CONTINUOUS MONITORING OF WHEY PROTEIN FOULING USING A NON-INTRUSIVE SENSOR

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ABSTRACT

In this work, a non-intrusive device to monitor fouling of a plate heat exchanger is presented. This device is composed of a flat electrical resistance covering a thermocouple located on the external face of a tubular holding section. The tubular holding section is placed immediately after the investigated plate heat exchanger, constituting the heating zone for which fouling monitoring is required.

The principle of detection consisted in following the evolution of the measured temperature with time when a fixed thermal heat flux imposed by the resistance is dissipated through the temperature sensor. The measured temperature is supposed to vary with time since the temperature on the inner surface of the holding tubular zone is linked to the fouling growth.

It is shown that the device response is highly correlated to the fouling occurring in the plate heat exchanger and could be a promising way for monitoring fouling rate (cheap and easy to implement avoiding cleanability drawbacks...).

INTRODUCTION

Fouling is a major drawback in industrial heat transfer operation. It induces the increase of pressure drop and a thermal resistance leading to an oversizing of heat transfer equipment. Environmental cost are also to be considered. Fouling induces cleaning difficulties with huge water and chemical detergent consumption, namely in the food industry where cleaning operations forms a large fraction of total production times.

In the dairy and egg products industry, plant downtime allocated to CIP (Cleaning In Place) ranges from 4 to 6 hours per day. This also means that supplementary investments are required (need of additional and over dimensioned food-transformation heat exchangers, need of cleaning lines and additional maintenance costs). The frequent cleaning generates excess effluent which significantly contributes to the environmental footprint of the plant. NIZO food research (Van Asselt *et al.*, 2005) attributes 80% of the production cost to the consequences of fouling and cleaning in the dairy industries. The cost of fouling for other industrial sectors is difficult to estimate but it reaches 1 million $ for a large plant like coal-fired power plant (Sheikh *et al.*, 2000) and many billions $ losses for all the industrial countries only in the refinery field (Bohnet, 1987). In order to diminish environmental and financial costs, many researchers work on the understanding of fouling growth and elimination of the deposit in heating equipment.

In particular, lot of work was done in milk industry. Numerous factors are assumed to have a crucial impact on β-lg fouling during heat treatment in heat exchangers (Lalande *et al.* 1985, Visser and Jeurnink, 1997; Bansal and Chen, 2006; Bennett, 2007; Petit *et al.*, 2013; Khaldi *et al.*, 2015, 2018):

- Physicochemistry of the heat treated solution: protein nature and concentration, salt especially calcium-concentration (Petit *et al.*, 2011), ionic strength, pH, presence of dissolved gases, and air bubbles (Grijspeerdt *et al.*, 2004),
- Thermal process: preheating, temperature profile in Khaldi *et al.* (2015, 2018) and temperature difference between hot and cold fluids,
- Plates of the heat exchanger: interfacial energy (Rosmaninho *et al.*, 2008; Boxler *et al.*, 2015), material type and rugosity.

However, even if many advances are done, fouling is not perfectly controlled and it's necessary to monitor installation in real time in order to avoid exceeding a certain fouling level that implies the dismantlement of equipment and a mechanical cleaning. It is widely recognized that CIP may be rationalized by the on-line and off-line use of sensors, to reduce operating time and the volume and load of effluents (Alvarez *et al.*, 2010). Currently, it is still very difficult to validate the cleaning end-point, in spite of numerous methods of fouling detection level in heat exchangers in the food industry (Wallhausser *et al.*, 2012).

In the next two sections, some monitoring methods for fouling detection are briefly mentioned and compared. It would go beyond the scope of this paper to shine a light on all possible methods and on all areas where fouling occurs. For that, readers can refer to review of Wallhausser *et al.* (2012). Therefore, the focus lies on fouling in heat exchangers in food processing industry and dairy fouling. For the presentation of the monitoring methods for fouling detection, it was decided to divide in a section concerning global measurements as well as local measurements. Of course other classifications could be established such as batch vs continuous process, intrusive or non-intrusive sensors and on-line or post-process analyses (Crattelet *et al.*, 2013).

Global measurement

As underlined in Wallhäußer *et al.* (2012), many researchers work on the development of fouling sensors. Post-process analysis like weighing of deposit is a reliable method to measure fouling but it requires dismantling the heat exchanger so it is limited to scientific studies. The on-line measurement of pressure drop (Corrieu *et al.*, 1986) is used by industrials to determine a global level of fouling inside the plate heat exchange (PHE). Temperature and flow rate measurements also give us a global level of fouling by the meaning of overall heat transfer coefficient. Numerical models have been proposed for the detection of fouling based on the use of temperature and flow rate. Wavelets (Ingimundardóttir and Lalot, 2009) or neural networks (Lalot and Pálsson, 2010) are two examples of technique able to detect fouling in real time. But the implementation on real process must be done to ascertain the ability of this technique to be used at an industrial scale.

Local measurement

The use of sound wave has been studied recently for a non-intrusive measurement of the level of fouling. Ultrasonic waves have been also investigated to estimate the fouling adhesion force (Collier *et al.*, 2015). Merheb *et al.* (2007) generated mechanical pulse with an electromagnetic device attached to an exchanger plate and analyze acoustic sensors response. These two methods are interesting but it requires expensive transformations, extensive equipment and quite complex signal analyses for increasing TRL. A more promising technology for monitoring fouling is based on a mechatronic surface sensor (Pereira *et al.*, 2006). This device gives information on the amount of deposit and elastic properties. The sensor is not intrusive but it requires a specific semi-cylindrical flow cell holding the mechatronic surface sensor. The work of Ali *et al.* (2013) reports a proof-of-concept on the ability of fluid dynamic gauging (FDG) for measuring fouling growth in real time at elevated pressures and temperatures. FDG is a non-contact measurement performed by a nozzle immersed inside the liquid and facing the fouling at the wall. Application to food process monitoring such as milk protein heat treatment is difficult because FDG is intrusive and will be also subjected to fouling. Electrical conductivity measurement is another way to monitor fouling in PHE. Chen *et al.* (2004) and Guérin *et al.* (2007) demonstrated the ability of this technology in monitoring milk fouling on-line. In these two examples, the mounting is quite complex. The electrodes must be correctly electrically isolated. The hot wire technology (Crattelet *et al.*, 2013) is used at an industrial scale. These sensors are placed inside the solution processed. Two operating modes, steady and periodic thermal regimes, were explored. It's a promising technology able to monitor fouling phenomena and evaluate deposit properties. This last example is an intrusive sensor.

Each of these methods presented above have advantages and disadvantages. The fouling sensor presented here examines the possibility to implement, in an easiest and cheapest way, a device for the monitoring of fouling and also cleaning. As shown below, the fouling sensor performance was validated at a pilot scale. This device generates a controlled heat flux at the outside surface of a straight duct section and measures the outside surface temperature. This temperature increases with a deposit growth by means of fouling thermal resistance increases. This is similar to the "neosens FS-1000" fouling probe principle but is mounted on the outer side of the tube, not in the tube wall. This non-intrusive and local measurement is an interesting way for continuous monitoring of whey protein fouling.

MATERIALS AND METHODS

Experimental pilot plant

Fouling experiments were conducted on the pilot plant presented in Fig. 1. The whey protein powder is dissolved in the mixing tank. The flow rate is adjusted by setting the volumetric pump mechanical variator. An electromagnetic flowmeter records the flow rate. Two PHE (VICARB, model V7) were used for pre-heating from ambient temperature 22 °C to 65 °C and for heating from 65 °C to 80 or 82 °C. Two hot water flow loops allow to adjust product pre-heating and heating outlet temperatures separately. The fouling sensor is installed just after the product PHE heating zone.

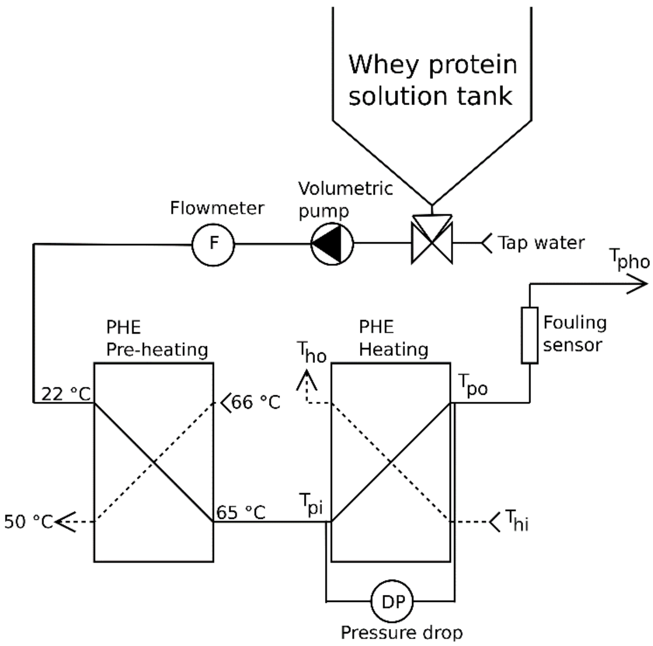


Fig. 1 Schematic diagram of pilot plant. Latin letters T_{hi}, T_{ho}, T_{pi}, T_{po} and T_{pho} correspond respectively to the inlet and outler hot water temperature, the inlet and outlet product temperature and the outlet temperature of the maintain section. Dotted lines indicate the hot water flows.

The heating zone is composed of 10 plates; making 5 channels for the whey solution and 4 channels for the hot water. The whey protein concentrate temperature is maintained constant by increasing the inlet hot water temperature T_{hi}. The solution flow rate is also kept constant at 0.833×10^{-4} m^3/s by using a volumetric pump. The overall heat transfer coefficient in the heating zone is defined as:

$$U = \frac{Q_p}{A \times LMTD} \quad (1)$$

The fouling thermal resistance is defined by:

$$R_f = \frac{1}{U_f} - \frac{1}{U_c} \quad (2)$$

Non-intrusive fouling sensor

The sensor (Fig. 2) is a stack in contact with the external surface of a straight duct. It is composed of a thin thermocouple temperature sensor (T type), a thin copper resistance (50x50 mm, 27.5 Ω) and an insulating elastomeric foam. The duct supporting the sensor is mounted vertically. This position minimize the effect of gravity on deposition fouling.

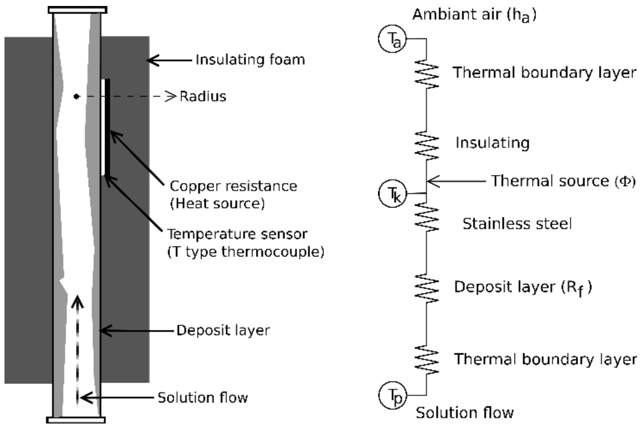


Fig. 2 Sectional drawing of the sensor and thermal equivalent electric circuit following radius. T_p, T_k and T_p represent respectively the solution flow, the sensor and ambient air temperature. h_a, ϕ and R_f are respectively the heat transfer coefficient to ambient air, the surface heat flux and the fouling thermal resistance.

A tension lower than 10 V is applied to the resistance with a stabilized power supply. A data logger system records the temperature and voltage during each test. Assuming a simplified 1-dimension model in stationary conditions, the expression of the fouling resistance is obtained by considering the thermal equivalent circuit presented in Fig. 2.

$$R_s = \frac{(T_{kf}-T_{kc})-(T_{pf}-T_{pc})}{\Phi+h_a(T_a-T_k)} = \frac{\Delta T_f - \Delta T_c}{\Phi+h_a(T_a-T_k)} \quad (3)$$

Then an estimation of the fouling thickness is possible under some hypothesis on deposit physical properties.

$$d_f = R_s k \quad (4)$$

The thermal conductivity, k, of the fouling deposit is unknown but some authors have done some measurements. The value generally cited in the literature is between 0.13 to 0.38 W/m K (Tuladhar *et al.*, 2002). For all the calculations in the paper, the averaged and assessed value of k is arbitrary fixed at 0.25 W/m K.

Fouling experiments

Three experimental conditions (A to C) were used in the final heating zone corresponding to different temperature and mass flow. Condition A stands for outlet product temperature of 82 °C and hot water flow rate of 0.833×10^{-4} m^3/s. Respectively 82 °C and 2.777×10^{-4} m^3/s for case B; 80 °C and 2.777×10^{-4} m^3/s for case C. The product bulk profile corresponding to each condition is presented Fig. 3. The fouling trials were repeated 5, 4 and 2 times respectively for profile A, B and C.

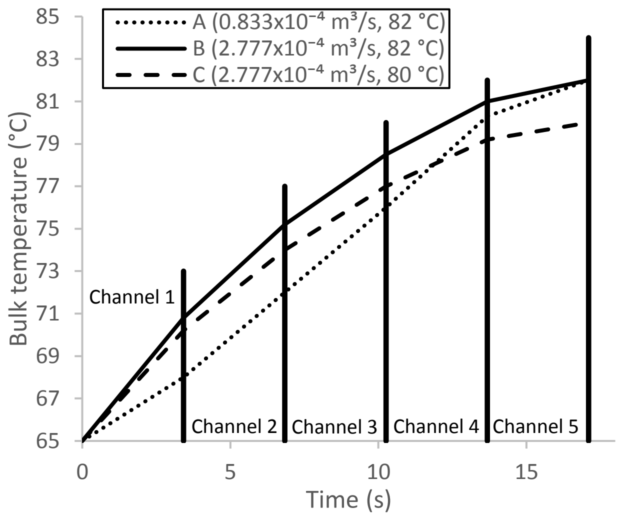


Fig. 3 Temperature profile for clean condition in the PHE obtained by a combination of two different hot water flow rates and bulk product temperatures.

The solution is prepared with whey protein powder from one unique batch (Promilk 852 FB1, Ingredia, France) dissolved in osmotic water (1 % w/w). The calcium concentration is adjusted to 95±5 ppm by adding $CaCl_2$. The calcium control is important as it influences the fouling level. It is measured using an atomic absorption apparatus with the same method as Khaldi *et al.* (2015, 2018). With such low dry material concentration, the physical properties of the solution are considered to be the same as water. Each experiment starts with tap water to heat up the heat exchanger plates. In this case, there is no transient behavior for fouling. This takes approximately 30 minutes. When the temperatures are stabilized at the desired value, the circuit is switched to the solution for 3 hours. During all the experiments (temperature profile A to C), the solution flow was kept at a constant rate of 0.833×10^{-4} m^3/s. The Reynolds number varies from 3000 for the solution at ambient temperature to 8500 in the duct maintain section indicating a turbulent regime. The flow regime is also turbulent in all the channels of the plate heat exchangers. The outlet product temperature is maintained constant by continuously adjusting the inlet hot water temperature. After ten minutes rinsing, the PHE is dismantled and the dry deposit on each plate are weighed with an accuracy of ± 0.1 g. The dry deposit in the duct section supporting the sensor is also weighed. In a last step, the PHE is remounted and cleaned. The cleaning procedure consists of 3 basic operations which are the following ones. The PHE is rinsed for 10 min with tap water. A caustic soda

2 % (w/w) solution is used at 1.666x10^{-4} m^3/s for at less 30 min until the pressure drop value reaches the initial pressure drop. The cleaning step finishes with 10 min rinsing with tap water. The PHE cleanliness is checked visually before any other fouling experiment. The measurements obtained with the fouling sensor are compared with usual fouling measurement such as pressure drop, heat transfer and dry deposit mass weighing.

RESULTS AND DISCUSSION

Figure 4 shows three different deposit mass distributions in the PHE corresponding to the three different experimental conditions explored. The repeatability is good except for channel 1 to 3 with profile A.

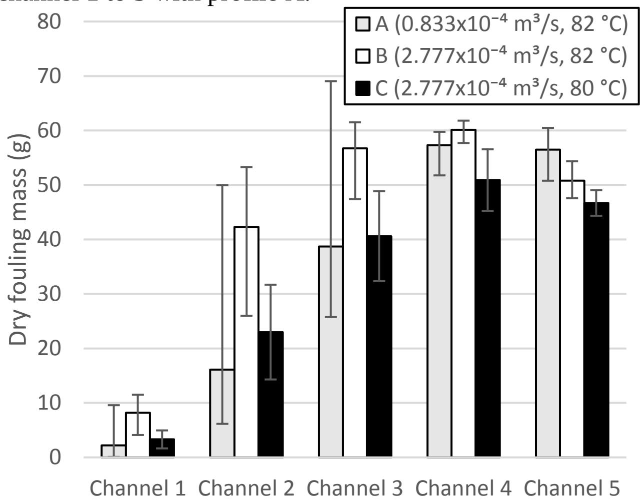


Fig. 4 Dry deposit mass (minimum, maximum and mean value) in the PHE for temperature profile A, B and C. Hot water flow rate and solution outlet temperature are indicated after each temperature profile letter.

The deposit amount increases from a very low value in the first channel to a maximum value in the two last channels. A significant deposit amount is observed when the bulk temperature exceeds 70 °C as observed by many researchers (Khaldi *et al.*, 2015, 2018). The protein solution essentially contains beta-lactoglobulin (66.0 % w/w in the powder). The heat-induced denaturation reaction of beta-lactoglobulin in presence of calcium is responsible for the deposit growth (Lalande *et al.*, 1985). These experiments confirm that denaturation of beta-lactoglobulin begins when the temperature is greater than 70 °C; i.e. in the second channel. The strongest heat treatment (profile B of Fig. 3) corresponds to the highest dry mass deposit. It also confirms this theory. The pressure drop recorded at the end of the test is compared to the total PHE dry deposit mass in Fig. 5. The pressure drop globally increases with dry deposit mass but there's no reliable correlation. The pressure drop is a global measurement and is very sensitive to local fouling. For the same deposit mass, the pressure drop can increase 4 folds. The deposit growths not homogeneously. It's the reason why this data is very scattered. There's no direct correlation between the total dry deposit mass and the pressure drop.

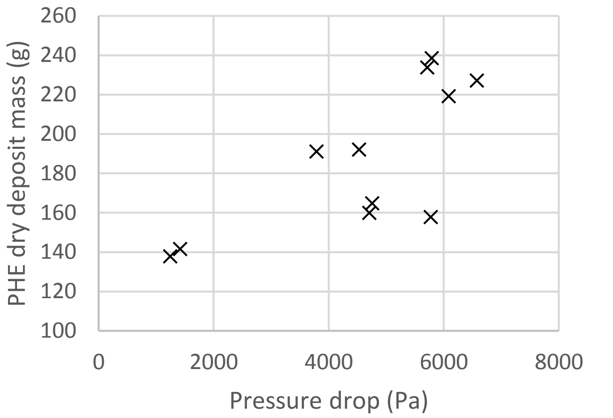


Fig. 5 Dry deposit mass in function of pressure drop for all the experiments.

The fouling sensor measurement is based on the measurement of the product bulk temperature and the external wall temperature T_k. Figure 6 is a representative example of temperature recording. If the sensor temperature is shifted by the difference between the sensor and the product temperature at the beginning of the experiment $(T_k-T_p)_{t=0}$ or ΔT_c, the increase of the difference becomes visible. This increase is directly linked to the increase of the fouling thermal resistance as described in Eq. (3).

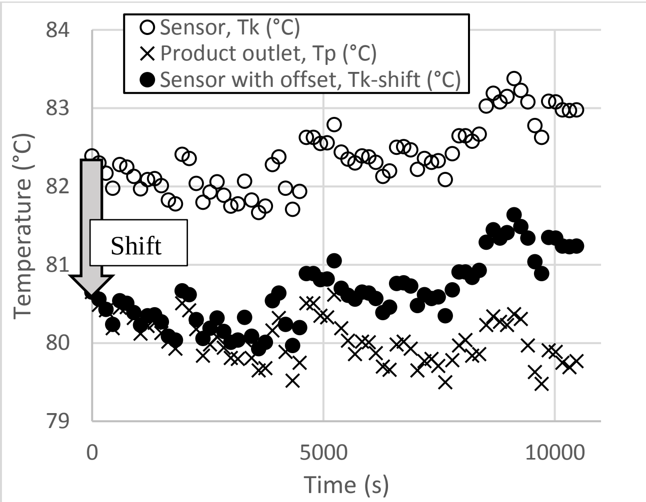


Fig. 6 Temperature recording for profile C.

The PHE thermal performance is represented by the surface thermal resistance. The fouling sensor continuous monitoring of surface thermal resistance (R_s) was compared with the monitoring in the PHE (R_f) in the following figure (Fig. 7).

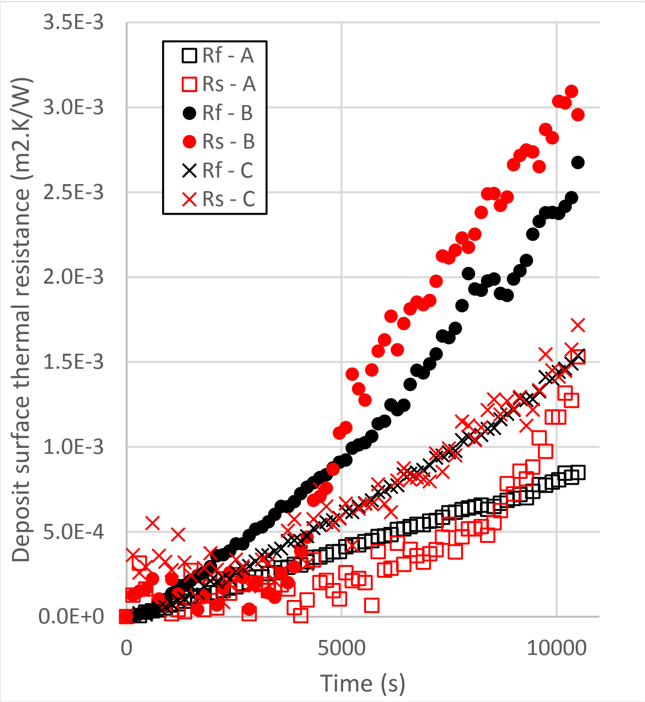
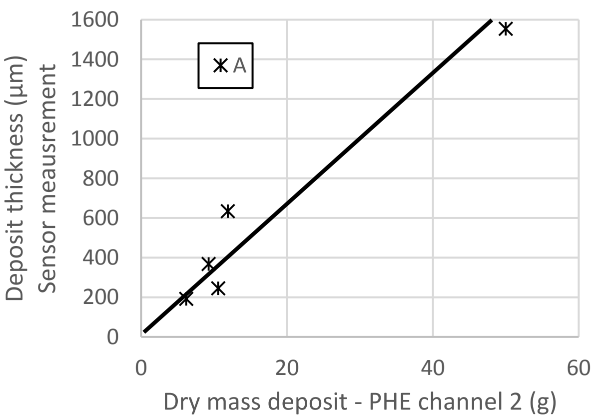


Fig. 7 Comparison of deposit surface thermal resistance computed with PHE inlet/outlet temperatures (R_f, in black) and with the sensor measurement (R_s, in red).

The surface thermal resistance measured with the fouling sensor is closed to the thermal resistance in the PHE for the bulk temperature profile C, corresponding to the lowest outlet temperature treatment. In the cases of profile A and B, the surface thermal resistance is overestimated at the end of the experiment. The estimation of the thickness obtained with the sensor is compared to dry mass deposit in the PHE channel 2 in Fig. 8. Channel 3 gives the same results as channel 2. Dry mass deposit in the first channel is not high enough that the measurement precision is insufficient to use data. Concerning the last two channels, the dry deposit mass doesn't vary enough for any interpretation.



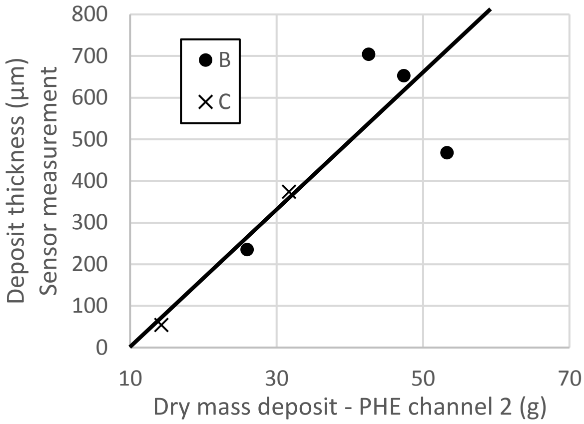


Fig. 8 Deposit thickness sensor in function of PHE channel 2 dry deposit mass for temperature profile A, B and C.

Although there are no clear explanations for the variation of the dry mass deposit in the second channel for given operating conditions, Figure 8 shows a quite good relation between the dry mass deposit and the deposit thickness measurement obtained by the fouling sensor for temperature profile B and C. There's a clear relationship between the fouling sensor measurement and fouling growth. These results show the ability of the fouling sensor to monitor fouling growth inside a PHE in different temperature treatment conditions.

CONCLUSIONS

Detection is a major concern in the field of heat exchangers fouling. The intrusiveness is the main drawback of sensors in food industry. The main advantages of the sensor device described can be list as following.

1. The device sensor is very cheap. It needs standard components like a plate resistor, a temperature sensor and a power supply. Moreover one power supply can be used to supply several device sensors.
2. The sensor mounting is easy. The temperature sensor is stuck outside a duct wall. The resistor is stuck on the temperature sensor and an insulating foam is placed over. It's not necessary to stick the resistor and the sensor, they could be maintained in touch by any convenient method.
3. The sensor is non-intrusive. Not any part of the fouling sensor is in contact with the product.

The main drawback is that the calculation of the fouling thermal resistance needs the bulk temperature measurement. This is usually measured in any installation using an intrusive sensor. The calibration is also difficult to do if a high precision is required. The sensor can be improved in different ways. The precision can be increased by the replacement of the thermocouple sensor by two or more. It will be easy to place several sensors in different places to show the evolution of deposit along the duct at the PHE outlet. Another improvement is to mount the fouling sensor as close as possible to the PHE outlet.

The fouling sensor described is found to be able to monitor in real time whey protein fouling in a plate heat exchanger. This sensor may also permit the monitoring of cleaning and determine the cleaning duration when the deposit thermal resistance cancels. New experiments and physicochemical analyses are planned to investigate the influence of the thermal profile on the dry deposit mass.

NOMENCLATURE

A plate surface area, m^2
C_p heat capacity, J/K
d depth, m
h heat transfer coefficient, W/m² K
k protein deposit thermal conductivity, W/m K
U overall heat transfer coefficient, W/m² K
LMTD logarithmic mean temperature difference, $\frac{(T_{hi}-T_{po})-(T_{ho}-T_{pi})}{ln\left(\frac{T_{hi}-T_{po}}{T_{ho}-T_{pi}}\right)}$, K
$\dot{m}$ mass flow rate, kg/s
Q_p exchanged heat duty to product, $\rho\dot{m}_p C_p(T_{po}-T_{pi})$, W
R electric resistance, Ω
R_f PHE fouling thermal resistance, m² K/W
R_s Sensor fouling thermal resistance, m² K/W
S electric resistance surface, m^2
T temperature, °C
V tension applied to the resistance, V
Φ surface heat flux produced by the resistance, $\frac{V^2}{RS}$ W/m^2
ρ density, kg/m^3

Subscript

a ambient air
c clean condition
f fouling condition
h hot water or holding section
i inlet
k thermocouple K sensor
o outlet
p product, whey protein solution

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