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Novel Process Synthesis in Ultra High Temperature Plants

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Meinen Eltern gewidmet.

For my parents.

...

Was man nicht weiß, das eben brauchte man,

Und was man weiß, kann man nicht brauchen.

(Goethe, Faust – Der Tragödie erster Teil)

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Abstract

The basic idea of the presented work was to contribute to the optimisation of heating processes in dairy industry by investigation of structural synthesis based on the analysis of the performance of individual plant parts. Hereby the simulated modification of an existing plant was carried out to improve its performance and lengthen its running time without expensive and time consuming experiments.

To obtain an advanced simulation a model based on classical mathematics was enhanced by application of fuzzy logic elements. With this approach the detection of the fouling phases, treatment of β-lactoglobulin and salt deposition and the calculation of pressure drop could be expanded to wider parameter ranges by consideration of literature data and expert knowledge.

The developed simulation tool was then used to simulate various plant configurations and processing parameters. A reference plant was defined, which was split into different sections of individual functionality. It was shown, that it is practicable to test single sections as stand-alone units first and only in case of positive results in the environment of a complete setup.

Evaluation of the performance was done by compairing heat transfer and pressure behaviour with the unchanged section. Additionally, when simulating the complete plant, product quality was observed by calculating B*- and C*-value and lactulose concentration.

By simulation of the UHT section with respect to the volume flow of heating medium an improvement of the run time of approximately 20% and less energy consumption was obtained. This modification was implemented in a local dairy and resulted in an improved energy usage without leading to any run time problems.

To further improve the performance of the simulation tool laboratory and pilot plant experiments are necessary. This could enable a progress in testing the software by implementing and running proposed modifications. The result would be to improve the validation of results and the accuracy of prediction. Additionally, it could help in adapting and improving the model used, especially with view on the applied fuzzy systems.

Zusammenfassung

Die grundlegende Idee der vorgestellten Arbeit ist es, einen Beitrag zur Optimierung von Erhitzungsprozessen in der Milchindustrie durch Untersuchungen anhand struktureller Synthese, aufbauend auf der Analyse individueller Anlagenteile, zu leisten. Dazu wurden Modifikationen einer bestehenden Anlage simuliert, um deren Betriebszeit zu verlängern, ohne kosten- und zeitintensive Experimente durchführen zu müssen.

Zur Verbesserung der Simulation wurde ein mathematisch basiertes Modell durch die Anwendung von Fuzzy Logik erweitert. Die Erkennung der Foulingphasen, die β-Laktoglobulin- und Salzanlagerung, sowie die Bestimmung des Druckverlustes konnten so durch Berücksichtigung von Literaturdaten und Expertenwissen an größere Parameterbereiche angepaßt werden.

Damit wurden dann unterschiedliche Anlagenkonfigurationen und Prozeßparameter simuliert. Dazu wurde eine Referenzanlage definiert, die in einzelne Sektionen individueller Funktionalität unterteilt wurde. Es zeigte sich, daß es sinnvoll ist, diese Sektionen zunächst als Stand-Alone Einheiten und erst im Falle vorteilhafter Ergebnisse innerhalb der ganzen Anlage zu simulieren.

Zur Bewertung einer Modifikation wurden Wärmeübertragung und Druckverhalten mit der unveränderten Sektionen verglichen. Zusätzlich wurde bei der Simulationen der vollständigen Anlage die Qualitätsparameter B*- und C*-Wert sowie die Laktulosekonzentration verfolgt.

Die Simulation eines veränderten Volumenstromes des Heizmediums in der UHT-Sektion zeigte eine Verlängerung der Anlagenlaufzeit von etwa 20% bei gleichzeitiger Energieeinsparung auf. Diese Modifikation wurde in einer örtlichen Molkerei implementiert und resultierte in einer verbesserten Energienutzung, ohne die Betriebszeit zu verkürzen.

Um die Leistung des Simulationswerkzeuges weiter zu verbessern, sind sowohl Labor- als auch Pilotversuche notwendig. Dies würde einen Fortschritt bei der Prüfung der Software durch Implementierung und Austesten vorgeschlagener Modifikationen ermöglichen und damit die Ergebnisvalidierung und Ergebnisgenauigkeit verbessern. Zusätzlich wäre damit eine Modellverbesserung möglich, vor allem in Hinblick auf die verwendeten Fuzzy-Systeme.

1 Introduction and Problem Description

Heat transfer is an essential step in many production processes in food industry, designed to guarantee product safety and to induce product stability [Changani, Belmar-Beiny & Fryer 1997]. Strict hygiene standards for food safety – enforced by law – and complex food composition lead to the fact that non-thermal procedures have to be estimated as problematic [Grandison 1996] and various versions of heat treatment are applied [Pellegrino, Resmini & Luf 1995; Kessler 1996]. Due to the extreme complexity of the matrix "food" and the strong interrelation of the reactions taking place during thermal treatment, available knowledge of heat transfer processes in chemical reaction engineering in process industry can not be fully transferred to the food industry [Rene, Leuliet & Lalande 1991; Sandu & Singh 1991].

The influence of fouling upon processing is one of the major problems in dairy industry, resulting from the undesired deposition of material from the processed liquid food onto the heat exchanging surface. By its low thermal conductivity [Davies et al. 1997; Freeman, Middis & Müller-Steinhagen 1990], the deposit causes a decrease in heat transfer and consequently a reduction in the thermal treatment of the processed fluid. After a certain run time of the heat exchanger the deposit will disturb the flow pattern [Swartzel 1983] as well as the heat balance in the heat exchanger [Foster, Britten & Green 1989; Turakhia, Charaklis & Zelver 1984]. If the process becomes unstable two consequences have to be considered. The first one is insufficient heat treatment with the risk of surviving pathogenic micro-organisms, organisms that lead to spoilage of the product [Delplace, Leuliet & Tissier 1994] or insufficient enzyme deactivation. The opposite effect is the load with locally excessive heat, causing

- discolouration, i.e. browning [O’Brian 1995 ;Pellegrino, Resmini & Luf 1995],
- formation of undesired chemical substances as hydroxy-methyl-furfural (HMF) [Berg & van Boeckel 1994], furosine [Mortier et al. 2002] or lactulose [O’Brian 1995; Geier & Klostermeyer 1983],
- loss of nutritional value [Berg & van Boeckel 1994; de Jong & van der Linden 1992], and

- change of taste [Pellegrino, Resmini & Luf 1995].

Besides their impact on product quality and the health of the consumer, problems related to fouling also have consequences for process economy and for the environment [Visser & Jeurnink 1997; Sandu & Singh 1991; Brinkmann 1986]. An obvious result of fouling is the necessary interruption of the production for cleaning, involving the use of cleaning agents and large amounts of rinsing water. Therefore, product waste accumulates and leads to poor utilization of energy and supplies.

The dimensions of heat exchangers are usually calculated with the knowledge of available temperature and mass flow of the heating medium, projected volume flow of the product and, consequently, necessary heat transfer. As fouling and the linked decrease in heat transfer cannot be predicted precisely enough, heat exchangers are often empirically oversized [Müller-Steinhagen 1995], thus raising investment costs, especially with conservative estimations of the chosen oversizing [Mukherjee 1996; Fryer, Belmar-Beiny & Schreier 1995]. It is very desirable to extend the running time of a dairy plant or improve energy usage and simultaneously guarantee product quality and consumer safety.

Based on these facts it was the principal target of the presented thesis to point out possibilities for lengthening the running time of a tubular UHT plant for milk. The main idea, presented in this paper, was to simulate technological modifications and adapt process strategies of an existing dairy plant with a software tool in order to reach the predefined target. An important further condition was to restrict the modifications to those, which are technically practicable at industrial plants. As similiar configurations and heating pocesses can be assumed for other UHT plants in dairy industry and research [Robbins et al. 1999], the used plant configurations possess a high degree of generality. Simultaneously, product quality standards, as usually defined by producers, are observed. Rating of modification approaches is done by evaluation of technological and product parameters. Design, development and validation of the applied model are described in detail elsewhere [Petermeier et al. 2002]. A refinement of this model is accomplished by making use of fuzzy logic and is part of this thesis.

The applied modification procedure leads to a local rating of modifications, that is valid within the modified section of the plant, and to a global rating, which regards the complete plant. The highest local improvement of 50% was found for a modification of product velocity in heater III. The most advantageous global improvement with a value of approx. 20% was reached for adjusting the hot water volume flow in the UHT heating section. Due to the easy implementation of this suggested approach, it was realised at a local dairy plant without causing any problems with respect to run time.

2 State of the Art

2.1 Simulation Approaches

This chapter gives a short summary of literature work concerned with the simulation and/or optimisation of heating processes, mainly the ones where the focus is upon milk as a product.

One of the first works in the area of fouling by Kern and Seaton [1959] deals with a general approach to the problem, describing anorganic deposit formation in a tubular heat exchanger (THE) in general. They define fouling as a deposition of unpolar particles, named “dirt”, on the heat exchanging surface and calculate it as the difference between deposition and removal. The goal is to obtain the deposit thickness as a function of time and its effect upon pressure. Some numerical simulations are given regarding heating and cooling problems.

Delpace & Leuliet [1995] derive a fouling model directly from experiments with a plate heat exchanger (PHE), set up with different plate configurations, at pasteurisation temperatures, that are below 97°C. The component they focus on is β-lactoglobulin. The goal is to predict dry mass of deposit and the overall heat transfer coefficient k. Additionally, a so called “apparent conductivity” of the deposit was extracted from the results. To make modelling easier, a solution from whey protein concentrate was used to model milk. The accuracy of the mass prediction was better than 20%. When investigating the thermal conductivity λ of the layer, they found that is was exponentially decreasing with time. They calculated inlet and outlet temperatures, mean residence times and dry masses of deposit for five experimental trials.

Also using a PHE, Lalande et al. [1985] build a model, concentrating on β-lactoglobulin, to predict deposit distribution and fouling curves. They experiment with whole milk at pasteurisation temperatures not above 83°C. Values for deposit conductivity and specific mass are estimated and kept constant. The agreement between simulation and experiment is rated as good, although the authors find underestimated fouling in the heating section and an overestimation in the holding part of the heater. This observation is explained by a smaller concentration of calcium involved in protein fouling in the holding section.

Fryer [1989] fits the Kern-Seaton approach [Kern and Seaton 1959] to calculate the Biot number Bi, which is a dimensionless fouling resistance. Necessary for calculation are the wall and bulk fluid temperatures. Furthermore, this simulation is used for optimising tubular heat exchanger design [Fryer, Hobin & Mawer 1988].

Fryer and Slater [1986] carry out a simulation of controlling a heating device with the intention to mitigate fouling while maintaining the outlet temperature of the product constant. Three strategies are enumerated, which are

- decreasing tube-side flow rate
- increasing shell-side temperature and
- increasing shell-side flow rate.

From the simulation results they can derive some statements on general heat exchanger design and they found that adjustment of shell-side inlet temperature is a most efficient control strategy.

In another study of the same authors more detailed simulation is given [Fryer & Slater 1985]. Kinetic values are obtained from experimental data, describing fouling as a deposition of material, without differentiating individual proteins and salts. Special focus is given to re-entrainment of material. Under investigation are heaters with constant wall temperature, cocurrent and counter-current respectively. For these examples Biot number Bi and fluid temperatures are evaluated. The authors conclude that short heaters are of disadvantage compared to long heaters when the same heat duty is required. Additionally, with decreasing diameter of the tubes fouling also decreases due to the higher shear stress τ.

Simple models are used by Schreier and Fryer [1995] to simulate fouling in laboratory-scale heaters and full-scale plants. As the full-scale plant is assumed to be built from greater diameters, The intention is to show which problems arise with the scale-up of laboratory data. For scale-up three parameters are selected:

- constant Reynolds number,
- constant surface shear stress, and
- constant temperature change for the fouling fluid.

They conclude that although their parameters might have been not optimal, other approaches also would lead to the same problems as they encountered, i.e. without good understanding of the ongoing processes, a scale-up is not possible as the nature of the governing reactions might change with the volumes considered.

Another simulation by Belmar-Beiny et al. [1993] is fit to experimental data and assumes the amount of deposit to be proportional to the fluid volume hot enough to foul. Goal of the investigation was to show whether fouling is mass transfer or reaction controlled. Influence of temperature is neglected. Additionally, the influence of the Reynolds number Re upon the activation energy of fouling is simulated.

De Jong [1996] calculates the distribution of deposit and the temperature profiles for temperatures not above 120°C in a THE. Kinetics are restricted to describe β-lactoglobulin behaviour. Casein is explicitely assumed to be of minor interest. Kinetic data that are used in the simulation are experimentally determined by use of a PHE. The simulation is also used to treat a direct heating system. The author applies the simulation software to different industrial heating problems and suggests modified processes. Although there is no transfer of the suggested modifications there is an estimation of the results reliability.

Giorgiadis, Rotstein and Macchietto [1998a] apply a strictly mathematical model to simulate various heater configurations. The goal is to find the optimum from an economic point of view by choosing the optimal control strategy out of the cases

- constant wall temperature and steam as heating medium,
- cocurrent mode with milk and any heating medium and
- counter-current operation with milk and any heating medium.

A further study of Giorgiadis, Rotstein and Macchietto [1998b] deals with the simulation of PHE configuration and predicts the overall heat transfer coefficient. Only β-lactoglobulin is taken into consideration for the underlying fouling model, which is then coupled with the model for PHEs. The applied approach is strictly mathematical. Finally, three PHE setups are simulated and the predictions are compared to experimental results.

A similar approach is applied by these authors for THE setups [Giorgiadis, Rotstein & Macchietto 1998c]. An important feature is that fluid outlet temperature is not kept constant by a control algorithm but its drift is used as an evaluation criterion. After verification with experimental results, simulations are carried out for four different configurations, including steam as heating medium and cocurrent and counter-current modus with heating water. They find that for given heat duties short heaters are more prone to fouling than longer ones.

2.2 Some Aspects of Simulating Fouling

2.2.1 Phases of Fouling

One of the most interesting conclusions in literature is the fact that the progress of fouling with time can be separated into up to three different phases [Delplace, Leuliet & Tissier 1994; Fryer 1989; Delsing & Hiddink 1983]. The first one is the induction phase. It is regarded as the time that is necessary to prepare the surface of the tubes for fouling [Fryer 1997]. Although a protein film forms on the surface almost immediately after contact with proteinaceous solutions [Visser 1998; Karlsson, Wahlgren & Trägårdh 1996], in some cases it takes time until significant changes of heat transfer do begin within the fouling period [Elofsson et al. 1996; Delsing & Hiddink 1983]. Due to fluid dynamical characteristics the three phases are more distinct in THEs than in PHEs, which offer enough starting points for fouling. These are areas with low Reynolds numbers due to their construction, so the higher shear stress in THEs makes phases better observable [de Jong 1997; Belmar-Beiny et al. 1993]. In PHEs phases can be observed not at all or only in a smaller extent [Delplace, Leuliet & Tissier 1994; Belmar-Beiny et al. 1993]. The length of induction depends on the plant setup and process characteristics. In reality this is attributed to different governing reactions within induction and fouling phase [Fryer 1989].

After a short transition phase, mentioned only by Delplace, Leuliet & Tissier [1994], where a reduction of fouling resistence is possible due to increased turbulence, fouling is reached. During this phase the reactions, as assumed within the model, take place. Postfouling is treated by some authors as final stage of fouling and its sign is an asymptotic behaviour of the fouling resistance [Fryer & Slater 1987]. The development of the phases is depicted in Fig. 2-1.

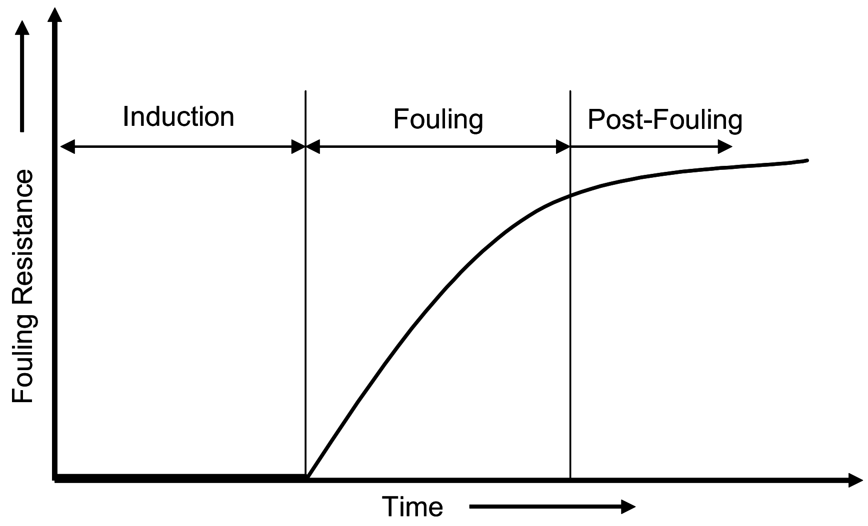


Figure 2-1: Change of the phases with run time. As transition cannot always be observed, it is not included here.

2.2.2 Salt Precipitation

The second aspect to be pointed out here is salt precipitation. In many simulation approaches only pasteurisation is considered where salt precipitation is not of major interest. In ultra-high temperature (UHT) plants the temperature range where salt precipitation starts to dominate, begins approximately at 110°C as was shown by examination of the deposit composition for various temperatures [Burton 1968; Lyster 1965]. No kinetic formulation of salt deposition was found that could be used for modelling [Petermeier et al. 2002]. This is most probably due to the necessary experimental setup under pressurized conditions. Only the approach of Hege [1984] supplies the deposition rate as a function of temperature, but only considers temperatures below 95°C.

2.3 Fuzzy Logic

Fuzzy logic is a cognitive technique that allows the integration of semi-quantitative, imprecise or linguistic knowledge from experts or experimental results into computational algorithms. This knowledge is translated into a mathematical format

[Sii, Ruxton & Wang 2001], that way making use of available partial knowledge of a problem [Sjöberg et al. 1995]. It also allows to avoid a not-existing sharpness in discrimination of different ranges of a variable and enables smooth transitions between neighbouring states [Bárdossy & Duckstein 1995]. Input and output variables have to be transferred into so called fuzzy sets, the relationship between the variables is established by "IF-THEN" rules [Zadeh 1996; Yager & Filev 1994; Zimmermann 1993]. Among the fields of application are control problems [Murnleitner, Becker & Delgado 2002; Guillaume & Charnomordic 2001; Ridgway, Henthorn & Hull 1999; Perrot et al. 1998], modelling [Saeki et al. 2002; Bolotin 2001], fault diagnosis and detection [Chen & Lin 2001; Genovesi, Harmand & Steyer 2000; Genovesi, Harmand & Steyer 1999; Frank & Koeppen-Seeliger 1997] and decision support [Becker et al. 1997]. In food industry a multitude of applications is still expected to come [Linko 1998].

There are different ways in building fuzzy systems, depending on the problem to be solved and available resources [Ghiaus 2001; Sugeno & Yasukawa 1993]. In the presented thesis the rules are formulated by linguistic terms.

The source of the linguistic model can be observation and numerical data [Sugeno & Yasukawa 1993]. For constructing a model from these various methods are possible [Bárdossy & Duckstein 1995]:

- rules are known and formulated by experts,
- rules are known by experts and supported by data,
- only the variables of the systems are specified,
- rules have to be extracted from data.

Rule assessment from data can be done by any algorithmic approaches [Krone 1999], or by translating the data into fitting rules. It is also acknowledged, that trial and error has to be used in defining the final rules to some extent [Costa Branco & Dente 2001]. Principally, it is possible to weigh the individual rules.

The code used within the simulation was developed at the Chair for Fluid Dynamics and Process Automation, Technical University Munich.

3 Theoretic Considerations

3.1 Reference Plant

As explained above, the basis of the simulations was an existing indirect UHT plant for milk in a local dairy, which is heated with hot water in counter-current mode. To make the setup of the simulation and the evaluation of results better manageable, the existing plant was divided into individual parts of different functionality. The heating sections between storage tank and homogenizer, the homogenizer itself and the cooling section were not integrated into the simulation process, as their share in terms of fouling and product quality could be neglected within the presented thesis. Additionally, a smaller plant results in less complex and less numerous computations and consequently in shorter computation times. The plant as depicted in Fig. 3-1 is referred to as “reference plant”. Volume flows of product and water were adopted from the plant at the local dairy. The volume flows of product and water in the lower temperature circuit as well as heat transferring surface had the same values in all simulations, unless otherwise specified. There was no modification done with the UHT holding section as its parameters are given by legal requirements concerning the holding time.

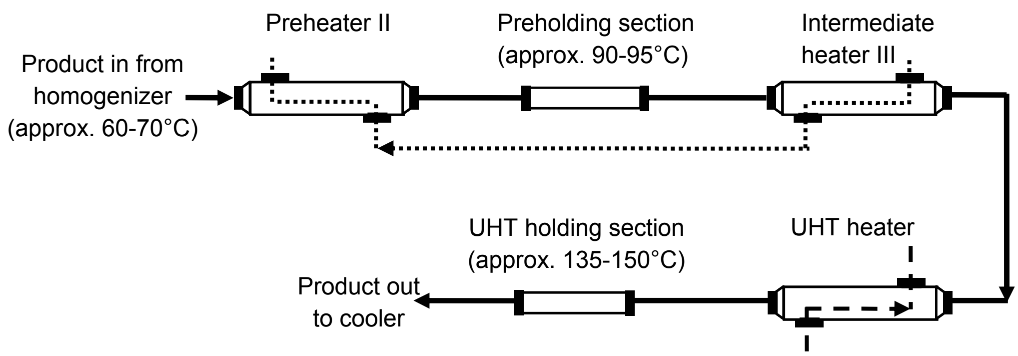


Figure 3-1: Sketch of the reference plant used for simulation. Dotted: warm water circuit; dashed: UHT heating water (independent from the warm water circuit), solid: product path. The approximate temperatures are given by Kessler [1996].

3.2 Simulation

The applied numero-fuzzy simulation tool combines deterministic differential equations with cognitive elements, in this case fuzzy logic. The models used are taken from generally accepted approaches in literature, e.g. the models for protein denaturation and deposition from de Jong, Bouman & van der Linden [1992] and Toyoda, Schreier & Fryer [1994], or from experimental data, published in literature like those for salt precipitation [Hege 1984]. One major problem in the application of models to practical problems is that the fouling of model solutions seems to be significantly different from reality. Therefore, the upgrade of information from laboratory experiments to industrial plant scale might prove difficult [Robbins et al. 1999; Schreier & Fryer 1995; Foster & Green 1990]. Additionally, the changing composition of milk due to seasonal and lactational variations makes reproducible experiments hardly possible [Auldist, Walsh & Thomson 1998].

In the applied approach such problems are solved by the integration of fuzzy logic. The use of fuzzy methods enables the description of the plant state and allows to enhance the theoretical model with experimental results and expert knowledge. This allows the estimation of plant configurations and processing conditions in order to find new strategies for the prolonging of operation time whilst maintaining product quality. In order to thoroughly validate the process model, measured data from the commercial UHT plant were used. The calculated temperature profiles and pressure drops were in reasonable agreement with the experimental data [Petermeier et al. 2002]. Thus, the model can be used to predict and improve the UHT plant performance by optimisation of its processing variables and by synthesis of individually optimised sections.

Based on the results of the model validation with real plant data, all comparisons within this paper have been done by simulation. Investigating the modifications is carried out in two steps, namely with individual sections and complete plant.

The first step is to test a selected improvement within an individual section run as a stand-alone unit. In this case a section can be treated as an independent unit without interaction with other parts of the plant. Inlet values of the resp. section, necessary for the simulation, are obtained from measurements at the plant, as far as possible, or by reasonable assumptions. Results of the simulation are then compared to the values of the unchanged reference section, also simulated as stand-alone unit. Rating of the variation is done by pressure difference between inlet and outlet of the section, calculation of the overall heat transfer coefficient of the individual section and temperature of the heating water, if reasonable.

Beneficial modifications are further tested within the complete plant and global criteria as for running a real plant are applied for rating. Two parameters here are of special interest. Neither the pressure loss over the plant nor the water temperature at the inlet of the UHT heater are allowed to exceed predefined threshold values. That way, a modification can be classified as advantageous or not by comparing the critical parameters of the simulated reference plant and modified plant. This procedure is necessary in most cases for two reasons. In the first place, the two stopping criteria can only be observed, if the UHT section is included in the experiment. Secondly, a change does not always influence them in a satisfactory extent. This can be caused by compensating effects within different sections or by feedback via water circuits. It can easily be seen that the percentage improvement normally differs for both parameters. Therefore, for a real plant it has to be defined which one of them is the more critical one.

Furthermore, the effect of the modifications might be noticeable only in a downstream section. It also has to be noted that in modifications where the length of a section is under consideration, the influence of the length upon pressure can hardly be separated from the influence of changed fouling behaviour.

All in all, those sections that have a major influence upon plant performance have to be identified. They can be seen as a kind of “bottle neck” of the complete plant and must be the primary target for investigations.

For rating product quality legal regulations require a F_0-value equal or greater than 1.0. Kessler [1996] specifies the disadvantages of applying this factor and describes the derivation of the corresponding B*- and C*-value, which are used for observing product quality in the simulation runs instead. The B*-value is related to the reduction of thermophilic spores and is a measure for the hygienic success of the heat treatment and has to be greater than 1.0. The C*-value is calculated from thiamine (vitamin B_1) loss and states to what extent the product is damaged during heating. Therefore, a C*-value below 1.0 is the target. Product quality for all simulation runs is mainly observed by B*-, C*-value. Additionally, lactulose concentration [De Rafael, Villamiel & Olano 1997] is used as it indicates sufficient or excessive heat treatment. The chosen limits are discussed by European legislation and were set to 100 mg/kg and 600 mg/kg respectively [Mortier et al. 2000; Drusch 1999].

Another factor to be considered is the Reynolds number Re. Heat exchangers are operated at turbulent flow conditions. The critical Reynolds number for circular tubes, where flow turns from laminar into turbulent, is Re_{crit} = 2200. Although laminar flow can occur for higher Reynolds numbers at suitable experimental setups, under usual conditions of heat exchanger design fully developed turbulent flow can practically be assumed for Reynolds numbers greater than 10,000 [Soumerai 1987]. By using the geometric data and the volume flows of a commercial plant turbulent flow regime was ensured.

3.3 Constraints

The inlet pressure of the product at preheater II was kept constant with the exception of some diameter optimisations, where inlet pressure had to be increased to ensure flow through the complete plant.

As far as possible, the modifications were restricted to such, that are feasible at an existing plant. This concerns influence on the warmwater circuits temperatures (see Fig. 3-1) and the use of commercial values when geometric data (e.g. lengths, diameters) are regarded. As similar plant setups and processing steps can be assumed for other UHT plants, this does not impair the evaluation of the results.

With the exception of chapter 4.2, the commercially defined bovine whole milk used within the simulation was of average composition as given by Kessler [Kessler 1996] and listed in Table 3-1. Fat is included, although it only has no or only a minor influence upon fouling [Hiddink et al. 1986], but is used for calculating milk characteristics by the model.

Table 3-1: Composition of the simulated milk. Values are supplied by Kessler [1996].

Component	*Value*
Dry mass	0.74%
Fat	3.5%
β-lactoglobulin, native	0.3%
Protein	3.2%
Lactose	4.5%
Thiamine (vitamin B_1)	0.3 mg/kg
Ca^{2+}	$10.3 \cdot 10^{-6}$ kg/kg
PO_4^{3-}	$11.3 \cdot 10^{-6}$ kg/kg

The simulated run time was set to a constant value for all the software experiments described in the following. Besides corresponding to a reasonably long running time in reality the value guaranteed that a stable state has been reached and the resulting curves can be assumed to be representative. Simulation time of ‘1.0’ means that the fixed value for the run time is reached. The basic absolute time was doubled for simulation of the complete plants to obtain more strengthened statements about the development of individual values with respect to time.

3.4 Evaluation

For a general presentation of the results, most data are given in normalised form, so results of different runs can easily be compared.

Unless otherwise stated, normalisation was done as described in the following. The overall heat transfer coefficient (OHTC) and temperatures were normalised with respect to the reference setups start value after a relative run time of 0.1 for stand alone sections and 0.05 for complete plants. Normalisation of temperature increase, pressure and pressure loss was done with respect to the reference value at a run time of ‘1.0’.

4 Results

4.1 Integration of Fuzzy Systems

4.1.1 General Remarks on Applied Fuzzy Approach

There are different ways in building fuzzy systems, depending on the problem to be solved and available resources [Ghiaus 2001; Sugeno & Yasukawa 1993]. In the presented thesis the rules are formulated by linguistic terms.

In the following chapters the design of the integrated fuzzy systems is explained. More details of the integration within the model are described elsewhere [Petermeier et al. 2002]. The following characteristics were applied within the presented work (detailed information is given in appendix A):

- fuzzyfication of input variables by triangular and trapezoid membership functions, which are not necessarily symmetric, and left or right open piecewise linear membership functions,
- fuzzyfication of output variables by triangular and trapezoid membership functions as described above,
- operators AND, OR and NOT,
- max – inference for evaluation of rules,
- defuzzyfication by the center of gravity method.

The completeness of the systems is assured by using left or right open membership functions for the input values, where necessary. Additionally consistency and continuity were assured by corresponding formulation of the rules [Sii, Ruxton & Wang 2001].

In defining the membership functions values that surely or most surely own the described feature, which may be given by literature or experts, are assigned a membership value of ‘1.0’. Values not owning the feature are assigned a value of ‘0.0’ [Bárdossy & Duckstein 1995].

The used fuzzy systems consist of two parts from the users view, i.e. the sets for in- and output, as described above, and the rulebase, which is the core of the system. In the described linguistic approach the sources of the model are observation and numerical data [Sugeno & Yasukawa 1993]. For constructing a model from these various methods are possible [Bárdossy & Duckstein 1995] and are made use of (concrete examples are given in brackets):

- rules are known by experts and supported by data (phase recognition, roughness).
- only the variables of the system are specified (protein and salt deposition, roughness).
- rules have to be extracted from data (phase recognition, protein and salt deposition).

Rule assessment from data was done by translating the data into fitting rules as the number of data was small in these cases. As can be seen from the examples in brackets, more than one approach was used in formulating the various rule bases and is often an effective method of creating rules [Sii, Ruxton & Wang 2001]. Basically, it is possible to weigh the individual rules, which was not done within the presented work.

With the implementation of fuzzy logic it is intended to quantify the impact of various parameters as described in the following.

4.1.2 Phase Recognition

One of the central features of the model is the recognition of the fouling processes phase at a given time. To set up the fuzzy system a possibility had to be found to describe the phases in terms of a variable that can be calculated from given values. The solution was to introduce a variable named "coverage", proposed by Hege [1984] and Dannenberg [1986], that summarises protein and salt deposition. They suggest to couple the beginning of fouling with the amount of already deposited material and propose values of 1.0 g/m^2 [Hege 1984] and 1.3 g/m^2 (Dannenberg 1986], respectively. When these values are reached, then fouling takes place. Induction may not directly be replaced by fouling, so the transition between induction and fouling is described by the respective phase [Gondorf 2001]. Finally, the designed fuzzy system uses an approach consisting of the three phases

- induction,

- transition, and
- fouling.

As heating plants in dairy industry usually are cleaned before post-fouling occurs, this phase is left out.

The short transition phase in the described approach was used to define a smoother transfer from induction to fouling. The simulated development is depicted in Fig. 4.1-1.

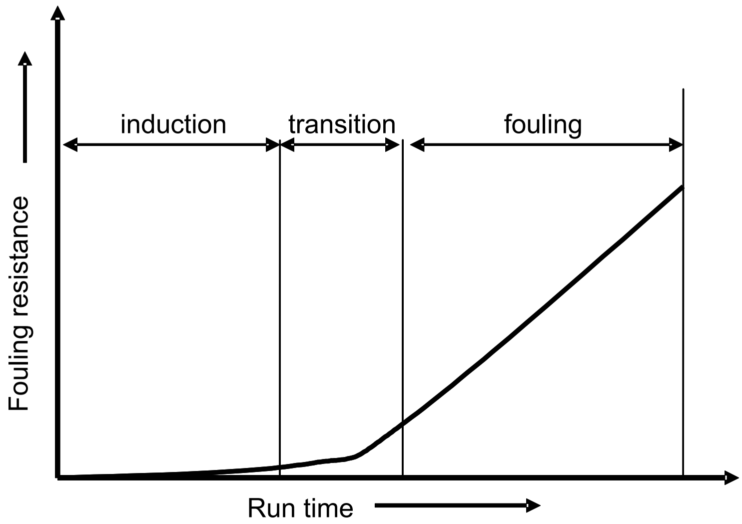


Figure 4.1-1: Change of the phases with run time as defined in the presented approach.

Fig. 4.1-2 shows the development of the phase distribution along the whole plant for two points of time. The axial length has been normalised by plant length. Therefore, milk inlet is marked with '0.0' and the value '1.0' corresponds with the outlet of heater III. The truth value marks the degree of membership to the respective fuzzy set. After a relative run time of 0.025 (top) most of the plant still is in induction and only the UHT part already shows fouling behaviour. The bottom figure is calculated for a relative time of 0.125 when fouling is the governing period and only at the entrance, which is the beginning of preheater II, there is still partial transition.

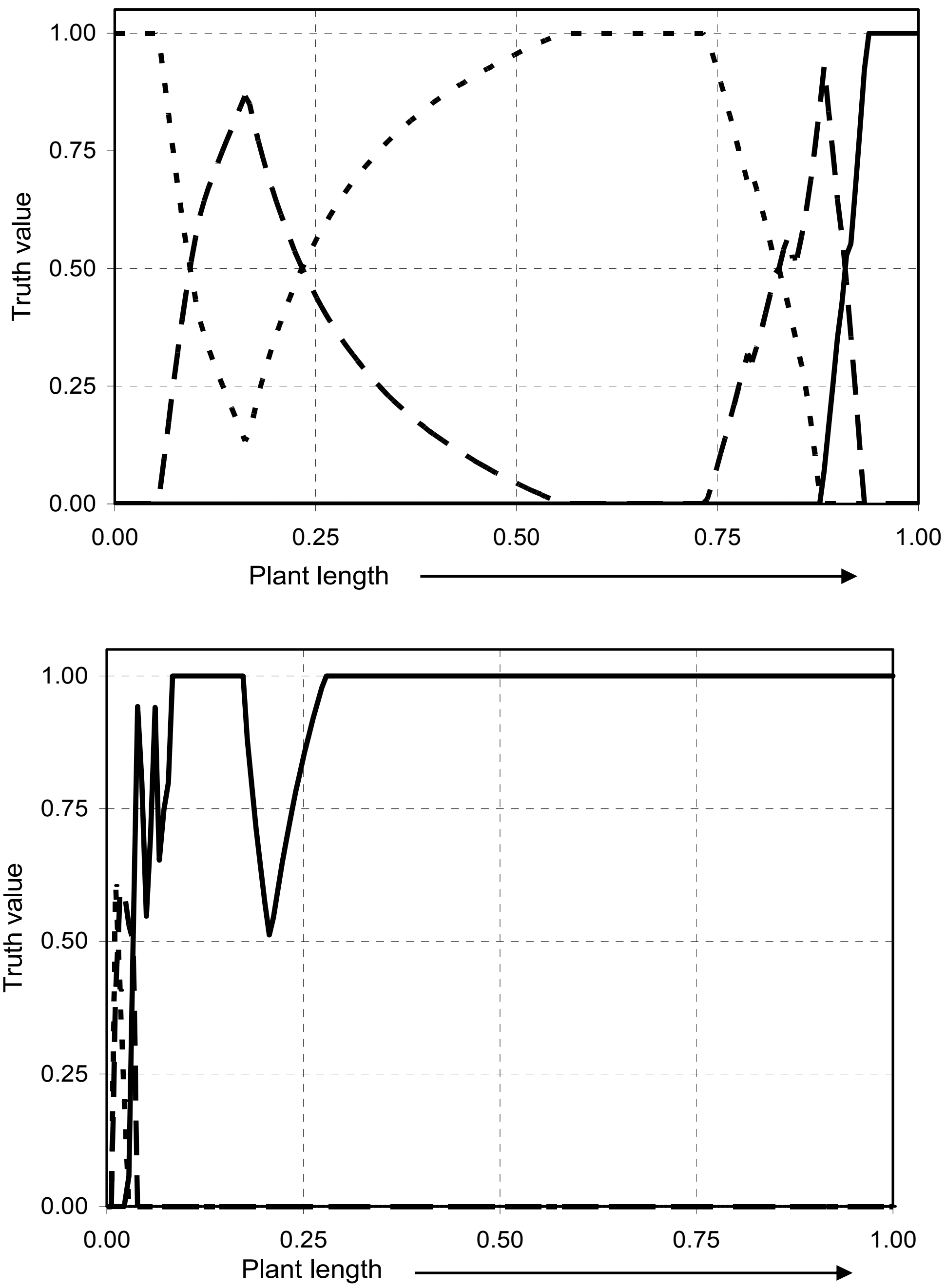


Figure 4.1-2: Distribution of the phases induction (dotted), transition (dashed) and fouling (straight) over the plant length (y-axis: membership values; x-axis: 0.0 is product inlet at preheater II, 1.0 marks product outlet of heater III) after relative run times of 0.025 (top) and 0.125 (bottom).

In Fig. 4.1-3 the pressure at the outlet of preheater II is shown for the beginning of a production run. The pressure shows a distinct induction period before the pressure loss begins to develop at a run time of approx. 0.04 due the beginning phase of ‘fouling’.

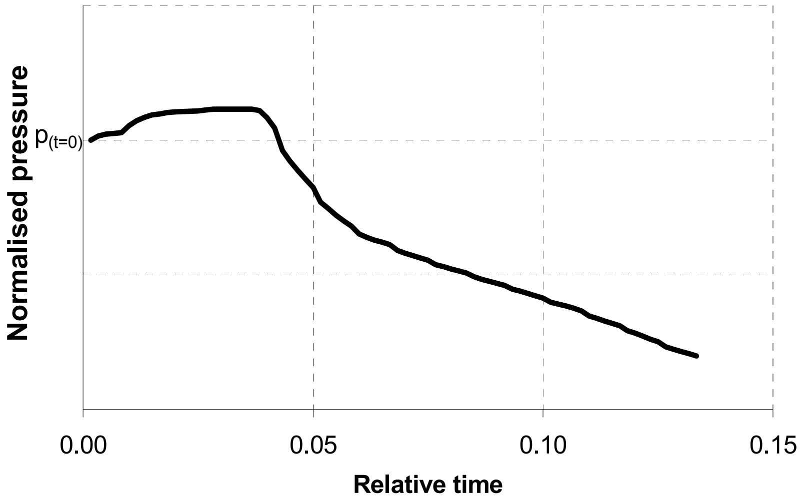


Figure 4.1-3: Pressure development at the product outlet of preheater II. The induction phase can be clearly distinguished from fouling.

4.1.3 Surface Characteristics

The state of the tube surface is responsible for a part of the overall pressure drop. For turbulent flow with Re > 10,000 the relationship for the tubular friction factor

$$\lambda^* = \frac{0.25}{\left[\lg\left(3.715\,\frac{d_{tube}}{k^*}\right)\right]^2} \qquad (4.1\text{-}1)$$

with

λ^* tubular friction factor

d_{tube} tube diameter and

k^* absolute roughness

holds, where k* has to be estimated from data given in literature [Kessler 1996]. To replace this estimation a fuzzy system was designed to directly supply the absolute roughness which is inserted into equation 4.1-1.

The first parameter to be considered is the phase. At the beginning of production the surfaces are defined to be clean and, consequently, as smooth as the tube. The smooth state is left when the phase leaves induction and goes to transition as at this stage crystallisation nuclei are built and represent a resistance towards flow. During fouling itself smooth and rough states are principally possible.

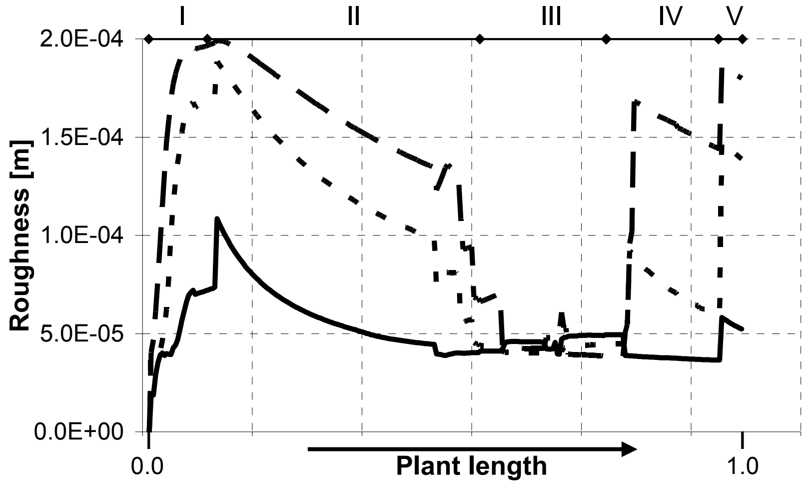
The deposit thickness has to be taken account for as it limits the surface roughness. By including this variable it should be avoided that the absolute roughness exceeds the thickness of the deposit.

The bulk temperature is included as it determines the governing processes of fouling, i.e. protein fouling or salt crystallisation. Consequently, by assuming that the particles forming the deposit can roughly be seen as spheres, salt deposit should result in a smoother surface than protein deposit as it is described by Burton [1968] and Lyster [1965].

Finally, the deposit density is considered. Here it can be assumed that lower density, i.e. a spongy deposit, results in a rougher surface than a high density, brittle deposit. To a certain extent this value corresponds with bulk temperature.

Figure 4.1-4a shows the progress of the estimated roughness over the plant at run times of ‘0.1’, ‘0.5’ and ‘1.0’. Again the x-axis has been normalised by plant length, which corresponds to the bulk temperature of the product. The values and the curves have to be seen in context with figure 4.1-4b. At the beginning it can be clearly seen, that the roughness in the UHT section is smaller than in the preheating section. This is due to the different composition (preheating section: mainly protein; UHT section: mainly salts), as proteins and salt particles are regarded as circles, with diameter of the proteins to be approx. ten times bigger than that of salts [Kessler 1996]. Additionally, the thin deposit thickness limits the absolute value of the roughness. At the end of the run, i.e. a run time of ‘1.0’, the roughness of the surface in the UHT section is nearly as big as in the preheating section. This is expressed by the rule set for roughness = rough (see appendix A). It allows the roughness to increase, i.e. to become rougher, with increasing deposit thickness and high temperatures. But the Figs. 4.1-4a and 4.1-4b also show that the deposit thickness and the roughness remain on a low level in heater III. As in a fuzzy system normally more than one rule is valid for a given situation, it could not in all cases be ensured that the roughness is smaller than the thickness. Although this does not impair the simulations preformance it should be a target of future investigations.

a)



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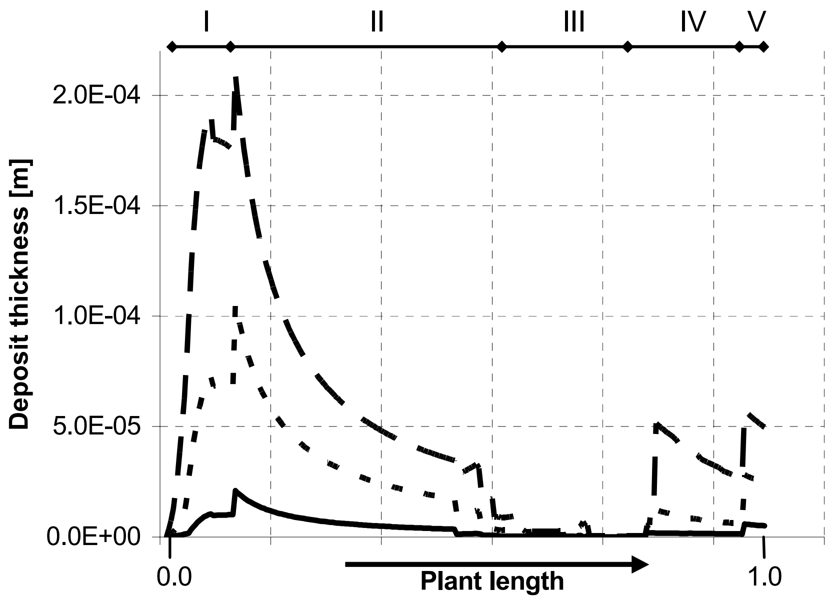


Figure 4.1-4: Fuzzy-estimated roughness of the surface (a) depicted for three run times. The values must be evaluated with respect to the thickness of the deposit (b) which is shown along the plant. Run times are marked by solid ('0.1'), dotted ('0.5') and dashed ('1.0') lines. The x-axis is normalised with the plant length, so '0.0' marks product inlet at the preheater and '1.0' product outlet at UHT holding section. Plant sections are indicated as follows, I: preheating section, II: preholding section, III: intermediate heater, IV: UHT heater, V: UHT holding section.

4.1.4 β-Lactoglobulin Deposition

The basis of the model for β-lactoglobulin denaturation and deposition is taken from literature [Toyoda, Schreier & Fryer 1994; de Jong, Bouman & van der Linden 1992], with choice of the values for the main genetic variant B [Belitz &

Grosch 1992]. The chosen approach is enhanced by a fuzzy system, as depicted in Fig. 4.1-5, which generalises the performance of the model. After the deposition rate is calculated from the model a correction factor is determined by fuzzy methods and the final "hybrid" deposition rate is given by the product of both values.

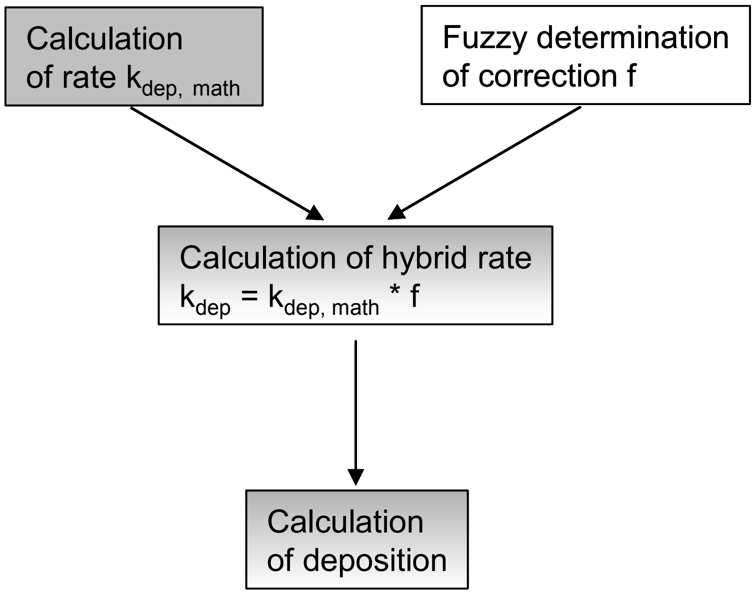


Figure 4.1-5: The rate for β-lactoglobulin deposition is calculated by the chosen modelling approach and corrected by a fuzzy factor, that takes into account further processing parameters. This hybrid value then is used for consecutive calculations.

The necessary work within this part was to determine the relevant variables for the fuzzy input. Although β-lactoglobulin denaturation has been identified as bulk reaction [Patterson & Fryer 1988], the temperature difference between product and medium is known to be of influence [Jeurnink 1996; Jeurnink, Walstra & de Kruif 1996]. By assuming a temperature difference of 10K to be "medium", which is in the order of the average temperature difference in the commercial reference, 5K were defined to be small and 15K to be high.

A similiar approach holds for the bulk temperature. Kinetic data in the applied model are valid for temperatures between 70…150°C [de Jong 1996]. From industrial plants it is known, that a small amount of fouling even occurs while heating up the product from storage temperature to homogenisation (septic plant) or preheater (aseptic plant) temperature and should be of scientific interest. As a consequence, temperatures below 353K are defined to be "small", temperatures above 358K as "high". In this case a trapezoid membership function for "medium", with a membership degree of ‘1.0’ for a temperature range from 353K to 358K, proves to be of advantage.

The actual phase of the fouling process, i.e. induction, transition or fouling, must be taken into account as it generally influences the rate of deposition. The basic fouling model gives fairly good results within the fouling phase, so this phase is assigned a value of ‘1.0’ and above, which fairly corresponds to the variable “coverage”, introduced in section 4.1.2. The input value for induction is a triangular set with the peak at ‘0.5’. This has the consequence that for values below ‘0.5’ the membership value approaches ‘0.0’ and the resulting share in calculating the correction decreases.

Finally, the pH has to be considered, as it influences amount and composition of the deposit. Skudder et al. [1986] show for pH adjusted milk samples that milk with reduced pH tends to deposit more protein and less minerals than milk with natural pH. The casein fraction of the proteins tends to deposit during the heating process when the pH approaches the isoelectric point at values between ‘4.5’ and ‘6.5’ [Beyer 1990]. Although this is not of relevance for serum proteins, it is taken into account as β-lactoglobulin represents all proteins and pH value is of special importance with respect to the caseins [Singh & Fox 1987; Singh & Fox 1985]. Here the pH of the unprocessed milk is used as it is done in many publications [Calvo & de Rafael 1995; Yoon & Lund 1989; Skudder et al. 1986].

Deposition caused by α-lactalbumin and casein, which interacts with β-lactoglobulin, is not explicitely included in the underlying model.

4.1.5 Salt Crystallisation

The choice was taken to extend the approach of Hege [1984] to temperatures up to 140°C. The corrective here was to calculate an adaptation factor for salt crystallisation.

The selected variables for consideration in the fuzzy system were phase, temperature difference [Fryer 1997], as was found out during setup and testing of the fuzzy system, and pH, according to protein deposition and having bulk temperature already included in the basic function. The phase has a basic influence upon fouling processes as explained before (see chapter 4.1.4).

Therefore, the sets can be the same as above. The same fact is found for the sets of temperature difference.

Additionally, the pH is of interest here because it influences the degree of dissociation of the salts. In contrast to the sets in protein deposition rates the values had to be changed such that a higher pH causes increased deposition. This can be explained by the fact, that protein deposition increases with lower pH while salt crystallisation is intensified by higher pH values, as here dissociation is diminished and solubility decreases. According to protein deposition the pH here is that of the raw milk.

4.2 Application of Various Product Characteristics

4.2.1 β-Lactoglobulin Concentration

4.2.1.1 Global Remarks

Literature identifies β-lactoglobulin as the key component of milk, that is involved in fouling, especially at pasteurisation temperatures [de Jong, Bouman & van der Linden 1992; Hege & Kessler 1986]. The use of these statements in the model was to replace protein fouling by β-lactoglobulin fouling. For simulation this means that plant performance should significantly depend on the content of native β-lactoglobulin of the raw milk. In the following software runs, the original amount of this protein was varied by ±10%. All simulations were carried out with the setup of the reference plant.

4.2.1.2 Results

Table 4.2.1-1 shows the parameters for the normalised pressure loss (with respect to $\Delta p_{reference}$ (t=0)) over time for the preheater section, expressed as a straight line as the curves change into linear progress after a relative run time of ‘0.2’.

Table 4.2.1-1: Parameters of the straight lines for pressure loss over preheater section for the different β-lactoglobulin concentrations.

Simulated milk	*Slope*	*x-axis intercept*	*Correlation coefficient*
β-lactoglobulin enriched	0.66	1.24	0.99
reference	0.64	1.23	0.99
β-lactoglobulin diminished	0.63	1.22	0.99

The reason for the different equations are the deposit thicknesses, depicted in Fig. 4.2.1-1. Additionally, it is shown that the various β-lactoglobulin concentrations mainly affect the preheater section and here in particular the end of the heater and the beginning of the holding section. Heater III and UHT section are not shown here as no differences could be detected between the three concentrations.

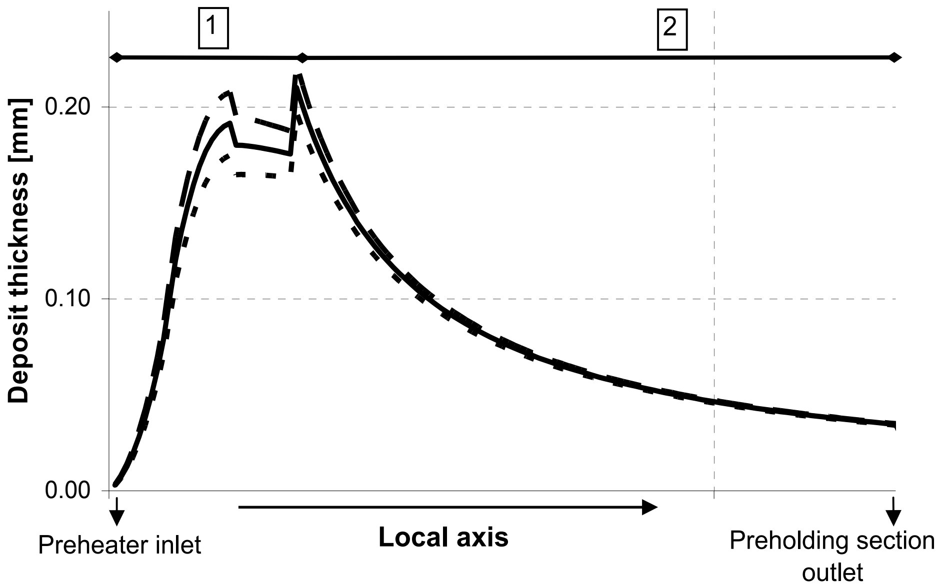


Figure 4.2.1-1: The deposit thicknesses along the preheating section are given for β-lactoglobulin enriched (dashed), reference (solid) and β-lactoglobulin diminished (dotted) milk. Main differences can be observed at the end of preheater II (1) and at the first tubes of the preheater holding section (2). At the end of the holding section the differences have vanished.

4.2.2 pH Value

4.2.2.1 Global Remarks

The pH value of raw milk, which usually is approximately 6.7 at 20°C [Walstra et al. 1999], has a relevant impact on the fouling behaviour of heat exchangers in dairy industry. The effects of pH are very complicated and include interactions between κ-casein, β-lactoglobulin and casein micelles.

Both fractions of foulants in milk (proteins, salts) are contrarily affected. At pH above normal, complexes of κ-casein and β-lactoglobulin dissociate from the micelles, thus decreasing the micelles heat stability [Singh & Fox 1987; Singh & Fox 1985]. With a lower pH compared to its average value the amount of deposited protein increases [Robbins et al. 1999; Gotham, Fryer, & Pritschard 1992; Patil & Reuter 1988], partially due to additional casein precipitation [Visser & Jeurnink 1997; Skudder et al. 1986]. This is due to their IEP (isoelectric point) at pH between 4.5 and 6.5 [Beyer 1990]. Additionally, a falling pH reduces electrostatic repulsion between whey proteins and supports the deposition of β-lactoglobulin [Jeurnink 1996].

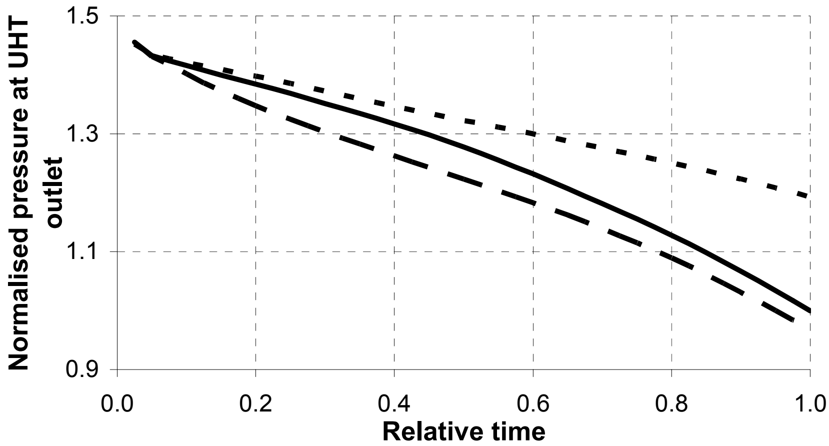
In contrast a higher pH raises the charge of proteins [Fox & Morrissey 1977] and increases their solubility [de Wit & Klarenbeek 1984]. In case of salts, the increased value of the pH reduces their dissociation, thus making them more prone to crystallisation. For this component a low pH would be of advantage [Visser & Jeurnink 1997; Foster & Green 1990; Kessler 1989; Yoon & Lund 1989].

The investigations carried out next show the effect of various pH values upon the simulated fouling process. Besides the average milk composition (see table milk) at pH 6.7, four pH values were investigated, two of them acid (6.5 and 6.0) and the other two basic (6.9 and 7.4). The applied plant setup was that of the reference. Assuming a defined pH value for fresh milk, this section is mainly of interest for evaluating the simulations features and limitations.

4.2.2.2 Results

Fig. 4.2-1a shows the effect of pH on the pressure at UHT outlet. Considering that the values should not fall below the one of the reference setup, the milk with the lowest pH gives the best results here. Fig. 4.2-1b depicts the pressure loss over UHT heater and UHT holding section which is the smallest for the acid milk, which is logical as salt fouling should be diminished under these conditions. Additionally, this is the only milk were a significant influence is made upon the temperature of the UHT water, as given in Fig. 4.2-1c. The deposit thickness is shown in Fig. 4.2-1d. There is a high increase in the preholding section with the basic milk, while acid and reference milk have approximately the same values here. Within the intermediate heater no significant difference is found between the various runs. Small differences are found in the simulated UHT heater while the basic milk shows quite a different behaviour in the UHT holding section and causes the thickest deposit.

a)



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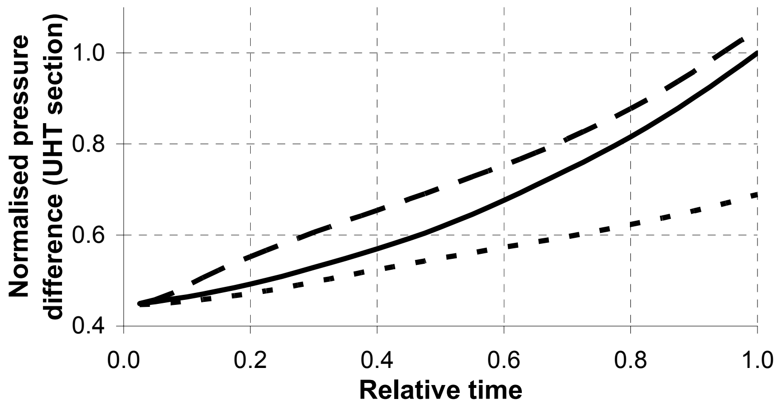
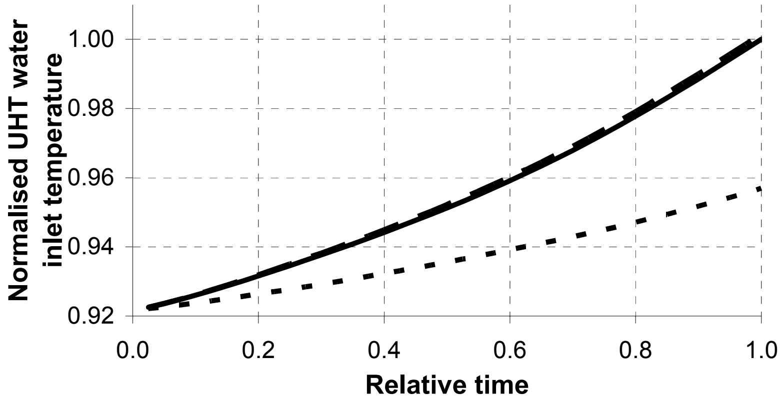


c)



d)

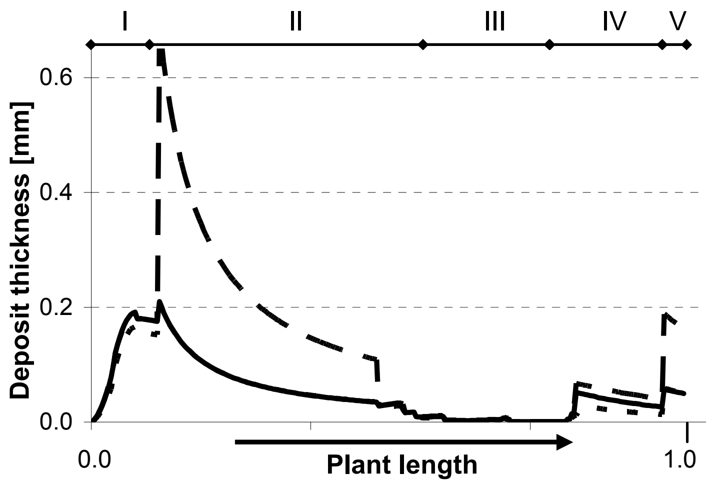
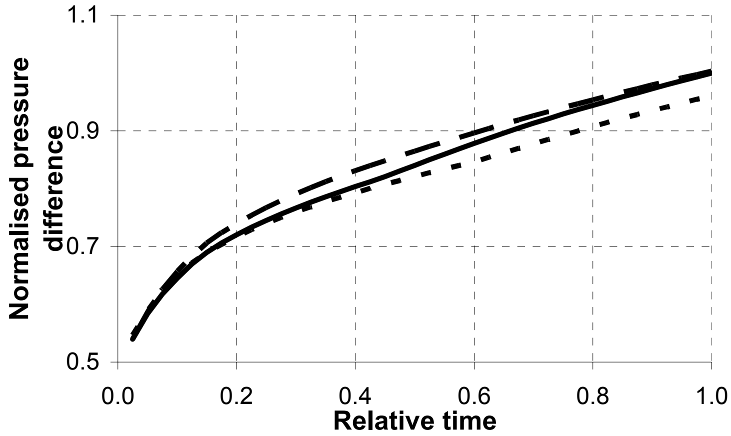


Figure 4.2-1: Process parameters in relation to different product pH values. The curves (a)-(c) are normalised with respect to the respective value of the reference plant at run time 1.0. In (d) the x-axis is normalised with plant length. Plant sections are indicated as follows, I: preheating section, II: preholding section, III: intermediate heater, IV: UHT heater, V: UHT holding section. The following pH values are simulated: 6.0=dotted, 6.75(reference)=solid, 7.4=dashed.

The observed effects are similar but not so distinct in the preheating section as shown in Fig. 4.2-2a and 4.2-2b. Special attention should be given to the reference curve of the pressure difference, which follows the curve of the basic milk in its first half and the behaviour of the acid milk in its last quarter, similar to what is shown in Fig. 4.2-2a. No difference is found in the development of water temperature at the inlet of heater III, as depicted in Fig. 4.2-2b.

a)



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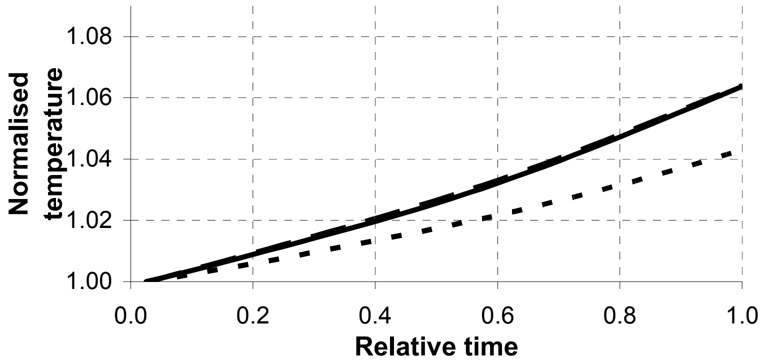


Fig. 4.2-2: Pressure loss over preheater (a), normalised with respect to the reference after a relative run time of 1.0, and water inlet temperature of heater III (b), normalised with respect to the reference after a relative run time of 0.025, for simulated milk of different pH: reference (solid), 6.0 (dotted), 7.4 (dashed).

4.2.3 Discussion

4.2.3.1 Various β-Lactoglobulin Concentrations

The comparison of the equations in table 4.2.1-1 gives the impression that the relation between β-lactoglobulin content and local running time elongation is not linear. Therefore additional runs were carried out with the concentrations changed by ±20%. The results confirm the observations as can be seen in figure 4.2.3-1. The curves (the horizontal black lines are inserted for help) cause the impression that the difference between reference and β-lactoglobulin diminished milk is higher than that between reference and enriched product. This effect can be assigned to the different phase development. Due to the higher β-lactoglobulin, the fouling phase is reached at an earlier time and β-lactoglobulin deposition increases due to the valid fuzzy rules.

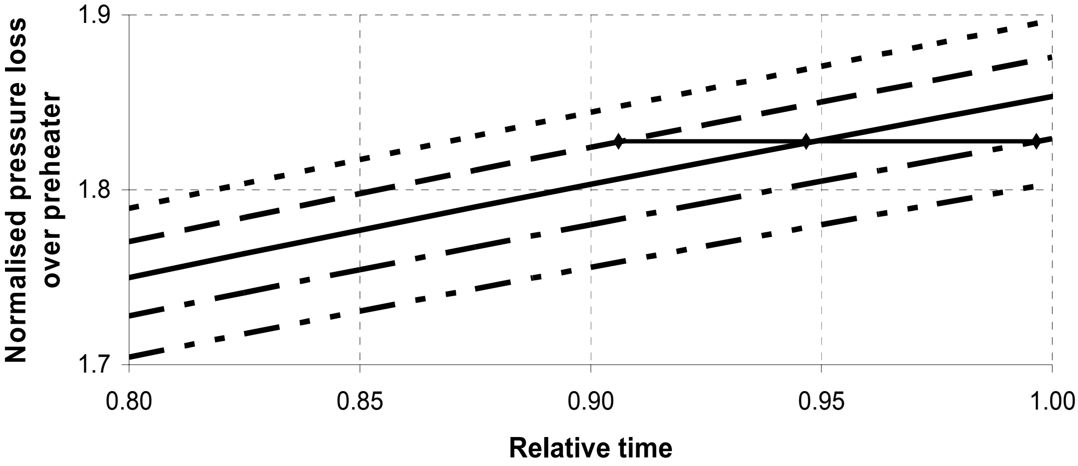


Figure 4.2.3-3: Part of the pressure loss over preheater section for all five β-lactoglobulin concentrations (normalised with respect to reference composition after a relative run time of 0.05). The thick black lines in the upper right corner indicate the time difference between the curves. Solid: reference concentration, dotted: reference plus 20%, dashed: plus 10%, dash – dash - dot: minus 10%, dash – dot - dot: minus 20%.

4.2.3.2 Change of Raw Milk pH

Although there are theoretical approaches to the influence of pH on the different milk components, the impact on fouling is controversally discussed.

Mulvihill and Donovan [1987] give a review of the research on whey protein solutions and find conflicting data, regarding the pH dependency of the thermal stability of the whey proteins. Especially, the maxima of precipitation are found to be in a wide range, depending on the method of preparing the solution, its compositions and other experimental characteristics. Foster and Green [1990] find mass and thickness of the deposit to be increased by approx. 4.5 times at a temperature of 140°C with a rotating disk apparatus, when the pH was decreased from 6.7 to 6.3. Furthermore, Foster, Britten and Green [1989] observed a non-linear relationship between increase of deposit and pH reduction. In this case the original pH of 6.8 was reduced to 6.3. Using whey protein solutions, Hege [1984] detects a significant increase of deposit at 85°C only for pH (ϑ = 20°C) < 6.0. Due to his conclusion the caseins are of great impact due to a decreased repulsion between them and β-lactoglobulin in skim milk. Skudder et al. [1986] find an increase in deposition at higher temperatures with a pH reduced to 6.51. Skim and whole milk were treated in a plate heat exchanger. Only to a small extend the increase was caused by protein but very much by fat. The denaturation of whey proteins does not differ significantly. Lyster [1970] carried out experiments which show that the rate of denaturation for α-lactalbumin and β-lactoglobulin is independent from pH within a range of 6.2-6.9.

As conclusion for the presented thesis, the difficulty of simulating the fouling behaviour of milk with respect to the pH is caused by the fact, that the approach uses β-lactoglobulin to model deposition of all proteins. From experimental investigations it is known that the various protein components show a quite different behaviour with respect to heat and pH. While β-lactoglobulin is heat sensitive but does not precipitate at its IEP, the caseins are not heat sensitive but precipitate when reaching their IEP at pH between 4.5 and 6.5 [Beyer 1990]. There is a smaller electrostatic repulsion between molecules of β-lactoglobulin, when pH approaches the IEP, such enabling an increased deposition [Jeurnink 1996].

Fig. 4.2-1b depicts the pressure loss over UHT heater and UHT holding section which is the smallest for the acid milk. This result was anticipated as salt fouling is diminished under these conditions.

4.3 Structural Process Synthesis

4.3.1 Preheater and Preholding Section

4.3.1.1 Functionality and Modification Approaches

As stated before, β-lactoglobulin is one of the most important milk components involved in fouling (see 4.2.1). As a consequence, first investigations concern the goal of minimising the formation of protein deposit. It was found that pretreated milk shows less fouling during a second heat treatment [Patil & Reuter 1986; Arnebrant, Barton & Nylander 1986; Burton 1956; Bell & Sanders 1944] and this leads to the integration of a holding section where the milk is hot enough for unfolding and aggregation of whey proteins. The wall is not heated and therefore only little deposition occurs due to the temperature difference of zero between wall and fluid. The goal of the complete section, i.e. preheater and preholding tubes, is to minimise the amount of native β-lactoglobulin [de Jong, Bouman & van der Linden 1992; Agrawala & Reuter 1979], thus prolonging the plants running time [Kessler & Beyer 1991].

In the considered reference plant, the product enters preheater II with homogenisation temperature and is heated up to holding temperature. Expert knowledge and literature [Mottar & Moermanns 1988] indicate that protein stability depends on the forewarming history of milk. Consequently, the optimal holding temperature depends on the specific heating process under investigation [de Jong & van der Linden 1992].

The processes within this section can be affected by two parameters. The first one is the holding temperature, the second one the holding time. During evaluation of measurements at the local dairy, it was noticed that preholding temperatures change with production time and between consecutive runs. Therefore, it was investigated, which the reference plants optimum temperature would be. As the denaturation of the proteins does not depend on temperature alone, but also on time, it is the temperature/time profile which results in a specific effect. Therefore, a further modification of this section is the length of the holding section, which – together with the constant volume flow of product – determines holding time. Summarised, it was investigated which improvement could be possible by varying

- holding temperature and
- holding time.

For all theoretical investigations preheater II and preholding section were treated as one section.

4.3.1.2 Results of the Change of the Preholding Temperature

As Fig. 3-1 shows for the reference plant, the preholding temperature can not be simply changed as it is determined e.g. by the setup of the preheating section. Therefore, the temperature for an optimal β-lactoglobulin behaviour had to be found first and then the way to realise the modification by adapting the plant setup.

The first experiment was the variation of water inlet temperature of the stand alone preheater II to find a probably more advantageous holding temperature. The velocity of the denaturation reaction increases with the bulk temperature of the product, but this also holds for the velocity of deposit formation. Therefore, an extremum can be expected. The existence of this temperature is proven by Fig. 4.3.1-1 and is a few Kelvin below the holding temperature of the reference plant.

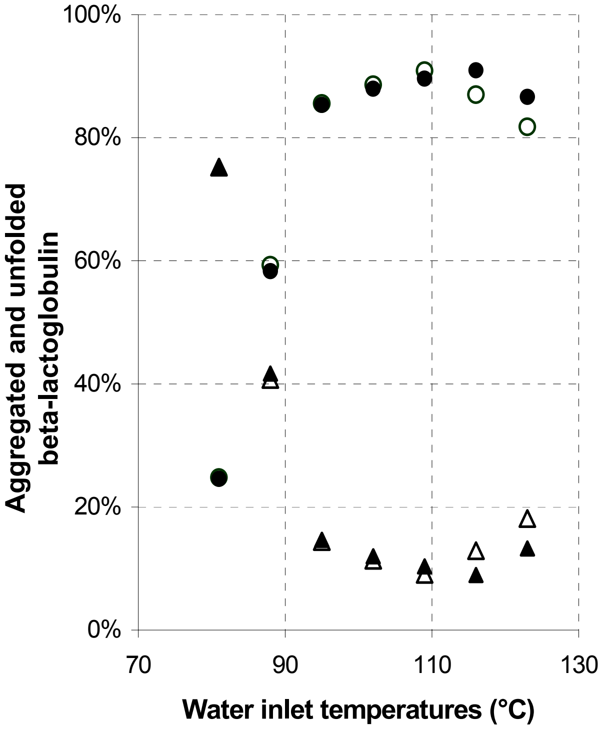


Figure 4.3.1-1: Influence of water inlet temperature upon denaturation state of β-lactoglobulin. A suitable temperature with respect to denaturation and time is in the range of 100°C to 110°C. Triangles symbolize unfolded, circles aggregated β-lactoglobulin, hollow symbols represent the state after a relative run time of 0.1, full ones the state after 1.0.

The next step was to determine the new position of the holding tubes within the complete section. From the temperature distribution within the preheater it is found that the holding section had to be shifted upstream by one tube, assuming that the tubes of the commercial preheater permit this modification. The number of tubes was not changed, consequently, by heating the product after the holding tubes within the preheater section, there is no difference for the following section of the plant in terms of temperature. Both configurations are depicted in Fig. 4.3.1-2.

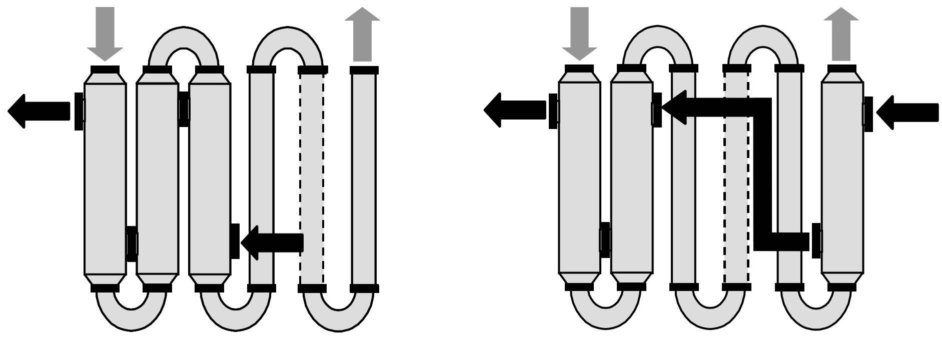


Figure 4.3.1-2: Setup of both preheater configurations, used for simulation. The reference is shown on the left, the modification on the right side. Black arrows indicate water, the grey ones product in- and outlet.

A result of the modification in comparison with the standard configuration on the basis of the overall heat transfer coefficient, averaged over the complete section, is depicted in Fig. 4.3.1-3.

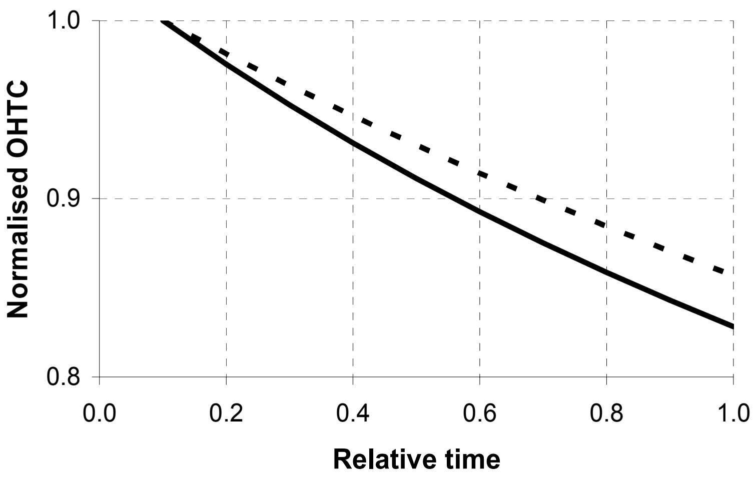


Figure 4.3.1-3: Comparison of the overall heat transfer coefficient of the reference (solid) and the modified (dotted) setup of the preheater section. Both modifications consist of the same number of tubes, only the sequence is different. The values are normalised with respect to the reference value at a relative run time of 0.1.

The evaluation in connection with the complete plant is depicted in Figs. 4.3.1-4 – 4.3.1-6. In Fig. 4.3.1-4 the pressure curves at the outlet of the UHT section of both configurations are shown. At approximately half of the run time a distinct improvement becomes visible.

That the processes, responsible for the similiarity of the curves, mainly take place before the UHT heater is suggested by Figs. 4.3.1-5 and 4.3.1-6, that show the pressure drop over the preheater section and the water inlet temperature at the end of intermediate heater III. They also prove that the better fouling behaviour still is valid for the integrated modification. A local improvement of approx. 15% with respect to pressure loss can be seen in Fig. 4.3.1-5.

Fig. 4.3.1-6 depicts a bend in the temperature progress after half of the running time, too, that confirms the above drawn conclusions. For all curves the advantage of the modified setup not only lies in a smaller slope but also in less sharp bends that appear a little later than at the reference plant.

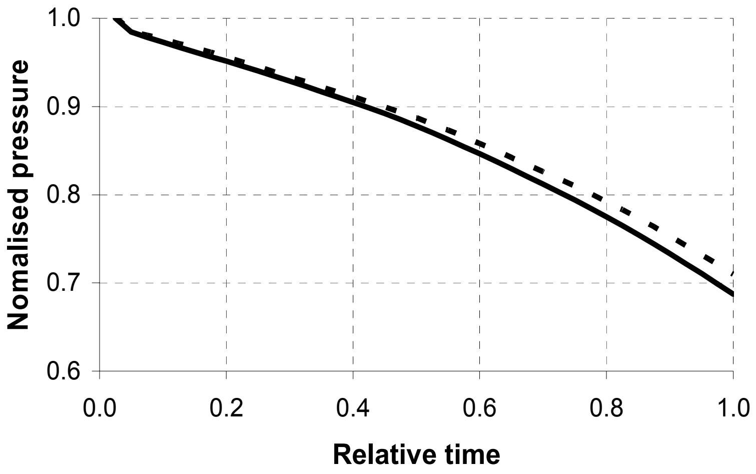


Figure 4.3.1-4: The comparison of the normalised (with respect to reference setup after a relative run time of 0.025) pressure values at the product outlet of the UHT section gives an improvement of approx. 4% (reference: solid, modification: dotted).

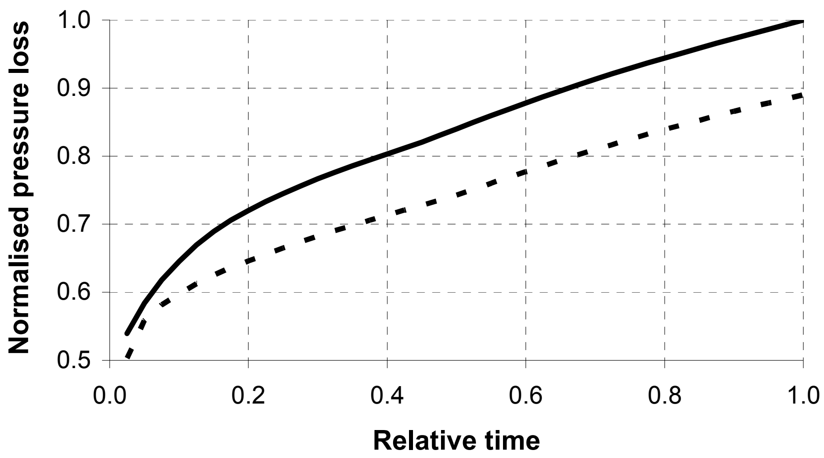


Figure 4.3.1-5: The normalised pressure loss of the preheater section results in an improvement of approx. 15% (reference: solid, modification: dotted). Normalisation was carried out with the value of the reference setup after a relative time of 1.0.

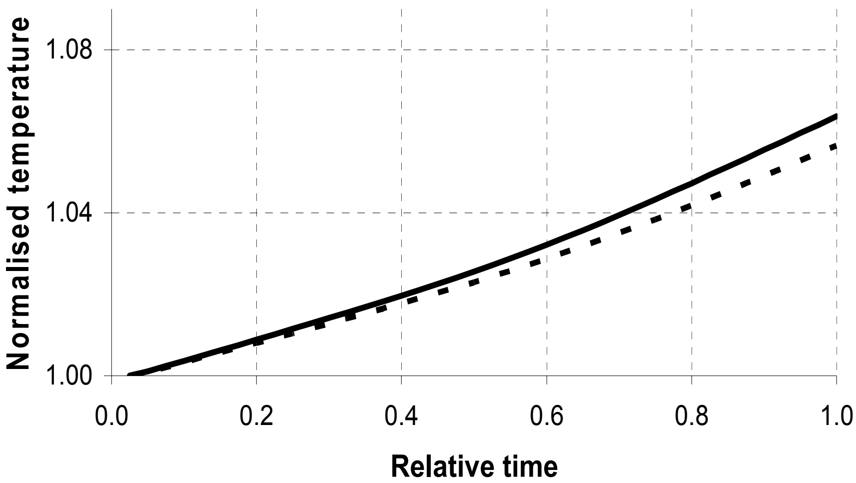


Figure 4.3.1-6: The consequences for the warm water circuit are shown by the normalised (with respect to reference setup after a relative run time of 0.025) temperature of the water inlet at heater III over running time (reference: solid, modification: dotted).

4.3.1.3 Results of the Modification of the Holding Time

As explained before, it is also possible to vary the holding time instead of holding temperature. In the considered plant this is done by omission or addition of holding tubes, as

$$t_{hold} = \frac{l_{hold}}{v_{product}} \qquad (4.3\text{-}1)$$

with

t_{hold} holding time

l_{hold} length of holding section

$v_{product}$ velocity of product, and

$$v_{product} = \frac{4 \cdot \dot{V}_{product}}{d^2_{tube} \cdot \pi} \qquad (4.3\text{-}2)$$

where

$v_{product}$ velocity of product

d_{tube} diameter of heating tube

$\dot{V}_{product}$ volumetric flow of product.

As the volumetric flow of the product has to be kept constant, this is the only possibility of changing this parameter. To obtain substantial effects, holding time was modified to 50% resp. 150% of the reference value. There were no further changes with respect to the reference setup.

Fig. 4.3.1-7 depicts the results of the simulation. The plant setup with the lengthened holding section shows increased fouling in the preheating section. In the intermediate heater and the UHT section the shortes holding section causes higher fouling than the reference, while the longer holding section leads to a diminished fouling layer.

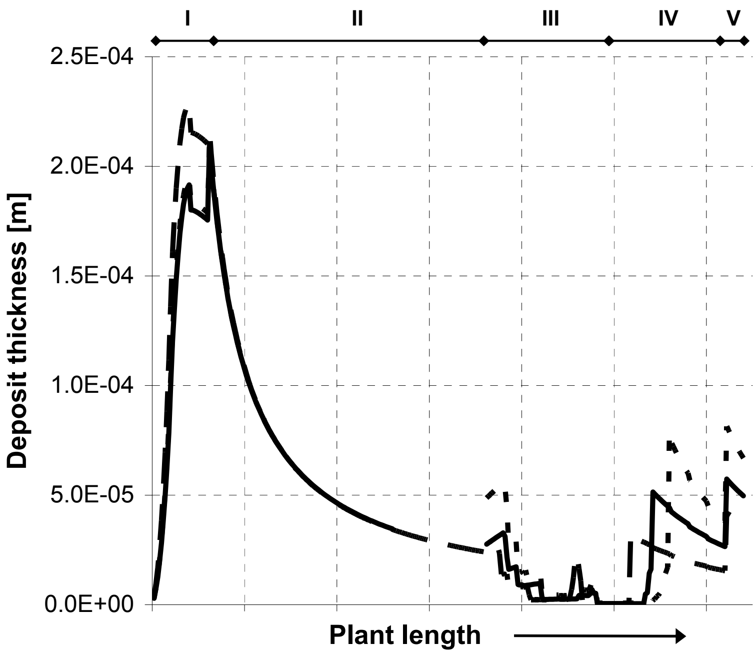


Figure 4.3.1-7: Deposit thickness over plant configurations with different holding times (reference: solid; half holding time: dotted; holding time lengthened by 50%: dashed). The plant sections are indicated as follows, I: preheating section, II: preholding section, III: intermediate heater, IV: UHT heater, V: UHT holding section.

4.3.1.4 Discussion

4.3.1.4.1 Remark

Product quality has not been observed in the context of this section. As Fig. 4.3.1-8 shows the respective parameters are not of importance in this heating section. The highest influence upon product quality is exerted by the UHT section, although there is some influence upon C*-value and lactulose by heater III.

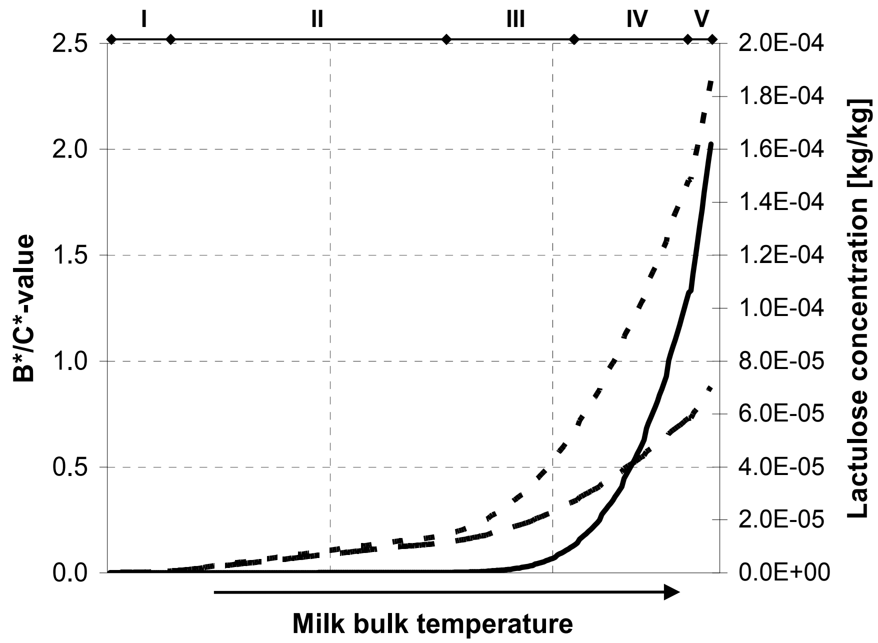


Figure 4.3.1-8: Development of the considered quality parameters B-value (solid), C*-value (dashed) and lactulose concentration (dotted) with milk bulk temperature (corresponds to plant length). The plant sections are indicated as follows, I: preheating section, II: preholding section, III: intermediate heater, IV: UHT heater, V: UHT holding section.*

4.3.1.4.2 Change of Holding Temperature

A result of the modification in comparison to the standard configuration in terms of the heat transfer coefficient, averaged over the complete section, is depicted in Fig. 4.3.1-3. By comparing the curves for both setups an improvement of approx. 15% was found. By looking at the values of the overall heat transfer coefficient (OHTC) of the single tubes (not shown), it can be noted, that the heating tube after the holding section in the modified setup reaches a higher OHTC value than when located before the holding part in the reference version. As the preheating/preholding section fulfills its task within the modified configuration this tube is less prone to protein fouling.

The evaluation in connection with the complete plant is depicted in Figs. 4.3.1-4 – 4.3.1-6. In Fig. 4.3.1-4 the pressure curves at the outlet of the UHT section of both configurations is shown. At approximately half of the run time a distinct improvement becomes visible. This effect could be assigned to the preheating section, where the pressure drop with respect to time advances less in the modified set up but there are also small changes in fouling behaviour in the other sections of the plant. A possibly stronger improvement is inhibited by the following sections. Downstream of the modified section the amount of native β-lactoglobulin is approximately twice compared to the reference. This causes an increased deposit thickness in heater III and UHT section. All these these effects sum up to the pressure curve in Fig. 4.3.1-4 and an improvement of approx. 4%. Finally, the similiar progress of the curves implies that the same governing chemical reactions take place, but at different levels. If these reactions can be identified more exactly in future investigations, well directed modifications are possible.

Figs. 4.3.1-5 and 4.3.1-6 suggest that the processes, responsible for the similiarity of the curves, mainly take place in the preheater and intermediate heater section, depicting the pressure drop over the preheater section and the water inlet temperature at the end of intermediate heater III. They also prove that the better fouling behaviour still is valid when the modification is integrated into the complete plant. A local improvement of approx. 10% with respect to pressure loss can be seen in Fig. 4.3.1-5. The similar progress of the curves again implies that the same basic processes are taking place, but at different levels. Together with the fact, that the results have been achieved after modifying the preheater section the curves show that it is most probable that the findings here are caused by the protein behaviour. Fig. 4.3.1-6 depicts a changing slope in the temperature progress after half of the running time, too. This confirms the above drawn conclusions. For all plant modifications the advantage of the modified setup lies in a smaller slope and in a reduced fouling rate from simulated run times of 0.2 on.

According to the findings of Mottar and Moermanns [1988], heat stability of caseins affects the formation of complexes of β-lactoglobulin and casein. This could explain the comparatively small effect of the modification onto the complete plant as these interactions are not yet implemented in the model. Even if this modification alone does not result in a distinct prolongation of runing time of the whole plant according to the simulation, a potential in saving energy by decreased consumption of pumping and heating energy is indicated.

4.3.1.4.3 Change of Holding Time

The most interesting result of the simulated runs is the fact that the addition of holding tubes leads to more fouling in the preceeding heating section. This is caused by the temperature of the heating water which is approx. 5K warmer in the case of the longer heater in comparison to the reference. Nevertheless, the proportional control algorithm is not able to keep the product temperature constant in the modified case. While in the reference setup this temperature only varies by approx. 0.1K, the temperature in the lengthened section constantly decreases, all in all by 1K. As a conclusion it seems to be the proportional control that can not handle the lengthened dead time [Samal 1991], introduced by the holding section. For realisation in a commercial plant this indicates that control algorithms probably have to be adapted in case of geometric changes or that not all modifications are practical for transfer to a real plant. Another problem might be the heat induced structure of β-lactoglobulin in this lengthened modification [Kennel 1994], which could require an adaptation of the model.

As expected a shortened holding section and, consequently, holding time, causes higher fouling levels in the following sections as the amount of reactive β-lactoglobulin increases in this setup.

4.3.2 Intermediate Heater III

4.3.2.1 Functionality and Modification Approaches

The purpose of this section is to heat the product from preheater holding temperature to a controlled constant temperature before it enters the UHT section.

In this case study, it was the question whether a variation of the heater length or the tube diameters could be of beneficial influence. Literature supported this approach as heating time influences deposit formation [Foster, Britten & Green 1989]. Additionally, the investigated temperature region was expected to show valuable effects with respect to heat transfer under various conditions as mentioned by the same authors, and noteworthy salt fouling is expected to start within this heater. Therefore, different residence times, heat transfer areas and temperature gradients were obtained by varying the length of heater III and the diameter of the tubes.

To explore the effects of various heater lengths two modifications were tested, one was lengthened in comparison to the reference section, the second one shortened. The consequences of modifying the heater length are opposed to each other. A short heater results in a shorter residence time but demands a higher temperature difference between product and heating medium. This should cause increased fouling and, as a consequence, problems with a higher pressure drop. In the elongated section the product is exposed to a lengthened heat treatment and the share of pressure related to the length of the section is higher. Finally, the dominating effects have to be evaluated by simulation.

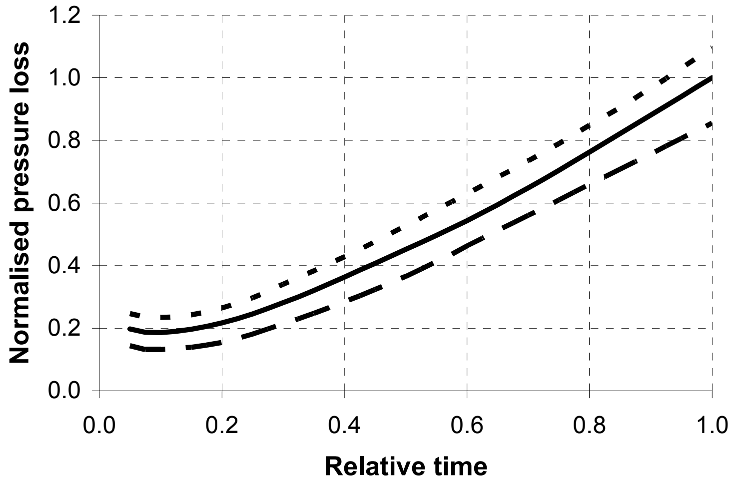
For the diameter investigations two consequences are expected. A smaller diameter supports turbulent flow and such the heat transfer. On the other hand the pressure loss is greater. Therefore, the main focus should be heat transfer and product quality.

4.3.2.2 Change of Surface Area

To implement modifications that also could be accomplished in reality, the reference heater was lengthened, resp. shortened, by addition resp. leaving out of one complete tube, which corresponds to a length modification of 20%. Fig. 4.3.2-1a shows the effect of the different lengths upon pressure loss within this plant section. It must be stated that the advantage of the short version at least partially is caused by the proportional influence of the length upon pressure drop. This effect then becomes more important when fouling progresses with time.

Implementing both variations into the complete plant showed only small changes at the end of the UHT section and, therefore, possible running time elongations were not more than approx. 5%. A second reason for revising a plant apart from longer running time are energy savings. To investigate this point the inlet temperature of the water in heater III is shown in Fig. 4.3.2-1b. In contrast to the results above, the long version is of advantage here.

a)



b)

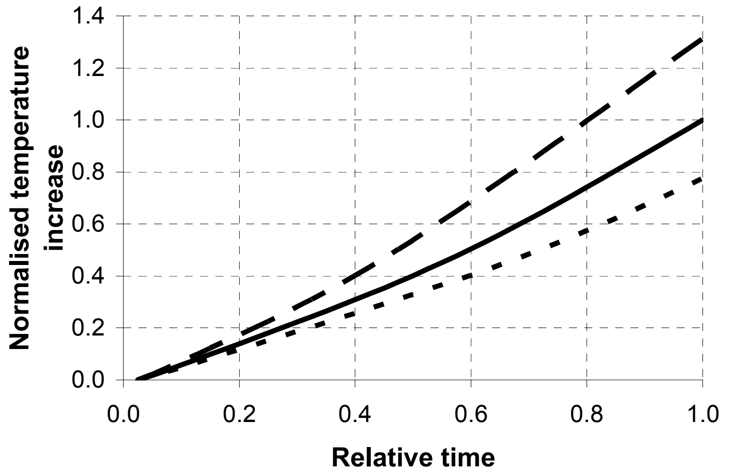
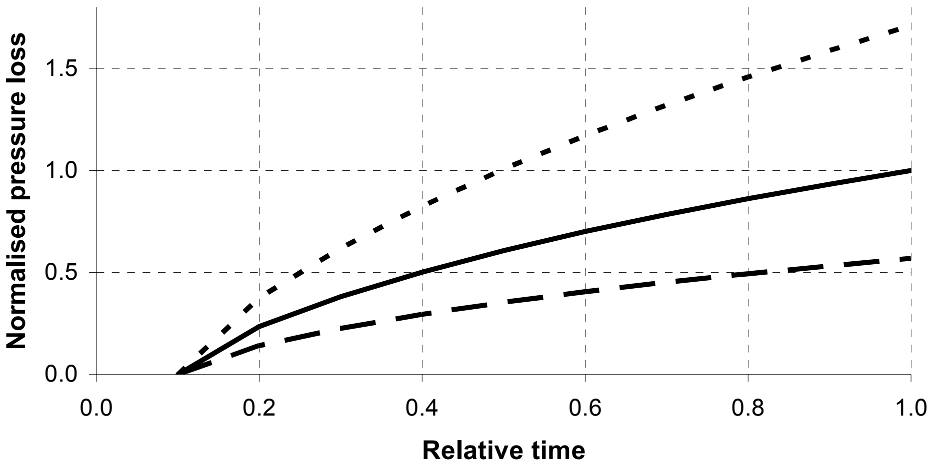


Figure 4.3.2-1: The normalised pressure loss (a) and temperature increase of heating water (b) for two length modifications of heater III in comparison to the reference sections values are shown (reference: solid, dashed: short heater, dotted: long heater). Normalisation is done with respect to the reference setups value at a relative run time of 1.0.

4.3.2.3 Variation of Tube Diameters

For the modifications of this chapter the tube diameters were changed by ± 2 mm. Figure 4.3.2-2 proves the validity of the discussed assumptions. While a small diameter enhances heat transfer, as depicted in 4.3.2-2b, the pressure drop and, consequently, the necessary pumping energy, is increased, see 4.3.2-2a. On the other hand, a larger diameter would lengthen running time by approx. 50% when the pressure loss is considered (Fig. 4.3.2-2a).

a)



b)

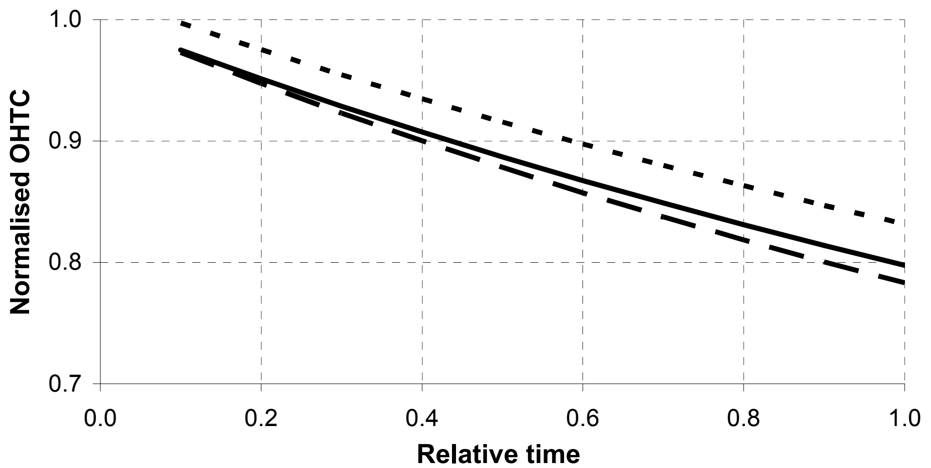


Figure 4.3.2-2: The normalised pressure drop (a, with respect to reference value at run time 1.0) and the normalised OHTC (b) are shown for different heater III tube diameters. The setups are reference (solid), diameter decreased by 2 mm (dotted) and diameter increased by 2 mm (dashed).

From simulation runs with preheater (see section 4.3.1) and heater III (see section 4.3.2.2) it is known that the modifications often show a smaller effect when simulated in the synthesised form as when tested as stand alone. In this case the changes of the diameters were increased to ±4 mm to obtain more substantial effects. With this approach the diminished diameters could not be evaluated, as the pressure at the UHT outlet soon develops towards a negative value. Figure 4.3.2-3 shows the expected effect, that the normalised pressure at the plant outlet increases with the bigger diameter.

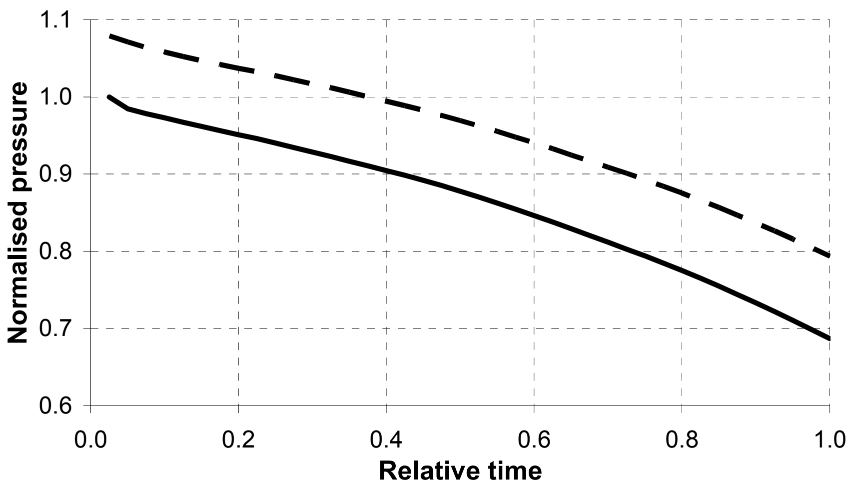


Figure 4.3.2-3: The development of the pressure (normalised with respect to reference value at run time 0.025) at the outlet of the UHT holding section is shown. It is very similar for the reference (solid) and the modification (reference + 4 mm, dashed). The diminished version could not be simulated as the pressure very soon undergoes the value of zero in the considered plant setup.

4.3.2.4 Discussion

Literature review shows, that for a fixed heat load to be transferred low thermal driving forces, as obtained in a longer section with low temperature differences between milk and heating medium, are of advantage compared to fast heating with high temperature differences [Fryer 1989]. These statements are verified in this chapter. Furthermore, for a given heat load a slower and longer heating process, which corresponds to a longer heating section, is of advantage for process control [Fryer & Slater 1986] and fouling [Georgiadis, Rotstein & Macchietto 1998c; Fryer & Slater 1985]. As mentioned in the preceeding discussion to this chapter, this is logical as a larger heat transfer area is provided in this case.

The higher slope of the short sections curve also implies that there is stronger fouling due to the higher temperature difference.

As in Fig. 4.3.1.3 – 4.3.1.6, there are bends in the curves, located between relative times of 0.4 and 0.6, which are more distinct here. The better observable effect in heater III has two reasons. The first one is the higher water temperature, necessary in the short version to obtain the defined outlet temperature, within the modified section, that favours faster reactions. The second one is, that in this temperature range salt crystallisation becomes important.

By looking at the value for the fuzzy corrected of salt deposition rate in Fig. 4.3.2-4, two facts are observed. The first one is that salt crystallisation is more distinct at the end of heater III. This could be expected, as the product temperature is higher there and it is especially in that region, where this part of fouling becomes more important. The second observation is that salt deposition is higher in the short heater up to approx. 50%. The fuzzy sets apply a higher correction factor here as the temperature difference between water and milk is higher.

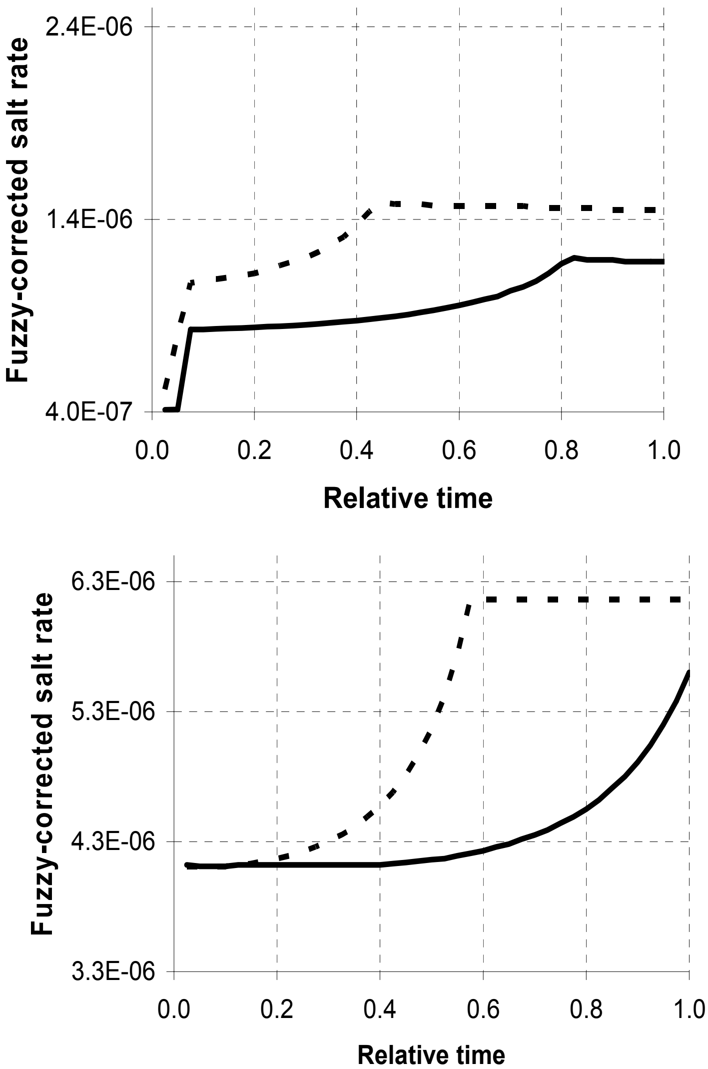


Figure 4.3.2-4: Fuzzy corrected salt deposition rate for the long (solid) and the short (dotted) heater III modification. The smaller inlet temperatures lead to a lower deposition rate at the product inlet of the heater (top), while the higher temperature values at the heaters product outlet cause a higher rate (bottom). Generally, the long heater is advantageous in terms of salt crystallisation as the lower rate values, compared to the short version, show.

Additionally, the higher water temperature in the shortened plant results in advanced fouling in the preheater section (not shown). The advantageous behaviour, especially for the long heater, and the lower water temperatures in the preheater agree with the findings of the previous section.

As mentioned before, the diameter changes had to be doubled for evaluation of the complete plant performance. The resulting pressure drop for the small diameter modification was too big for the given system. As has been discussed in a previous section (section 4.3.1.4.1), the part of the plant mainly responsible for product quality is the UHT section. Therefore, it is not necessary to evaluate the quality parameters in this chapter.

4.3.3 UHT Heater and UHT Holding Section

4.3.3.1 Functionality and Modification Approaches

With these plant sections the heating success as demanded by law, that means B*>1.0 (see section 3.2), has to be ensured.

The heat transfer depends on the mass flows of water and product, its temperatures and on the size of the heat transfer area and its surface state. The state of the surface area depends on the extent of fouling, induced by the thermal load. In the UHT section inlet and outlet temperature of the product and its mass flow are constant and, consequently, the amount of heat to be transferred. The necessary heat flow can be adjusted by water temperature and mass flow. A higher mass flow allows smaller temperature differences, which are advantageous in terms of fouling [Jeurnink 1996; Jeurnink, Walstra & de Kruif 1996], but results in higher costs for supplying heating medium. The target now is to find a water temperature which can reduce fouling combined with a water mass flow that is advantageous in terms of energy consumed by heating.

4.3.3.2 Adjustment of Volume Flow of Heating Medium

In the reference plants UHT section, a volume flow ratio of 1:1.4 (product flow – water flow) is adjusted. For investigation a volume flow ratio of 1:1 was chosen, assuming equal heat capacities of water and milk. Fig. 4.3.3-1 shows the temperature curves that result from this modification and are responsible for the different behaviour of both setups.

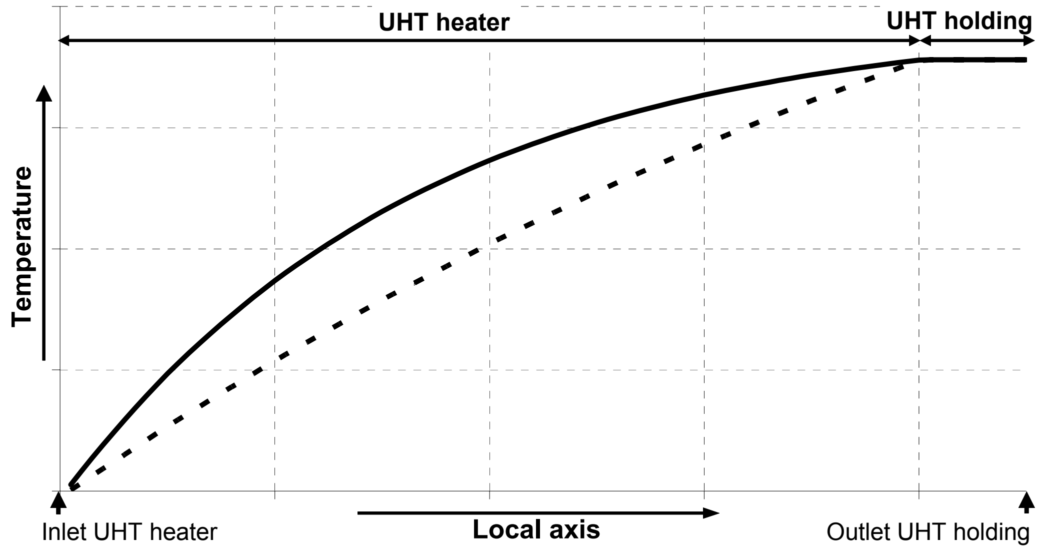


Figure 4.3.3-1: Increase in product temperature for both reference (solid) and modified setup (dotted) after a relative run time of 0.1. The modification exposes the product to a less severe treatment.

The resulting pressure curves are given in Fig. 4.3.3-2. After a steep rise during the beginning of the simulated run time, that corresponds to a running-in of the plant, the increase in pressure loss could be described by a straight line. The advantage of the modification is given by a smaller slope of 0.27 in comparison to the reference with a slope of 0.31.

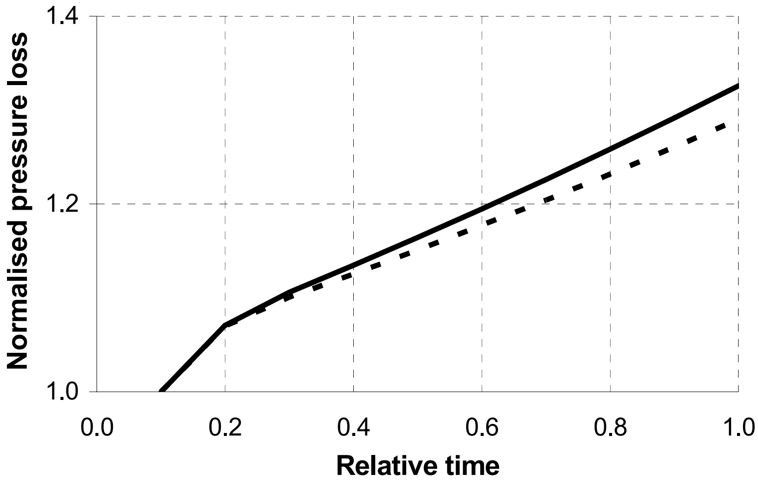


Figure 4.3.3-2: Pressure loss over UHT heater with respect to relative running time. The solid line indicates a ratio of 1:1.4, the dotted one the modified value of 1:1. The values were normalised with respect to the reference values after a relative time of 0.1.

The OHTC shows an even higher improvement of the modification of approx. 20% in comparison to the reference setup.

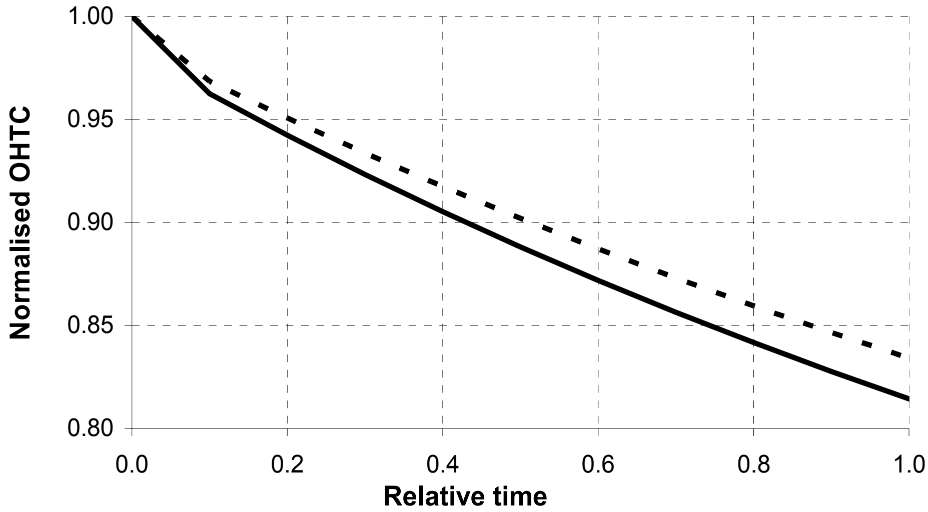


Figure 4.3.3-3: Overall heat transfer coefficient of the UHT section, normalised with the value of the reference at relative run time of 0.0, for two volumetric flow ratios (solid: 1:1.4; dotted: 1:1).

Finally the modification comes up with an expected run time improvement of approx. 20%, besides the energy savings due to less hot water consumption.

To observe product quality, the B*- and C*-values were calculated for run times of 0.1 and 1.0 respectively. The decrease of the B*-value for the original flow ratio was 0.49 units compared to 0.2 for the modification. The C*-value fell by 0.09 units for the reference and by 0.06 for the modification. Table 4.3.3-1 summarises the calculated values.

Table 4.3.3-1: Comparison of B and C*-values of original and modified volume flow ratio in UHT heater.*

	$B^*_{original}$	$C^*_{original}$	$B^*_{modified}$	$C^*_{modified}$
rel. run time 0.1	2.56	0.73	1.7	0.62
rel. run time 1.0	2.07	0.64	1.5	0.56
ΔB*	0.49	-	0.2	-
ΔC*	-	0.09	-	0.06

4.3.3.3 Variation of Tube Diameter

An advantage of direct heating processes in comparison to indirect processes is, that milk is more rapidly heated from pasteurisation to UHT temperatures, independent from the realised techniques. Smaller tube diameters might help to imitate these heating conditions by indirect processes. As a result product quality should be improved.

To keep the continuity of this thesis, at first technological parameters are investigated. Fig. 4.3.3-4 depicts normalised pressure loss and normalised OHTC over the UHT section for various tube diameters.

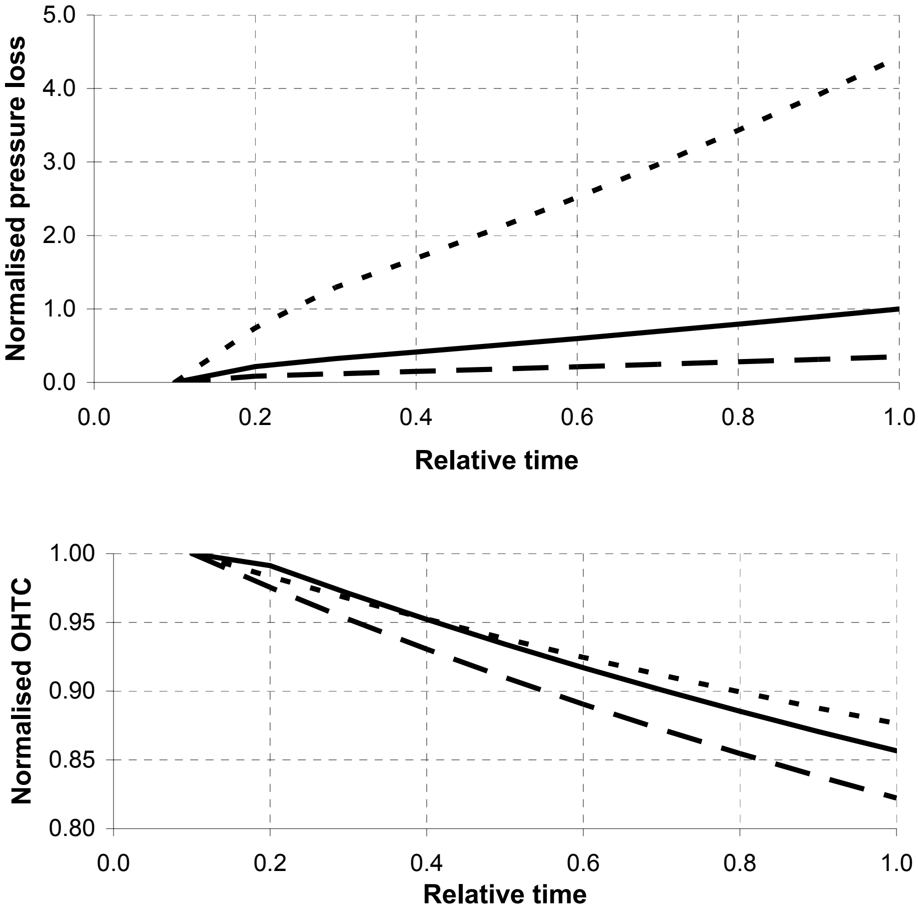


Figure 4.3.3-4: The pressure loss (top) and the OHTC (bottom) are shown for different UHT heater tube diameters. The investigated setups are reference (solid), diameter decreased by 4 mm (dotted) and diameter increased by 4 mm (dashed).

For integration in the complete plant the necessary inlet pressure had to be increased to find stable operating conditions. Nevertheless, the tube diameters could only be decreased by 2 mm instead of 4 mm to obtain a simulated run time of 1.0.

Temperature development is not shown as there is only a marginal difference between the different setups despite the different fouling behaviour.

As a quality parameter lactulose was chosen and is depicted in Figure 4.3.3-5. All curves show the same characteristic progress although at different concentrations.

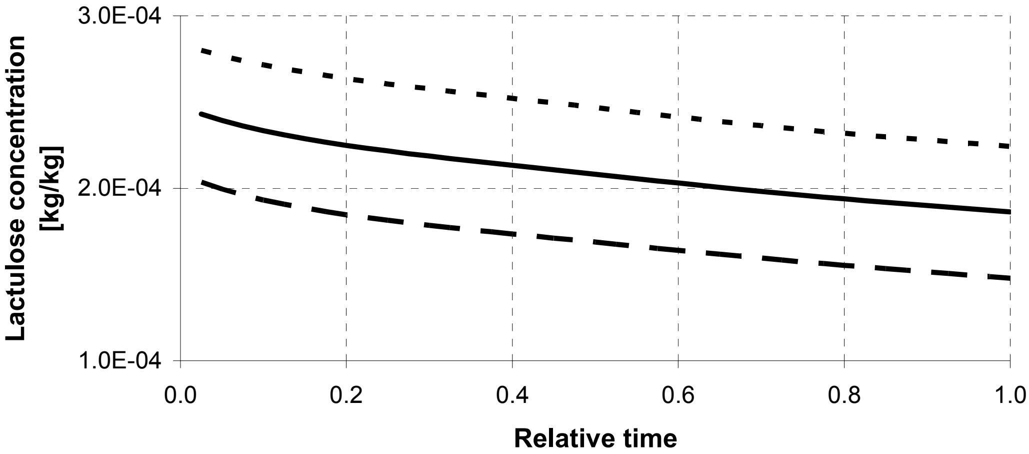


Figure 4.3.3-5: Progress of lactulose concentration during running time for different diameters in stand alone UHT sections: reference (solid), diameter increased by 4 mm (dotted) and diameter diminished by 4 mm (dashed).

4.3.3.4 Discussion

4.3.3.4.1 Volumetric Flow Rates

Due to the smaller volume flow of heating medium and the resulting different temperature gradient the values for B* and C* decreased. However, the B*-value remained higher than the required value of 1.0. A diminished C*-value is always advantageous in terms of product quality. The smaller drop of both values with respect to time shows that fouling of the modified UHT section proceeds more slowly than in the original which also can be seen from investigating the pressure loss in Fig. 4.3.3-1. Finally, this shows that the mass flow of heating medium was oversized in the unchanged reference setup.

Modifying the UHT water circuit is easily possible, as it is independent from the low temperature warm water circuit (see Fig. 3-1) and the water is not used for energy recovery after use. Therefore, it was already realised at the local plant and proved to be of economic advantage without provoking problems with respect to running time or product quality.

4.3.3.4.2 Tube Diameter

The variation of the tube diameter constitutes a problem in comparing the modification with the reference insofar as there is a massive change in pressure drop, which is proportional to the square of the diameter. For this section – and section 5 – it is assumed that the underlying model is also valid for the higher shear rates, caused by decreased diameters under the precondition of a constant volumetric flow rate of product. Hereby it is presumed that milk behaves like an Newtonian fluid [Walstra et al. 1999], where the shear velocity is a function of the Reynolds number [Delgado 1986], which is increased under the applied conditions. The assumption of validity of the model with respect to increased shear velocity might be doubted as the pressure loss rises to a very high value when diameters are decreased compared to a falling pressure loss with wider diameters.

In the above presentation of the results temperature development has been omitted due to the small differences between the curves. Only at the start of the run time an advantage of the small diameter can be observed. At the end both curves show the same progress despite the different fouling behaviour. But the smaller diameters, together with constant volume flows, cause higher Reynolds numbers, that consequently lead to an increased local heat transfer coefficient α (tube – product fluid) and an improved heat transfer.

Lactulose was chosen as a quality parameter to rate the level of damage caused by the heat treatment. With the applied simulation the principal shape of all three curves is similiar, but the thinner the tubes the lower the concentration. Therefore, smaller tubes support a less severe but sufficient heat treatment, indicated by a lactulose concentration not falling below the limit of 100 mg/kg.

It also has to be mentioned that the adaptation of the model plant was done with as little effort as possible. In a real plant it is assumed that advanced changes of the setup could be necessary in the presented case. This was not done here as it is not the intention of the presented work.

5 Case Study: Synthesised Configurations

One of the most important aspects in process and plant design – besides run time - is the final quality of the product. The approach within this thesis was to split up the complete plant into individual sections and investigate the effect of these sections upon product quality. The effects of the individual sections upon the parameters B*, C* and lactulose concentration have been shown in Figure 4.3.1-8.

Based on the results of the software runs described in chapter 4, four plant configurations with major modifications were developed by structural synthesis and tested. As a result of the previous investigations, the simulated plants consisted of

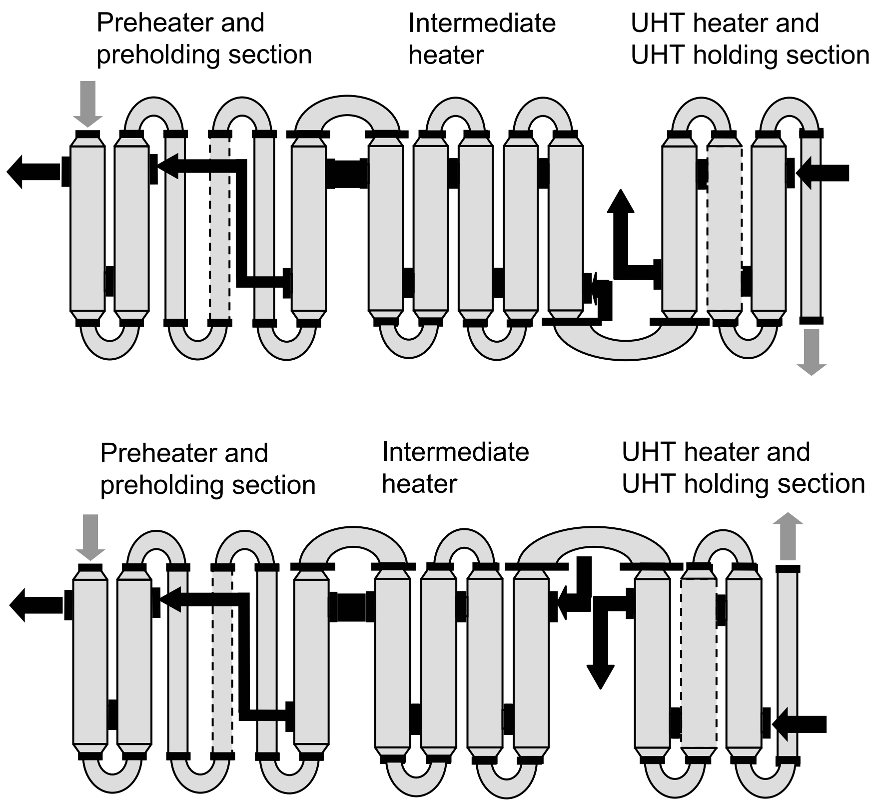
- modified preheater with shifted preholding section,
- intermediate heater of various lengths,
- UHT heater with different tube diameters and volumetric flow ratio adjusted to 1:1, and
- UHT holding section (original setup).

The modification of the preheating section had been rated as advantageous to such an extend, that it was implemented in all four versions. In plant 1 and 2 heater III is set up according to the reference plant to investigate the effect of the preheater modification together with two UHT heater alternatives which had both shown advantages in the previous tests (see section 4.3.3.3). Plants 3 and 4 combine the smaller UHT heater diameters with two different heater III setups to test further possibilities of modification. The volumetric flow ratio of product and heating water was set to the value of 1:1 according section 4.3.3.2. Table 5-1 summarises the various setups.

Table 5-1: Setups of the synthesised configurations.

	Plant 1	Plant 2	Plant 3	Plant 4
Preheater and Holding section	Shifted holding section according chapter 4.3.1.2			
Intermediate heater	Number of tubes			
	5 tubes	5 tubes	4 tubes	6 tubes
UHT heater	Tube diameter in comparison to reference			
	∅ = + 4 mm	∅ = – 4 mm	∅ = – 4 mm	∅ = – 4 mm

Figure 5-1 shows sketches of the setup of the synthesised plants. The number of heating tubes of the UHT heater is kept constant for all setups.



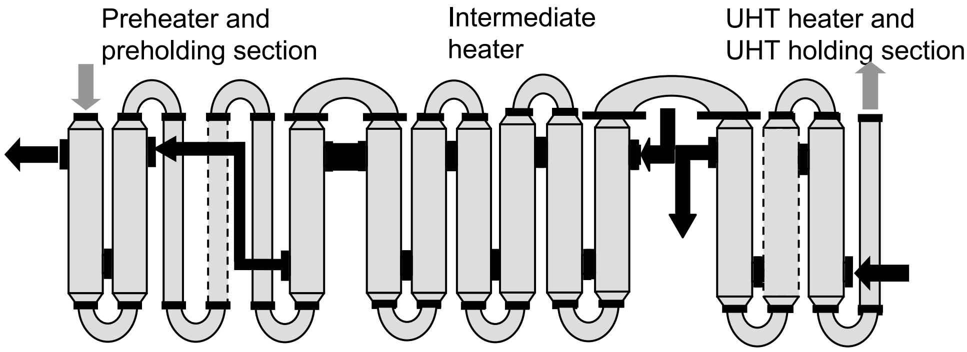


Figure 5-1: Sketch of the synthesised plants used for this section. The sketch at the top outlines the setup of plants 1 and 2, where only the diameters of the bundled tubes are different. The middle figure shows plant 3 while plant 4 is depicted at the bottom. Black arrows indicate the in- and outlets of the heating media, grey arrows depict in- and outlet of the product.

As alterations in the setup included diameter variations in the UHT heating section, the inlet pressure was set to a value high enough to obtain a simulated running time of 1.0 and assuming that the tubes work with the chosen pressure. For comparison the reference setup was also simulated with this inlet pressure. Although the evaluation of the pressures during running is problematic as the prerequisites are different due to the geometry, its calculation gives a hint of the development of the fouling layer. Together with the waterside temperature developments the efficiency of the various modifications can be estimated. In the following figures the values are made dimensionless with the value of the respective plant setup after a run time of 0.025, when the first values are put out, to show the progress of the variables with respect to running time. Nevertheless, the main focus was put upon product quality characteristics.

Figure 5-2 depicts the relative pressure at the end of the plant, i.e. the outlet of the UHT holding section. The curves imply that there is only a minor influence of the plant length, but a strong one by the tube diameters in the UHT heating section. Consequently, there is a small increase in available pressure for plant 1, but sharp decreases for the plants with smaller diameters. Plant 2 was left out as it shows similiar behaviour as plants 3 and 4.

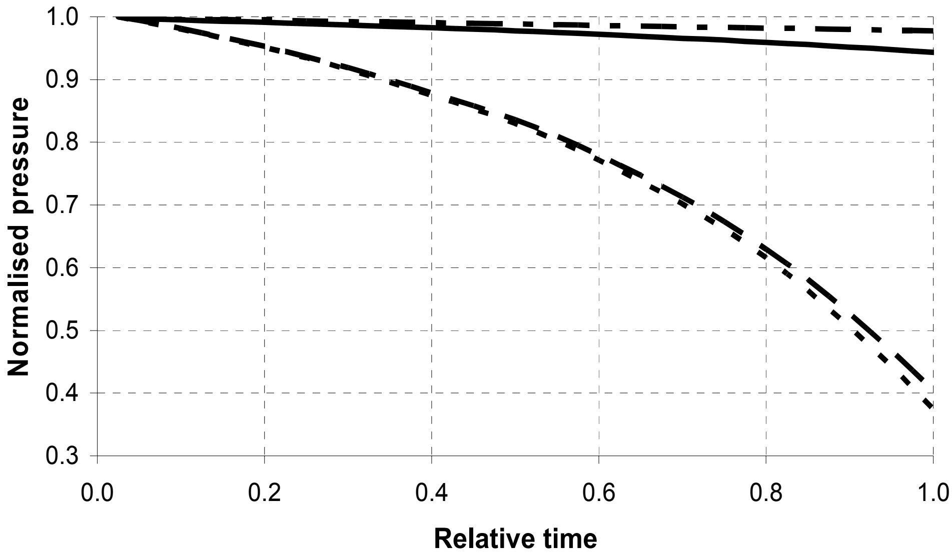


Figure 5-2: Relative pressure at the outlet of the UHT holding section (reference: solid, plant 1: dash-dotted, plant 3: dashed, plant 4: dotted). The curve of plant 2 has been left out due to its similiarity with plants 3 and 4. The values were normalised with respect to the pressure at a run time of 0.025 of each plant.

Due to the pressure curves it is assumed that there is a considerable influence of deposition. Nevertheless, there is no significant difference in the development of the temperature of the UHT heating water which is not shown here. These observations coincide with those made in section 4.3.3.4.2 and are explained there.

For evaluation of the obtained product quality, lactulose concentration was chosen. As plants 2, 3 and 4 show similiar results, only pant setup 2 is depicted in Fig. 5-3. The setups with decreased tube diameters reach only approx. 70% of the references lactulose concentration. This still indicates a sufficient heat treatment, but the decreased value also stands for a better production in the sense of a minimal processing which offer a better naturalness of the product and less employment of energy and ressources. Plant 1, which is advantageous in terms of processing parameters results in a higher lactulose level, indicating a higher heat load.

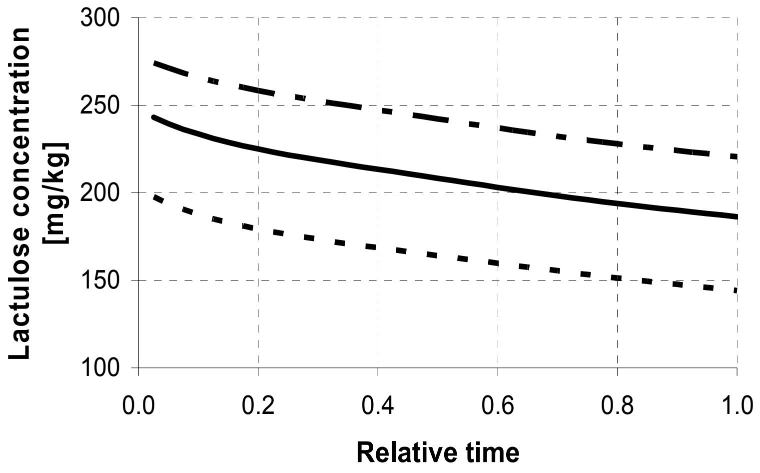


Figure 5-3: Progress of the lactulose concentration with respect to running time (reference: solid, plant 1: dash-dotted, plant 2: dotted). Plants 3 and 4 are similiar to no. 2 and not shown here.

Finally, these results show that in case of design of new plants a decision has to be made which is also influenced by economic considerations. It has to be made between plants that supply a higher product quality at the expense of more pumping power needed and presumably higher investment costs or a cheaper plant with lower running costs, but just acceptable product quality.

6 Conclusion and Outlook

Fouling is one of the most important problems to be considered in heat transfer processes and in the design of heat exchanging equipment. Especially in the dairy industry is the latter a complicated procedure due to the complexity of the raw material and the incomplete understanding of heating effects.

The basic idea of the presented work was to contribute to the optimisation of heating processes in dairy industry by investigation of structural synthesis based on the analysis of the performance of individual plant parts. Hereby the simulated modification of an existing plant was carried out to improve its performance and energy usage and lengthen its run time without expensive and time consuming experiments.

After deleting all parts that were supposed to be of minor interest in terms of the defined objectives, a reference plant remained, which was split into different sections of individual functionality. Most of the modifications in the presented work were based upon industrial plant components and were selected with respect to practicability, e.g. there were no alterations done within the warm water circuit, which is integrated into the energy recovery process, or changes of tube lengths.

Although the chosen ideas principally aimed upon improvement of an existing plant at a local dairy, there is no restriction of generality in the approach. It was shown, that it is practicable to test single sections as stand-alone units as well as in the environment of a complete setup. Simulating an individual section gives results within comparatively short times and only, if a positive result, i.e. a local effect, is obtained, the test within the complete plant is necessary.

Treatment of the complete plant has to ensure, that the modification does not have any negative effects upon other sections, because there are two possible ways of interaction between different sections. The first is given by the product flow which transports changes of product characteristics to succeeding sections. The second one appears in heat exchangers, run in counter-current mode as the considered one. Here any changes within the temperatures of the water circuits cause a feed back to upstream sections. By adjusting to new balances the improvement of a single section may be equalled out within the context of the complete plant. The results, obtained from the simulation runs, were mainly treated as trends such being very convenient in comparing various processing or product parameters. This enables the selection of the most interesting modifications with respect to chosen values.

Evaluation of the performance of a stand-alone section was done by comparing the overall heat transfer coefficient and the pressure drop over the section with the values of the unchanged section. When simulating the complete plant mainly the pressure drop over the plant and the inlet temperature of the UHT heating water of both modified and reference setups were compared. As the percentage improvements differ for the individual parameters, it has to be taken into account which value is more critical at a considered plant. Additionally, product quality was observed at this stage by calculating B*- and C*-value and lactulose concentration. The following values represented a sufficient, but not excessive, heating:

- B* > 1.0,
- C* < 1.0 and
- 100 mg/kg < lactulose concentration < 600 mg/kg.

In the presented thesis the following structural synthesis were investigated:

- preheater and preholding section
    - holding temperature
    - holding time
- intermediate heater
    - length
    - tube diameters
- UHT heater
    - tube diameters
    - volumetric flow ratio (product – heating medium).

The simulation of the preheater and its holding section was carried out to optimise the denaturation of β-lactoglobulin. Here the holding temperature and the holding time are the parameters that can be varied. A local running time elongation up to 20% was possible when adapting the holding temperature.

For the complete plant smaller elongations with a maximum of 4% are found, plus an improvement in energy usage. The change of holding time showed that the aggregation behaviour of β-lactoglobulin should be a point to be considered in future enhancements of the model.

Modifications were also implemented within the intermediate heater III. Various tube diameters and heater lengths were tested and supplied different residence times and heat transfer areas. Furthermore, it was shown that this section is not critical in terms of quality as rated by the applied parameters. Finally, by increase of the tube diameters a local running time elongation of approx. 50% was obtained, while the modification of the surface area resulted in an improvement of approx. 5%.

The simulation of the UHT section, modified with respect to the volume flow of hot water, gives an approx. 20% elongation of the run time and, additionally, an improved energy usage. The described modification was implemented in the local dairy and resulted in an predicted improved energy usage without leading to any run time problems. In real world design processes this would have required costly experiments where the most are ineffective in the end and here the special benefit of the simulation lies. The implementation of this alternative without any troubles in production proved the simulations capabilities.

Further runs included changes of the tube diameters in the UHT heating section. These setups led to modified residence times of the product. To reach the desired holding temperatures, higher water temperatures and, consequently, a higher temperature gradient was obtained. With this approach an approximation of a direct heating process within an indirect plant by small tube diameters could be the target. Evaluation showed that an improved product quality is obtained this way while, on the other hand, higher pumping power is necessary. Questions regarding the underlying model arise here. It has to be investigated whether the applied approach is able to predict the build-up of the fouling layer in a correct manner under these conditions. This has to be done with respect to the increased shear stresses that theoretically could lead to a diminished fouling deposition or to more reentrainment.

The obtained results showed the potential of the software at its current state. To improve the performance of the simulation tool experiments at a pilot plant are necessary. This would enable the test of the software by implementing and running proposed modifications of process parameters. The result would be an improvement of the validation and rating of the values, that were obtained by the software as well as the accuracy of prediction. Additionally, it could support the adaptation and improvement of the applied model, and especially the fuzzy systems, used. A further step then could be a modification of the plant hardware. The limits of this procedure must be set by the plant manufacturers and would finally result in the design of new plants.

Basic future research, including laboratory experiments, should aim at an improvement of the underlying model, e.g. the shear stress dependency of the deposition, the formation of different molecular structures, pH development during heating or salt deposition at elevated temperatures. An extended product model is expected to give more insight into the reactions taking place while dairy products are heated. One of the most interesting aspects here is the behaviour of casein and especially its interactions with β-lactoglobulin and the salt fraction of the milk. Additionally, the concentration of lactose seems to be of interest, not only as it influences the final lactulose concentration but also as it protects β-lactoglobulin against denaturation [van Bockel 1996; Berg & van Bockel 1994; Plock 1994; Pappas & Rothwell 1991].

Furthermore, with taking into account additional product components and increasing the number of interactions, the reaction of the product during processing can be described in more detail. This would not only support the user of the simulation in finding suitable plants but also extend the range of applicable products which might be particularly interesting with respect to functional foods and their simulation [Desiere et al. 2002].

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Appendix A: Fuzzy Sets and Rules

A.1 General Remarks

In the following chapters the sets and rulebases for the integrated fuzzy systems are described. Details of the implementation into the model are given by Petermeier [2003]. To obtain better readability the rules are not given in the syntax expected by the software but in unequivocal tables. Although names of variables are equal, different sets are possible as the effect of the variables value depends on the process under consideration.

The shapes of the membership functions are defined the following way. Each set is defined by four numbers x_i, i = 1, 2, 3, 4, which determine the structure of the sets as defined in Table 8.1-1.

Table A.1-1: Realisation of the desired shape of a membership function by definition of the four necessary parameters.

Condition	*Shape*
$x_1 = x_2 < x_3 < x_4$	left open
$x_1 < x_2 < x_3 < x_4$	trapezoid
$x_1 < x_2 = x_3 < x_4$	triangular
$x_1 < x_2 < x_3 = x_4$	right open

The operators, that are used within this thesis are defined as follows:

- AND: $\mu_A(x_1)$ AND $\mu_B(x_2) = \min\{\mu_A(x_1); \mu_B(x_2)\}$
- OR: $\mu_A(x_1)$ OR $\mu_B(x_2) = \max\{\mu_A(x_1); \mu_B(x_2)\}$
- NOT: NOT $\mu_A(x_1) = 1 - \mu_A(x_1)$

Evaluation of the rules is done from left to the right and from top to the bottom. Additionally, the results of various rules are accumulated by a max-evaluation, if more than one rule ‘fires’ for a given input tuple.

Defuzzification, i.e. the translation of the fuzzy result into a crisp value, is done by a modified center-of-gravity method.

A.2 Phase Recognition

The fuzzy system for phase recognition supplies one of the three phases INDUCTION, TRANSITION and FOULING. The developed sets are given here. The variable "specific mass" was the same way defined for protein, salt and total mass. Therefore, the input sets are the same for all three linguistic variables and only one table is shown here.

Table A.2-1: Input set for specific mass, defined for protein, salt and total mass.

Specific Mass [g/m^2]				
low	0.00	0.00	1.00	2.00
medium	1.00	2.00	2.00	3.00
high	2.00	3.00	4.00	4.00

Table A.2-2: Output set for the linguistic variable fouling phase.

Phase [-]				
induction	0.00	0.50	0.50	0.75
transition	0.50	0.75	0.75	1.00
fouling	0.75	1.00	1.00	1.25

Table A.2-3: The following three rules were applied to the fuzzy sets.

IF	THEN
((Specific Mass of Protein = low OR Specific Mass of Protein = medium) AND (Specific Mass of Salts = low OR Specific Mass of Salts = medium)) AND Total Specific Mass = low	Phase = induction
((Specific Mass of Protein = low OR Specific Mass of Protein = medium) AND (Specific Mass of Salts = low OR Specific Mass of Salts = medium)) AND Total Specific Mass = medium	Phase = transition

IF	THEN
((Specific Mass of Protein = low OR Specific Mass of Protein = medium OR Specific Mass of Protein = high) AND (Specific Mass of Salts = low OR Specific Mass of Salts = medium OR Specific Mass of Salts = high)) AND Total Specific Mass = high	Phase = fouling

A.3 Surface Roughness

The output of this fuzzy system is the surface roughness, that directly is used for calculation of pressure loss. The following tables show the parts of the fuzzy system.

Table A.3-1: Input set for the linguistic variable fouling phase.

Phase [-]				
induction	0.00	0.50	0.50	0.75
transition	0.50	0.75	0.75	1.00
fouling	0.75	1.00	1.00	1.25

Table A.3-2: Input set for the linguistic variable bulk temperature of product.

Bulk Temperature [K]				
low	273.0	353.0	353.0	363.0
medium	353.0	363.0	363.0	383.0
high	363.0	383.0	383.0	425.0

Table A.3-3: Input set of the linguistic variable thickness of deposit.

Thickness of Deposit [m]				
low	0.0	5.0E-7	5.0E-7	5.0E-6
medium	5.0E-7	5.0E-6	5.0E-6	5.0E-4
high	5.0E-6	5.0E-4	5.0E-4	5.0E-3

Table A.3-4: Input set of the linguistic variable deposit density.

Deposit Density [kg/m^3]				
low	500.0	500.0	750.0	800.0
medium	750.0	800.0	800.0	1000.0
high	800.0	1000.0	1100.0	1100.0

Table A.3-5: Output set of the linguistic variable deposit roughness.

Roughness [m]				
smooth	1.0E-6	5.0E-6	5.0E-6	5.0E-5
medium	5.0E-6	5.0E-5	5.0E-5	1.0E-4
rough	5.0E-5	1.0E-4	1.0E-4	5.0E-4

Table A.3-6: Rule set for the fuzzy system deposit roughness.

<table>
<tr><td>IF</td><td>THEN</td></tr>
<tr><td>Phase = induction</td><td rowspan="3">Roughness = smooth</td></tr>
<tr><td>Bulk Temperature of Product = low</td></tr>
<tr><td>Thickness of Deposit = low</td></tr>
<tr><td>Phase = transition</td><td rowspan="4">Roughness = medium</td></tr>
<tr><td>Phase = fouling AND Bulk Temperature of Product = low</td></tr>
<tr><td>Phase = fouling AND Bulk Temperature of Product = medium</td></tr>
<tr><td>Phase = fouling AND Bulk Temperature of Product = high AND Deposit Density = high</td></tr>
</table>

IF	THEN
Phase = fouling AND Bulk Temperature of Product = high AND Deposit Density = medium	Roughness = medium
Phase = fouling AND Bulk Temperature of Product = high AND Deposit Density = low	Roughness = rough
Thickness of Deposit = high AND Bulk Temperature of Product = low	
Thickness of Deposit = high AND Bulk Temperature of Product = medium	
Thickness of Deposit = high AND Bulk Temperature of Product = high	

A.4 β-Lactoglobulin Deposition

The output of the fuzzy system is a correction factor that modifies the deposition rate, calculated by the mathematical approach. It proved to be of advantage, that the output was devided into five sets, thus obtaining a finer subdivision of the various states.

Table A.4-1: Input set for the linguistic variable fouling phase.

Phase [-]				
induction	0.00	0.50	0.50	0.75
transition	0.50	0.75	0.75	1.00
fouling	0.75	1.00	1.00	1.25

Table A.4-2: Input set for the linguistic variable bulk temperature of product.

Bulk Temperature [K]				
low	333.0	333.0	343.0	353.0
medium	343.0	353.0	358.0	368.0
high	358.0	368.0	373.0	373.0

Table A.4-3: Input set for the linguistic variable temperature difference between product and heating medium.

Temperature Difference [K]				
low	0.0	0.0	5.0	10.0
medium	5.0	10.0	10.0	15.0
high	10.0	15.0	20.0	20.0

Table A.4-4: Input set for the linguistic variable pH value of the unprocessed milk.

pH [-]				
low	5.00	5.00	6.20	6.65
medium	6.20	6.65	6.65	7.10
high	6.65	7.10	7.20	7.20

Table A.4-5: Output set for the linguistic variable rate correction of protein deposition.

Rate Correction [-]				
very low	0.0	0.3	0.3	0.6
low	0.3	0.6	0.6	1.2
medium	0.6	1.2	1.2	2.0
high	1.2	2.0	2.0	2.5
very high	2.0	2.5	2.5	3.0

Table A.4-6: Rules for the fuzzy system β-lactoglobulin deposition.

<table>
<tr><th>IF</th><th>THEN</th></tr>
<tr><td>Phase = induction</td><td rowspan="2">Rate Correction = very low</td></tr>
<tr><td>Temperature Difference = low</td></tr>
<tr><td>Phase = fouling AND pH = high AND Bulk Temperature of Product = low</td><td rowspan="3">Rate Correction = low</td></tr>
<tr><td>Phase = fouling AND pH = high AND Bulk Temperature of Product = low</td></tr>
<tr><td>Phase = transition AND Bulk Temperature of Product = low AND NOT Temperature Difference = high</td></tr>
<tr><td>Phase = transition AND Temperature Difference = high</td><td rowspan="3">Rate Correction = medium</td></tr>
<tr><td>Phase = fouling AND pH = high</td></tr>
<tr><td>Phase = fouling AND Bulk Temperature of Product = high AND Temperature Difference = medium</td></tr>
<tr><td>Phase = fouling AND pH = low AND Temperature Difference = high</td><td rowspan="3">Rate Correction = high</td></tr>
<tr><td>Phase = fouling AND Temperature Difference = high</td></tr>
<tr><td>Phase = fouling AND Bulk Temperature of Product = high AND Temperature Difference = high</td></tr>
<tr><td>Phase = fouling AND Bulk Temperature of Product = high AND Temperature Difference = high</td><td>Rate Correction = very high</td></tr>
</table>

A.5 Salt Cristallisation

This fuzzy system supplies a correction factor to adapt the model based deposition rate to a higher temperature interval and to a wider range of product and process characteristics.

Table A.5-1: Input set for the linguistic variable fouling phase.

Phase [-]				
induction	0.00	0.50	0.50	0.75
transition	0.50	0.75	0.75	1.00
fouling	0.75	1.00	1.00	1.25

Table A.5-2: Input set for the linguistic variable temperature difference between product and heating medium.

Temperature Difference [K]				
low	0.0	0.0	5.0	10.0
medium	5.0	10.0	10.0	15.0
high	10.0	15.0	20.0	20.0

Table A.5-3: Input set for the linguistic variable pH value of the unprocessed milk.

pH [-]				
low	5.00	5.00	5.50	6.00
medium	5.50	6.00	6.00	6.50
high	6.00	6.50	7.00	7.00

Table A.5-4: Output set for the linguistic variable rate correction of salt deposition.

Rate Correction [-]				
low	0.00	0.05	0.05	0.1
medium	0.05	0.1	0.1	0.15
high	0.1	0.15	0.15	0.2

Table A.5-5: Rule set for the fuzzy system salt deposition.

IF	THEN
Phase = induction	Rate Correction = low
Temperature Difference = low	
Temperature Difference = high AND pH = low	Rate Correction = medium
pH = high AND Temperature Difference = high AND Phase = transition	
Temperature Difference = medium AND pH = medium	
pH = high AND Phase = fouling	Rate Correction = high
Temperature Difference = high AND Phase = fouling	

Appendix B: List of Abbreviations and Symbols

B.1 Abbreviations

IEP	Isoelectric point
HMF	Hydroxy-methyl-furfural
OHTC	Overall heat transfer coefficient
PHE	Plate heat exchanger
THE	Tubular heat exchanger

B.2 Symbols

Symbol	Unit	Name/Definition
α	W/m^2K	Local heat transfer coefficient
B*	-	Biological value
Bi	-	Biot number
C*	-	Chemical value
d_{tube}	m	Tube diameter
f	-	Fuzzy based correction factor
k	$W/m^2 K$	Overall heat transfer coefficient
k_{dep}	s^{-1}	Deposition rate, fuzzy corrected
$k_{dep, math}$	s^{-1}	Deposition rate, calculated
k*	m	Absolute surface roughness
l	m	Length
λ	W/mK	Thermal conductivity
λ*	-	Tubular friction factor
μ	-	Degree of membership
p	Pa	Pressure
Re	-	Reynolds number
Re_{crit}	-	Critical Reynolds number
T	K	Temperature

t	s	Time
v	m/s	Velocity
$\dot{V}$	m^3/s	Volumetric flow rate
τ	N/m^2	Shear stress