

Continuous ohmic heating unit under whey protein fouling

M. A. Ayadi^{a,*}, J. C. Leuliet^a, F. Chopard^b, M. Berthou^c, M. Lebouché^d

^aINRA (Institut National de la Recherche Agronomique), LGPTA (Laboratoire de Génie des Procédés et Technologie Alimentaires), 369, rue Jules Guesde-59650 Villeneuve D'Ascq cedex, France

^bALFA LAVAL VICARB, rue du Rif Tronchard, 38120 Fontanil Cornillon, France

^cEDF-R&D, Les Renardières, 77818 Moret Sur Loing Cedex, France

^dLEMTA, 2, Avenue de la forêt de Haye 54504 Vandoeuvre-lès-Nancy, France

Abstract

An evaluation of a continuous ohmic heating apparatus performance was carried out, using a whey protein solution. It was thereby shown that, as with conventional heat exchangers, ohmic processing of dairy product generates fouling on electrode surfaces. The presence of this motionless deposit causes an increase in electricity consumption and leads to an increase in the temperature of the electrode surfaces. During the observation of 4- and 6-h processes, three stages were noted: (i) at first, the deposit thickness was not significant for a short period and ohmic process was observed to operate satisfactorily (balance power, electrode temperature), (ii) then the deposit thickness was observed to gradually increase with processing time, provoking a corresponding simultaneous increase in both electricity consumption and electrode temperature, (iii) finally, the electrode temperature reached boiling point, as did the deposit, leading to deposit adhesion and removal changes. © 2004 Elsevier Ltd. All rights reserved.

Keywords: Ohmic heating; Dairy fluid; Fouling monitoring

Industrial relevance: This paper is of relevance because it deals in contrast to most existing studies, not with particulates in liquid systems but with fairly homogenous model fluids alone. Interestingly, while biofilms on the heat transfer surfaces of conventional heat exchangers create increasing heat resistance, during ohmic heating deposit layers on the electrodes contribute to additional electrical resistance.

1. Introduction

Fouling of heat exchangers in the dairy industry is quite a severe problem. In addition to the cost of the cleaning operations, fouling causes a significant loss of the hydraulic and thermal performances of conventional heat exchangers (plate and tube heat exchangers). As yet no solution to this problem has been found. The presence of deposit layers on the surfaces induces a significant decrease in the overall heat transfer coefficient and a drastic increase in pressure drop (Lalande, Tissier, & Corrieu, 1985; René, Leuliet & Lalande, 1991). The fouling of plate heat exchangers with treated milk has already been extensively investigated (Belmar-Beiny, Gothan, Paterson, & Fryer, 1993; Changani, Belmar-Beiny,

& Fryer, 1997; Delplace & Leuliet, 1995; Grijspeert, Hazarika, & Vucinic, 2003). However, these works focused on the effect of the fouling phenomena encountered in heat exchangers. Until now, the deposit impact on thermal and hydrodynamic exchanger performance has been estimated by the measurement of the pressure drop increase and the overall heat coefficient decrease. Based on these works, the design and the geometry of the heat exchangers have been optimized to minimize fouling phenomena (Butterworth, 2002; Fryer, 1989). Despite improvements due to these studies, conventional heat exchangers are still limited by fouling phenomena.

Development of new technologies for continuous thermal food treatment is still of great industrial and scientific interest. Ohmic heating is one of these new technologies, which consists of the direct passage of electric current through the product. The permanent motion of electrical charges creates heat in the product in agreement with Joule's

* Corresponding author. Tel.: +33 3 20 43 54 40; fax: +33 3 20 43 54 26.

E-mail address: ayadimedali@yahoo.fr (M.A. Ayadi).

law. According to this principle, ohmic technology could be considered as purely bulk heating.

Ohmic technology was used in the 19th century (Anderson & Finkelsten, 1919; Prescott, 1927) for milk heating. Unfortunately, such a technology did not succeed at that time because of technical limitations (electrode materials, process regulation, etc.). During the past 20 years, new improved materials and equipment design for ohmic heating have become available (Amatore, Berthou, & Hébert, 1998; Roberts, Balaban, & Luzuriaga, 1998). However, most of the studies concerning the sterilization of food products are dedicated to the heat treatment of fluids containing particles using tubular geometry (De Alwis, Halden, & Fryer, 1989; Fryer & De Alwis, 1998; Wadad, Sudhir & Sastry, 1996; Benabderrahmane & Pain, 2000; Eliot-Godéreaux, Zuber, & Goullieux, 2001; Zareifard, Ramaswamy, Trigui, & Marcotte, 2003). Quite a few scientific and technical works have been dedicated to the heat treatment of homogenous food fluids by ohmic technology (Marcotte, 1999; Ould Elmoktar, Peerhossani, & Peurian, 1993).

Fouling experiments with a model fluid are proposed in this paper in order to evaluate a continuous rectangular ohmic apparatus performance under heavy whey protein fouling.

2. Materials and methods

2.1. Geometry and instrumentation of the ohmic heater

The ohmic heater was made up of five ohmic cells, three of them ensuring heating and the two side cells ensuring electric insulation and the recovery of leakage currents. Each cell can be compared to a rectangular channel (length=240 mm, width=75 mm and thickness=5 mm), the electrodes constituting side surfaces. Cell no. 4 was instrumented by 16 thermocouples located on the surface of the two electrodes. The location of these thermocouples is presented in Fig. 1.

2.2. Fouling model fluid

Whey protein concentrate powder (PROTARMOR 750, Armor proteins, France) and xanthan gum (Degussa, Texturant Systems, France) were used to prepare the model fouling fluid. An aqueous solution of whey protein–xanthan gum mixture (1% w/w of protein powder and 0.2% w/w of xanthan gum) was chosen as a model fouling fluid for all the experiments. The composition of the whey protein powder was essentially β -lactoglobulin (more than 65%), α -lactalbumin (less than 10%), fat (less than 5%) and lactose (less than 10%). Minerals represent less than 5% of the total dry weight. The model fluid obtained at a constant pH value and was then kept in a storage tank for approximately 12 h at 4 °C in order to prevent bacterial proliferation. As reported by Delplace, Leuliet, and Tissier (1994), the use of such a model fluid enables reproducible fouling experiments.

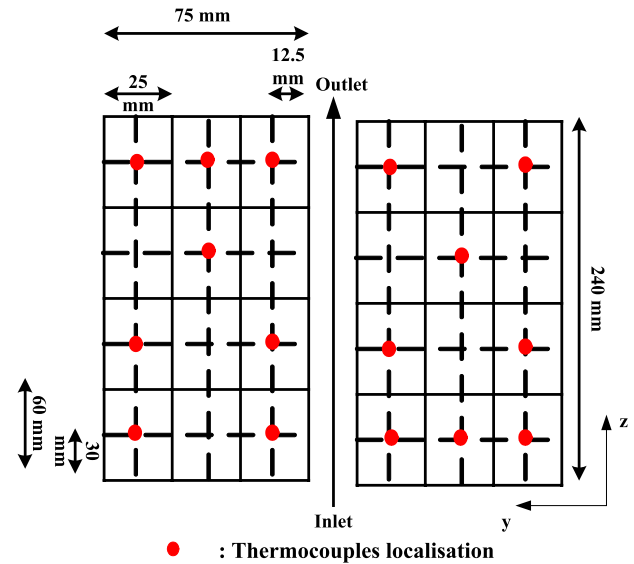


Fig. 1. Thermocouple locations on the electrode surfaces of cell no. 4.

The model fluid was prepared with great care to ensure that its physical properties remained constant for all the tests:

- pH=7.
- Shear thinning behaviour: described by Ostwald's law: $n=0.0023\theta+0.234$ and $k=6.78\theta^{-0.663}$ with θ from 20 to 80 °C and γ from 0.4 to 700 s⁻¹.
- Electric conductivity progressing linearly with temperature and described by the following relation: $\sigma=1.35+0.0383(\theta-20)$ for temperatures varying from 0 to 100 °C.

All the other physical properties (density, specific heat, and thermal conductivity) were very close to those of water.

2.3. Fouling experiments

The pilot-plant test rig used in fouling experiments is shown in Fig. 2. It consists of three parts: (i) a preheating zone with a conventional PHE, (ii) a heating zone with the ohmic apparatus and (iii) a cooling zone with a tubular heat exchanger. In addition, a storage tank (2 m³), a constant level tank and a volumetric feed pump were necessary to perform the experiments. A manual back-pressure valve at the plant-outlet allowed the pressure in the pilot-plant to be maintained at 3 bar. The flow rate was measured using an electromagnetic flowmeter (Khrone, type IFM 10807K) with a precision of 1% of the full range. Temperatures were measured by means of platinum resistance probes (Sensor-Nite, type: Pt 100) placed at the inlet and outlet of each zone. The precision of temperature measurements was ± 0.1 °C for the platinum resistance probes and ± 0.3 °C for the thermocouples. A differential pressure sensor (Schlumberger, type D) was used to follow the pressure drop increase between the inlet and outlet of

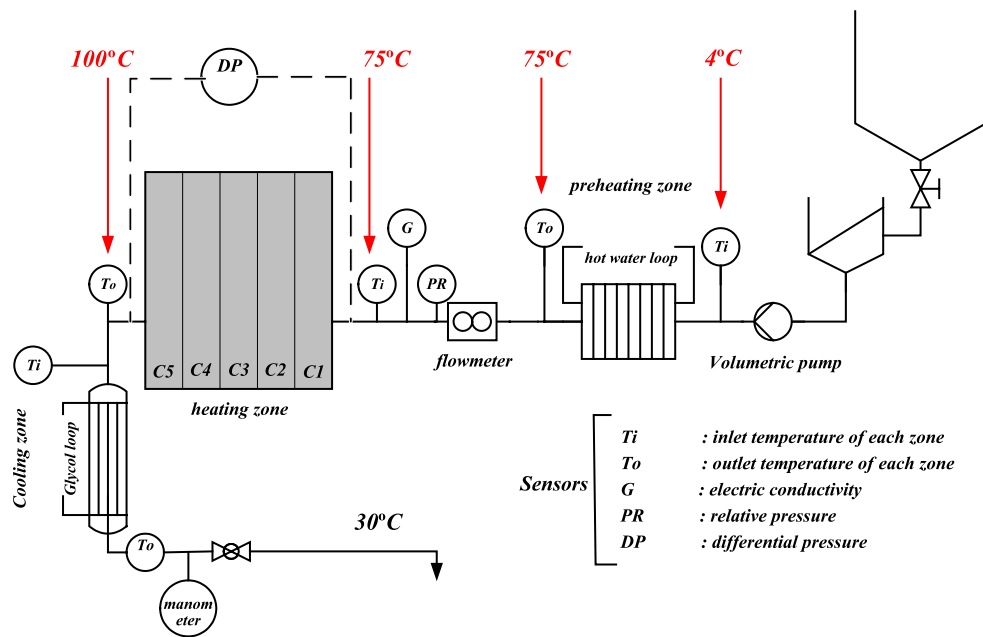


Fig. 2. Fouling pilot plant test rig.

the ohmic heater. Two relative pressure sensors were used to measure the relative pressure in the ohmic cells. The electric power was applied using a 15-kW generator and a three-phase system. Voltage (voltmeter 0-250V, Sineax U504, Chauvin Arnoux) and current intensity (Ammeter 0-200A, type AC22, Camille Bauer) was measured in the third phase. All these measurements were collected (module SCX-1) and processed using a data acquisition card (AT-MOI-16E-10). A software driver (Ni-DAQ) provided the configuration and control of the data acquisition system.

The flow rate was fixed at 300 l/h ($Re=63$) and the inlet and outlet temperatures, in the ohmic heater, were fixed at 75 and 100 °C, respectively. Under these operating conditions, several fouling experiments were carried out in order to monitor fouling in the ohmic cells for varying durations (1, 2, 3, 4 and 6 h).

The general steps of the fouling experiment are summarized below:

- The experiment started by heating water. Once the temperature at the cell inlet reached 75 °C, the water electric conductivity was adjusted to the electric conductivity of the fouling fluid.
- Ohmic processing commenced once the system stabilized the data acquisition ran for 30 min and then switched to the fouling model fluid.
- At the end of each fouling run, the system was dismantled and photographs of the fouled electrodes were taken.
- Electrodes and spacers were dried for 6 h at 100 °C and the dried deposit mass per cell was measured using a Mettler PM 3000 apparatus (± 0.1 g).
- Acquisition data were retrieved and analyzed.

2.4. Fouling measurements

Fouling of heat exchangers is commonly observed during experiments through pressure drop and overall heat transfer coefficient measurements (Delplace et al., 1994; Ling & Lund, 1978; Lalande, René & Tissier, 1989). At the end of fouling experiments, the dry and wet weight of a given deposit can be determined (Lalande, Tissier, & Corrieu, 1984; Delplace et al., 1994) along the heat transfer area, in order to give local information. Pressure drop measurements are useful for characterising the changes in channel geometry as fouling takes place. Delplace et al. (1994) and Schreir, Green, Pritchard, and Fryer (1994) have shown that a rapid increase in the pressure drop can be observed in the heat exchanger when channels are blocked by deposit. Nevertheless, an overall heat transfer coefficient seems to be the most representative variable to account for the fouling layer formed on heat transfer surfaces. Taking into account the totally different way of heating in ohmic technology, fouling was measured during experiments through the evolution versus time of: dry deposit mass, pressure drop, local temperature gradient between electrodes and bulk and electric power consumed.

3. Results

3.1. Fouling results

Fig. 3 presents photographs of the fourth cell electrode surfaces after 1-, 2-, 3-, 4- and 6-h fouling experiments. This figure shows that after 3 h of processing, the surfaces of the electrodes are almost entirely covered by a fouling deposit. This deposit exactly corresponds to that of type “A” described

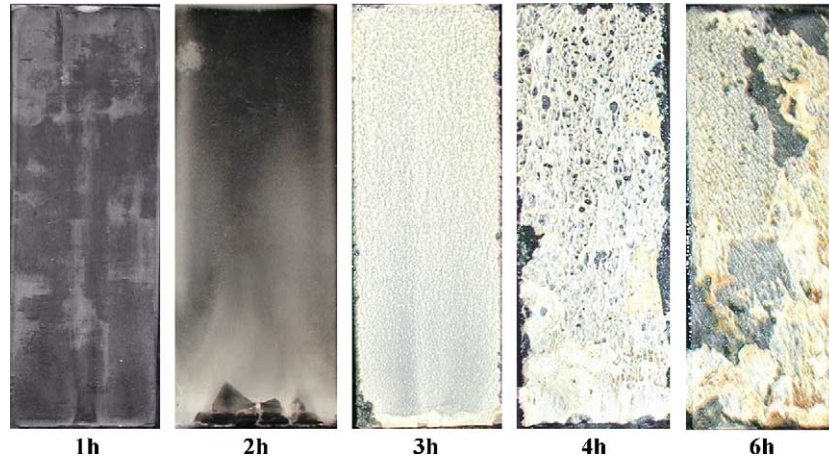


Fig. 3. Photographs of cell no. 4 electrode surface after 1-, 2-, 3-, 4- and 6-h fouling experiments.

by Burton (1968): it is voluminous, spongy and of a whitish colour. This is hardly surprising given the fluid chosen (protein based) and the temperatures considered (≤ 100 °C). The photograph of the electrode surface after a 4-h fouling test shows a change in the deposit aspect (appearance of a local over-heated zone and the trace of tiny bubbles). The photograph of the electrode surface after a 6-h fouling test shows the presence of an over-heated deposit and some deposit removal.

The dry deposit mass distribution on the electrode surfaces of each ohmic cell after fouling experiments is shown in Fig. 4. Low deposit quantities were observed in cell no. 1 after fouling experiments. Considering the temperature (no heating, fouling fluid 75 °C) and the residence time in this cell, we can see that no β -lactoglobulin adhesion occurred in this cell and, thus, no fouling took place. Dry deposit mass distribution clearly shows that fouling was relatively low after 2-h fouling experiments and became much heavier for an operating time longer than 3 h. This leads us to suppose that, as in plate and joint heat exchangers (Lalande et al.,

1985) and tubular heat exchangers (Fryer, 1989), a fouling induction period exists before it reaches very high levels.

For the 4- and 6-h fouling experiments, it would appear that the deposit mass increases from cell no. 2 to cell no. 5. These results seem to be quite logical taking into account the temperature profile in the ohmic cells. Indeed, if we assume a linear temperature profile, the outlet temperature ($T_{o2} \approx 83$ °C, $T_{o3} \approx 92$ °C and $T_{o5} \approx T_{o4} \approx 100$ °C) and the residence time in each ohmic cell (cell nos. 2, 3, 4 and 5) were sufficient to denature and adhere β -lactoglobulin onto the electrode surfaces.

Pressure drop evolution during the fouling experiments is shown in Fig. 5. Classical curves can be observed for all the fouling experiments: the pressure drop remained almost constant for the two first hours, with only a very slight increase. After this period, a quick transition to a much more rapid rise in the pressure drop was observed. These pressure drop curves reinforce the previous conclusion concerning the deposit visualisation and dry deposit mass evolution (after 2-h processing the deposit become greater). For 4- and

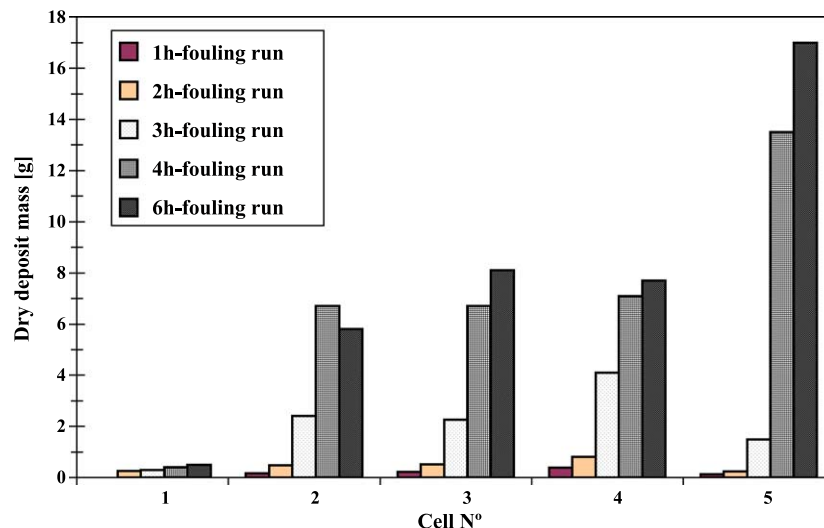


Fig. 4. Dry deposit mass after fouling experiments.

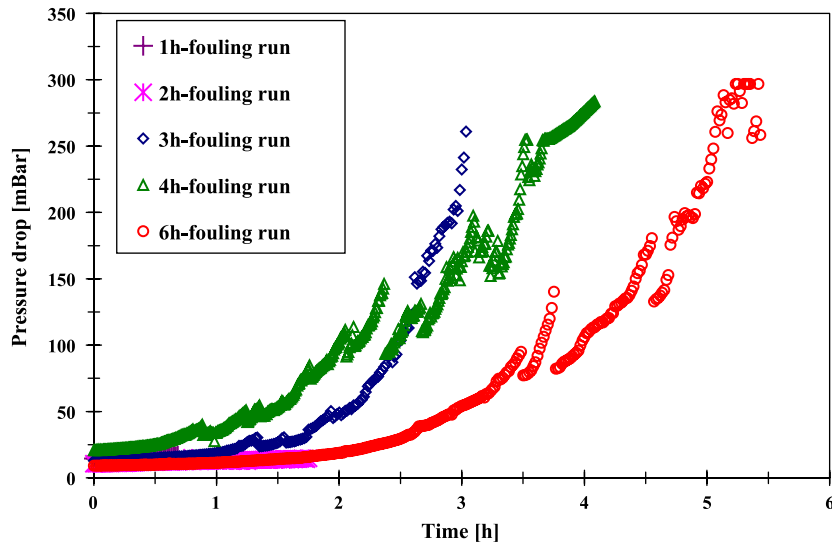


Fig. 5. Pressure drop evolution during fouling experiments.

6-h fouling experiments, the “zigzag” shapes were observed which suggest some deposit removal.

3.2. Impact of fouling on electricity consumption and local temperature gradient

As mentioned previously, the ohmic cells used in the present study were connected to a three-phase system. The voltage and the current intensity were measured only for the third phase. As the system was assumed to be equilibrated and purely resistive, the electric power consumed by the fluid and the deposit in the ohmic cells during the experiment was calculated according to the following equation:

$$P(t) = \sqrt{3}U(t)I(t) \tag{1}$$

where, $P(t)$ the electric power consumed by the fluid and the deposit during the experiments, $U(t)$ and $I(t)$ were

respectively the voltage and the electric current intensity evolution during the experiments. Fig. 6 illustrates the evolution in the electricity consumed during the fouling experiments. As for the pressure drop evolution, the electricity consumption curves show a very slight increase during the first hour and an exponential evolution after 2 h. These evolutions clearly show that the fouling build-up causes an increase in the electric power required and the deposit on the electrode surfaces acts as an additional electrical resistance. Given the fact that motionless deposit is continually subject to the Joule effect, the electrode surface temperature should increase during the experiment.

Using thermocouples placed in the fourth cell (cell no. 4) electrode surfaces, the wall temperatures were measured during the fouling experiments and the bulk temperature was estimated versus y and z coordinates ($0 < y < Y = 75$ mm and $0 < z < Z = 240$ mm). We assumed a linear temperature profile in

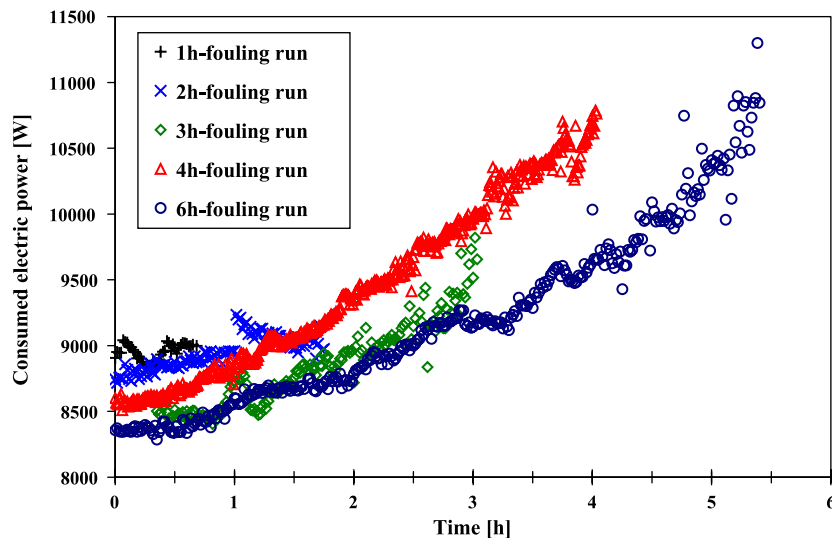


Fig. 6. Consumed electric power evolution during fouling experiments.

the ohmic cells and isothermal conditions in the first and the fifth cells (no heating). The reduced local temperature gradients, between the electrode surfaces and bulk, in the fourth cell were estimated as follows:

Isothermal hypothesis for the first and the fifth cells:

$$T_{i1} = T_{i11} = T_{o1} = T_{i2} \text{ and } T_o = T_{o5} = T_{i5} = T_{o4}$$

Linear temperature profile in the ohmic heater:

$$\text{For } z = 0; T_{i4} = T_i + 2/3(T_0 - T_i) \quad (2)$$

In cell no. 4, for $0 < z < Z$, the local bulk temperature was estimated as follows:

$$T_{z4} = T_i + (T_0 - T_i) * z / Z \quad (3)$$

The local temperature variation, between wall and bulk, in cell no. 4, at (y, z) coordinate is:

$$\Delta T(y, z) = TC(y, z) - T_{z4}(y, z) \quad (4)$$

The reduced local temperature variation, between wall and bulk, in cell no. 4, at (y, z) coordinate is:

$$T^*(y, z) = \Delta T(y, z) / (T_o - T_{i4}) \quad (5)$$

Similar reduced local temperature gradient evolutions were obtained at fixed z coordinates and various x coordinates. For reasons of clarity, only representative local

reduced temperature gradients versus z coordinate are presented in Fig. 7. Note that no temperature gradient was observed when heating water, except a slight overheating in the inlet zones ($z=30$ and 90 mm). This slight overheating could be explained by the presence of re-circulation zones in this area (Ayadi, Chopard, Berthou, Fillaudeau, & Leuliet, 2003). Instantaneous overheating was observed when switching from water to the fouling model fluid. This could be explained by the viscosity change. Indeed, when the experiments started with water, the electrode surfaces are clean and the flow regime was close to the turbulent regime ($Re=1900$), so that no temperature gradient was observed. When switched, viscosity changed and the flow regime became close to a laminar regime ($Re=65$). Therefore, a low velocity close to the wall was observed, which then lead to a slight overheating. After the switchover, the local temperature gradient curves present three different evolutions:

- Depending on the fouling experiment and the thermocouple location, the temperature gradient remained almost constant for a short period.
- Linear evolutions were observed after this short period until a high temperature gradient value was reached.

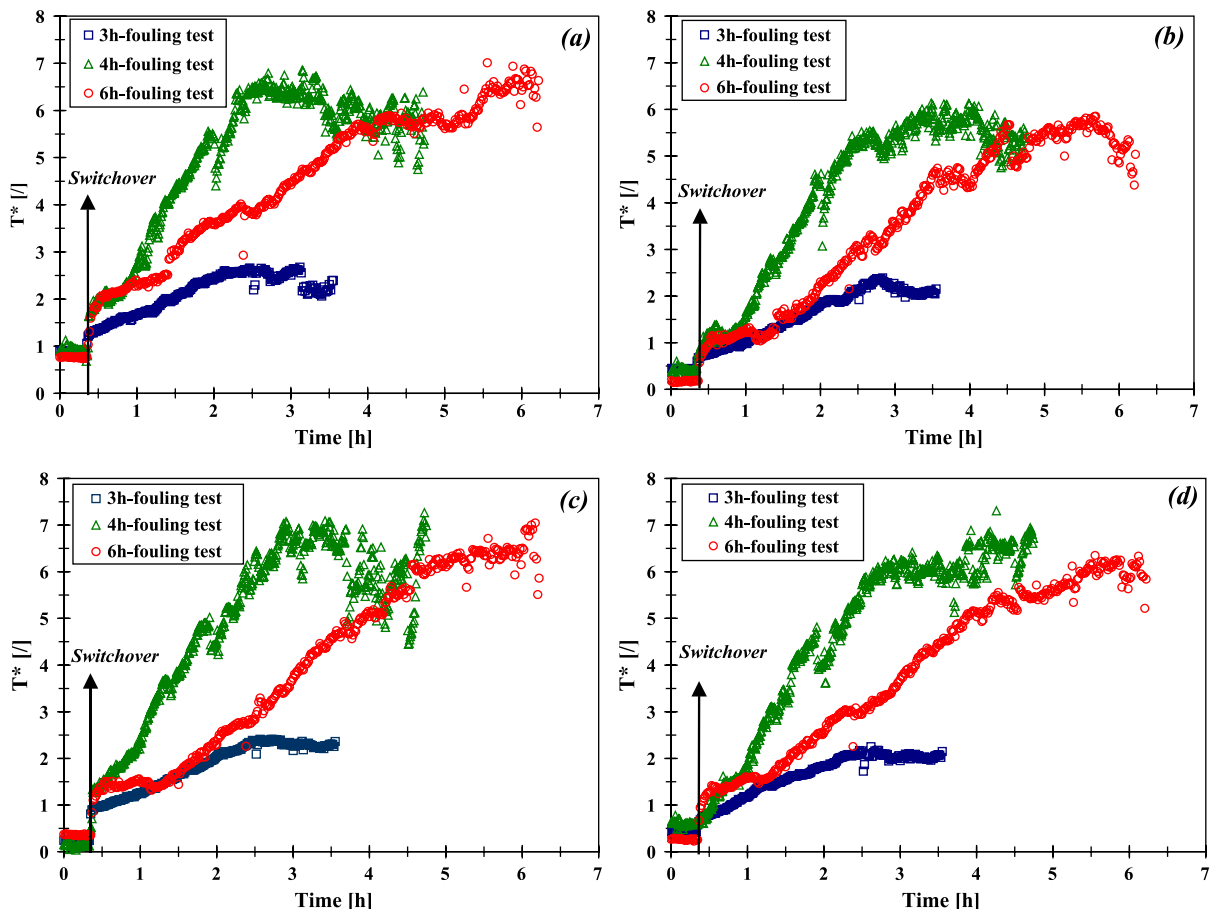


Fig. 7. Reduce local temperature gradient evolution versus z coordinate: (a) $z=30$ mm, (b) $z=90$ mm, (c) $z=150$ mm and (d) $z=210$ mm.

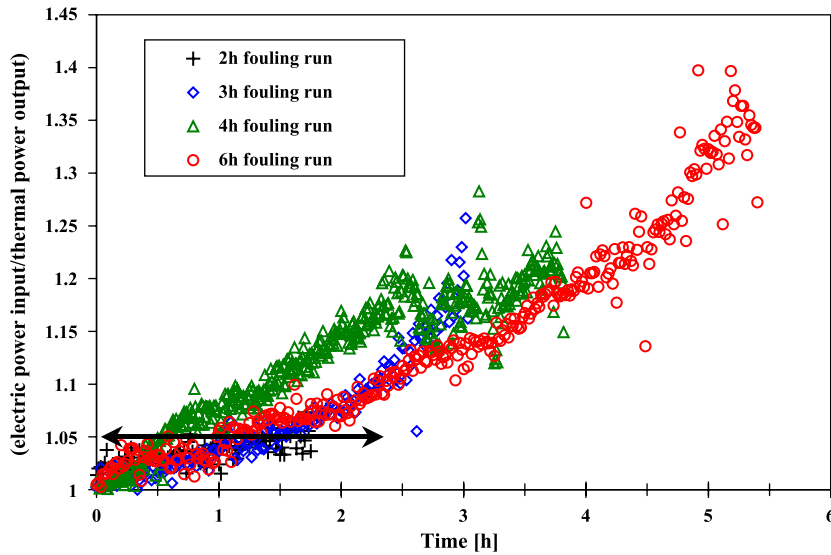


Fig. 8. Power balance during fouling experiments.

- At the end of the 4- and 6-h fouling experiments, asymptotic shapes and local perturbations of temperature gradients were observed.

4. Discussion

The results obtained in this study clearly show that as with conventional heat exchangers, continuous ohmic processing of whey protein solution generates fouling layers on the electrode surfaces. A classical fouling evolution was obtained: a first period with low deposit quantities and an exponential evolution after this period. Deposit layers on the heat transfer surfaces of conventional heat exchangers act as a resistance to the heat transfer. However, in the case of ohmic technology, heat is generated in the product and, consequently, deposit layers on the electrode surfaces act as

an additional electrical resistance. Evolution in the electric power consumed during the fouling experiments could be explained by one of these three hypotheses:

- The first hypothesis and the most obvious place for energy to go is the electrolysis phenomena. This hypothesis is unlikely to be valid because of the current frequency (50 Hz) and the electrode materials (Berthou & Aussudre, 1999) used in this study (titan electrodes).
- The second hypothesis could be formulated by the dissipation of this additional electric power into the deposit layers to a point where the conduction/convection loss into the fluid and the outlet temperature will increase. To check this hypothesis, the power balance (electric power input/thermal power output) of the process is presented in Fig. 8. This figure shows clearly that for the first period of the runs, the electric

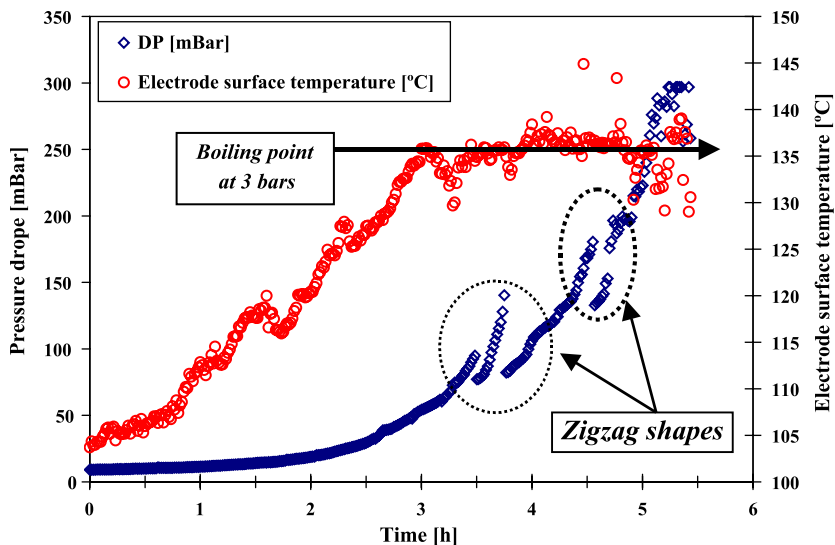


Fig. 9. Pressure drop and electrode surface temperature evolutions during the 6-h fouling run.

power input is almost equal to the thermal power output (less than 5%). When the deposit takes place on the electrode surfaces, the electric power input increases linearly and the thermal power output remains constant. This clearly shows that the second hypothesis is highly unlikely.

- The third hypothesis, which seems to be the most likely, could be formulated as follows: during the first period of the run, the fouling process starts and the deposit layer thickness is insufficient to enable any electric power to be dissipated within it to be detected. After this step, the fouling build-up starts, progressively receiving more and more electric energy, so that its temperature continuously increases until boiling point is reached. After that, a local perturbation takes place due to the boiling process and the change in deposit adhesion level (deposit removal). Fig. 9 shows pressure drop and a local temperature gradient obtained after a 6-h fouling run. These curves show that the “zigzag” shapes in the pressure drop curves and the asymptotic evolution of the temperature gradient appear when electrode temperatures reach almost 135 °C. This temperature corresponds to the boiling point at 3 bar.

5. Conclusions and future works

The study of a rectangular continuous ohmic unit under whey protein fouling shows that as with conventional heat exchangers, continuous ohmic processing of whey protein solution generates fouling layers on the electrode surfaces. As soon as deposit on the electrode surfaces takes place, it acts as an additional electrical resistance and is subject to the Joule effect. The dissipation of the electrical energy into the deposit layers causes an increase in its temperature until boiling point is reached and boiling process and deposit removal start. It would appear that the evolution in electrical power consumption is very sensitive and provides an accurate means of detecting and monitoring fouling in the ohmic cells before boiling point is reached.

Based on this experimental study, future works will be dedicated to the improvement of the electric measurements (local measurement) and the development of a model for deposit thickness prediction, using electric evolution parameters.

Nomenclature

Y	cell length, mm
Z	cell height, mm
X	cell thick, mm
x	x-axis coordinate, mm
y	y-axis coordinate, mm
z	z-axis coordinate, mm
Re_g	generalized Reynolds number

T	bulk temperature, °C
$T(y,z)$	bulk temperature in the fourth cell at y,z coordinate, °C
$TC(y,z)$	fourth electrode surfaces temperature at y,z coordinate, °C
$\Delta T(y,z)$	temperature variation between bulk and electrodes surfaces at y,z coordinate, °C
$T^*(y,z)$	reduced temperature variation between bulk and electrodes surfaces at y,z coordinate
n	flow behaviour index
k	consistency index, Pa s ^{<i>n</i>}
σ	electrical conductivity, mS cm ⁻¹

Subscript

i	inlet
o	outlet
1, 2, 3, 4 and 5	cell numbers

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