézech, T.; Legrand, J.; Le Gentil-Lelièvre, C. Application of turbulent pulsating flows to the bacterial removal during a cleaning in place procedure. Part 2: Effects on cleaning efficiency. *J. Food Eng.* **2009**, *90*, 433–440. [CrossRef]
21. Blel, W.; Bénézech, T.; Legentilhomme, P.; Legrand, J.; Le Gentil-Lelièvre, C. Effect of flow arrangement on the removal of Bacillus spores from stainless steel equipment surfaces during a Cleaning in Place procedure. *Chem. Eng. Sci.* **2007**, *62*, 3798–3808. [CrossRef]
22. Bode, K.; Hooper, R.J.; Paterson, W.R.; Ian Wilson, D.; Augustin, W.; Scholl, S. Pulsed Flow Cleaning of Whey Protein Fouling Layers. *Heat Transf. Eng.* **2007**, *28*, 202–209. [CrossRef]
23. Silva, L.D.; Filho, U.C.; Naves, E.A.A.; Gedraite, R. Pulsed flow in clean-in-place sanitization to improve hygiene and energy savings in dairy industry. *J. Food Process Eng.* **2021**, *44*, e13590. [CrossRef]
24. Yang, J.; Kjellberg, K.; Jensen, B.B.B.; Nordkvist, M.; Gernaey, K.V.; Krühne, U. Investigation of the cleaning of egg yolk deposits from tank surfaces using continuous and pulsed flows. *Food Bioprod. Process.* **2019**, *113*, 154–167. [CrossRef]
25. Furumoto, K.; Narita, T.; Fukasawa, T.; Ishigami, T.; Kuo, H.-P.; Huang, A.-N.; Fukui, K. Influence of pulse-jet cleaning interval on performance of compact dust collector with pleated filter. *Sep. Purif. Technol.* **2021**, *279*, 119688. [CrossRef]
26. He, C.; Yan, C.; Tang, C.; Huang, M.; Ren, L.; Zhang, M. Nitrogen pulse jet cleaning of the pleated filter cartridge clogged with adhesive hygroscopic dusts. *Process Saf. Environ. Prot.* **2021**, *147*, 430–438. [CrossRef]
27. Zhang, Q.; Liu, D.; Wang, M.; Shu, Y.; Xu, H.; Chen, H. Characteristics and evaluation index of pulse-jet dust cleaning of filter cartridge. *Process Saf. Environ. Prot.* **2022**, *157*, 362–374. [CrossRef]
28. Li, J.; Wu, D.; Wu, Q.; Luo, M.; Li, J. Design and performance evaluation of novel colliding pulse jet for dust filter cleaning. *Sep. Purif. Technol.* **2019**, *213*, 101–113. [CrossRef]
29. Morsch, P. Detachment of Fine-Grained Thin Particle Layers from Filter Media. Ph.D. Dissertation, Institute of Mechanical Process Engineering and Mechanics (MVM), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, 2021. [CrossRef]
30. Werner, R.A.; Schappals, L.; Geier, D.U.; Becker, T. Pulsed forward flushes as a novel method for cleaning spent grains-loaded filter cloth. *Int. J. Food Sci. Technol.* 2022. [CrossRef]
31. Jacob, F. *MEBAK Brautechnische Analysenmethoden—Rohstoffe: Rohfrucht, Gerste, Malz, Hopfen und Hopfenprodukte: Methodensammlung der Mitteleuropäischen Brautechnischen Analysenkommission*; Selbstverlag der MEBAK: Freising-Weihenstephan, Germany, 2016; ISBN 978-3981596021.
32. Mussatto, S.I.; Roberto, I.C. Acid hydrolysis and fermentation of brewer's spent grain to produce xylitol. *J. Sci. Food Agric.* **2005**, *85*, 2453–2460. [CrossRef]
33. Steiner, J.; Procopio, S.; Becker, T. Brewer's spent grain: Source of value-added polysaccharides for the food industry in reference to the health claims. *Eur. Food Res. Technol.* **2015**, *241*, 303–315. [CrossRef]
34. Lelieveld, H.L.M.; Mostert, M.A.; Holah, J.T. *Handbook of Hygiene Control in the Food Industry*; CRC Press: Boca Raton, FL, USA; Woodhead Publisher: Cambridge, UK, 2016; ISBN 978-1-85573-957-4.
35. Jennings, W.; McKillop, A.; Luick, J. Circulation Cleaning. *J. Dairy Sci.* **1957**, *40*, 1471–1479. [CrossRef]
36. Gallot-Lavallee, T.; Lalande, M.; Corrieu, G. Cleaning Kinetics Modeling of Holding Tubes Fouled During Milk Pasteurization. *J. Food Process Eng.* **1984**, *7*, 123–142. [CrossRef]
37. Tamime, A.Y. *Cleaning-in-Place: Dairy, Food and Beverage Operations*, 3rd ed.; Blackwell Publishing Ltd.: Oxford, UK; Ames, IA, USA, 2009; ISBN 978-1-4051-5503-8.
38. Schöler, M.; Fuchs, T.; Helbig, M.; Augustin, W.; Scholl, S.; Majschak, J.-P. Monitoring of the local cleaning efficiency of pulsed flow cleaning procedures. In Proceedings of the International Conference on Heat Exchanger Fouling and Cleaning VIII 2009, Schladming, Austria, 14–19 June 2009; pp. 455–463.

6 Discussion

In state-of-the-art, filter cloth cleaning in numerous industrial sectors is still backward and often inefficient. Recently, an increasing number of research projects [53; 55; 63] have been focusing on this issue, intending to provide more general knowledge on efficient cloth cleaning processes that are both more economical and ecological. Above all, more resource-efficient processes are needed in the future, reducing the use of cleaning agents and saving valuable process water. The mentioned issues are particular problems in the food industry, where rigid cleaning regimes still predominate. Here, good filtration performance is focused on when selecting filter cloths, while cleaning efficiency is of secondary importance. Based on the available literature, many open questions require answers to enable processes in numerous industrial applications.

This thesis focuses on the problems of filter cloth cleaning in the beverage and food industry and reveals promising new ways with the example of mash separation in breweries. The general problems of cloth cleaning in beverage applications are discussed in detail in 5.2 and the literature review of this thesis [18]. For instance, it is not only the material properties of the filter cloths that limit the results of possible cleaning processes but also the biophysical properties of possible retentates in combination with complex cloth geometries. The review also highlights possible approaches to implementing efficient, fast, and demand-oriented cleaning processes with jet cleaning. In particular, various fluid-mechanical variables are discussed in detail with their impact on the cleaning result. Ultimately, pulsatory cleaning is identified as a promising concept, which can be applied to the cloth by forward jets or backflushing.

Consequently, the theoretical findings were studied in the experimental Sections 5.3, 5.4, and 5.5. Here, the corresponding publications [59–61] addressed the open questions of the literature review by the four research hypotheses listed in Chapter 3. The results revealed the high potential of using pulsed jet cleaning in mash filters. Additionally, the advantages and disadvantages of forward and backflush cleaning were investigated. Essential cloth properties with significant influence on cloth cleaning were presented.

In the following, the results based on the research hypotheses are further discussed. Finally, the findings are presented based on the main objectives of this thesis. The conducted research studies are based on spent grains as model residues contaminating the filter cloths, enabling industry-oriented application.

6.1 RH 1: Residue detection of spent grains

The precise identification of the remaining spent grains on the filter cloths was the essential first step in the method design of this thesis. Accurate and detailed contamination detection was one of the critical factors in developing a suitable cleaning sensor. These aspects enable a detailed analysis of the influence of the cloth properties on the cleaning result and the comparability between different process modes. This subchapter, therefore, primarily addresses RH 1.

The precise detection of spent grains on filter cloths can be achieved with contactless image processing techniques, enabling efficient residue detection in an industrial environment.

Firstly, an analysis of existing methods for detecting contamination was necessary. Conventional cleaning tests for surfaces and components have been published in Europe and Germany by the EHEDG [64–66] and the VDMA [67]. In most cases, these are based on model contamination with certain colorants or indicator microorganisms. Thus, a poor cleaning result can be detected by remaining discoloration or positive results in microbiological swab tests. Stahl et al. [56] subsequently developed the first method based on the EHEDG test to measure the cleanability of filter media. The developed test could determine a filter media's cleanability based on microbiological model contamination. A visible color reaction is caused by the remaining model microorganisms indicating poor cleanability. However, the methods mentioned are not suitable for the cleaning evaluation in the investigations conducted here due to the focus on real contamination. Since invasive techniques could destroy or at least irreversibly affect the existing contaminated areas, a non-contact measurement based on image recognition was necessary. Such techniques are also often used in the food industry, as they offer significant advantages regarding hygiene and food safety. They register an actual state of the production environment and thus avoid additional contamination through contact with an analysis instrument.

Several image analysis methods have already been published concerning filter cloth cleaning. Weidemann [53] developed a contamination method based on fluorescent model particles of melamine resin and a riboflavin solution. Under a fluorescence microscope, particles remaining after cleaning could be revealed without interference from the surrounding filter surface. Möller [54] continued developing an analytical method for woven cloths, which are used, in particular, in bakeries. The method was based on a combination of periodicity detection, threshold, and outlier determination, thus eliminating the influence of the remaining cloth properties. Morsch et al. [55; 68; 69] finally developed a more practical method, measuring contamination based on spent grains. The gradient-reduction-threshold-reduction (GRSR) method was applied in the study, a robust method against spontaneous changes in ambient light. Here, the image of a contaminated cloth was iterated with a clean reference image to identify contaminated areas in pixels. However, this method is associated with high computational effort, resulting in long analysis times. It was only partly applicable, as it was essential to efficiently measure a higher sample throughput with adaptability to two different cleaning devices. Additionally, a time-efficient and precise image recognition method enables direct application in industrial processes, such as mash filters in breweries. In conclusion, a simpler and faster procedure was necessary for this study.

The choice of method development thus fell on a detection method based on the color and brightness contrast between the contamination and the filter cloth. The same principle as in GRSR using the HSV-colorspace was applied, leaving out the more computation-intensive iteration. This aspect allowed the measurement to be made directly based on the specified contrast between the contamination and the cloth, thus enabling rapid residue detection. Nevertheless, the exclusion of the iteration leaves out the aspect of a changing cloth surface. In addition, in direct industrial applications, cloth aging must also be taken into account, which was not considered in this study. However, the detection of spent grains on monochrome filter cloths is mainly a matter of detecting the coarse residues on the cloth surface and insoluble finer particles in the mesh. In order to keep the efficiency of subsequent product batches and the overall process at a high level, it is essential to detect these efficiently and quickly. The analysis concept adopted here fulfills these prerequisites, which is why it was used in all the experiments.

In comparison to the GRSR method, the H, S, and V values of the HSV color space in these experimental runs had to be determined more precisely based on the contamination present. For this purpose, numerous pre-studies had to be performed in order to be able to determine suitable values via MATLAB. The use of HSV, especially of the S and V values, required homogeneous lighting of the experimental setup. Excellent and continuous illumination without a flickering light enables a standardized measurement environment. So, the lighting was achieved by using LED ring lights in both cleaning systems. These technical installations enabled precise determination of the necessary color space values and reproducible measurements without needing ongoing adjustments. In industrial applications, attention has to be paid to the light source and the wavelength when using PP filter cloths. The material can be degraded under ultraviolet light if the illumination is too long and intense.

The residue detection was carried out by processing corresponding single images using the algorithm described in Chapters 4 and 5 and publications 2, 3, and 4 [59–61]. The results showed high reproducibility and measurement accuracy, allowing a detailed cleaning process analysis. A significant advantage was also that the images from different sensors (microscope and high-speed camera) could be analyzed using the same algorithm. This aspect allowed high comparability between the two systems, enabling easy transferability into industrial applications.

A further advantage was the feasibility of analyzing high-speed videos with the help of prior segmentation into individual images. This aspect enabled time-resolved cleaning process monitoring of cloths for the first time. In addition, the short analysis time compared to the existing tests in the literature made it possible to measure large sample volumes, facilitating detailed results with high measurement resolution in the three research publications [59–61] in Chapter 5.

In conclusion, the presented method accurately identified spent grains adhering to filter cloths. The great advantage of the method is the fast analysis of the contamination state, which also allows suitable conclusions to be drawn about necessary actions in an industrial context. Another advantage of the developed procedure is the fast adaptation to different camera systems and, thus, the wide range of possible applications. The disadvantage that the saturation (S) and value (V) settings always have to be adapted to the ambient light could be solved by efficient illumination of the operating room and the surface with LED lights. In many cases, filter presses are operated in poorly or insufficiently illuminated rooms, which is why an additional illumination system is necessary. The fast and reliable detection of food-related residues is critical in fully automated and optimized cleaning concepts. With the help of such a sensor, cleaning digitalization with fast and easy storage of large datasets becomes achievable. This aspect could enable demand-oriented and predictable cleaning applications.

6.2 RH 2: Cleaning influence of cloth structure

Several properties of a filter cloth can influence cleaning. Besides the applied material, the surface finish is decisive for the success of a cleaning procedure. As filter cloths differ, especially in their weave type, mesh sizes, and thread thicknesses, a significant influence on cleaning is hypothesized, given in RH 2.

The filter cloth’s structure (e.g., mesh size, weave type) significantly influences the cleaning efficiency and requires individual hygienic design concepts.

All publication results in 5 showed a high dependency of the cleaning efficiency of filter cloths on their filter structure, like weave type and mesh size. The individual filter geometry is primarily attributed to the weave, thread thickness, and material. Their corresponding combination leads to individual mesh sizes and filter structures, which are essential for forming a filter cake on the cloth's surface and, thus, for the solid-liquid separation and filtration of specific particle sizes.

Firstly, publication 2 [61] in 5.3 treated the cleaning of filter cloths regarding their measured roughness values *Ra* and *Sa*. Here, most filter types ranged between a line roughness of 2.5 and 10.0 µm. However, three filters (*F6-PP-PLN-20*, *F7-PET-PRD-20*, and *F11-PA6.6-STN-80/100*) were different and showed higher *Ra* values. *F6-PP-PLN-20*, which represented a multifilament fabric, had the highest value. The twisted multi-thread increased the roughness of its surface with significantly thicker and more inflexible threads, resulting in more pronounced valley-like structures. Regarding the weaves, there were no significant differences, although *STN* seemed to result in slightly higher roughness values. The mesh sizes did not exhibit specific distinctness. In many cases, slightly narrow-meshed woven filters produced smaller roughness profiles. The calendaring effect also seemed to play a minor role in surface roughness. According to the *EHEDG* [40], the measured values exceeded the recommendation by a factor of ten, implying that the woven filter cloth surface is challenging to clean. In conclusion, the cleaning experiments showed that smaller meshes resulting from thinner threads and more homogenous surfaces had better cleaning efficiency.

Secondly, publication 2 [61] (see 5.3) also highlighted the most critical cloth characteristics. With high-speed video analysis, the cleaning progress during an impacting jet was monitored time-resolved. The cleaning effect in the direct impact zone was similar for all used filter types, but the surrounding area to be cleaned differed significantly. However, the degree of detail was worse due to the system used and the slow-motion monitoring. For this reason, the in-depth analysis of possible cleaning concepts with a significant level of detail was carried out using static images from a digital microscope so that differentiation could be observed between the impact area (cleaning phase 1) and the surrounding cleaning area (phase 2). According to the literature [70; 71], the impact area and its direct surrounding could be considered the same as the *Radial Flow Zone* (*RFZ*) because the fluid mechanical effects on the adhering contamination predominated over all other interfering factors. In particular, the initial jet impact forces and pressures had a substantial effect here, which will be discussed later. Further out from the impact zone, decelerating effects on the flow dominated and reduced the cleaning effect. The wall shear stress τ by the impacting jet correlated with the increasing friction between the fluid and the filter surface. In addition, the laminar boundary layer thickness δ increased due to the decreasing fluid velocity, which additionally caused a decreasing cleaning effect due to the growth of the protective boundary layer on the contamination. Thus, it could be stated that the cleaning effect decreased and even stopped at a certain distance from the impact point (transition to cleaning phase 3). The equations required here for calculating the wall shear stress and laminar boundary layer thickness can be found in publication 1 [18] in 5.2.

Regarding the cleaning surface and the necessary contamination removal, another cloth characteristic also had to be included in the cleaning design. In many cases, the weave of the applied cloth created individual flow channels on the surface of the cloth, which favored the flow of the fluid-contamination mixture alongside these canals. However, if flows collided with the channel walls, the opposite was achieved, which minimized the cleaning effects and impeded contamination transport. In the thesis experiments, this aspect was visually observed in the inhomogeneous, non-circular cleaning shapes, first described by the homogeneity factor *H.F.* in publication 2 [61] (see 5.3). Twill weaves, in particular, showed heterogeneous cleaning results, while the more uniformly woven filters in satin weaves displayed good cleaning. In addition to the flow channels, gravity also has to be considered in a filter press since the cloths are often placed vertically, reducing cleaning effects above the impact zone.

Another critical aspect of filter cloth cleaning was the type of contamination targeted. Here, biophysical effects due to adhesive forces between the contaminant and the surface and cohesive forces between the individual contaminant components played a significant role. According to the cleaning map of Fryer et al. [34], the applied spent grains matrix was a type 3 contamination, reflecting a complex composition. Even after cake removal, numerous spent grain residues usually remain on the cloth in a brewery mash filter, which can even represent miniature filter cakes. Thus, such deposits are adhesive and cohesive and have to be addressed with a suitable adjusted cleaning method. However, in this thesis, no measurements were included that can directly determine the value of specific adhesive or cohesive forces. Corresponding measurements with contamination, such as the highly heterogeneous spent grains, are often not reproducible in this respect. Therefore, the focus of this thesis was mainly on a theoretical consideration of these forces in combination with the experimental cleaning studies and cloth properties.

Ultimately, the influence of the cloth material needs to be discussed. Concerning adhesive forces between surface and contamination, the surface's type and properties are essential in cleaning processes (e.g., adsorptive effects). In the experiments, all cloth material was composed of the polymers *PP*, *PET,* and *PA6.6*. The results in Section 5 showed a considerable influence of the cloth structure and surface finish on the cleaning success. So, only a minor influence of the material could be assumed at first glance. Leipert et al. [72] also support this assumption for filter cloth, where there was no significant influence between *PET*, *PA6,* and *PP* polymers. This study utilized a separation method based on ultracentrifugation to determine a possible material influence on adhesion. The measured separation forces moved within a narrow measurement interval, with *PP* showing the smallest separation force from contamination.

However, as already described in Section 2.4.6, the influence of the material generally has to be considered as high in cleaning processes. Especially wettability and surface tension have to be considered when choosing an appropriate material. Figure 6 shows the experimental results of the surface tensions of several filter cloths listed and compared to literature values, using contact angle analysis.

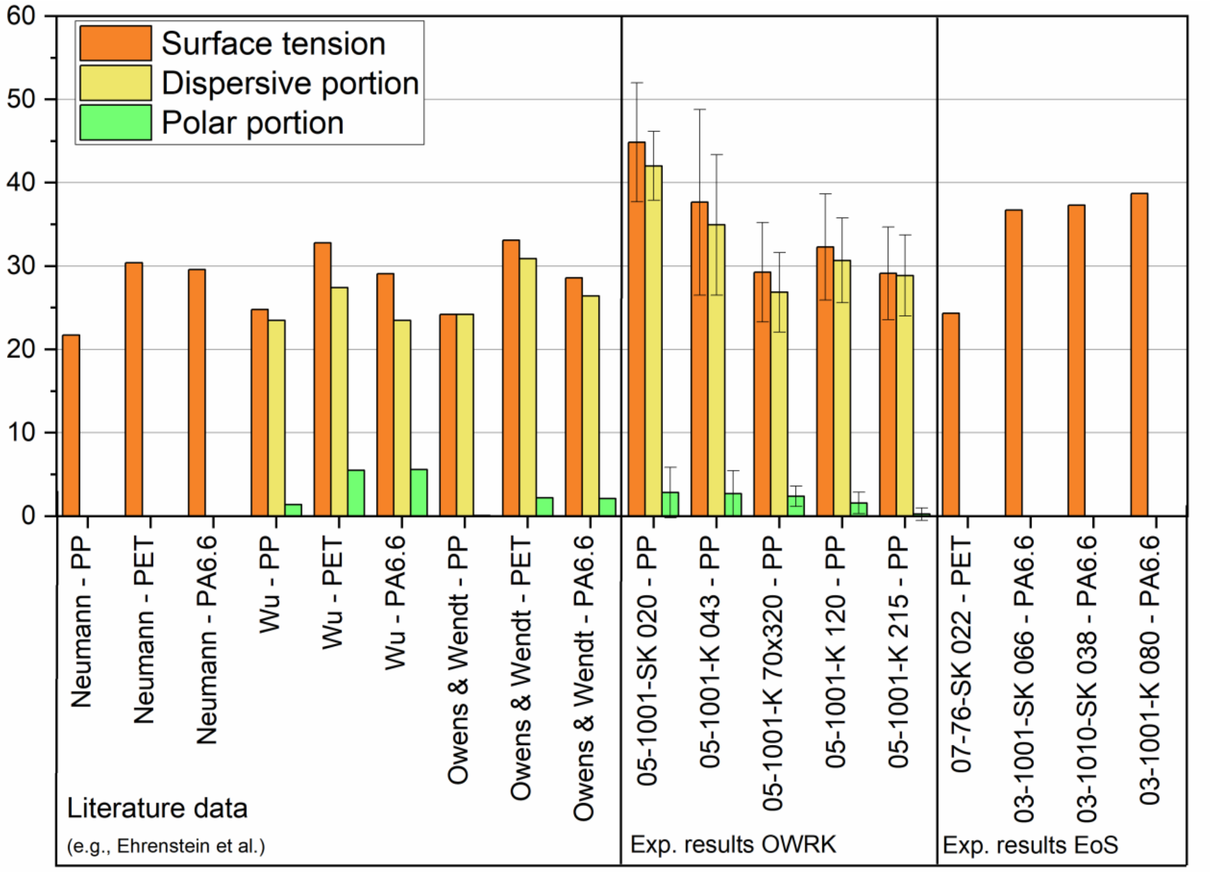

Figure 6: Surface tensions, the dispersive, and polar portions of the applied materials referring to literature values [73–75] and direct measurements of several filter cloths

In general, filter cloths are more challenging to measure in this context than smooth surfaces due to their complex structures. Besides, PET and PA6.6 are more polar polymers and have a higher wettability than PP, resulting in difficult measurability with the drop shape analysis method [76]. So, cloths of PET and PA6.6 were only analyzable using the EoS method as the unipolar measurement liquid could not create a visible drop on the surface.

In Figure 6, the comparison of the literature data on smooth polymer surfaces and the experimental results of the filter cloth reveal higher values for the latter. Only the value of the PET fabric 07-76-SK 022 is minor. This aspect indicates a specific differentiation measuring a filter cloth by observing higher contact angles that can result from the weave or a different measurement setting. In the end, the values did not deviate significantly between the different materials considering the standard deviation. Of course, the influence of the wettability of surfaces on cleaning is crucial, especially with smooth ones. However, there was also no significant difference in the corresponding levels of cleanliness using the same cloth types with different materials in the cleaning experiments in Chapter 5. The filter cakes (consisting of a particle suspension) had good adhesion to the filter cloth in all cases. In the experimental results, the location of small particles in the mesh structure, the fluid dynamical effects on the contamination, and the number of contact points seemed to be more critical. This is why other parameters of the filter cloth case are more influential. In principle, however, the material surface must be expected to influence cleaning significantly. In other applications, it is a crucial cleaning aspect whether a surface of stainless steel or polymer is considered.

The conclusion of the results discussing RH 2 provides several important aspects that can improve the establishment of hygienic design guidelines for filter cloths. The most important aspect is the structure of the filter cloth. Here, smoother surfaces due to smaller mesh sizes, using more homogeneous weaves and uniform thread thicknesses, plus surfaces with good wettability provide many advances. However, these parameters can be particularly disadvantageous for the actual filtration process, so a mutual balance has to be found. Also, durable materials must be selected that withstand any corrosive effects of agents and mechanical pressures. In this context, however, the list of applicable materials is limited as these have to be designed for food contact in compliance with, e.g., Regulation (EC) No 1935/2004 [77] and Commission Regulation (EU) No 10/2011 [78]. Here, a high potential is in easily cleanable metallic fabrics, which should be increasingly investigated in the food and beverage sector in the future.

6.3 RH 3: Comparison of forward and backflushes

Backflush cleaning is well-known in membrane or dust filter applications. Weidemann [53] also applied this cleaning method for filter media using several model contaminants. On the other hand, forward flushes are applied in various systems, such as vessels and filter presses. Thus, there are numerous starting points for investigating and comparing both cleaning modes for real applications in the food sector, particularly for mash filters in breweries. The following subsection primarily addresses RH 3.

Backflushing and forward flushing are beneficial cleaning methods and have individual advantages, like releasing and transporting contamination.

In publications 3 and 4 [59; 60], in Chapter 5, pulsatile cleaning of spent-grain-loaded filter cloth is performed in forward and backflush modes. Additionally, relevant jet parameters are varied to identify the most suitable configuration. Both procedures have advantages and disadvantages, so their cleaning efficiency in mash filters has to be more detailed. Following the results observed in this thesis, the aspects below can be considered and discussed.

If the results of both modes are compared directly, it can be seen that the forward flush cleaning showed more cleaning efficiency. Higher levels of cleanliness could be achieved here with the same cleaning times dependent on the filter cloth. The advantage of forward flush cleaning is that the contamination on the cloth surface can be accessed directly by the jet. Thus, the fluid mechanical cleaning effects can unfold fully, leading initially to strong pressures on the contamination by shock wave pressure $p_{S,F}$, water hammer pressure p_{WH}, and subsequently to significant wall shear stress τ. Moreover, the results in publication 3 in 5.4 [59] also showed that almost complete contamination removal could be achieved in forward flush cleaning. However, it has to be noted that the impinging jet also has a high potential to rinse deposited contaminants deeper into the meshes. This aspect is hazardous because of the small particles already adhering deeper in the mesh and thus contributing to substantial mesh blocking. Such clogging cannot subsequently be removed by jet cleaning alone.

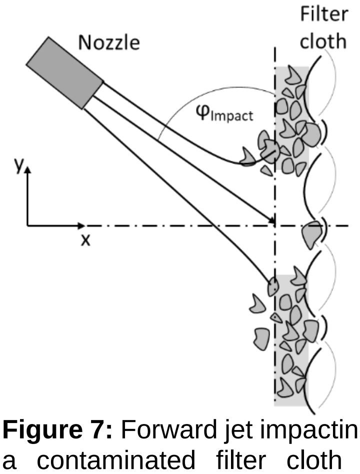

Figure 7: Forward jet impacting on a contaminated filter cloth with incidence angle φ_{Impact}

For this reason, it is advantageous if the jet impinges on the fabric at an incidence angle of $\varphi_{Impact} < 90$ ° (see Figure 7). Thus, particles adhering to the mesh are captured more laterally by the impinging flow and rinsed out of the fabric. A flatter angle also improves the general removal of contamination, thus enabling an improved cleaning process. However, according to the momentum equation, it has to be noted that a flatter angle reduces the impact force and subsequent pressures on the contamination. This aspect was also confirmed in publication 3 in 5.4 [59]. Here, flatter φ_{Impact} angles resulted in decreased levels of cleanliness as the impact effects were reduced. The pressures acting on contamination are essential to break it up and destroy inter-particle interactions, such as cohesive forces. Another aspect of forward flush cleaning is sufficient contamination transport away from the cloth. The impact velocity also leads to a certain velocity in the trickle flow.

In conclusion, a particular flow velocity is necessary to effect sufficient wall shear stress τ and remove adhering contamination. Additionally, several mechanisms like diffusion favor the contamination's detachment from the surface, which is why a specific soaking time of the water on the contamination is necessary (advantages of longer pulse pauses in publication 3 in 5.4 [59]).

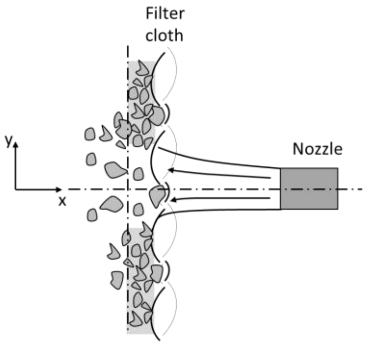

Figure 8: Backflush impacting vertically on the filtrate side of a woven filter cloth

The mentioned factors of forward flushing partly contrast with backflush cleaning. The filter cloth is backwashed with a jet or a cleaning stream from the filtrate side (see Figure 8). Thus, the cleaning fluid has to first pass through the filter cloth, i.e., the meshes. On the retentate side, the fluid finally reaches the contamination and facilitates removal in a specific sequence if the flow strength can overcome the adhesion and cohesion forces.

The first significant disadvantage of backflushing is the reduction in flow effects during cloth passage due to friction. In contrast to the forward flush method, not all available fluid can reach the contamination, thus contributing to cleaning. Only a certain amount can pass through the cloth depending on the mesh size (weave type and thread thickness). A large percentage is deflected at the thread bridges and interweaving points of the filter cloth and flows off to the side on the filtrate side. Backflow Factor X in publication 4 in 5.5 [60] also confirmed this observation, where a very close-meshed filter cloth allowed only 15% of the fluid applied to permeate the cloth. Another filter sample at least reached approximately 35%, which still is low compared to forward flushes.

The second disadvantage is the flow velocity that needs to be applied. Publication 4 [60] showed that a certain inflow velocity on the filtrate side was necessary to enable sufficient flow effects after cloth passage to the retentate side. The required inflow velocity is usually higher than forward flush cleaning, dependent on the selected cloth geometry. This factor is also confirmed in a comparison of publications 3 (5.4) and 4 (5.5) [59; 60], where a cleaning effect was observed with forward flow cleaning at an incident flow velocity as low as 1.5 m/s.

The last disadvantage of backwash cleaning is the need for more complex and cost-intensive technical installations. In order to ensure targeted cleaning, either technical equipment with nozzle systems in the filter plate or a pump system capable of reversing the flow is required. Compared to the positionable nozzle beams of a forward flow cleaning system in front of the cloth, higher installation and operating costs can undoubtedly be expected.

Despite the disadvantages mentioned above, backflushing has advantages, which can still generate efficient cleaning. For example, it can lead to precise cleaning effects in a defined area if the correct cleaning parameters have been identified and adjusted. These parameters always require detailed prior knowledge about the surface and contamination. Another significant advantage is that particles stuck in meshes can be flushed out of the mesh again in counterflow to the filtration direction. As mentioned above, this aspect is a significant disadvantage in forward flow cleaning, where too intensive cleaning can even lead to more severe blocking of the filter cloth. In addition, the precision of the removal of detached contamination is better. Here, the contamination is flushed away directly from the cloth, whereas in forward flow cleaning, large quantities also have to be transported along the cloth's surface. This aspect requires appropriate amounts of cleaning fluid and a certain amount of wall shear stress to ensure sufficient removal.

Both processes can efficiently clean the filter cloth between two filtration cycles. The design of the cleaning system and the necessary cleaning parameters must be adapted to the selected cloth geometry (surface) and the targeted contamination. In addition, it has to be noted that due to the complex surface structures, both cleaning types only ensure process efficiency and cannot contribute to microbiological safety according to the current state of the art. For this purpose, a combination with a disinfection step can be considered.

6.4 RH 4: Pulsatile jet cleaning

Cleaning with pulsed streams is already known for several other applications in the food industry, such as pipes, dust filters, or heat exchangers [79–87]. It has also been used to clean filter media loaded with model particles [53]. Thus, it is also a promising technique for cleaning woven filter cloths used in the beverage industry. The advantages of this cleaning method are highlighted in detail with RH 4 in the following.

Pulsatile jets enhance cloth cleaning significantly and enable ecological and economical cleaning processes in mash filters.

First, the jet's fluid dynamical cleaning effects depend on various nozzle properties and corresponding adjustments. For instance, the nozzle geometry, the nozzle pressure, the resulting jet velocity, and the distance from the filter cloth are vital factors.

On the other hand, the cloth's geometry and the jet's impact conditions on the cloth are decisive for the cleaning effect. Here, during the impact, it is primarily the pressure distribution in the form of initial shock waves due to fluid compression up to the water hammer pressure p_{WH} [26]. After a particular time, the jet stabilizes, and dynamic pressure on the cloth surface occurs. However, the corresponding cleaning effect is significantly lower than the initial water hammer pressure p_{WH}. Concerning the experimental cleaning velocities selected for publications 3 (5.4) and 4 (5.5) [59; 60], the pressure progression was determined qualitatively using the equations in Section 2.4.3 during the cleaning process (see Figure 9).

The results show a significant pressure increase at the beginning of the jet impact. Here, the water hammer pressure p_{WH} applied to the filter cloth is higher, resulting in considerable cleaning effects. After a specific time interval, the pressure values decreased to quasi-static dynamic $p_{Dynamic}$, which is substantially lower. The first conclusion is that it can be assumed that the initial impact effect is the most decisive cleaning factor.

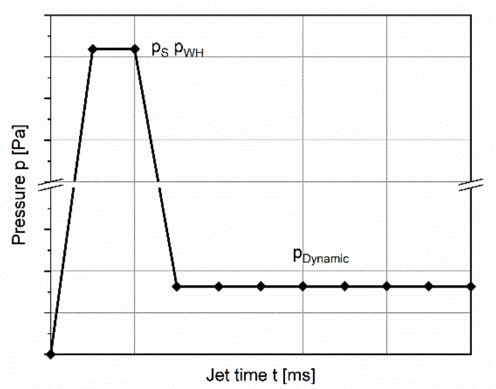

Figure 9: Pressure progression of an impacting jet on the cloth's surface

This aspect underlines the application of pulsatile cleaning of filter cloths in food applications. This method relies on a pulsed jet, which consequently renews the most efficient cleaning effects of the jet on a cloth's surface at specific intervals. In publications 3 [59] (5.4) and 4 [60] (5.5), pulsed cleaning was studied in detail for the forward and backflush methods. The results highlighted a significant improvement in cleaning when using pulsed jets. For all filter cloth types and both methods, identical cleaning results were primarily achieved more quickly than with continuous jets. It should also be noted that pulsed jets consumed only half as much cleaning fluid as the continuous modes in the same time interval.

Thus, this indicates a high potential for resource efficiency and economic advantages. Fluid mechanically, a certain waviness occurs on the cloth's surface due to the pulsing impacts. With sufficient waviness, further detachment of the laminar sublayer close to the surface ultimately takes place, improving the removal of smaller particles and other contaminants adhering to the meshes [88]. Concerning the application in a filter press, the vertical positioning of the filter cloths on the filter plates can also be a significant advantage. Due to a correspondingly calibrated pulse pause, the cleaning fluid of the previous pulse has sufficient time to flow off, which prevents the constant presence of a liquid protective layer on the cloth surface. Thus, the following pulse jet can have the corresponding effects of full pressure on the contamination on the cloth surface. In addition, a higher number of pulse pauses allows the dissolved contamination to be removed. Confirming observations have already been made by [79; 81; 83].

Some other crucial findings could be seen when comparing forward and backflush cleaning. The difference between pulsed and continuous cleaning is most apparent with using forward flushes. Here, the cleaning efficiency could be significantly increased by up to 30% higher levels of cleanliness, while the cleaning time and fluid use could be reduced [59]. In contrast, the influence on the degree of cleaning was insignificant in backflush cleaning. Depending on the filter sample used, similar levels of cleanliness were often achieved in pulsed and continuous modes in the same time interval. However, it has to be noted that the pulsed cleaning mode consumed only half as much cleaning fluid [60]. Thus, both cleaning modes are strongly advantaged by using pulsatory cleaning.

From an ecological and economic point of view, it can, thus, be stated that pulsed cleaning not only has significant advantages regarding cleaning efficiency but can also significantly save cleaning time and fluid. It thus offers the food industry, especially breweries, substantial potential for improvement in the cleaning of filter cloths in the context of a modern cleaning process.

7 Conclusion and Outlook

The research hypotheses of the thesis's big picture in Figure 5 were examined profoundly in Chapters 5 and 6. The jet cleaning of woven filter cloths was studied by investigating the cloth's cleanability and several cleaning concepts. Industry-oriented applicability of the research findings was achieved by using a brewery use case by cleaning spent-grain-loaded filter cloths. The results help to understand filter cloth cleaning better and find new ways to clean mash filters efficiently in terms of a modern procedural and hygiene state of the art. In the following, the results are primarily addressing the main research question in Chapter 3.

Firstly, a cleaning sensor based on image processing was developed to quantify spent-grain-contaminated areas. Sufficient identification of the remaining contamination on the cloths and subsequent evaluation of the cleaning impact is crucial in the food industry, where high hygienic standards are required to ensure high product safety and quality. The developed sensor included a measurement rig and automated residue detection using the contrast threshold between contamination and filter cloth surface. The concept was selected based on its adaptability to the two cleaning systems employed and rapid image processing with less computation time. The detection method enabled fast identification and transferability to an industrial process. In the next step, the developed method must be tested in a large-scale mash filter in an industrial environment.

Secondly, several key parameters were identified that significantly influenced the cloth's cleanability. The weave type plus thread thickness and mesh sizes were the decisive criteria. They facilitate different cleaning cycles that can be divided into three specific phases. Especially in phase two, the filter cloth structure showed significant differences in the level of cleanliness and homogeneity. Smooth surfaces depending on smaller mesh sizes and specifically structured weaves, e.g., STN, are advantageous. In the experiments, only a minor influence of the material was observable. However, the material-dependant wettability of the surface always requires consideration. Further investigations can now transfer the findings to other application areas concerning the used contamination, such as the pharmaceutical or mining industry. Also, the influence of the material has to be considered in more detail, applying different methods to identify the adhesion of contamination to the cloth surface.

Thirdly, forward and backflush cleaning was investigated using considerable parameter variation. Here, the advantages and disadvantages of both cleaning concepts were discussed. While forward flush cleaning results in higher cleaning efficiency, backflush cleaning can have advantages in specific applications as it can better remove individual mesh-blocking particles.

Lastly, the pulsatile cleaning was examined and compared to continuous cleaning methods that used longer flow and jet lengths. Here, the pulsed method showed promising results in reaching higher levels of cleanliness faster while using less cleaning fluid. The difference was significant in using forward flushes. In conclusion, using pulsed jets is a promising concept for future cleaning technologies of woven filter cloths. The technique should be directly tested in large-scale mash filters in the next step. Here, more development in finding the most appropriate cleaning rig will be necessary. Using a single nozzle will not keep cleaning times as short as possible. One possible design concept would be a traverse equipped with several nozzles. Such a system can be placed in front of the cloth and moved across it from top to bottom. A pre-analysis of the contamination state can be communicated to the cleaning system, triggering it at specific points. Combined with the pulsatory method, this enables a high level of cleaning success and saves cleaning time and fluid.

In the end, the thesis findings provide a better understanding of the cleaning of spent-grain-loaded complex surfaces, such as filter cloths, and the capability of various cleaning processes. The knowledge gained can also be directly integrated into the development of automated and demand-oriented cleaning processes, as described above. Furthermore, the developed setup on a pilot scale with an optomechanical cleaning device could be a starting point for enabling new equipment development to clean filter presses, particularly mash filters. Such developments further strengthen food equipment engineering and lead to critical enhancements in the context of a modern understanding of hygiene, with simultaneous resource efficiency.

Digitalized cleaning concepts should be focused on in further research. The selected residue sensors showed high potential and served as a good starting point for further contactless and digital cleaning monitoring development. With such image sensors, cleaning effects in individual machines or even locations on the cloth will become visible. This aspect can optimize cleaning further and help facilitate complete predictability of cleaning processes. Following a modern understanding of hygiene, precise cleaning documentation has been mandatory for a long time. However, corresponding data on the specific location and amount of contamination on the cloth enables many more potentials. For instance, this data can also be used to optimize cleaning processes. In the future, Artificial Intelligence (AI) may even be used here for smart and autonomous control of cleaning systems. Such developments could also replace rigid CIP rigs in other areas of the food industry and lead to more economical and ecological processes.

8 References

[1] *DIN 10516:* Lebensmittelhygiene. Reinigung und Desinfektion. Berlin: Beuth Verlag GmbH (10.2020).

[2] *Hofmann, J.:* Stoffübergang bei der Reinigung als Qualifizierungsmethode der Reinigbarkeit. Ph.D. Thesis. Freising-Weihenstephan (2007).

[3] *Wildbrett, G.* (Hg.): Reinigung und Desinfektion in der Lebensmittelindustrie. 2nd Ed. Hamburg: Behr (2006).

[4] *Hauser, G.:* Hygienische Produktionstechnologie. 1st Ed. Weinheim: Wiley-VCH (2008).

[5] *3-A:* 3A 10-04 Sanitary Standards for Filters Using Single Service Filter Media. https://www.techstreet.com/3a/standards/3a-10-04?product_id=740497, 22.10.2022.

[6] *Horrocks, A. R., Anand, S. C.:* Handbook of technical textiles. Cambridge: Woodhead Publishing Limited (2000).

[7] *Anlauf, H.:* Wet cake filtration. Fundamentals, equipment, and strategies. Weinheim, Germany: Wiley-VCH (2019).

[8] *Hamatschek, J.:* Lebensmitteltechnologie. Die industrielle Herstellung von Lebensmitteln aus landwirtschaftlichen Rohstoffen. 2nd Ed. Stuttgart: Verlag Eugen Ulmer (2021).

[9] *Heiss, R.:* Lebensmitteltechnologie. Biotechnologische, Chemische, Mechanische und Thermische Verfahren der Lebensmittelverarbeitung. 6th Ed. Berlin, Heidelberg: Springer (2004).

[10] *DIN EN 1672-2:* Food processing machinery - Basic concepts - Part 2: Hygiene and cleanability requirements: Beuth Verlag GmbH (05.2021).

[11] *Tamime, A. Y.:* Cleaning-in place. Dairy, food and beverage operations. 3rd Ed. Oxford: Blackwell (2008).

[12] *Vlková, H., Babák, V., Seydlová, R., Üavlík, I., Schlegelová, J.:* Biofilms and Hygiene on Dairy Farms and in the Dairy Industry: Sanitation Chemical Products and their Effectiveness on Biofilms – a Review. In: Czech Journal of Food Sciences 26 (2008), 309–323.

[13] *Kulkarni, M., Patil-Sen, Y., Junkar, I., Kulkarni, C. V., Lorenzetti, M., Iglic, A.:* Wettability studies of topologically distinct titanium surfaces. In: Colloids and surfaces B: Biointerfaces 129 (2015), 47–53.

[14] *Hauser, G.:* Hygienegerechte Apparate und Anlagen. Für die Lebensmittel-, Pharma- und Kosmetikindustrie. 1st Ed. Weinheim: Wiley-VCH (2008).

[15] *Valentas, K. J.:* Handbook of food engineering practice. 1st Ed. Boca Raton, Fla.: CRC Press (1997).

[16] *Bobe, U.:* Die Reinigbarkeit technischer Oberflächen im immergierten System. Ph.D. Thesis. Freising-Weihenstephan (2008).

[17] *Fick, A.:* Ueber Diffusion. In: Annalen der Physik und Chemie 170 (1855), 59–86.

[18] *Werner, R. A., Geier, D. U., Becker, T.:* The Challenge of Cleaning Woven Filter Cloth in the Beverage Industry—Wash Jets as an Appropriate Solution. In: Food Engineering Reviews 12 (2020), 520–545.

[19] *Milchers, W.:* Abtrag von Polymeren mit dem reinen Wasserstrahl. Düsseldorf: VDI-Verlag (2001).

[20] *Mauermann, M.:* Methode zur Analyse von Reinigungsprozessen in nicht immergierten Systemen der Lebensmittelindustrie. Dissertation. Dresden (2012).

[21] *Rose, G.:* Untersuchungen zur Reinigung bei der Feldverpackung von Frischgemüse. Stuttgart: Grauer (1997).

[22] *Range, K., Feuillebois, F.:* Influence of Surface Roughness on Liquid Drop Impact. In: Journal of Colloid and Interface Science 203 (1998), 16–30.

[23] *Aganin, A. A., Guseva, T. S.:* Liquid jet impact on a wet wall. In: European Journal of Mechanics - B/Fluids 79 (2020), 141–150.

[24] *Aganin, A., Guseva, T.:* Numerical simulation of liquid mass collision with a wall. In: Progress in Computational Fluid Dynamics, An International Journal 19 (2019), 293.

[25] *Joukowsky, N.:* Über den hydraulischen Stoss in Wasserleitungsrohren. St. Petersburg, Russia (1900).

[26] *Sigloch, H.:* Technische Fluidmechanik. 9th Ed. Berlin, Heidelberg: Springer Vieweg (2014).

[27] *Adler, W. F.:* Waterdrop impact modeling. In: Wear 186-187 (1995), 341–351.

[28] *Lesser, M. B., Field, J. E.:* The Impact of Compressible Liquids. In: Annual Review of Fluid Mechanics 15 (1983), 97–122.

[29] *Heymann, F. J.:* High-Speed Impact between a Liquid Drop and a Solid Surface. In: Journal of Applied Physics 40 (1969), 5113–5122.

[30] *Hammitt, F. G., Huang, Y. C., Hwang, J. B., Do, L., Hammitt, F. G., Jr., Timm, E. E., Hughes, R. D.:* Experimental and theoretical research on liquid droplet impact. In: In: International Conference on Rain Erosion and Associated Phenomena 1 (1975), 319–345.

[31] *Evans, A. G., Ito, Y. M., Rosenblatt, M.:* Impact damage thresholds in brittle materials impacted by water drops. In: Journal of Applied Physics 51 (1980), 2473.

[32] *Rochester, M. C.:* The Impact of a Liquid Drop with a Solid Surface and the Effects of the Properties of the Liquid on the Erosion of Solids. Ph.D. Thesis. Cambridge (1977).

[33] *Rochester, M. C., Brunton, J. H.:* Pressure Distribution during Drop Impact. In: Proceedings of the 8th International Conference on Erosion by Solid and Liquid Impact (1979), 61–67.

[34] *Fryer, P. J., Asteriadou, K.:* A prototype cleaning map: A classification of industrial cleaning processes. In: Trends in Food Science & Technology 20 (2009), 255–262.

[35] *Weigl, B.:* Trennkräfte zwischen Mikroorganismen, Partikeln und Oberflächen. Ph.D. Thesis. Freising-Weihenstephan (2003).

[36] *European Hygienic Engineering & Design Group:* EHDG Guidelines. https://www.ehedg.org/guidelines-working-groups/guidelines/guidelines, 22.10.2022.

[37] *3-A:* 3-A Sanitary Standards. https://www.techstreet.com/3a/subgroups/2342, 22.10.2022.

[38] *DIN EN ISO 21920-2:2022-12:* Geometrical product specifications (GPS) - Surface texture: Profile - Part 2: Terms, definitions and surface texture parameters. Berlin: Beuth Verlag GmbH (12.2022).

[39] *DIN EN ISO 25178-2:* Geometrical product specifications (GPS) - Surface texture: Areal - Part 2: Terms, definitions and surface texture parameters: Beuth Verlag GmbH (09.2012).

[40] *European Hygienic Engineering & Design Group:* Hygienic Design Principles. DOC 8. 3rd Ed. Frankfurt (2018).

[41] *Young, T.:* An essay on the cohesion of fluids. In: Philosophical Transactions of the Royal Society of London 95 (1805), 65–87.

[42] *Fowkes, F. M.:* Attractive Forces at Interfaces. In: Industrial & Engineering Chemistry 56 (1964), 40–52.

[43] *Owens, D. K., Wendt, R. C.:* Estimation of the surface free energy of polymers. In: Journal of Applied Polymer Science 13 (1969), 1741–1747.

[44] *KRÜSS GmbH:* Kontaktwinkel - Contact Angle Determination Methods. https://www.kruss-scientific.com/de-DE/know-how/glossar/kontaktwinkel, 29.01.2023.

[45] *van Oss, C. J., Chaudhury, M. K., Good, R. J.:* Interfacial Lifshitz-van der Waals and polar interactions in macroscopic systems. In: Chemical Reviews 88 (1988), 927–941.

[46] *Wu, S.:* Calculation of interfacial tension in polymer systems. In: Journal of Polymer Science Part C: Polymer Symposia 34 (1971), 19–30.

[47] *Li, D., Neumann, A.:* Contact angles on hydrophobic solid surfaces and their interpretation. In: Journal of Colloid and Interface Science 148 (1992), 190–200.

[48] *KRÜSS GmbH:* Methode nach Owens, Wendt, Rabel und Kaelble (OWRK). https://www.kruss-scientific.com/de-DE/know-how/glossar/methode-nach-owens-wendt-rabel-und-kaelble-owrk, 28.01.2023.

[49] *Rabel, W.:* Einige Aspekte der Benetzungstheorie und ihre Anwendung auf die Untersuchung und Veränderung der Oberflächeneigenschaften von Polymeren. In: Farbe und Lack 77 (1971), 997–1005.

[50] *Kaelble, D. H.:* Dispersion-Polar Surface Tension Properties of Organic Solids. In: The Journal of Adhesion 2 (1970), 66–81.

[51] *Kwok, D. Y., Gietzelt, T., Grundke, K., Jacobasch, H.-J., Neumann, A. W.:* Contact Angle Measurements and Contact Angle Interpretation. 1. Contact Angle Measurements by Axisymmetric Drop Shape Analysis and a Goniometer Sessile Drop Technique. In: Langmuir 13 (1997), 2880–2894.

[52] *Li, D., Neumann, A. W.:* Equation of state for interfacial tensions of solid-liquid systems. In: Advances in Colloid and Interface Science 39 (1992), 299–345.

[53] *Weidemann, C.:* Reinigungsfähigkeit mithilfe kontinuierlicher und pulsierender Strömung. Ph.D. Thesis. Karlsruhe (2014).

[54] *Moeller, R.-S.:* Haftkräfte, Alterung und Überwachung funktionaler Oberflächen - Gärtücher im Gebrauch. Ph.D. Thesis. Karlsruhe (2018).

[55] *Morsch, P.:* Detachment of fine-grained thin particle layers from filter media. Ph.D. Thesis. Karlsruhe (2021).

[56] *Stahl, S., Siggelkow, S., Nirschl, H.:* A Microbiological Test Method to Determine the Cleanability of Filter Media in Solid-Liquid-Separation Applications. In: Engineering in Life Sciences 7 (2007), 136–142.

[57] *Weidemann, C., Vogt, S., Nirschl, H.:* Cleaning of filter media by pulsed flow – Establishment of dimensionless operation numbers describing the cleaning result. In: Journal of Food Engineering 132 (2014), 29–38.

[58] *Ulmer, M.:* Analyse der Reinigung von Sieb- und Filtergeweben im Querstrom mit Hilfe der Gesetze des Stoff¨ubergangs. Ph.D. Thesis. Freising-Weihenstephan (2014).

[59] *Werner, R. A., Schappals, L., Geier, D. U., Becker, T.:* Pulsed forward flushes as a novel method for cleaning spent grains-loaded filter cloth. In: International Journal of Food Science & Technology 57 (2022), 4575–4585.

[60] *Werner, R. A., Hummel, A. M., Geier, D. U., Becker, T.:* Investigations on Backflush Cleaning of Spent Grain-Contaminated Filter Cloths Using Continuous and Pulsed Jets. In: Foods 11 (2022).

[61] *Werner, R. A., Takacs, R., Morsch, P., Geier, D. U., Nirschl, H., Becker, T.:* Jet Cleaning of Filter Cloths Used in Solid-Liquid Separation: A High-Speed Video Evaluation. In: Chemical Engineering & Technology 46 (2023), 873–881.

[62] *Jacob, F.* (Hg.): MEBAK brautechnische Analysenmethoden - Rohstoffe. Rohfrucht, Gerste, Malz, Hopfen und Hopfenprodukte. Methodensammlung der Mitteleuropäischen Brautechnischen Analysenkommission. Freising-Weihenstephan: Selbstverlag der MEBAK (2016).

[63] *Stahl, S., Leipert, C., Nirschl, H.:* The cleanability of particle loaded woven filter media in solid–liquid separation. In: Separation and Purification Technology 110 (2013), 196–201.

[64] *European Hygienic Engineering & Design Group:* A method for assessing the in-place cleanability of food processing equipment. DOC 2.

[65] *European Hygienic Engineering & Design Group:* A method for the assessment of in-line steam sterilisability of food processing equipment. DOC 5.

[66] *European Hygienic Engineering & Design Group:* A method for the assesment of bacteria tightness of food processing equipment. DOC 7.

[67] *VDMA:* Merkblatt: Riboflavintest für keimarme oder sterile Verfahrenstechniken-Fluoreszenztest zur Prüfung der Reinigbarkeit.

[68] *Morsch, P., Arnold, A., Schulze, H., Werner, R., Anlauf, H., Geier, D. U., Becker, T., Nirschl, H.:* In-situ cleaning process of chamber filter presses with sensor-controlled and demand-oriented automation. In: Separation and Purification Technology 256 (2021), 117793.

[69] *Morsch, P., Kühn, J., Werner, R., Anlauf, H., Geier, D. U., Becker, T., Nirschl, H.:* Influence of the filter cloth and nozzles type on the in-situ cleaning procedure of filter presses. In: Chemical Engineering Science 226 (2020), 115889.

[70] *Wilson, D. I., Le, B. L., Dao, H., Lai, K. Y., Morison, K. R., Davidson, J. F.:* Surface flow and drainage films created by horizontal impinging liquid jets. In: Chemical Engineering Science 68 (2012), 449–460.

[71] *Wang, T., Davidson, J. F., Wilson, D. I.:* Flow patterns and cleaning behaviour of horizontal liquid jets impinging on angled walls. In: Food and Bioproducts Processing 93 (2015), 333–342.

[72] *Leipert, C., Nirschl, H.:* Untersuchung der Reinigungsfähigkeit von Filtergeweben aus Polymeren. In: Filtrieren und Separieren 25 (2011), 270–277.

[73] *Erhard, G.:* Konstruieren mit Kunststoffen. 4th Ed. München: Hanser (2008).

[74] *Ehrenstein, G. W.:* Strukturverhalten. Struktur und Eigenschaften von Kunststoffen, Oberflächenspannung, Spannungsrisse. München: Carl Hanser Verlag GmbH & Company KG (2021).

[75] *Wu, S.:* Interfacial and Surface Tensions of Polymers. In: Journal of Macromolecular Science, Part C: Polymer Reviews 10 (1974), 1–73.

[76] *Kopczynska, A., Ehrenstein, G. W.:* Sonderdrucke - Oberflächenspannung von Kunststoffen. Messmethoden am LKT. https://www.lkt.tf.fau.de/files/2017/06/Oberflaechenspannung.pdf, 29.01.2023.

[77] Regulation (EC) No 1935/2004 of the European Parliament and of the Council of 27 October 2004 on materials and articles intended to come into contact with food and repealing Directives 80/590/EEC and 89/109/EEC (Official Journal of the European Union OJ L 338, 13.11.2004, p. 4–17), lastly chaged 27.03.2021.

[78] Commission Regulation (EU) No 10/2011 of 14 January 2011 on plastic materials and articles intended to come into contact with food Text with EEA relevance (Official Journal of the European Union OJ L 12, 15.1.2011, p. 1–89), lastly changed 23.09.2020.

[79] *Gillham, C., Fryer, P., Hasting, A., Wilson, D.:* Enhanced cleaning of whey protein soils using pulsed flows. In: Journal of Food Engineering 46 (2000), 199–209.

[80] *Christian, G. K., Fryer, P. J.:* The Effect of Pulsing Cleaning Chemicals on the Cleaning of Whey Protein Deposits. In: Food and Bioproducts Processing 84 (2006), 320–328.

[81] *Augustin, W., Fuchs, T., Föste, H., Schöler, M., Majschak, J.-P., Scholl, S.:* Pulsed flow for enhanced cleaning in food processing. In: Food and Bioproducts Processing 88 (2010), 384–391.

[82] *Blel, W., Le Gentil-Lelièvre, C., Bénézech, T., Legrand, J., Legentilhomme, P.:* Application of turbulent pulsating flows to the bacterial removal during a cleaning in place procedure. Part 1: Experimental analysis of wall shear stress in a cylindrical pipe. In: Journal of Food Engineering 90 (2009), 422–432.

[83] *Blel, W., Legentilhomme, P., Bénézech, T., Legrand, J., Le Gentil-Lelièvre, C.:* Application of turbulent pulsating flows to the bacterial removal during a cleaning in place procedure. Part 2: Effects on cleaning efficiency. In: Journal of Food Engineering 90 (2009), 433–440.

[84] *Silva, L. D., Filho, U. C., Naves, E. A. A., Gedraite, R.:* Pulsed flow in clean-in-place sanitization to improve hygiene and energy savings in dairy industry. In: Journal of Food Process Engineering 44 (2021).

[85] *Yang, J., Kjellberg, K., Jensen, B. B. B., Nordkvist, M., Gernaey, K. V., Krühne, U.:* Investigation of the cleaning of egg yolk deposits from tank surfaces using continuous and pulsed flows. In: Food and Bioproducts Processing 113 (2019), 154–167.

[86] *Furumoto, K., Narita, T., Fukasawa, T., Ishigami, T., Kuo, H.-P., Huang, A.-N., Fukui, K.:* Influence of pulse-jet cleaning interval on performance of compact dust collector with pleated filter. In: Separation and Purification Technology 279 (2021), 119688.

[87] *He, C., Yan, C., Tang, C., Huang, M., Ren, L., Zhang, M.:* Nitrogen pulse jet cleaning of the pleated filter cartridge clogged with adhesive hygroscopic dusts. In: Process Safety and Environmental Protection 147 (2021), 430–438.

[88] *Bode, K., Hooper, R. J., Paterson, W. R., Ian Wilson, D., Augustin, W., Scholl, S.:* Pulsed Flow Cleaning of Whey Protein Fouling Layers. In: Heat Transfer Engineering 28 (2007), 202–209.

9 Appendix

9.1 Further peer-reviewed publications

Werner, R., Bollwein, B., Petersen, R., Tippmann, J., Beckert, T. (2017): Pulsatile Jet Cleaning of Filter Cloths Contaminated with Yeast Cells. In: Chemical Engineering & Technology, doi: https://doi.org/10.1002/ceat.201600049.

9.2 Non-reviewed publication

Werner, R., Tippmann, J., Becker, T.: Reinigung von Filtermedien mithilfe pulsatorischer Überströmung,. In: Der Weihenstephaner, 2016, 84, 26-31.

Werner, R. A.; Geier, D. U.; Becker, T.: Neue Lösungen zur Reinigung von Filterpressen – optimierte und ressourcensparende Methoden zur Entfernung von Biofouling. In: Chemie Ingenieur Technik, 2018, 90, 9, 1176, doi: 10.1002/cite.201855098.

Werner, R., Morsch, P., Anlauf, H., Geier, D., Becker, T., Nirschl, H.: Bedarfsorientierte und sensorgesteuerte In-situ-Reinigung von Maischefiltern. In: Brauwelt, 12-13, 2020, 352-355.

Werner, R., zur Strassen, P., Morsch, P., Geier, D., Nirschl, H., Becker, T.: Reinigung von Maischefiltern - Neues Verfahren zur bedarfsorientierten und automatisierten Reinigung von Maischefiltern. In: Brauindustrie, 6, 2021, 8-10.

Werner, R., Morsch, P., Anlauf, H., Geier, D., Nirschl, H., Becker, T.: Demand-based, sensor-controlled in-situ cleaning of mash filters. In: Brauwelt International, 2022, 35-38.

9.3 Oral presentations

Werner, R., Bollwein, B., Ulmen, D., Tippmann, J, Becker, T.: Cleaning of Filter Media contaminated with Yeast by pulsed Jets. Filtech Conference 2015, Cologne, 24. February 2015.

Werner, R., Tippmann, J., Becker, T.: Reinigung von Filtermedien und Membranen in der Getränkeindustrie. 49. Technologisches Seminar, 2016, Freising, 17. February 2016.

Werner, R., Tippmann, J., Becker, T.: Utilization of Model Particles as Contamination for the Cleaning of Filter Media in Food Industry. Partec 2016, Nuremberg, 21. April 2016.

Werner, R., Geier, D. U., Becker, T.: Using pulsatile target jets to clean spent grain loaded filter cloths. 35th EBC-European Brewing Convention, Ljubljana, 17. May 2017.

Werner, R.; Morsch, P.; Geier, D.; Anlauf, H., Nirschl, H.; Becker, T.: Bedarfsorientierte Reinigung von Membranfilterpressen durch Bildanalyse. 52. Technologisches Seminar Weihenstephan, Freising, Germany, 27. February 2019.

9.4 Poster presentations

Werner, R.; Tippmann, J.; Becker, T.: Cleaning of mash loaded woven filter media by pulsed and continuous jets. World Brewing Congress 2016, Denver, USA, 13. – 17. August 2016.

Werner, R. A.; Geier, D. U.; Becker, T.: Investigations on Backflush Cleaning of Spent Grain loaded Filter Cloth. ASBC & MBAA Brewing Summit San Diego, San Diego, USA, 12. – 15. August 2018.

Werner, R.; Takacs, R.; Geier, D.; Becker, T.: Neue Lösungen zur Reinigung von Filterpressen – optimierte und ressourcensparende Methoden zur Entfernung von Biofouling. ProcessNet-Jahrestagung und 33. DECHEMA-Jahrestagung der Biotechnologen 2018, Aachen, Germany, 10. – 13. September 2018.