Refereed Proceedings

Heat Exchanger Fouling and Cleaning:
Fundamentals and Applications

Engineering Conferences International *Year* 2003

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HEAT TREATMENT IMPROVEMENT OF DAIRY PRODUCTS VIA OHMIC HEATING PROCESSES : THERMAL AND HYRODYNAMIC EFFECT ON FOULING

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ABSTRACT

Fouling and consequently cleaning of heat exchangers in the dairy industry are nowadays a significant issue still not solved for the processing of quite a large variety of products. Ohmic heating processes for food products a priori are well known to minimize the fouling phenomenon due to a totally different way of heating food by admitting the current directly in the product. Such a technology could be a good alternative to counter both fouling and cleaning aspects when pasteurizing or sterilizing dairy desserts known to generate large amounts of soil on heated surfaces. The aim of this experimental study was to investigate the respective roles of both the hydrodynamic parameters and surface electrode temperatures on the fouling phenomenon when heating a simple dairy mix designed to mimic dairy product behaviors.

INTRODUCTION

The food industry in Europe, in particular the dairy industry, is faced with a very large environmental problem due to fouling of equipment during processing. In addition to the cost of effluent disposal, a large amount of money could be added for plant shut down for cleaning. As yet no solutions to such an issue can be given. In indirect heat transfer technologies (plate heat exchangers, tube heat exchangers) the presence of a fouling layer dramatically decreases the thermal performance and therefore the flow arrangement throughout the heat exchangers could deeply increase the fouling phenomenon. Fouling of plate heat exchanger treated milk has already been extensively investigated (Lalande et al., 1985; Leuliet, 1988; René et al., 1991; Belmar-Beiny et al., 1993; Delplace et al., 1995 and Changani et al., 1997). Recently Grijspeerdt et al., (2003) discussed the crucial effect of the hydrodynamic parameters on the fouling phenomena encountered in plate heat exchangers. All of these studies deal with the role of the plate design on the flow arrangement in the heated channels. Therefore any limitation of surface fouling is mainly due to the micro-mixing importance known to limit the attachment of the denatured whey proteins onto heated surfaces. Despite these studies, indirect heat technologies are still limited by fouling phenomena.

Development of new technologies for continuous thermal food treatment are still of great industrial and scientific interests. Ohmic heating is one of these new technologies, which consist of the direct passage of electric current through the product. Permanent motion of electrical charges creates heat in the product in agreement with Joule's law (Berthou and Aussudre, 2000). According to this principle ohmic technology could be considered as a purely bulk heating method.

Such a principle is well known and was first proposed by Anderson & Finkelstein (1919), and Prescott (1927) for milk heating. Unfortunately, the technology did not succeed at that time because of technical limitations (electrode materials, process regulation…). During the past 10 years, new improved materials and equipment design for ohmic heating have been available (Amatore et al., 1998 and Roberts et al., 1998). However most of the studies have concerned the sterilization of food products containing particles (Fryer et al., 1989; De Alwis et al., 1989; Wadad et al., 1996; Sudhir et al., 1998; Benabderrahmane et al., 2000; and Eliot-Godéreaux, 2001). A few scientific and technical studies (Ould Elmoktar, 1992 & Marcotte 1999) were dedicated to continuous food fluid treatment by ohmic heating.

The aim of this experimental study was to investigate the respective roles of both the hydrodynamic parameters and surface electrode temperatures on the fouling phenomenon when heating a simple dairy mix designed to mimic dairy dessert behaviors. The heat exchanger consisted of plates and frames similar to conventional plate heat exchangers, electrodes being inserted between plastic insulating spacers.

The first part of this paper was focused on the improvement of the flow arrangement to minimize the fouling phenomenon as demonstrated in plate heat exchangers. In a second part the role of the electrode surface temperature on the deposit formation was discussed.

MATERIALS AND METHODS

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 (L = 240 mm; *l* = 75 mm and thickness =15 mm), the electrodes constituting side surfaces. Figure 1 presents the schematic diagram of the ohmic heater.

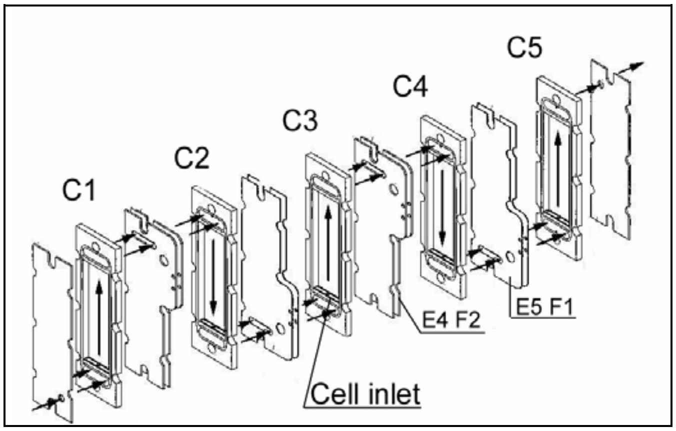


Figure 1: Ohmic heater apparatus.

Two inlet designs for the cells were proposed, as shown in Figure 2, to minimize any negative effect on the flow arrangement inside the ohmic heating cells.

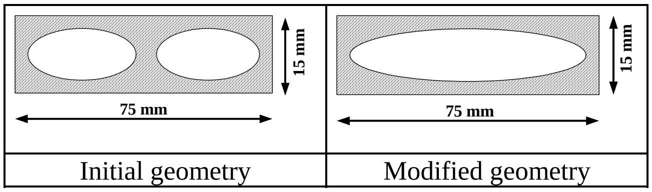


Figure 2: Geometry of cells inlets.

Cell number 4 was instrumented by 16 thermocouples located on the surface of the two electrodes (E4F2 and E5F1). The location of these thermocouples is presented in Figure 3.

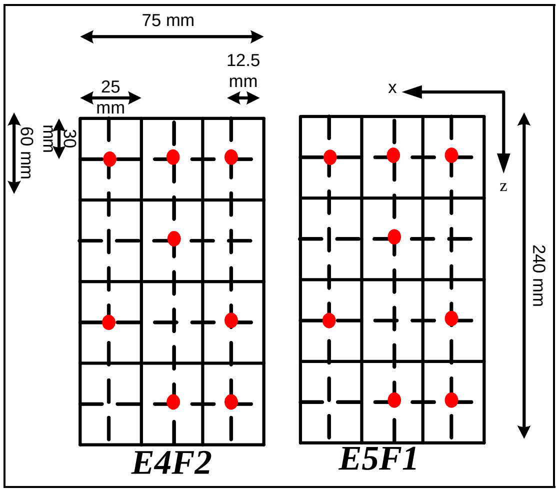


Figure 3: Thermocouple location on cell 4 (E4F2 and E5F1 refer to Figure 1).

Flow visualization with color tracer

The flow visualization study was carried out by means of a rig composed as follows: (i) a storage tank (200 l), (ii) a transparent model frame, (iii) a color tracer injection system, (iv) a digital video recorder (Philips PCVC 740K) connected to a computer for image analysis.

The flow rate was maintained at 300 l h^{-1}. Turbulent and laminar flow conditions were obtained using two model fluids (Ayadi, 2001): water (Re = 1900) and sucrose solution (55% w/w; Re = 63). All the flow visualization tests were carried out at 16°C.

One ml of color tracer was injected when steady state flow conditions were reached. The color tracer distribution in the flow was directly observed in the ohmic cells.

2D Velocity measurements

Quantitative velocity measurements were carried out with a Particle Image Velocimetry (PIV) technique. The PIV system included several main components (Figure 4): light source, light sheet optics, digital cross-correlation camera (Kodak Mega plus ES.1.0), synchronizer, computer and acquisition software. The light source included a crystal harmonic generator to produce the doubled- frequency green light. The laser beam diameter was 3 mm. With the light sheet the laser beam could be expanded into a fan-shaped light about 1 mm thick. An abundant quantity of buoyant particles was suspended in the installation (Dantec Measurement Technology; France, diameter 15 microns and density = 1400 kg m^{-3}).

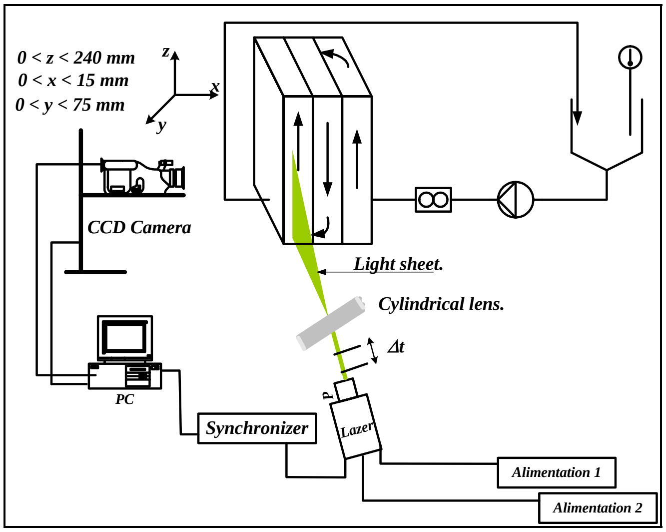


Figure 4: PIV measurement: pilot plant.

The operating conditions were the same as those used for the visualization tests.

Fouling experiments

The pilot-plant test rig used in the fouling experiments is shown in Figure 5. It consists in three parts: (i) a preheating zone with a plate heat exchanger (Alfa-Laval VicarbV7 type, 10 passes; 1 channel per pass), (ii) a heating zone with five ohmic cells, and (iii) a cooling zone with a tubular heat exchanger. In addition, a storage tank (2 m^3), a constant level tank and a volumetric feed pump were necessary to perform the tests. A manual throttling valve at the outlet allowed us to control the backpressure.

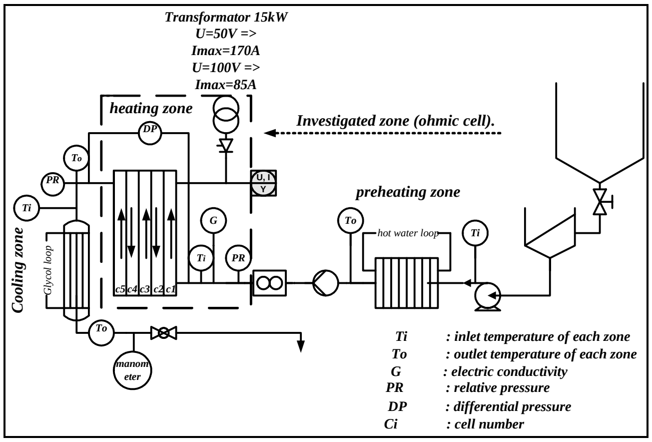


Figure 5: Fouling pilot-plant test rig.

The flowrate was measured using an electromagnetic flowmeter (Khrone, type: IFM 10807K). Temperatures were measured by means of platinum resistance probes (Sensor-Nite, type: Pt 100) placed at the inlet and outlet of each zone. A differential pressure sensor (Schlumberger, type: D) was used to follow the pressure drop increase in ohmic cells. The electric power supply was determined using voltage measurements between the second and third electrodes (Voltmeter 0-250V, Sineax U504, Chauvin Arnoux) and the intensity of the second phase of the electric transformer (Ammeter 0-200A, type AC22, Camille Bauer).

All signals were treated (module SCX-1) and collected using a data acquisition card (AT-MOI-16E-10). A software driver (Ni-DAQ) provided the configuration and control of data acquisition system. Data were stored using Labview software systems.

The model fluid used in the fouling experiments was an aqueous solution of β-lactoglobulin (1% w/w; Armor Proteins) and xanthan (0.2% w/w Degussa, Texturant Systems). The choice of this model fluid is based on the fact that the heat denaturation of the β-lactoglobulin protein governs the milk deposit formation when the temperature is higher to 75°C (Lalande et al., 1985). The xanthan gum, a dairy product thickener, was added to modify the viscosity of the model fluid.

The physical properties of the fluid remained constant:

-a shear thinning behavior corresponding to a flow behavior index n of 0.62 at 75°C,

-an electric conductivity varying linearly with the temperature (equation (1)):

$$\sigma = 1.35 + 0.0383 \cdot (\theta(°C) - 20) \tag{1}$$

Where σ is in mS cm^{-1} and the temperature between 4 and 100°C.

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

The fouling tests were carried out for different experimental times (1, 2, 3 and 6 hours).

RESULTS & DISCUSSION

Flow visualization

Figure 6, shows two representative pictures of the flow field in the cells with the two inlet designs. This technique of flow visualization was widely used to characterize the flow structure (Hugonnot, 1995; Van Santen et al., 2000 and Zitny and Thyn, 2001). Generally a laser sheet was used to illuminate the flow, allowing the visualization of different plans from the flow. In our case the entire cell is illuminated, so that the wall flow was visualized. The flow structure in the ohmic cells showed that the flow pattern is extremely sensitive to the entry design. It is clear that a large inlet design would improve the flow repartition in the cells, as clearly seen in Figure 6 under laminar flow conditions. However in turbulent flow regimes this issue was not as critical.

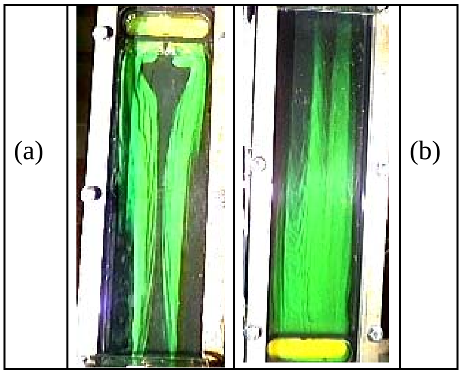


Figure 6: Flow pictures (Re = 63); (a): downward pass with initial inlet geometry; (b): upward pass with modified inlet geometry.

Flow structure and deposit profile

Quantitative measurements of the velocity distribution have been obtained by Particle Image Velocimetry. In Figure 7, two reconstructed velocity fields are plotted at the same Reynolds number (Re = 63). Velocities in the middle of the cell (100 < z < 150 mm) could not be measured because of optical accessibility.

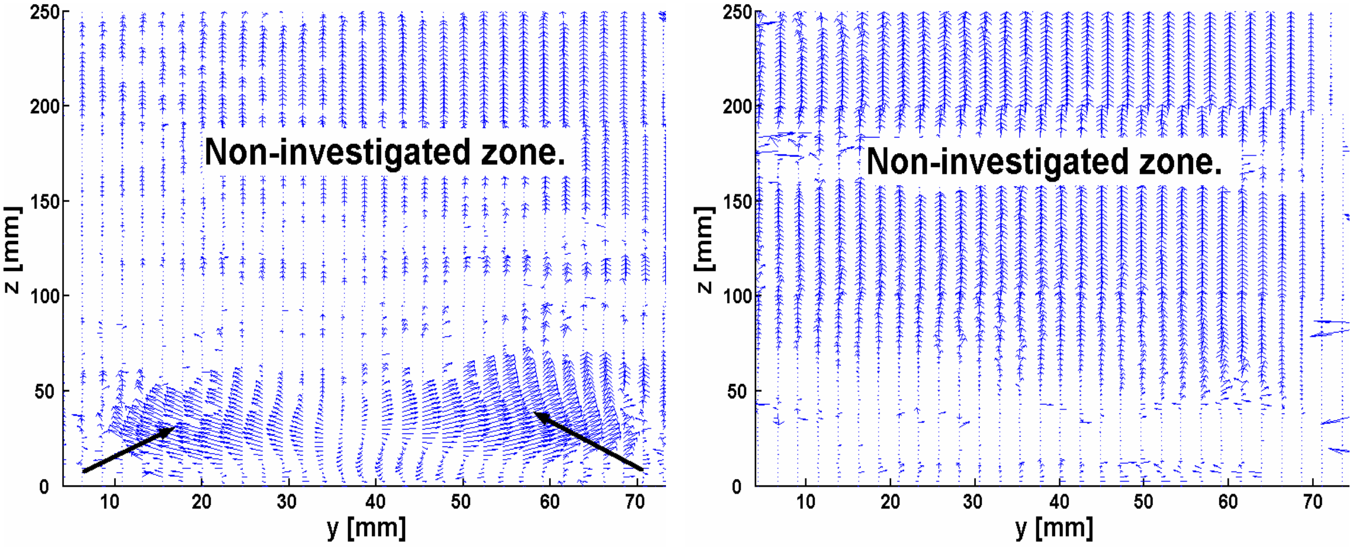
As observed previously in the laminar flow regime, the velocity vector map exhibited non-homogenous aspects in the areas between z (0 to 70 mm) and y between 1 to 30 and 50 to 70 mm.

The PIV measurements reinforced the conclusions drown at first from the flow visualization tests whatever the location in the width of the channel (x = 0.5, 3.5, 7.5, 11.5 and 14.5 mm). Flow instabilities clearly observed in Figure. 7 (a) at a Reynolds value of 63 would likely be due to re-circulation phenomenon at z from 0 to 50 mm. The shape of the initial inlet geometry as shown in Figure 2 would largely induces the flow instability even in such laminar flow conditions. The more simple is the opening shape the more stable the flow. Further investigations (3D PIV measurements) should be conducted in order to determine the 3D-velocity field in the cell with the modified opening geometry.

In Figure 8, a representative picture of electrode surfaces after the fouling tests are shown. Global electrode views and a focus on the entrance areas are presented.

Although the average temperature at the cell entrance is largely lower than that of the exit, we noted that the major part of the deposit was located at the entrance areas; moreover, the structure of the fouling layer profile is clearly the same as that of the flow field.

This deposit distribution can easily be explained by the presence of the re-circulation zones at the cell entrance. Such results confirmed those obtained previously by many authors in plate heat exchangers. Indeed the fluid residence time in the re-circulation zones would be higher than the average residence time, therefore the Joule effect in the product would be enhanced leading a higher amount of denatured β-lactoglobulin deposited onto the electrode surface. However, when the micro-mixing is quite high no deposit was observed as shown in Figure 8 (a). Conversely quite an homogeneous fouling layer was observed on electrodes (Figure 8 (b)) without any flow perturbations.



(a) *(b)*

Figure 7: Velocity vectors maps (Re = 63): upward pass (yz plane projection; x = 7.5 mm); (a) initial inlet geometry; (b) modified inlet geometry.

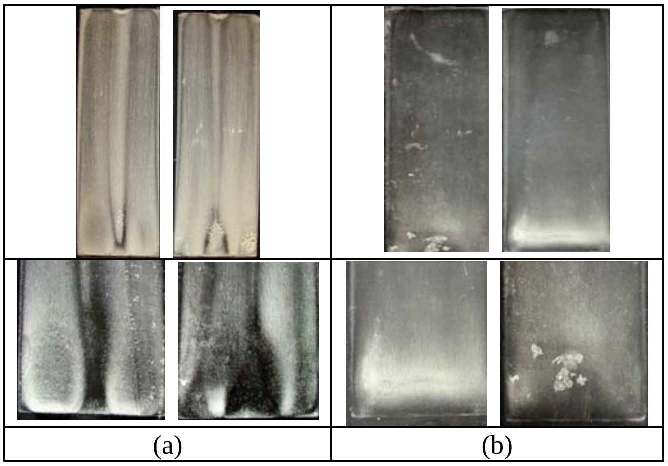

(a) (b)

Figure 8: Electrodes surfaces 2 hours fouling: (a) upward pass with initial inlet geometry; (b) upward pass with modified inlet geometry.

This study shows firstly the strong interaction between the flow field and the deposit profile, as already observed in plate heat exchangers, and secondly the importance of the inlet design on the electrode fouling behaviors in ohmic heating technology.

Local temperature measurements and fouling formation:

To evaluate the temperature variation between the bulk and the electrode surfaces linear variation of the temperature (constant heat flux conditions) and isothermal conditions in the first and the fifth cells (no heating) were assumed.

The temperature variation in the fourth ($0 < y < Y = 75$ mm and $0 < z < Z = 240$ mm) cell was estimated as follows:

Isothermal hypothesis for the first and the fifth cells:
$Ti = Ti_1 = T_{o1} = T_{i2}$ and $To = T_{o5} = T_{i5} = T_{o4}$
Linear temperature profile hypothesis:
For $z = 0$; $T_{i4} = T_i + 2/3\ (T_0 - T_i)$ (2)
And for $0 < z < Z$
$T_{z4} = T_i + (T_0 - T_i) * z/Z$ (3)

The temperature variation is:
$\Delta T\ (y,z) = TC\ (y,z) - T_{z4}(y,z)$ (4)
The reduced temperature variation is:
$DT\ (y,z) = \Delta T\ (y,z) / (T_o - T_{i4})$ (5)

Two fouling tests (3 h and 6 h) were carried out. In Figure 9 the local reduced temperature variations are represented versus operating time. Only the 6 hour fouling test is shown in Figure 9. Separate experiments have shown that the temperature variations were found to be reproducible (± 1.2°C).

The temperature gradient evolved differently with the location on the electrodes. Indeed for z at 30 and 90 mm a weak overheating (switching water/model fluid) was noted, and between 4 and 6 operating hours the reduced temperature rose the maximum (≈ 5). For z at 150 and 210 mm the overheating caused by the switch is more significant but the maximum reduced temperature doesn't exceed 4.

In Figure 10, the electrode surfaces were presented for the fourth cell after two fouling tests (3h and 6h). After 3 hours fouling, the deposit seemed to be quite homogeneous on to the electrode surfaces. However after 6 hours fouling, the deposit layer appeared to be removed and an overheated local zone appeared (cell entrance). These photos emphasized the strong link between the local temperature values and the deposit amount.

The temperature curves (Figure 9) and the fouling pictures (Figure 10) show the existence of fouling in the fourth ohmic cell (downward pass). During the first three hours homogenous deposit (Figure 10 (a)) and a constant temperature variation (Figure 9 for $1 < t < 4$ h) were observed. Indeed the deposit layer was not enough significant to perturb the cell function. After this step the temperature variation increased in an exponential manner and the deposit layer thickness was more significant. In this case, the deposit acts as an electrical resistance and it received more and more electrical energy so that its temperature continuously increases.

In addition, surface bubbles were observed on the electrode surfaces (Figure 10 (b); E5F1 z = 210 mm and y = 62.5 mm). According to De Jong (1997), the formation of air bubbles may be enhanced by solubility of air in milk if the local pressure is too low or by mechanical forces that are induced by valves, expansion vessels, free-falling streams (passage in the downward pass). Jeurnink (1995) suggested that air bubbles in milk encourage fouling only if it forms bubbles on the heating surface, which then act as nuclei for deposit formation. Qui and Dhir (2002) and Peng et al (2001) discussed the impact of air bubbles on the flow pattern, heat transfer and transport phenomenon in a downward surface. Recently Gongora-Nieto et al (2003) have studied the air bubble impact in a dielectric liquid subject to an electric field. It appears obvious that the formation, the detachment and the transport of air bubbles are the main causes of the local thermal instability observed in the forth-ohmic cell after 4 fouling hours.

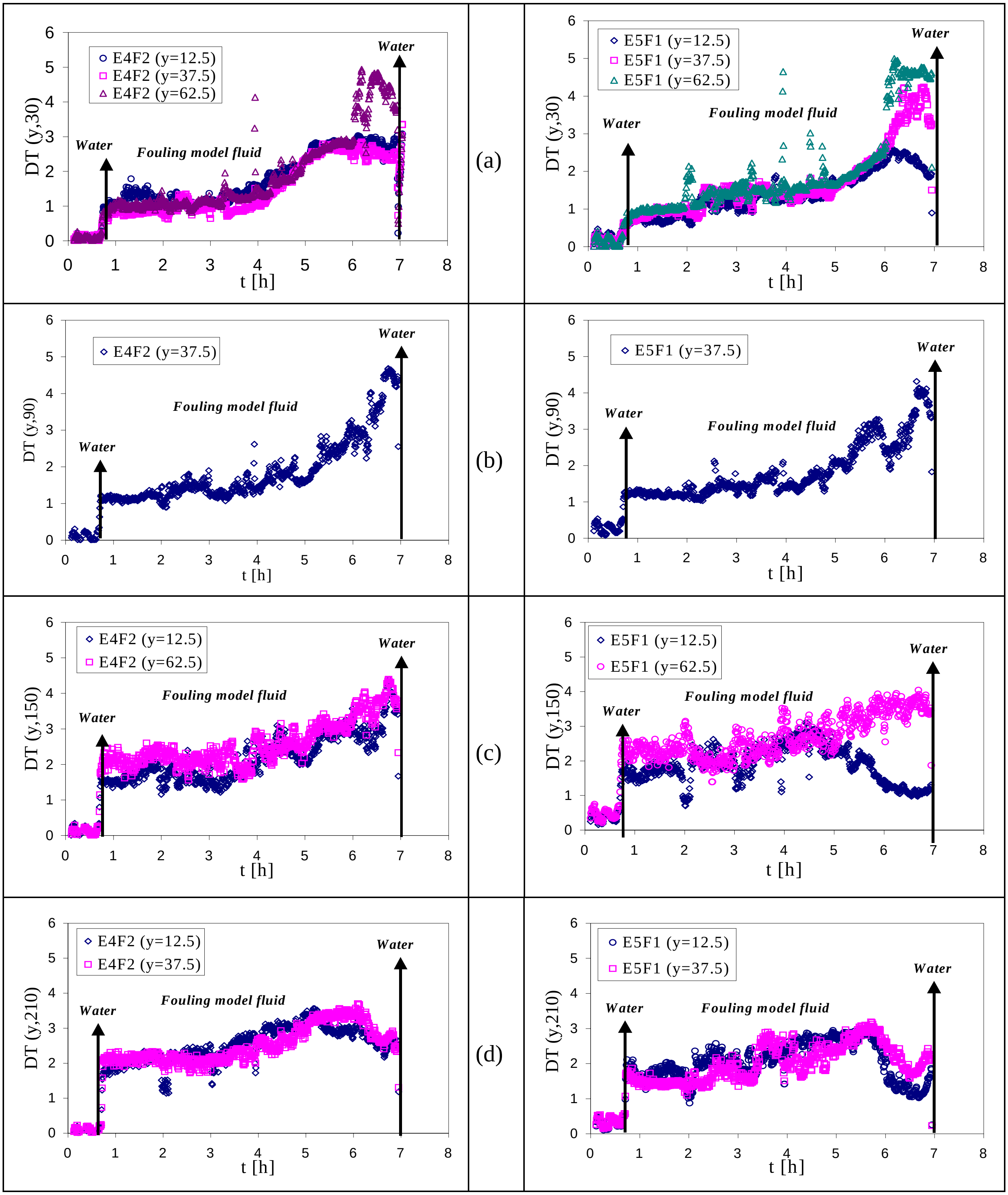


Figure 9: Local reduce temperature variation: (a) z = 30 mm; (b) z = 90 mm; (c) z = 150 mm; (d) z = 210 mm.

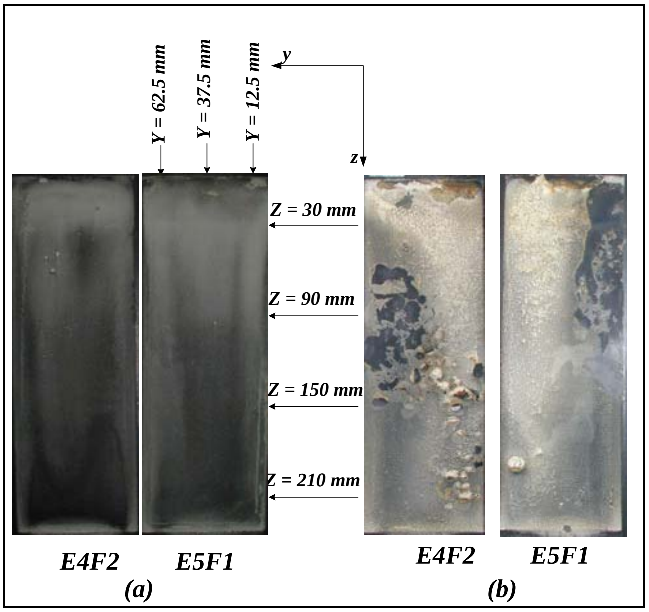


Figure 10: Fourth cell electrode photos: after (a) 3 hours fouling test duration; (b) 6 hours fouling test duration.

CONCLUSIONS AND FUTURE WORKS

As with conventional plate heat exchangers, in the continuous ohmic process the flow patterns play a significant role in generating fouling layers on the electrode surfaces. The optimization of ohmic heater design, in particular inlet cells, could reduce the fouling ability in the laminar flow regime. Wall local temperature measurements for a large duration test (6h) show an increase of the temperature difference between cell walls and the bulk. Such a behavior appeared to be dependent on the ohmic effect in the deposit layer.

After 6 hours fouling, the deposit layer seemed to be removed in some areas due to probably a local deposit overheat (presence of surface bubbles removed from time to time by the flow, nucleation phenomena…).

Based this experimental and essentially qualitative work, future work will be carried out to optimize the flow distribution in the ohmic cells.

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	Reynolds number
T	bulk temperature, °C
T (y,z)	bulk temperature in the fourth cell at y,z coordinate, °C
TC (y,z)	fourth electrodes surfaces temperature at y,z coordinate, °C
ΔT (y,z)	temperature variation between bulk and electrodes surfaces at y,z coordinate, °C
DT (y,z)	reduced temperature variation between bulk and electrodes surfaces at y,z coordinate.
n	flow behavior index.
σ	electrical conductivity, mS cm^{-1}

Subscript

i	inlet
o	outlet
1,2,3,4 and 5	cells number

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ACNOWLEDGEMENT:

The authors gratefully acknowledge the financial support from Alfa Laval Vicarb and Electricité de France. Our gratitude should also be addressed to Mr. Lebouché , Mr. Gradeck and Mr Fillaudeau for their contribution to the PIV measurement.