FOULING DYNAMICS OF SMUF ON A PLATE HEAT EXCHANGER

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ABSTRACT

In this paper, we present our first experimental results related to fouling taking place at heat exchangers during heat treatment of milk. Instead of milk we used simulated milk ultrafiltrate (SMUF), which is an aqueous solution simulating the mineral composition of milk. We did the experiments in a simplified model geometry consisting of one heating plate (dimensions 32 mm by 40 mm) made of stainless steel in a flat flow channel (height 2.0 mm) in a closed flow loop. The 3D deposit structure was measured in real time with Optical Coherence Tomography (OCT) with ca. 4 µm resolution. Fouling was observed in a wide flow rate range 300 - 1500 ml/min (Reynolds number 250 - 1250). The largest amount of deposited layer was 70 g/m^2 in 7.5 hours at flow rate 1500 ml/min. The thickness of the deposited layer was ca. 300 µm. The temperature of the heating element had to exceed 85 °C for fouling to happen. In some cases we observed detachment of deposit flocks, which was seen both in OCT images and in temporary decrease of the plate temperature (indicating improved heat transfer). The system seemed to be here in a dynamic equilibrium; reflocculation and floc detachment followed each other the plate temperature fluctuating in a range of a few degrees. The measured heat transfer from the heated plate to water flow was used to validate a CFD model that has been developed for this particular fouling process in a research study parallel to this experimental work. In the future, the model will be validated against experimental data for SMUF as well.

INTRODUCTION

The fouling of plant surfaces and the subsequent cleaning needed is a significant problem in various fields of the process industry (Bott 1995, Dürr and Thomason 2010). Filters, membranes and heat exchangers are especially sensitive to it, but the accumulation of deposits can take place on any surface when the conditions are favorable. Plate heat exchangers, e.g., are widely applied in dairy and other food processing industries, and are prone to fouling. The interest in studying fouling mechanisms has increased in recent years, since fouling is associated with increased costs of maintenance, downtime and decreasing energy efficiency, which is frequently compensated by oversizing of the process equipment.

Fouling is a function controlled by a variety of parameters, including the geometry of the system, surface material and roughness, surface energy, interface temperature, deposit temperature, free stream velocity, and fluid characteristics. At present, the mechanisms of fouling are not yet fully understood. Monitoring the development of the conditioning film and the subsequent deposition process is thus very important in order to understand and ultimately control fouling.

Fouling in dairy processes has been widely studied and the mechanisms of fouling from milk fluids is quite well understood (Visser and Jeurnink 1997). However, the behavior of the systems at ultrahigh temperature (UHT) processing, where the inorganic deposits also take place, is still not clearly understood (Sadeghinezhad et al., 2013).

Particulate fouling is a serial process of transport of particles into the vicinity of the surface and the adherence on the surface. A Computational Fluid Dynamics (CFD) model, developed earlier for adhesion of calcium carbonate particles from dense particulate suspension (Ojaniemi et al. 2012), has recently been modified for dairy processes by including precipitation of calcium phosphate, and the precipitates adherence on a heated wall (Ojaniemi et. al. 2019, Puhakka et al. 2019). Such a model can be applied in predicting the likely profile of milk deposition, and in designing the plate shape, corrugation profile and surface materials in order to reduce the costs due to fouling.

The experimental work described here was carried out parallel to the recent modelling efforts (Ojaniemi et. al. 2019, Puhakka et al. 2019). Measurements were done with simulated milk ultrafiltrate (SMUF), which is an aqueous solution simulating the mineral composition of milk, including the precipitating components of the CFD model. The motivation for the experimental work is two-fold, namely to make well-controlled measurements in order to quantify fouling of SMUF in real-time at high resolution, as well as to provide validation data for the modeling approach.

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EXPERIMENTAL SETUP AND MATERIALS

We used a simplified model geometry consisting of one heating plate (dimensions 32 mm by 40 mm) made of stainless steel grade AISI 316L in a flat flow channel (height 2.0 mm) in a closed flow loop. Instead of milk we use simulated milk ultrafiltrate (SMUF). In what follows, we will describe the flow loop setup, the flow module where the fouling process takes place, and the materials used in this study.

The flow loop

The experimental setup used in this study is shown in Fig. 1. The flow is driven by gravity from a vessel through a flow module, where the fouling process takes place. The fluid level of the source vessel is 130 cm above the flow module, equating ca. 13 kPa of driving pressure. The gravity-driven setup allows steady flows without any disturbances created by conventional pumps. The volume of the SMUF solution is ca. 15 liters, and it is immersed into heat bath of ca. 15 liter of deionized water. During an experiment, the temperature of the heat bath is kept at 45 °C (calcium in the SMUF solution would precipitate at ca. 50°C). The flow discharges from the flow module through a control valve to a vessel standing on a scale. The control valve is used for adjusting the volumetric flow rate, which can reach 1500 mL/min (mean velocity 0.31 m/s inside the flow module) in the current setup. The Reynolds number for a shallow flow geometry between two parallel plates is defines as

$$Re = \frac{\rho v L}{\mu}$$

where ρ and μ are the fluid density and viscosity, respectively, v is the average flow velocity, and the characteristic length scale L is twice the distance between the plates, i.e. 4 mm in the current case. For water at maximum velocity $v = 0.31$ m/s the Reynolds number is 1250. The sensors T1-T4 measure the temperature of the SMUF solution in the heat bath, at the inlet to the flow module, at the outlet from the module, and inside the vessel standing on the scale, respectively. The sensor T5 measures the temperature of the electric heating element attached to the bottom of the target plate. The hoses, the flow module, and the vessel standing on the scale are all heat insulated by covering them with a layer of foam rubber and/or EPS.

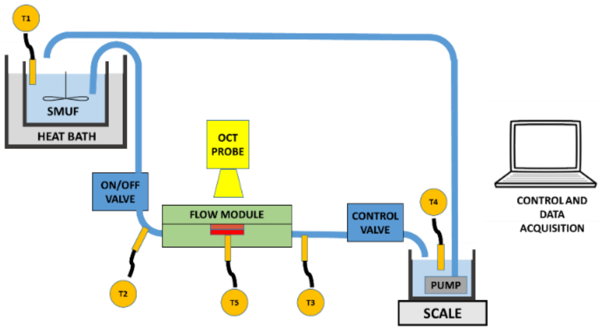

Fig. 1. Schematic drawing of the measurement setup.

Various probing fluid mechanical methods has been used in the past in order to quantify the thickness of a solid layer deposited at channel wall (Gordon et. al., 2010, and references therein). They are invasive techniques where a macroscopic probe is immersed into the flow, thus the probe interfere with the flow, and the flow geometry cannot be very small. In addition the lateral measurement resolution is limited by the size of the probe's tip. We use Optical Coherence Tomography (OCT) technique for real-time monitoring of the fouling process in a selected portion of the target plate, the maximum size of the imaged area is 10 mm by 10 mm (larger area can be measured by moving the OCT scanning head laterally) . OCT is a well-established technique introduced in 1991 (Huang et al. 1991). It is a light-based imaging method, which enables non-contact, micron-scale spatial resolution measurement of scattering opaque materials (Drexler and Fujimoto 2008). OCT uses interference of a low coherence light to record depth-dependent reflectivity profile (A-scan). By lateral scanning, 2D cross-sectional and 3D volumetric images can be generated. The maximum scanning depth of the OCT device used in this study (Telesto SD-OCT system by Thorlabs) is ca. 2 mm in water and the maximum rate of A-scans is 76 kHz. OCT has earlier been used for studying various fouling processes (Wagner and Horn 2017, Koponen and Haavisto 2018).

The flow module

The flow module used in this study is shown in Fig. 2. The body of the module is machined from PVC and it is made of separate bottom and top halves that are bolted together. The flow channel can be seen in the top image as the area surrounded by the black sealing glue. The flow channel is symmetric both in the flow direction and in the transverse direction. The dimensions of the flow channel are 140 mm in length, 40 mm in width, and 2 mm in thickness. The top window made of 3 mm thick glass is for visual inspection and OCT imaging.

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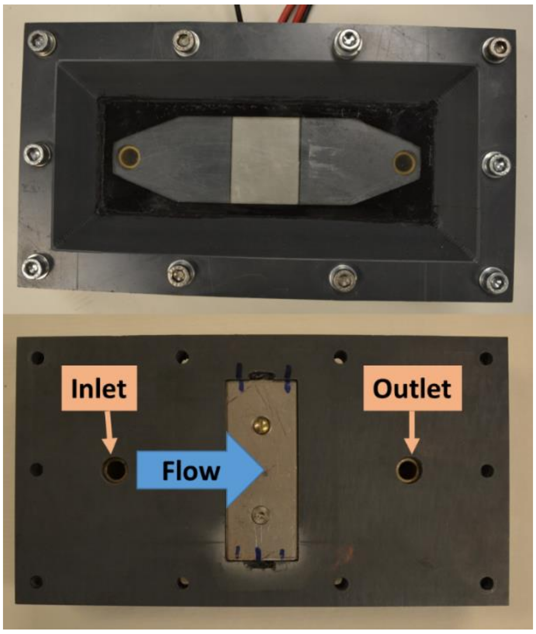

Fig. 2. The flow module assembled (top), and the top half removed (bottom). The dimensions of the flow channel are 140 mm in length, 40 mm in width, and 2 mm in thickness.

The bottom image of Fig. 2 shows the channel with the bottom half and the target plate. The electric heating element (not shown in the image) is attached to a 3 mm thick base plate with screws, and this stack is fixed into a rectangular cavity machined in to the base PVC plate. The target plate is dropped in and fixed in place by the top half of the module pushing it against the base plate. The size of the base plate and the target plate is 32 mm by 80 mm, and the active area of the target plate exposed to the flow (visible in the top image) is 32 mm by 40 mm. A heat transfer paste (grades used for attaching CPU heat sinks as well as conventional copper paste have been used) is applied at all the interfaces between the steel plates and heating element. The temperature of the stack consisting of the heating element, the base plate, and the target plate is measured at the bottom surface of the heating element. The power of the electric heating element at its nominal voltage (12 V) is 80 W. By overdriving the voltage, we have applied heating power up to 160 W.

Simulated milk ultrafiltrate (SMUF)

Our first tests with real milk revealed that despite thorough flushing and cleaning of the flow loop after an experiment, stinky residues of contaminated milk were found during the next experiment. Therefore, the measurements were run by using a simulated milk ultrafiltrate (SMUF) that simulates ultrafiltration permeate of milk (Dumpler et al. 2017).

The precipitation of the solution is very sensitive for the amount of calcium chloride. We had to reduce the original amount of $CaCl_2 \cdot 2H_2O$ given in reference (Dumpler et al. 2017) by 25% in order to keep the solution from precipitating below 50°C (visual observation). A 20 liter batch of the SMUF solution was prepared in advance without adding calcium chloride. Just before starting the experiment, calcium chloride was added, and pH was adjusted to 6.65 by adding 1 molar potassium hydroxide; this was done at room temperature. The addition of a certain amount of lactose is possible before the addition of calcium chloride or alternatively after the final pH adjustment by dissolution of lactose in a SMUF solution. However, lactose is good base for bacteria growth, thus we did not add it in our experiments.

Measurement procedure

Before each measurement, a new batch of SMUF is prepared and fine-tuned for pH 6.65. A new target plate is cleaned carefully with isopropyl alcohol, and the mass of the plate is measured with a high-precision scale. A thin layer of heat transfer paste is applied on the bottom of the target plate, and the plate is dropped on the base plate of the heater stack (heating element and the base plate). The flow module is finalized by attaching the bottom and the top halves of the module, thereby pushing the target plate tightly against the heater stack. In the latest measurements, we have ensured optimal heat contact by attaching the target plate to the heater stack with screws.

Measurement is started by preheating the heat bath (see Fig. 1) and the SMUF solution immersed in it to 45 °C, which is well below 50°C, the temperature where calcium in the used SMUF solution starts to precipitate. The flow circulation through the flow module and back to the upper container is started with deionized water, *i.e.* the end of the hoses in the upper container are in the water volume. The volumetric flow rate is checked by measuring the time needed for a selected mass to accumulate on the scale. The control valve is adjusted to reach the target flow rate.

While circulating water in the loop, the temperature of the target plate is raised up to a process temperature in a few discrete steps, and at each step the temperatures are let to stabilize. The purpose of recording the intermediate temperatures of the system is the estimation of the heat transfer coefficient of the interfaces between the metal plates. This value is needed in matching the CFD simulations to the experimental setup.

As the final step in the preheating phase, the temperature measured at the bottom surface of the heater stack is set to a selected process value (varies from 85 °C to 95 °C). The temperature at the steel-fluid interface (the top surface of the target plate exposed to fluid flow) is not measured, but can be estimated on the

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measured temperature of the fluid as it passes the plate. The water circulation is kept running steady while all the measured temperatures have been stabilized. At this point the flow is switched to SMUF mode by moving the hoses from the heat bath to the SMUF volume immersed in it. To this end, the flow is momentarily stopped with the on/off valve, and the target plate heating must be switched off as well to prevent overheating of the module since the heat transfer to stagnant flow is low. After moving the hoses, flow and heating are resumed, and the OCT apparatus is set to take images of the plate surface at a constant rate.

A run with one plate lasts usually for one working day, *i.e.* 7-8 hours. The electrical power to the heating element is adjusted in case the plate temperature drifts too far from the target value. The state of the fouling process can be monitored in real time by inspecting the scanned OCT images. After the experiment has been stopped, the flow channel is opened, and the target plate is detached from the module. The heat paste is removed carefully from the bottom surface of the plate, the water remaining on the plate is let to evaporate, and the mass of the plate with a deposited layer on it is measured. The plate is stored for later analysis and/or microscopic imaging.

RESULTS

We did test runs with water flow to calibrate the temperature sensors, and to estimate the heat transfer coefficient from the heating element to fluid. In the tests, we measured stationary temperatures for a discrete set of heating power. In Fig. 3 is shown the measured increase of the water temperature from the inlet to the outlet as a function of the temperature difference of the heater element relative to the incoming fluid at flow rates 300 ml/min (Reynolds number 250) and 600 ml/min (Reynolds number 500). The correlation is close to linear, *i.e.* doubling the plate-inlet temperature difference will double the outlet-inlet temperature difference (double the heat flow to water). The slope increases with decreasing flow rate due to increasing residence time on the heated plate of a definite fluid element. Halving the flow rate will double the residence time as well as the slope of the curve. The open squares mark the CFD results. In order to match the simulations with the measured temperature behavior, an additional heat exchange coefficient for the plate-plate interfaces had to be introduced to the CFD model (Ojaniemi et. al. 2019).

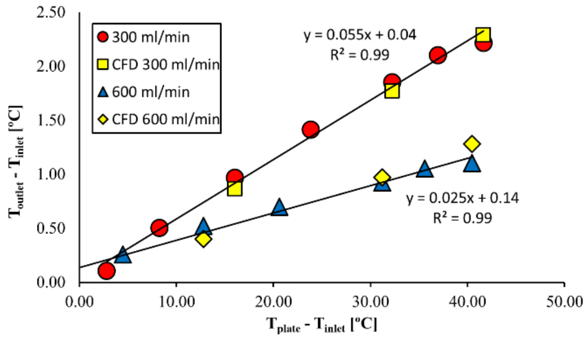

Fig. 3. Heating tests with water and comparison with CFD (Ojaniemi et. al. 2019).

In the experiments, we have observed fouling over a wide flow rate regime. The maximum amount of deposited layer so far observed is 87 mg (ca. 70 g/m^2), see Fig. 4. It was deposited during a 7 hours long run at hight flow rate 1500 ml/min (Reynolds number 1250). Based on the OCT images, the estimated thickness of the deposited layer was ca. 300 µm. As the left image of Fig. 4 clearly shows, the deposited layer is very thin at the upstream (leading) edge of the target plate marked with the vertical arrow. This tendency has been observed in the CFD simulations as well.

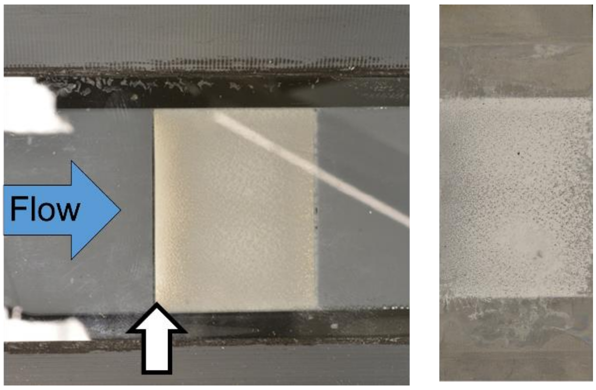

Fig. 4. An example of a deposited layer on the target plate. The left image is taken during the experiment, the right image after the plate was detached from the module. The vertical arrow marks the leading edge of the plate where the fouling layer is thin.

In Fig. 5 are shown the electrical power used for heating the target plate as well as the temporal evolution of the measured plate temperature during the experiment that resulted in the deposited layer shown in Fig. 4. The initial part of the graph until 200 minutes is the preheating phase with water circulation as well as some changes in the heating power to prevent thermal damage to the flow module or to the heating element. The slow increase in the plate temperature at constant heating power between 200 and 450 minutes is attributed to the lowered heat transfer to fluid due to a fouling layer.

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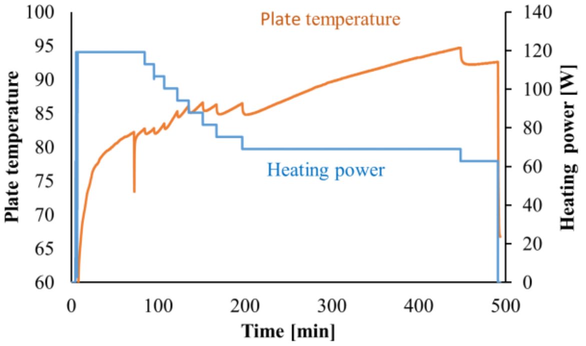

Fig. 5. The heating power and the temperature of the heating element during the experiment that resulted in the deposited layer shown in Fig. 4.

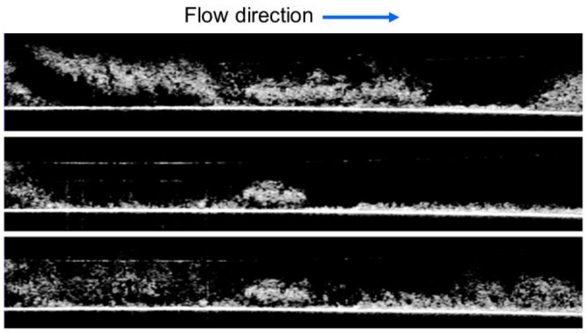

Fig. 6. A set of 2D OCT snapshots (OCT B-scans), from a measurements with dynamic fouling. The width and the height of the images are 8 mm and 1.2 mm, respectively, and the time difference between the images is ten minutes.

In a few cases we observed detachment of deposit flocks, which is seen both in OCT images and in the plate temperature. In Fig. 6 is shown three 2D OCT snapshots taken at a fixed location, with time separation of ten minutes. By comparing the top image to the middle image one can notice that a considerable amount of deposited layer has detached from the plate. After another ten minutes, a new deposited layer has grown in place of the detached material. Detachment of fouling layer enhances the heat transfer to fluid thereby decreasing the plate temperature while refouling recovers the state before the detachment. This can be clearly seen in the measured plate temperature where sudden drops correspond to detachment events, and gradual recovery of the plate temperature to refouling. The time span between the observed drops in the plate temperature varies between five and ten minutes, which correlates well with time separation of ten minutes between the detachment events observed in the OCT images.

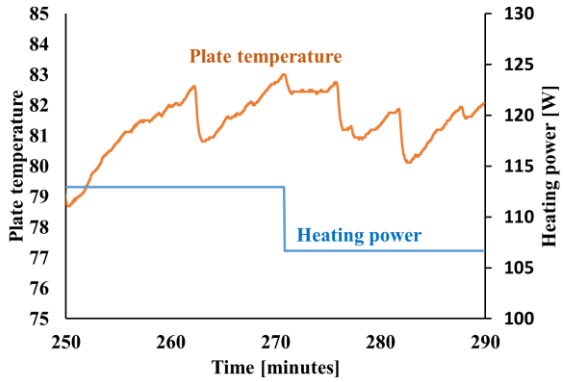

Fig. 7. Dynamic fouling shown in Fig. 6 is visible in the measured temperature data as sharp drops (detachment) and gradual increase to the original value (refouling).

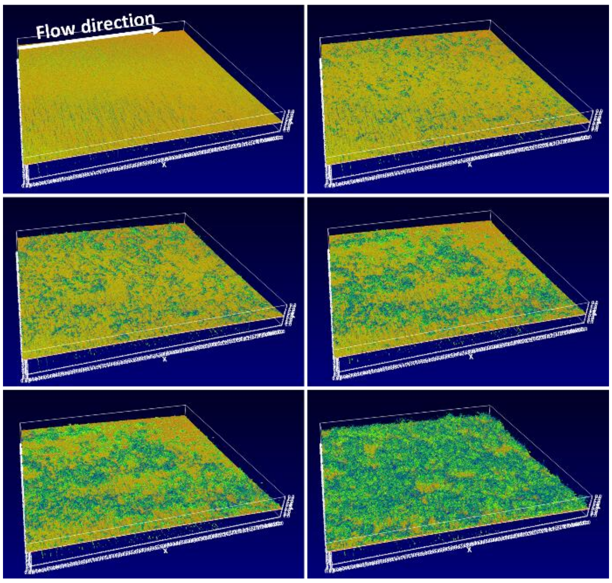

Fig. 8. OCT images of the target plate surface during 5 hours long measurement at flow rate 300 ml/min. The yellow color shows the target plate surface and the green color the deposited layer. The top left image is the starting point of the SMUF flow and the time of the rest of the images are (from left to right and from top to down) 105 minutes, 120 minutes, 150 minutes, 180 minutes, and 300 minutes.

In Fig. 8 is shown six OCT snapshots of the target plate during a run at flow rate 300 ml/min (Reynolds number 250). The imaged area is 10 mm by 10 mm and it is located next to the downstream edge of the target plate, centered in the transverse direction. The first indications of fouling in the snapshots can be seen 100 minutes after the start of SMUF flow, after which the deposited layer grows steadily, and reaches a total of 7 mg in five hours. During this fouling process, the plate temperature increased from 80 to over 90 degrees Celsius.

The time delay before the first observed fouling (either by direct probing or indirectly by decrease in the heat transfer coefficient), so called induction time,

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depends on the flow characteristics and turbulence level. In plate heat exchangers where the flow is fully turbulent, the induction period is extremely short (Mahdi et. al., 2009). Due to its unknown characteristics, this initial phase has been ignored in most mathematical models (Sadeghinezhad et al., 2013). Longer induction times have been reported for other types of heat exchangers where the turbulence level is lower, e.g. values between 1 minute and 60 minutes for tubular heat exchangers (Bansal et. al. 2006). This is qualitatively consistent with the results of our experiments, which were carried well below the turbulent regime (in Fig. 8 the Reynolds number is 250).

In Fig. 9 are shown four OCT snapshots from another run at 300 ml/min. The fouling is visible in the snapshots after two hours of SMUF run, and the amount of the total deposited layer in 7.5 hours is 20 mg. Again, the plate temperature increased from 80 to over 90 degrees Celsius during the SMUF flow. Interestingly, the deposited material is not spread evenly on the surface but forms rows or ridges in cross flow direction leaving an empty space between two neighboring rows. The reason for this kind of behavior is currently not known.

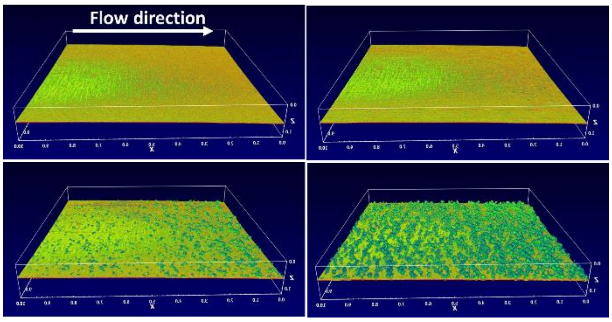

Fig. 9. OCT images from a run at flow rate 300 ml/min. Times of the image are start of SMUF flow, after two hours, after three hours, and after 7.5 hours.

CONCLUSIONS AND SUMMARY

In this paper we presented preliminary results on the fouling of simulated milk (SMUF) on a simplified model geometry for a heat exchanger. We found fouling over a wide flow rate range from 300 ml/min to 1500 ml/min (Reynolds number 250 - 1250). It took typically one to two hours before fouling was visible in the OCT scans. The largest amount of deposited layer was 70 g/m^2 in 7.5 hours at flow rate 1500 ml/min. The thickness of the deposition layer measured with OCT was then ca. 300 µm.

During this study we identified a few practical prerequisites for fouling to take place:

- pH of the SMUF solution has to be below but close to the limit for calcium precipitation
- the temperature of the target plate must be high enough (in the experiments the measured temperature of the heating element had to exceed 85°C)
- all the interfaces between the plates from the heating element to the target plate must have good heat conductivity

The last item in this list raised clearly the hardest challenges in building up the current experimental setup. Other practical challenges faced during building the experimental setup were the sealing of the flow module as well as thermal insulation to minimize unwanted thermal losses.

In a parallel study, a CFD model was developed for fouling in UHT dairy processes (Ojaniemi et. al. 2019). The results of this experimental work were used to validate the CFD model for heat transfer performance with water flow. In the future, the model will be validated against experimental data for fouling of SMUF. Notice that fouling layer reduces the heat transfer to fluid thereby increasing plate temperature at a constant heating power. This effect must be included in a realistic CFD model but is currently lacking in our model.

OCT is obviously a good tool for real time monitoring of the fouling process. A version of OCT, Doppler OCT, gives also information on fluid velocity (Drexler and Fujimoto 2008). Doppler OCT opens new possibilities for fouling studies as the time evolution of the flow conditions in the vicinity of the fouling plate can be measured *in situ*.

There is a lot of scope for further experiments. In the near future we will study the effect on the fouling process of the surface material by carrying out measurements with target plates coated with, e.g., titanium nitride, chromium nitride and chromium oxide. These results will be used to validate the CFD model, as well.

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