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Review

Critical review on an experimental design to measure and model milk fouling in heating equipment

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ABSTRACT

Fouling plays a major role in the Dairy industry. Five criteria: defined flow, no circulation, real factory product, defined product temperature and defined wall temperature, are used to review articles on this topic published between 2003 and 2020. To show the effect of those criteria in experiments, a simulation model is developed. For a good experimental design to measure fouling, the use of a dairy product in a tubular heater with a known developed flow is advised. The temperature-time history of the product and the wall temperature of the heater should be recorded. Circulation of a product will increase the fouling and decrease the flow. Although none of the reviewed articles complied to all criteria, 71% of the reviewed articles met at least two criteria. If not all criteria are met, the results are of less use for the application for process lines on industrial scale. A simulated computer model can be helpful.

1. Introduction

Deposition of milk proteins causes fouling of heating equipment in the dairy industry. Depending on operating temperatures fouling is caused by different phenomena or a combination of these: bio-fouling (below 80 °C), denaturation of proteins (80–120 °C) and crystallization and precipitation of salts (60–140 °C). At extreme high temperatures (140–180 °C) the fouling layer may consist of complex aggregates of proteins and minerals (P. De Jong, 1997). Fouling decreases heavily the capacity of process lines by roughly 10% (De Jong, 1997), due to decrease of run times and increase of cleaning times. In the Netherlands, about 14 billion kg milk is annually processed and as a consequence heated one or more times (Productschap Zuivel, 2020). It is obvious that deposited milk constituents means also product loss. For example, in case of 0.1% product loss due to fouling 14 million kg milk is lost. From LCA analyses it is known that it costs roughly 10 MJ to produce 1 kg of raw milk (Kramer, 2014) Hence, 0.1% product loss corresponds with 140 TJ energy loss. Given the fact that roughly 10% of processing time is needed for cleaning and up to 1% of the product is lost by fouling, deposition of milk components is a continuous subject of research for many decades.

In order to find the optimal design and operation to minimize the amount of fouling, computer models which predicts the amount of fouling, have been developed. In the dairy industry one of the first predictive fouling models to be used on industrial scale was developed in the early nineties (P. De Jong et al., 1993). From that point onwards a lot of authors have elaborated on the fouling mechanism based on the denaturation (i.e. molecular unfolding) of β-lactoglobulin (Petit et al., 2013; Marwa Khaldi et al., 2016; Blanpain-Avet et al., 2016; Truong et al., 2017). Predictive fouling models enable to translate lab and pilot plant data towards the impact of process design and operating conditions on fouling and product losses at industrial scale. (Ojaniemi et al., 2012; Laurent Bouvier et al., 2014; Erabit et al., 2016; Benning et al., 2003; Gu et al., 2019). Once a validated fouling model is available, the optimal temperature-time history of the heated product at which fouling is minimal can be estimated and all the other products requirements such as food safety are met (De Jong, 1996).

In order to determine the effect of process conditions and equipment design on the progress of fouling, several experimental set-ups are reported in literature. The results were used by the authors for example to determine the parameter values of a predictive fouling model. In literature a large variety of methods to measure fouling can be found. However, it is not always clear to what extent the experimental method itself is appropriate to use outcomes for the development of a useful predictive model for simulation of industrial processes. The setup should mimic not just the temperatures of the industrial process line, but relate

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local conditions such as wall temperatures, shear rates, product history (i.e. pre-treatment) to the local fouling rate. Ideally, the model should be based on a reaction kinetic description so that in principle it can be used at every scale.

This review article will present a critical evaluation of the experimental set-ups and procedures used to measure fouling reported in literature. The evaluation is based on four criteria with respect to experimental set-up: (1) defined flow, (2) defined product temperature-time history, (3) defined product composition, (4) defined wall temperatures. When one of these criteria is not met, the fouling model might have limited value as a tool for fouling reduction on industrial scale.

First, the criteria are described and illustrated by model simulations with a well-established fouling model based on the denaturation kinetics of β-lactoglobulin. Then, an overview of experimental set-ups used for model development in literature is given. Next, the set-ups are evaluated with the presented criteria. Finally, suggestions for an optimal experimental set-up will be given.

2. Material & methods

2.1. Fouling model

In this section the description of the fouling model is given, used to show the limitations of an experimental fouling set-up when conditions are undefined or incompletely reported. The core of the model is a well-established 1-dimensional reaction model for prediction of milk fouling in heat exchangers (P. De Jong et al., 1992; Jun and Puri, 2005; Petermeier et al., 2002). In this model it is assumed that the deposition rate of milk components (i.e. proteins) is proportional to the concentration of unfolded milk protein β-protein C_U and the surface temperature in the heat exchanger. The concentration C_U follows from the reaction rate equations:

$$\frac{dC_N}{dt} = -k_U C_N, \frac{dC_U}{dt} = k_U C_N - k_A C_U^2, \frac{dC_A}{dt} = k_A C_U^2,$$

Where C_N, C_U and C_A are the concentrations of resp. native, unfolded and aggregated proteins in g.l^{-1}, k_U and k_A are the reaction rate constants of resp. the unfolding and aggregation of proteins in s^{-1} and l.g. s^{-1}. The time t is the residence time of milk in the heat exchanger. The used activation energies were 261.4 kJ mol^{-1} for unfolding and 288.5 (70–90 °C) and 54.7 (90–150 °C) kJ.mol^{-1} for aggregation, respectively. The related natural logarithm of pre-exponential Arrhenius factors used were resp. 86.41, 91.32 and 13.99.

The deposition is also assumed to be dominated by thermal activation, and therefore by an activation energy (De Jong, 1996). The temperature dependency of the deposition rate is described by the Arrhenius equation:

$$k'' = k_0'' \, exp\left(-\frac{E_a}{RT_s}\right) \tag{I}$$

Where k'' is the adsorption rate of denatured protein in kg.m^{-2}. s^{-1}, k_0 is a pre-exponential constant, E_a is the activation energy in J. mole^{-1}, R is the gas constant J. mole^{-1}. K^{-1} and T_s the surface temperature in K.

This equation can also be written as:

$$\ln k'' = \ln k_0'' - \frac{E_a}{R}\frac{1}{T_s} \tag{II}$$

The deposition rate is described by:

$$J_f = k'' C_u^{1.2} \tag{III}$$

In which J_f is the fouling rate in kg.m^{-2}. s^{-1}, the constant k'' in m$^{3(n-1)+1}$. kg$^{(1-n)}$. s^{-1} and C_U is the concentration of unfolded β-lactoglobulin. The activation energy used was 45.1 kJ mol^{-1} with a ln (k_0) of −0.82 (De Jong, 1996).

A computer model in Excel was constructed in which the local fouling rate can be estimated in a virtual experimental set-up consisting of a heater, holder and cooling section. Dimensions, flow and temperatures can be adjusted. Effect of temperature, experimentation time, flow regime (laminar, turbulent) and flow circulation on the amount of fouling can be simulated. A schematic set-up is shown in Fig. 1.

The initial concentration of β-lactoglobulin is assumed to be 3.2 g/l. This is an average number (Walstra and Jenness, 1984). In practice this number will vary from case to case, however, it may affect the absolute outcome of the model but not the trends and conclusions used in this review. The same holds for the effect of fouling on the shape of the temperature profile in the heat exchanger. Further it is assumed that the amount of deposit is <1% of the total solids in milks that passed the heat exchanger. Hence, the effect of deposited solids on the heat exchanger surface on the bulk concentration of β-lactoglobulin is neglected. Milk is considered as a continuous single phase solution of proteins and other milk components in water. Any effects of protein size on reaction rates are neglected. Dimensionless numbers such as Reynolds and Sherwood are used for evaluation of flow effects on fouling near the surface of the heat exchanger.

2.2. Local effects

In turbulent plug flow it can be assumed that the bulk concentration of the unfolded proteins is more or less equal to the concentration near the surface. However, when the flow is laminar it might be more accurate to use the concentration at the mass transfer boundary layer (De Jong, 1996). The thickness of the boundary layer can be estimated by using of the following equations:

$$\delta_C = \frac{d}{Sh} \tag{IV}$$

Where *d* is the hydraulic diameter of and *Sh* the Sherwood number. *Sh* can be estimated from:

$$Sh = 0.027 Re^{0.8} Sc^{0.33} \tag{V}$$

With the Schmidt number defined as:

$$Sc = \frac{\eta}{\rho Đ} \tag{VI}$$

Where η is the dynamic viscosity of the bulk (kg.m^{-1}. s^{-1}), ρ the density of the bulk (kg.m^{-3}) and $Đ$ the diffusion coefficient of the protein (m^2. s^{-1}) For further details, see (De Jong, 1997). Depending on the flow regime the thickness δ_C lies between 10^{-5} and 10^{-4} m. In case of a fully developed laminar flow, the velocity of the liquid will be lower close to the wall according to the velocity profile of laminar flow (Stigler, 2014):

$$v_C = 2v\left[1 - \left(\frac{d - 2\delta_C}{d}\right)^2\right] \tag{VII}$$

Where ν is the bulk velocity (m^2. s^{-1}) and ν_c the velocity of the liquid at the boundary layer (m.s^{-1}). In general the velocity of the liquid will be lower near the surface and thus the residence time of the liquid be longer.

2.3. Criteria for experimental set-ups

In order to investigate the effect of process design and conditions on the fouling rate it is crucial to know as accurately as possible the local conditions at the steel surface applied in the experimental setup: surface temperature, bulk temperature, concentration of unfolded β-lactoglobulin and shear rate. Since the fouling rate is also depending on the degree of denaturation of β-lactoglobulin, also the temperature-time history of the product should be defined. In order to investigate the value of these local conditions in an experimental setup, some criteria have to be met.

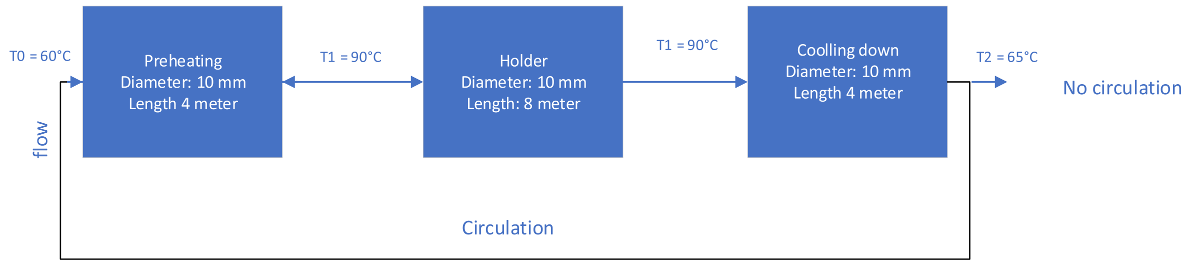

Fig. 1. Schematic overview of the used simulation model with the options for no-circulation and circulation.

2.3.1. *Defined flow*

Flow characteristics (i.e. developed laminar, developed turbulence, non-developed flow) have a major effect on the temperature-time history of the product exposed to heating. As a consequence the denaturation of β-lactoglobulin will be affected. Flow also influences local heat transfer and shear stress near the surface. Since the adsorption rate of deposits is also depending on shear (De Jong, 1997) and on the local wall temperature, knowing and quantifying the flow characteristics is crucial. As a consequence the flow should be developed, either laminar or turbulent. The use of static mixers, to enhance heat transfer, will result in an undefined flow and is therefore not appropriate for modelling purposes. In general, turbulent flow is more easy because flow can be considered as plug flow with a uniform radial temperature profile. However, turbulent flow with small hydraulic diameters, typically for experimental setups, is not easy to achieve. Velocities have to be high and consequently the overall pressure within the system increases. Instead developed laminar flow can be applied if heat transfer is defined and wall temperatures can be accurately measured or estimated.

2.3.2. *Defined product temperature-time history*

Temperature-time history needs to be known in order to estimate the local concentration of unfolded β-lactoglobulin. As described above the flow characteristics are important to be able to estimate the local temperatures. But also the temperature-time history of the product before it is used in an experiment must be considered. In most of the cases the milk was already standardized and (at least) heated at lower temperatures (68–72 °C). This modest pre-treatment will already initiate the unfolding of β-lactoglobulin. In this way, the initial concentration of unfolded β-lactoglobulin will not be 0 but an unknown value. It is clear that product circulation to realize a certain run time will also result in an undefined temperature-time history. As a consequence, the local concentrations of unfolded and aggregated β-lactoglobulin will change all the time, increasing towards complete denaturation/aggregation.

2.3.3. *Defined product composition*

It might be useful to apply model solutions (e.g. β-lactoglobulin in water) to study the effect of certain milk components on the fouling rates. However, it is known that the entire milk matrix has an effect on both denaturation kinetics (Hausmann et al., 2013) and adsorption rate (Balasubramanian and Puri, 2010). For that reason it is advised to use complete products for experimental trials and determination of the model fouling parameters. Only these parameters can be used for simulation of industrial processes in a useful way.

2.3.4. *Defined wall temperatures*

Since fouling is an adsorption reaction between milk components and the wall, it is important to know what the local conditions near the steel surface are. Flow characteristics are not determined by product and flow characteristics only. Also the surface roughness and structure and the process configuration plays a role. For example, in plate heat exchangers the surface is structured to enhance heat transfer. Also the flow (rate) between to plates is not uniform. All this makes it very difficult to estimate the local conditions at the surface. For that reason tubular heat exchangers, with comparable surface roughness and without static mixers, will give the most appropriate results.

2.4. *Evaluation of experimental set-ups in literature*

The literature was reviewed with respect to articles describing fouling measurements of bovine milk systems in a small scale setup (up to 250 L batch and 85 L per hour continuous). In total 56 articles have been reviewed. Publication dates were between 2013 and 2020. All those articles were listed on their main characteristics: material used, measuring principle (batch/continuously), recycling, method of quantifying the fouling, measuring details, scale, type of heat exchanger, temperature range, cleaning and sample area. In addition, from 35 articles the described experimental set-up was evaluated on four criteria described above: (1) defined flow, (2) defined product temperature-time history (no circulation), (3) product composition and (4) defined wall temperatures. The other 24 articles contained insufficient detail to make a complete evaluation. The used methods were not clearly described, the experiments were too small scale experiments, the product used was not milk or dairy and some articles were more focused on modelling, instead of the experimental part.

3. Results

3.1. *Impact of experimental setup to measure fouling rates*

In this section, simulations with the described fouling model show the effect of using a certain experimental set-up for measuring fouling rates, resulting in data to be used in a predictive model. In order to illustrate the effect of a certain configuration, the virtual experimental setup is used to perform simulations with the predictive fouling model described above. In this way the impact of the setup can be estimated. Evaluation of published articles is summarized in the next section.

3.1.1. *Circulation*

In order to create a certain run time and to use a limited amount of product, it could be decided to apply flow circulation in the experimental setup. However, as a consequence the temperature-time history of the product and more importantly, the local concentration of unfolded β-lactoglobulin will change during the experiment and thus is not defined. Fig. 2 shows the local fouling rates, when the product is circulated as a function of the number of cycles. Applied temperatures are 60 °C inlet, 90 °C holding and 65 °C outlet. In the first cycle the highest amount of fouling is seen in the holding section. A decrease of fouling is seen after every run, due to the succeeding aggregation of the unfolded protein. During the circulation, the concentration of the unfolded protein will change continuously. The exact concentration of the unfolded β-lactoglobulin is unknown and difficult to measure. This will lead to different conditions above the same surface. In general it can be stated that in case of long run times, realized by circulating flow, this will result into lower fouling rates than without circulation.

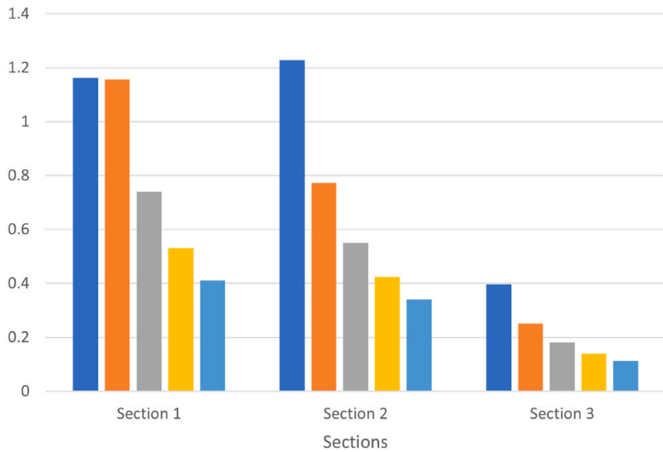

Fig. 2. Simulated fouling rate as a function of number of cycles. Five cycles were simulated with a flow of 0.15 m^3/h and a speed V = 0.53 m/s.

3.1.2. Wall temperature

Following from the fouling model, the fouling rate is directly controlled by the local concentration of β-lactoglobulin and the wall temperature, not the bulk temperature. Since the bulk temperature affects the denaturation, there is an indirect effect of this temperature on the fouling rate only. For example, in the heating section the wall temperatures will be higher than the bulk temperature. In case the measured fouling rates are related to bulk temperatures, the derived model will predict too high fouling rates at a given temperature and will not account for the effect of the wall temperatures. At industrial scale, depending on the equipment design, the difference between wall and bulk temperatures may be substantial (up to > 10 K). In Fig. 3 the effect of the surface temperature on the fouling rate is demonstrated. An increase of the wall temperature by 2 °C results in an increased fouling rate by 8.5%. In many reported cases the surface temperature is not measured or estimated. Only the liquid bulk temperature is measured. However, depending on the temperature of the heating medium (e.g. oil, water, steam) and the heat transfer coefficient, the local surface temperature will be somewhere between the temperature of the heating medium and the liquid bulk temperature. Also in case of no heating medium, for example with a holding tube, the surface temperature will differ from the bulk liquid temperature. This effect will increase when the holding tube is not or insufficiently isolated. It is not easy to measure the wall temperatures in an experimental setup. However, when the heat and mass balances and flows (product, heating and cooling water) are well defined, the wall temperatures can be estimated. For example, for tubular heat exchangers there are well established heat transfer models available.

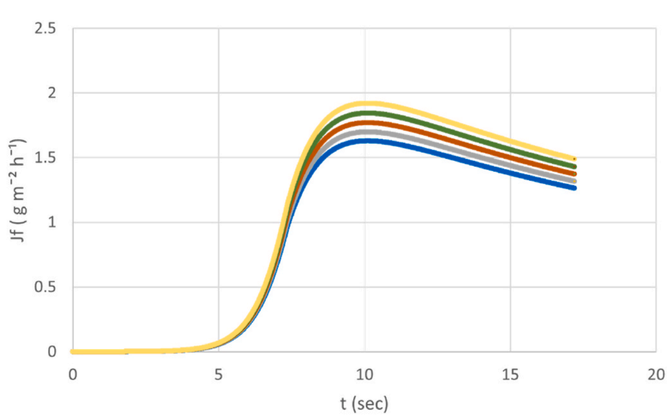

Fig. 3. Simulated fouling rates at the preheating (60–90 °C) and the holding section (90 °C) with different wall temperatures The red line shows the fouling at 90 °C. The two lower lines show the fouling with a change in wall temperature of respectively −1 °C and −2 °C, while the 2 top lines show the fouling with wall temperatures of respectively +1 °C and +2 °C.

3.1.3. Flow regime

Ideally the flow in the experimental setup is fully developed turbulent plug flow. In that case the concentration of unfolded β-lactoglobulin near the surface is more or less equal to the bulk concentration. However, in most systems this is hard to realize. The Reynolds number has to be above 2300. For example, with water at 80 °C and a tube with a diameter of 5 mm this means a minimal velocity of 0.5 m/s (~35 l/h in the virtual experimental setup). In case of a lower Reynolds number, the velocity near the surface will be lower meaning also a longer residence time of the liquid near the surface. As a consequence the denaturation degree will be higher and thus the fouling rate is influenced.

With equations (III) to (VII) the velocity and residence time of the milk at the concentration boundary layer near the surface was predicted using the fouling model and virtual setup. To achieve this, the boundary layer at $Re = 2300$ and a temperature of 90 °C was calculated. With this, the velocity in the boundary layer was determined. A flow was simulated, corresponding with $Re = 2300$ to determine the local fouling rate as function of the tube length. The last step was to simulate the fouling rate as function of velocity at the wall and boundary layer. The resulting numbers were used to calculate the local fouling rates.

In Fig. 4 the results are presented. It is obvious that with laminar flow the denaturation process has proceeded more and the local fouling rate is affected. This will immediately cause a higher fouling rate in the preheating section (section 1) where the majority of the β-lactoglobulin is denatured. With a local laminar flow the highest amount of fouling can be found in the heating section. For a turbulent flow the highest amount of fouling can be found at the holding section.

3.1.4. Plate versus tubular

General plate heat exchangers are more effective in terms of footprint and heat transfer when compared to tubular heaters. Structured plates enhance heat transfer. However, the flow is not uniform and not well defined. This makes it more difficult to accurately upscale the experimental results towards industrial scale. In addition plate heat exchangers are more sensitive to fouling (Finnis, 2009) due to the limited plate distance. Another consequence of the small plate distance is that the system is more sensitive to high viscous fluids, which might result in huge pressure drops.

3.1.5. Static mixer

Static mixers are used to enhance the heat transfer of the system or to continuously mix fluid ingredients. However, it is obvious that the use of a static mixer causes an undefined flow. The flow of the liquid is not constant and mostly chaotic. It is also known static mixers can cause unmixed regions (Qiao et al., 2012).

3.2. Review of experimental set-up reported in literature

In total 35 articles have been reviewed based on to what extend they meet the criteria for a proper experimental setup as described above. The work done by the authors is well respected and shows a big progress in the field. Note that not all research done fits completely to the aim off this article, because the focus lies on predictive modelling. The articles are shown in Table 1. Fig. 5 shows some general characteristics of the research described. It is obvious that most authors use temperatures at which protein denaturation takes place (80–120 °C). However, in the industry most serious fouling problems occurs at temperatures above 120 °C. To realize these temperatures in an experimental setup steam supply and higher operating pressures are needed. This might be the cause that the majority (>80%) of the experiments were performed at temperatures below 120 °C. It is remarkable that in roughly 50% of the articles the execution of cleaning was not mentioned. Looking at the

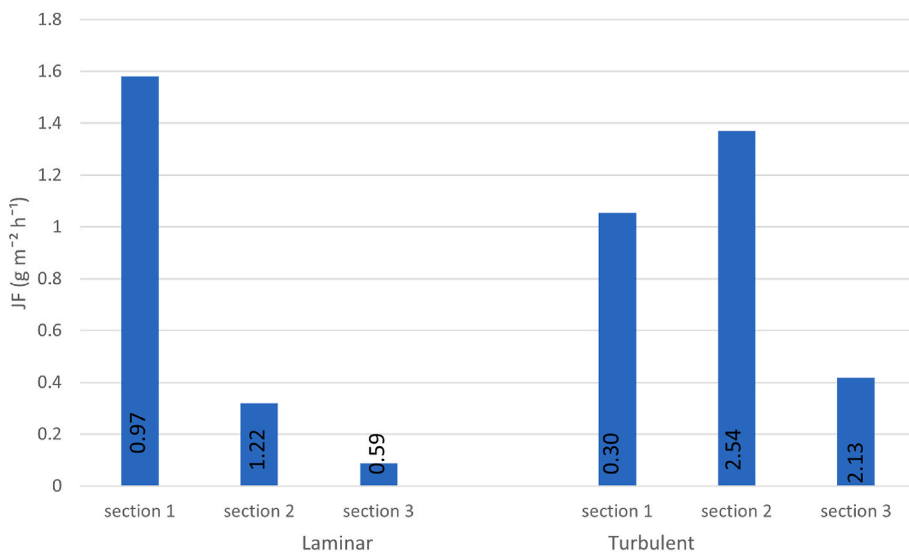

Fig. 4. Comparison between calculated fouling rates in different sections with turbulent and laminar flow (inlet 60 °C, holding 90 °C, outlet 60 °C) near the surface with $Re = 2300$. In the bars the average amount of denatured β-lactoglobulin is shown (g/l).

scale of the setup most experiments were done on lab-scale (<20 l/h). In most cases the follow rate was measured with a steel surface bigger than 10 cm^2. A significant part of the experiments were carried out on lab-scale or pilot plant-scale.

In Fig. 6 the results of evaluation of the reported experimental setups regarding the criteria described in this article are shown.

In about one fourth (26%) of the reviewed articles, milk is used as a product to determine fouling. In one fourth (28%) of the articles a WPI solution is used in different concentrations. β-lactoglobulin solutions are used in 10% of the evaluated articles. In the majority of the articles a Plate heat exchanger (PHE) (industrials scale, lab scale, modelling) is used for heating (51%), while only 17% were using a tubular heater; 29% used batch process, while 71% uses a continuous process. Recycling was not used in 77% of all methods. The rest uses circulation, or it was not clearly described. A variety of methods was used to measure the fouling rate. Often used is weighing of the amount of fouling (PHE dismantled, plates are dried and weighed). The scale of all the experiments varied from lab scale (<20 l/h); 34%) to pilot plant scale (20–200 l/h; 49%) and unknown (17%).

In one third of the articles (37%) cleaning was specifically mentioned, 54% did not clean or it was not mentioned in the article, 9% mentioned specifically that cleaning took place before use.

When looking at the sample area, it could be said that if a pilot plant PHE was used, the effective heating area varied between 0.074 m^2 and 0.095 m^2 in 31% of all articles. In about 2/3 of these heating areas (64%), 0.074 m^2 was used.

Of all articles used for this review article, a set flow was described for about 2/3 (68.6%) of the articles, although it must be said that when using a PHE the flow is not homogeneous in all parts of the PHE. For most of the reviewed articles, the conditions at the wall are not clear.

4. Discussion

4.1. Usefulness of reports of fouling research in literature

It should be noticed that not all authors performed their research to develop a predictive fouling model. In many cases the experimental setups were designed to study phenomena such as the effect of temperature or product type on the amount of fouling. However, the background motivation to perform the research was also to give advice to the industry on how to decrease the amount of fouling. If is taken into account to what extend the criteria described in this paper are met, the results still can be insightful. However, the results cannot be used for translating the results directly to the industrial process line, let alone, to develop a predictive fouling model.

Performing fouling experiments cost a lot of time. In order to get a sufficient (and realistic) amount of fouling on the steel surface, several hours of running time might be needed. In case of a valuable product and a continuous operating experimental setup, a substantial amount of product is needed for just one measurement of the fouling rate. This is another reason to carefully design your experimental set-up. In addition, well designed and described experimental setups, make it possible to reuse the measured fouling rates by other authors to develop a model and to estimate the value of the model parameters.

In summary, for an appropriate experimental setup to measure fouling rates on lab/pilot scale the following check list can be used.

- Tubular flow
- Reynolds >3000 (developed turbulent flow) or < 1500 (developed laminar flow)
- Continuous operation, without circulation of milk product
- Standardized cleaning to ensure that the steel surface is really clean
- Operation time per experiment >2 h or 0.5 h if the start of the fouling process is subject of study
- Make use of a fixed product (milk)
- If possible use a tubular heater with a constant, defined flow
- Use a well-defined temperature-time profile
- Monitor/determine the wall temperature

5. Conclusions

In this article recent publications on milk fouling research were critically reviewed for five described criteria: defined flow, no circulation, real factory product, defined product temperature-time history and

Table 1
Overview of articles which are checked on the mentioned criteria (defined flow; defined product temperature-time history; defined product composition and defined wall temperatures). The numbers 1–5 correspond with the characteristics mentioned in Fig. 6 (1 = continuous flow; 2 = tubular/plug flow; 3 = tubular heating system; 4 = no product circulation; 5 = real milk product (Ali et al., 2013; Blanpain-Avet et al., 2020; Bouvier et al., 2019; Boxler et al., 2014a,b; Challa et al., 2015; Chen et al., 2004; Gandhi et al., 2017; Graf et al., 2020; Hagsten et al., 2016; Huang and Goddard, 2015; Joanna et al., 2016; Khaldi et al., 2015; Liu et al., 2020; Lv et al., 2015; Pan et al., 2019; Phinney et al., 2017; Prakash et al., 2005, 2015, Shen et al., 2017a,b, Wallhäußer et al., 2012, 2013; Wilson, 2018; Yang et al., 2018).

■ (meets criteria completely) □ (does not meet criteria)completely

Article used	Authors	1	2	3	4	5
Process design for improved fouling behavior in dairy heat exchangers using hybrid modelling approach	(Benning et al., 2003)	□	□	□	■	■
On-line fouling/cleaning detection by measuring electric resistance- equipment development and application to milk fouling detection and chemical cleaning monitoring	(Chen et al., 2004)	□	□	□	■	□
Methods of detecting Fouling caused by heating of milk	(Prakash et al., 2005)	□	■	□	■	■
A critical review of milk fouling in heat exchangers	(Finnis, 2009)	□	■	□	■	□
Detection methods of fouling in heat exchangers in the food industry	(Wallhäußer et al., 2012)	□	■	□	■	■
Wall function model for particulate fouling applying XDLVO theory	(Ojaniemi et al., 2012)	□	■	□	■	□
A fluid dynamic gauging device for measuring fouling deposit thickness in opaque liquids at elevated temperature and pressure	(Ali et al., 2013)	□	□	□	□	□
Detection of dairy fouling: Combining ultrasonic measurements and classification methods	(Wallhäußer et al., 2013)	□	□	□	■	□
β-lactoglobulin denaturation, aggregation and fouling in a plate heat exchanger: Pilot scale experiments and dimensional analysis	(Petit et al., 2013)	□	■	□	■	□
A CFD model as tool to simulate β-lactoglobulin heat-induced denaturation and aggregation in a plate heat exchanger	(Laurent Bouvier et al., 2014)	□	■	□	■	□
Influence of surface modification on the composition of a calcium phosphate-rich whey protein deposit in a plate heat exchanger	(C. Boxler et al., 2014)	□	■	□	■	□
Composition of milk fouling deposits in a plate heat exchanger under pulsed flow conditions	(Cristiane Boxler et al., 2014)	□	■	□	□	□

Influence of fluid milk product composition on fouling and cleaning of Ni-PTFE modified stainless steel heat exchanger surfaces	(Huang & Goddard, 2015)	□	■	□	■	■
Fouling characteristics of model carbohydrate mixtures and their interaction effects	(Challa et al., 2015)	□	□	■	□	□
Effect of Calcium content and flow regime on whey protein fouling and cleaning in a plate heat exchanger	(M. Khaldi et al., 2015)	□	■	□	■	□
The effect of pre-adsorption of OVA or WPC on subsequent OVA or WPC fouling on heated stainless steel surface	(Lv et al., 2015)	□	□	□	□	□
Influence of pre-heat temperature, pre-heat holding time and high-heat temperature on fouling of reconstituted skim milk during UHT	(Prakash et al., 2015)	□	□	□	■	□
Coupling population balance model and residence time distribution for pilot-scale modelling of β-lactoglobulin aggregation process	(Erabit et al., 2016)	■	□	■	■	□
An analysis of milk fouling formed during heat treatment on a stainless steel surface with different degrees of roughness	(Joanna et al., 2016)	□	□	□	■	■
Composition and structure of high temperature dairy fouling	(Hagsten et al., 2016)	□	■	□	■	■
Predicting-the-distribution-of-whey-protein-fouling-in-a-plate-heat exchanger using kinetic parameters of the thermal denaturation reaction of B-lac and the bulk temp profiles	(Blanpain-Avet et al., 2016)	□	■	□	■	□
Denaturation kinetics of whey protein isolate solutions and fouling mass distribution in a plate heat exchanger	(Marwa Khaldi et al., 2016)	□	■	□	■	□
A novel fouling measurement system: Part I. design evaluation and description	(Shen et al., 2017a)	■	□	■	□	□
A novel fouling measurement system: Part II. Commissioning	(Shen et al., 2017b)	■	□	■	□	□
Role of β-lactoglobulin in the fouling of stainless steel surfaces by heated milk	(Truong et al., 2017)	□	□	□	■	□
Effect of milk protein concentrate (MPC80) quality on susceptibility to fouling during thermal processing	(Gandhi et al., 2017)	□	■	□	■	□

Modelling high protein liquid beverage fouling during pilot plant scale ultra-high temperature (UHT) processing	(Phinney et al., 2017)	□	□	□	□	□
Effect of calcium on the fouling of whey protein isolate on stainless steel using QCM-D	(Yang et al., 2018)	□	□	□	■	□
Fouling during food processing-progress in tackling this inconvenient truth	(Wilson, 2018)	□	■	□	■	□
Numerical simulation of milk fouling: Taking fouling layer domain and localized surface reaction kinetics into account	(Pan et al., 2019)	□	■	□	■	■
Effect of swirl flow on whey protein fouling and cleaning in a straight duct	(L. Bouvier et al., 2019)	■	□	■	■	□
A mathematical model for the prediction of the whey protein fouling mass in a pilot scale plate heat exchanger	(Gu et al., 2019)	□	■	□	■	□
Mechanical comparison of milk and whey protein isolate fouling deposits using indentation testings	(Liu et al., 2020)	■	□	■	■	■
New experimental set-up for testing microwave technology to continuously heat fouling-sensitive food products like milk concentrates	(Graf et al., 2020)	■	■	■	■	■
Effect of Phosphate/calcium molar ration on fouling deposits generated by the processing of a whey protein isolate in a plate heat exchanger	(Blanpain-Avet et al., 2020)	■	■	□	■	□

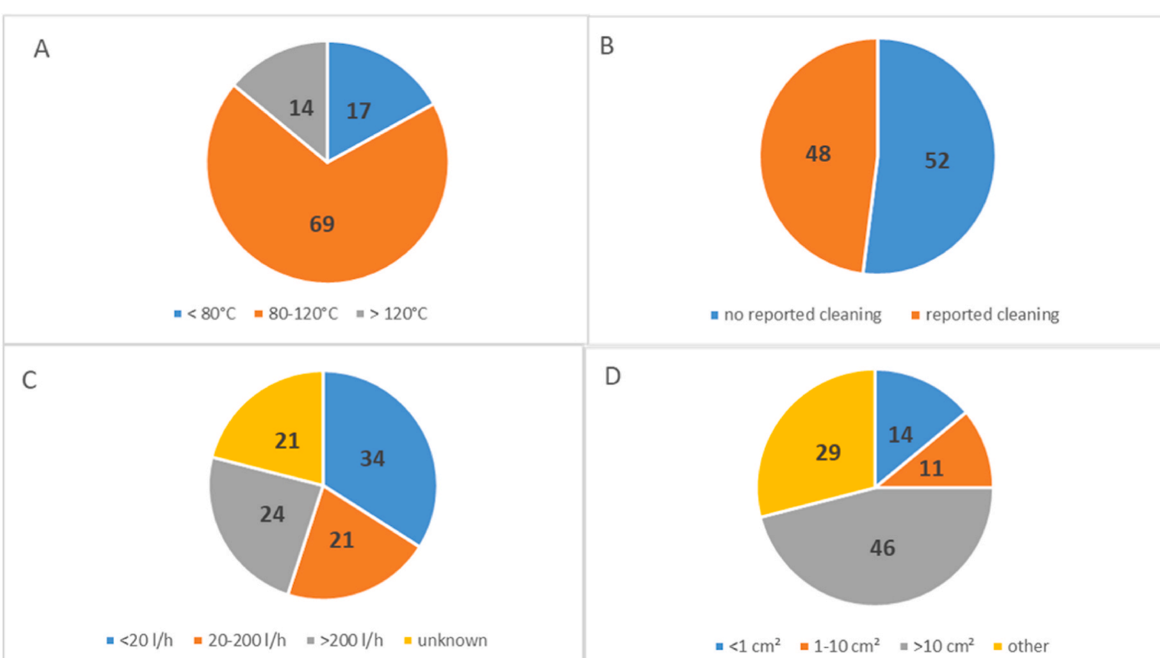

Fig. 5. General characteristics of the experimental setup to measure and study fouling behaviour in research recently reported in 32 articles. (a) Operating temperature, (b) Reported cleaning of the setup, (c) Capacity of the setup defined by product flow, (d) Area of surface at which fouling was measured.

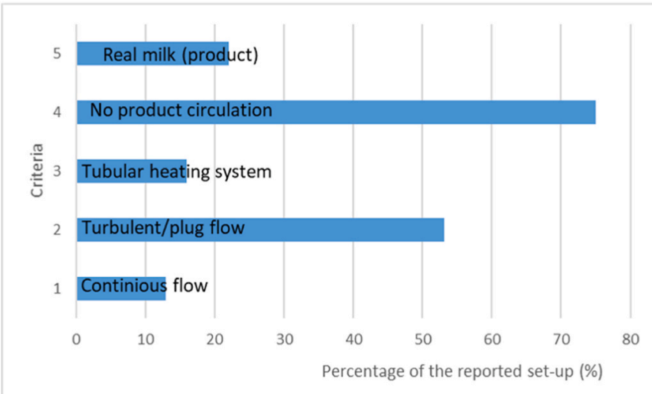

Fig. 6. Characteristics of the reported setups related to the described criteria to be met.

defined wall temperatures. This to be used for a fouling model with a direct link to the industry. It turned out that 70% of the reviewed articles met 2 or more criteria. None of the reviewed articles complied to all criteria. As a consequence the results have a limited application for process lines on industrial scale. For future fouling research it is advised to use a real milk product of interest, turbulent flow, continuous operation without circulation of product, thorough and validated cleaning procedures and sufficient operating times. A computer model can help to simulate the industrial circumstances and to demonstrate the effect of, for example, different wall temperatures on fouling.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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