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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

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the lifetime that the manufacturer guarantees. Thus, it 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

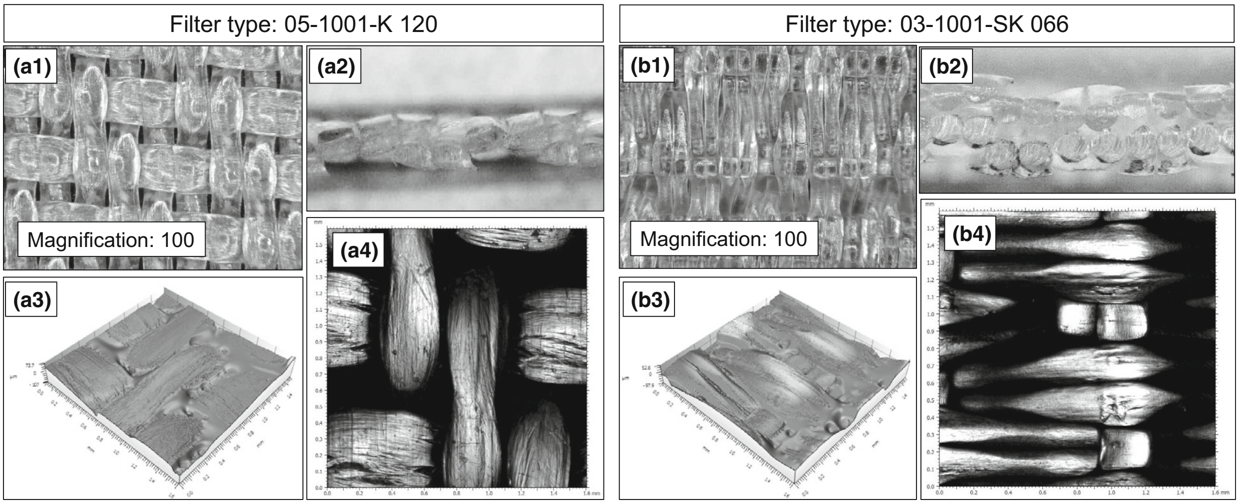
The experimental investigations were carried out on two different Sefar filter cloths (Sefar Holding AG, Thal, Switzerland), illustrated in Fig. 1. These monofil cloths possessed different materials, construction, and mesh sizes. Thus, transferring pulsed cleaning and the presented residue analysis to 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

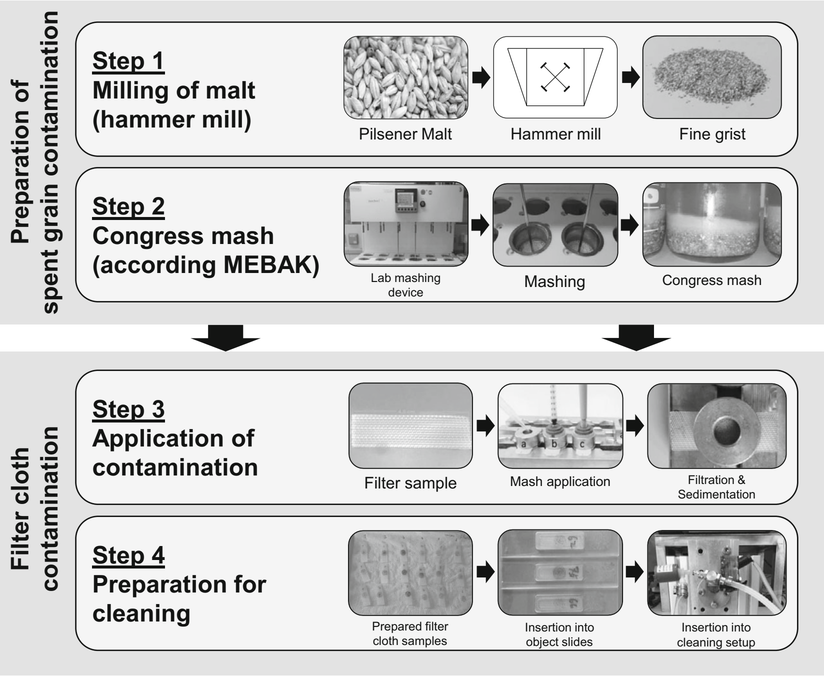


Figure 2 Overview of the developed contamination method—segregated in the different steps from the spent grains preparation until the contamination of the filter cloth sample (figure illustrates subchapters 2.2 and 2.3).

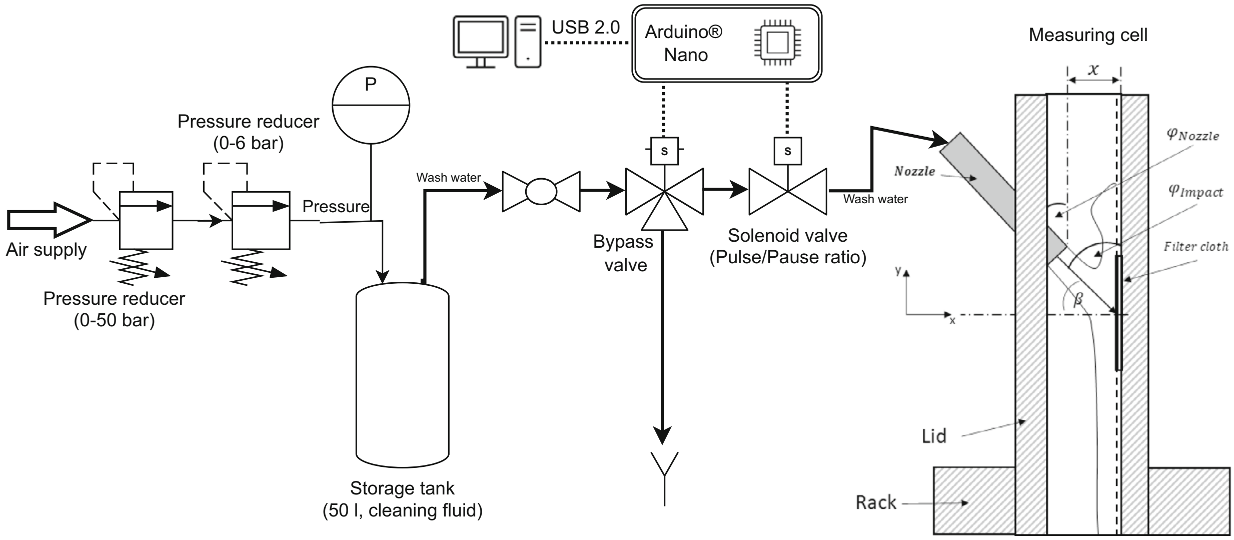


Figure 3 Schematic P&ID drawing of the experimental set-up and an illustration of the corresponding flow conditions in the measuring cell.

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 $\varphi_{\mathrm{Nozzle}}$ and the incidence flow angle $\varphi_{\mathrm{Impact}}$ 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.

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

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, $\rho_{\text{Fluid}} = 998.2 \text{ kg m}^{-3}$ 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

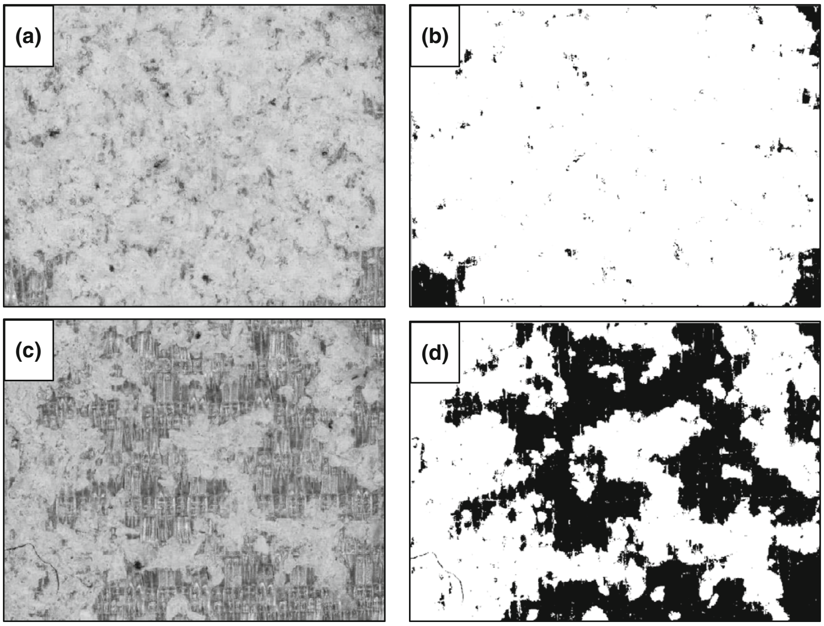


Figure 4 Exemplary images of the thoroughly contaminated and the cleaned filter surface. (a) Original image before cleaning, (b) Binary image before cleaning, (c) Original image after cleaning, and (d) Binary image after cleaning.

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

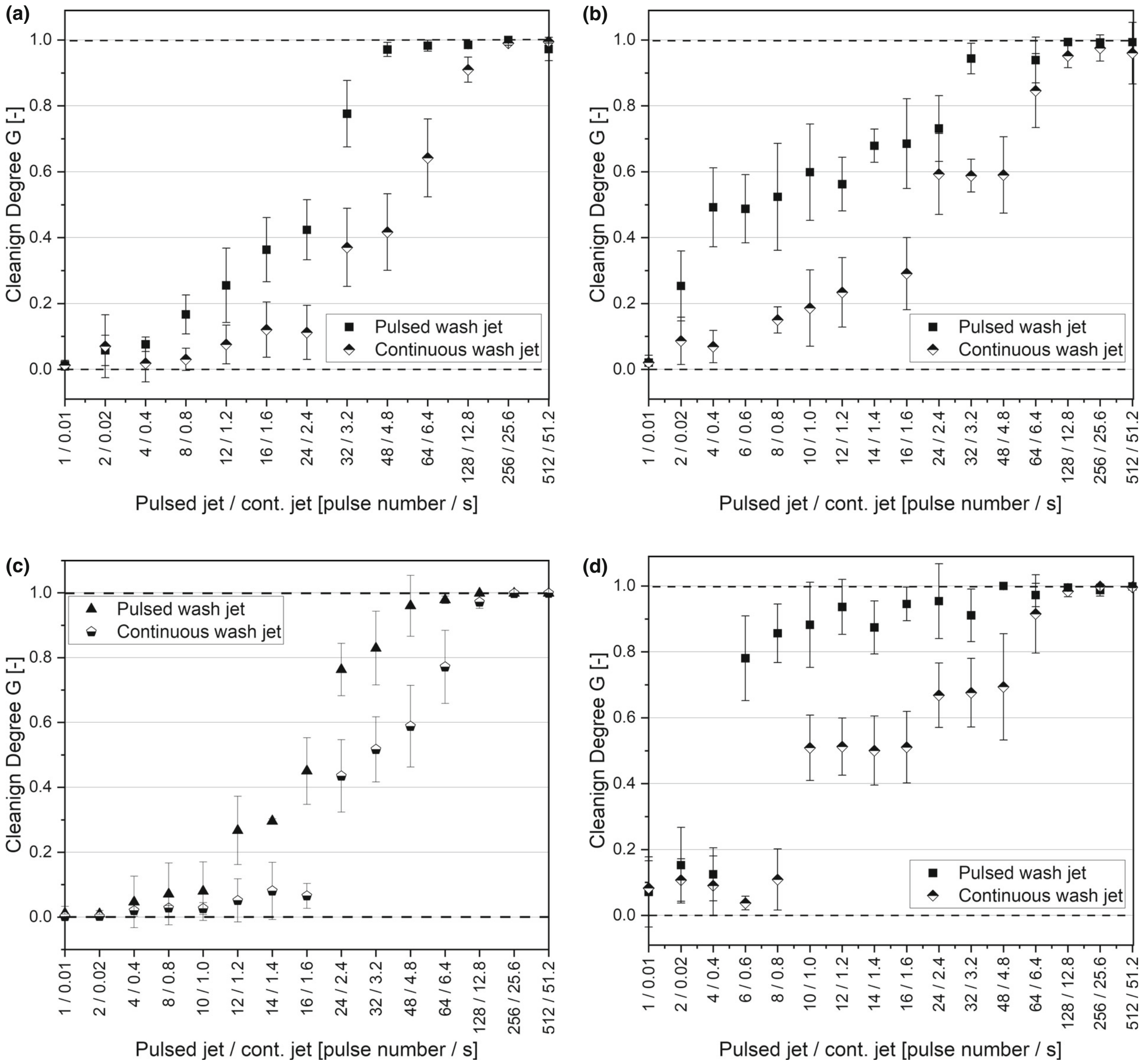


Figure 5 Comparison of continuous cloth washing and the use of pulsed jets for $v_{\mathrm{Impact}} = 3$ m/s; $n > 6$; a: Filter cloth 03-1001-SK 066, $\varphi_{\mathrm{Impact}} = 43$ °; b: Filter cloth 05-1001-K 120, $\varphi_{\mathrm{Impact}} = 43$ °; c: Filter cloth 03-1001-SK 066, $\varphi_{\mathrm{Impact}}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

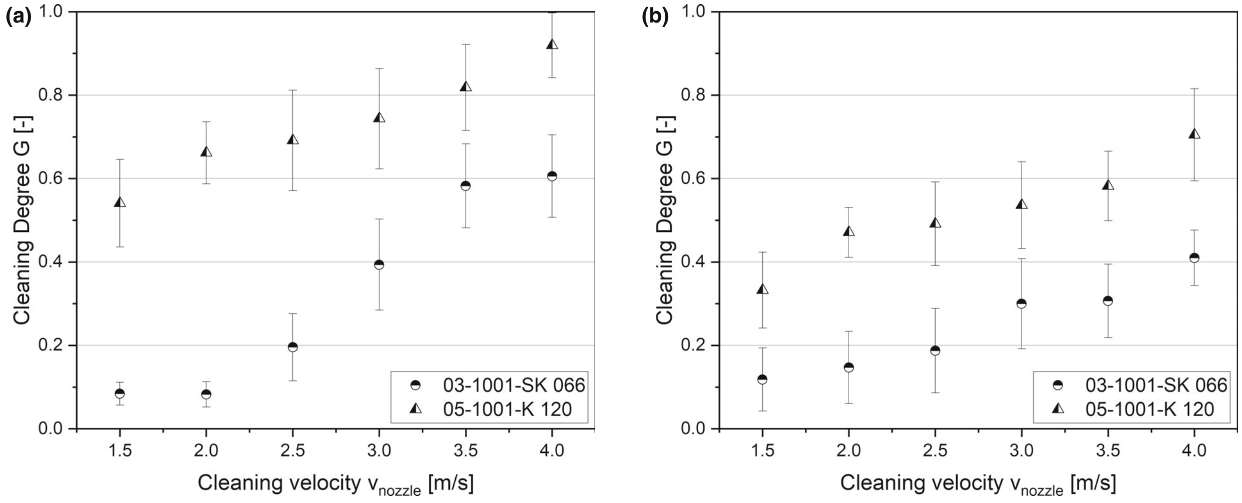


Figure 6 Variation of cleaning velocity v_{Impact} with a nozzle angle φ_{Nozzle} of a: 70°; and b: 43°; $f_{Pulse} = 5$ Hz; $n \geq 6$, confidence intervals with $\alpha = 0.05$.

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.

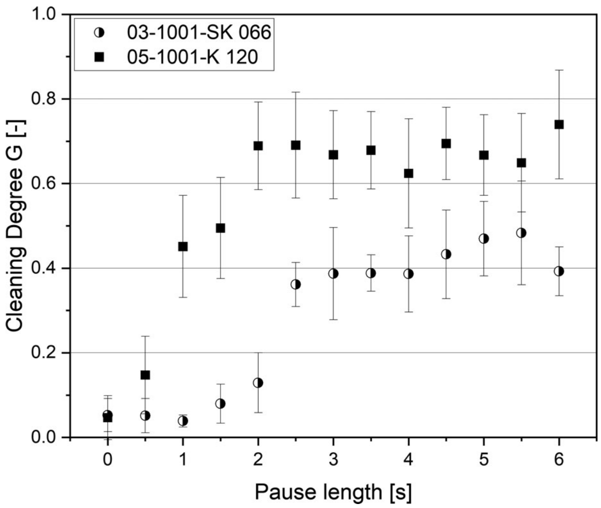


Figure 7 Influence of the pause length on the cleaning degree G, $\varphi_{\mathrm{Impact}} = 70°$; $n_{\mathrm{Pulses}} = 2$; $n_{\mathrm{Trials}} \geq 6$, confidence intervals with $\alpha = 0.05$.

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.

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

The peer review history for this article is available at https://publons.com/publon/10.1111/ijfs.15795.

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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