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FOULING MONITORING DURING OHMIC HEATING OF DAIRY PRODUCTS WITH A CELL JET

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Abstract: The development of alternative technologies like direct Joule effect heater to pasteurise and sterilise liquid food product in a continuous process is of great scientific and industrial interest. Heat treatment by direct Joule effect exhibits numerous advantages because rapid heating kinetics or homogeneous heat treatment is required. However, fouling of electrode surfaces in this kind of apparatus is extensively problematic compared to conventional heat exchangers. In present study, a new continuous ohmic heating apparatus (Emmepiemme®, Piacenza, Italy) in which an alternative electrical current is applied directly to the falling jet between the two stainless steel electrodes is investigated. Conventional fouling measurements (pressure drop, heat transfer or electrical parameters) could not be used in such heater. Heat treatment of model dairy product is reported and fouling is investigated with an innovative fouling sensor using hot wire technique.

Keywords: Joule effect, ohmic heating, fouling, sensor, jet, heat transfer, dairy product

1. INTRODUCTION

Heat treatment remains the oldest and the most frequently used process in the food industry (heating, pasteurisation, sterilisation, cooking and cooling). To perform this operation, heat exchangers are fundamental equipment. In spite of great improvement in conventional technologies over the last few decades, heat treatment of dairy products remains a complex operation. Firstly fouling occurs during heat treatment and reduces the process performances as well as the duration of the production cycle. Secondly, industrial and legal requirements in terms of sterilisation level involve higher temperatures in order to eliminate all thermal-resistant germs. In this context, the development of new technologies to pasteurise or sterilise food in continuous process by thermal treatment (geometrical modification, joule effect heating, ohmic heating) or by non-thermal treatment (cross-flow filtration, high pressure process, high intensity light emission, radiation, cell lyses) is of great scientific and industrial interests.

Ohmic heating is based on a simple mechanism: to generate heat directly inside the product by Joule effect. It consists of causing an electric current to flow directly through the flowing media between a pair of electrodes. This technique can be applied to liquids containing free ions, and therefore which are electric conductors. Constant movement of electrical charges creates heat in the product according to Joule's law. Heat generation is a direct function of geometry, the electrical conductivity of a given product and voltage. Ohmic heating is a purely volume and direct resistance heating, in opposition to heating by convection from a hot surface heat exchanger. As a consequence, the heat transfer coefficient between the hot wall and the fluid is supposed to be irrelevant as there is theoretically no hot wall. From a fundamental point of view, direct resistance heating of liquids is a complex physical problem in which strong interactions of heat transfer, hydrodynamic and electric phenomena can be observed (Ould-El-Moctar et al., 1993). The non-existence of hot wall should constitute a major advantage for food applications thereby avoiding the degradation of thermo sensitive compounds through overheating (change in taste, undesirable reactions, burning) and reducing the fouling of electrode surface. Other advantages are related to electricity use because energy conversion (electric into heat energy) is close to 100% and the uniformity of heating

is greatly improved. This technology gives a short thermal inertia and fast, simple and precise regulation is possible. Heat transfer is formulated through electric and thermal parameters.

Fouling stands as a complex and misunderstood phenomena. Continuous or batch processes are carried out in food industry and fouling occurs in the equipment with a large widespread of kinetics (from minutes up to years) and propensity (from micrometers up to centimetres). The control and understanding of fouling phenomena is of evident industrial interest: reduction of process performances, energetic consumption and water management. Monitoring fouling during ohmic heating and the consequent cleaning processes can provide useful information for operational decision-makers in dairy products plants. Fouling is usually not visible from outside the industrial processing equipment, and thus can only be ascertained from its effects, such as by measuring heat transfers (Bott, 1995; Lalande *et al.*, 1989) or pressure drops (Burton, 1968; Delplace, 1995) which in the case of small, local deposits may not be significant enough to allow an operational decision to be made. Other sophisticated methods have been developed to monitor fouling such as silicon sensors (Stenberg *et al.*, 1988), micro-strip monitoring technique (Root and Kaufman, 1992), photo-thermal deflection method (Fujimori *et al.*, 1987), optical techniques (Withers, 1996), ultrasonic method (Withers, 1996, Pereira *et al.*, 2006) or flux-meters (Davies *et al.*, 1997). Unfortunately, most of them (i) require important instrumentation; (ii) are not always adapted to non-transparent equipment; (iii) are not compatible with an industrial environment since they are often restricted to laboratory use and (iv) are not adapted to cleaning requirements encountered in the food industry (Janknecht and Melo, 2003).

In present work, a new continuous ohmic heating apparatus, by using fluid jet is investigated. The developed design is based on the elimination of hot surfaces by modifying the product-wall interface. It consists in applying an alternative electrical current directly in the falling jet between two stainless steel electrodes (Ghnimi, 2008). Conventional fouling measurements (pressure drop, heat transfer or electrical parameters) could not be used in such heater. Our study focussed on heat treatment of model dairy product and fouling monitoring with an innovative fouling sensor.

2. MATERIALS AND METHODS

2.1 Ohmic heating cell by fluid jet.

This new continuous ohmic heating apparatus (Emmpiemme®, Piacenza, Italy) includes three modules: heater assembly, power supply and control panel. Heating consists of the application of an alternative electrical current directly to the falling jet between two stainless steel electrodes.

The cell design is based on the elimination of the product-wall interface in the heating zone. The flow domain consists of a cylindrical glass tube ($\varnothing=0.145\text{m}$, length=0,155m, thickness=0.005m) connected to the electrodes; which are tightly held in position using rubber rings and four iron bars with nuts and bolts. In this heating zone the essential temperature rise occurs because the current density in the holding zone is negligible compared to that in the fluid jet. The inlet, a round jet of small cross-section through which liquid leaves from the nozzle tip ($\varnothing=0.013\text{m}$), is connected to the phase. The outlet, a conical receptacle ($h_c=0,045\text{m}$, $\alpha=45^\circ$) through which the liquid is taken out, is connected to the mass. The electric power was applied using a 50 kW generator. This power supply delivers bipolar potential pulses. Electrolysis is prevented by the use of high frequency alternating voltage (up to 25kHz with switching voltage up to 3500V). The delivered tension was measured by a high voltage probe with large bandwidth to ensure that transients and fast signals edges will be captured (Tektronix P6015A, 75MHz, attenuation 1000X, Oregon, USA). The current was measured using a current probe (Pearson, 20MHz, California, USA) with specified rise time which ensures the intact seizure of the transients and the faces of signals of fast rise. For fluid level detection inside the ohmic heater, two load cells were used. The length of the jet is controlled and maintained constant by working two air valves that depressurize or pressurizing the ohmic cell (Ghnimi *et al.*, 2008).

All the experimental parameters were recorded versus time on a data logger (PCMCIA type II) connected to a computer (Eurotherm Chessel 4180M type, West Sussex, UK).

2.2 Experimental set-up and operating conditions.

The pilot-plant test rig used in fouling experiments is shown in Figure 1. It consisted of three parts: (i) a preheating zone with a conventional PHE, (ii) a heating zone with the ohmic heating cell and (iii) a cooling zone with a tubular

heat exchanger. In addition, a storage tank (2m³), a constant level tank and a volumetric feed pump (PCM Moineau, Vanves, France) were necessary to perform the experiments. A manual counter-pressure valve at the plant-outlet allowed the pressure in the pilot-plant to be maintained at 2bar. 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 $\pm 0.1^{\circ}\text{C}$ for the platinum resistance probes and $\pm 0.3^{\circ}\text{C}$ for the thermocouples. Relative pressure was measured with manometers (JUMO, type 4AP30, Fulda, Germany) at the inlet and outlet of each zone with a precision of 0.1%

An aqueous solution of native whey proteins (1% wt/wt; Armor proteins, France) with chloride sodium (0.5% wt/wt) in water, were formulated to study deposit thickness evolution in fouled ohmic cell. The composition of the whey protein powder was essentially β -lactoglobulin (more than 65% w/w), α -lactalbumin (less than 10% w/w), fat (less than 5% w/w) and lactose (less than 10% w/w). 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 *et al.* (1994), the use of such a model fluid enables reproducible fouling experiments. During experiments, the flowrate was fixed at 206L/h and the inlet and outlet temperatures of the ohmic heater were fixed respectively at 62°C and 91°C.

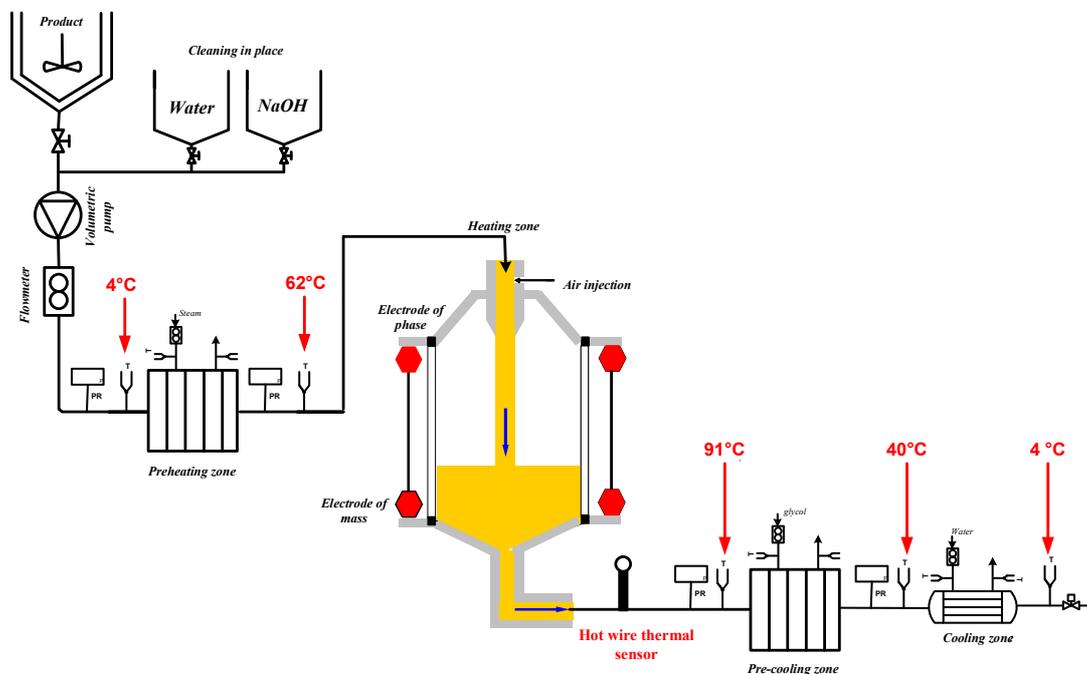


Fig. 1. Scheme of experimental set-up – Temperature profile of fluid .

2.3 Fouling sensor.

During the last two decades, the hot wire technique has been scrutinized and validated as an accurate method of controlling milk coagulation or gelation of macromolecular food constituents and several scientific works have been published on this subject. However investigations have been limited to static fluids (batch process) under isothermal conditions. In the same way, no direct measurement of the wall temperature at the fluid-product interface has been carried out. In the present work, a thermal sensor, based on the hot wire sensor associated with heat flux, bulk and wall temperature measurements (Fillaudeau *et al.*, 2005), was investigated in order to monitor fouling phenomena in a continuous ohmic heating system. The thermal sensor was made of two platinum probes (Heraeus, probe UE go2327, class B, L=25mm, \varnothing =3mm) and one thermocouple (Thermo-electric, type K, ref. MTS-56025-2500-1500, \varnothing =250 μm). One platinum probe acted as a sheathed hot wire sensor. A platinum wire with ceramic and stainless steel sheathes ensured the electric insulation between the stainless and the platinum hot wire. The thermocouple was

stuck half way along the platinum probe and measured the wall temperature at the sensor – product or deposit interface. The second platinum probe measured the bulk temperature. The hot wire was connected to a direct current generator (0-50mA). The electric current (I), potential (U), bulk temperature (T_b) and wall temperature (T_w) were recorded and the heat power (P, 0-250mW) and the flux (ϕ , 0-2kW/m²) calculated (Fillaudeau, 2006a). An overview of the heat transfer in the probe and the product leads to a calculation of the evolution of the deposit thickness in the ohmic cell as follows:

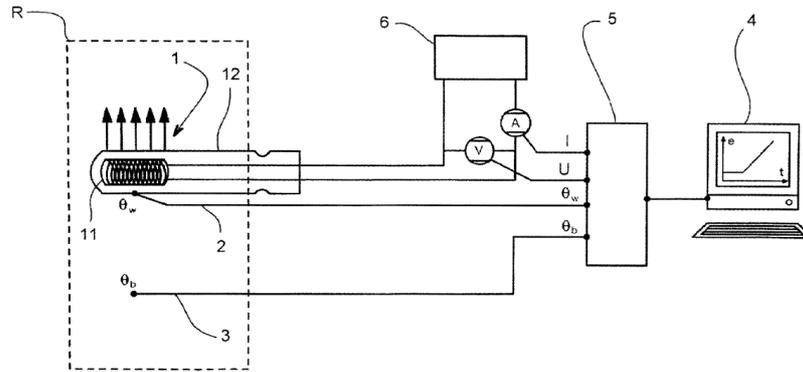


Fig. 2. Principle of fouling sensor.

$$\Delta T = T_w - T_b = \frac{P}{2 \cdot \pi \cdot L} \cdot \left(\frac{1}{h \cdot (r + e_{d-HW})} + \frac{\text{Ln} \left(1 + \frac{e_{d-HW}}{r} \right)}{\lambda_d} \right) \quad (1)$$

Each sensor signal (I, U, T_w , T_b) was converted using a specific conversion card (Sté Analog Device, module 6B) and recorded on a computer (PC type 386) with specific acquisition software. After calibration and in our experimental conditions, the expected precision were for temperature, $\pm 0.5^\circ\text{C}$, electric current, $\pm 0.1\%$ and potential, $\pm 0.1\%$ respectively.

3. RESULTS AND DISCUSSION

Fouling experiments were performed under specified operating conditions. Typical fouling conditions are shown in Fig. 3 and hydrodynamic, thermal and electric variables are reported in Table 1. Ohmic heating presents several advantages, but for efficient implementation in the food industry, different factors such as fouling propensity have to be considered and accurately quantified. However, ohmic heating within a fluid jet makes fouling measurement at electrodes surface almost impossible. Experiments demonstrate that pressure drop measurements are inconsistent. Heat dissipation coefficient, R_{hCO} (Fillaudeau et al., 2006b) based on electrical and thermal power will be significant for ohmic heater with large electrode area but is inaccurate in cell system.

Table 1 hydrodynamic, thermal and electric variables in the ohmic heating cell

Hydrodynamic variables	Pressure drop in the ohmic cell, (mbar)	5.70 ± 0.15
	Flowrate, ($\text{l}\cdot\text{h}^{-1}$)	206 ± 3
Thermal variables	Inlet Temperature, ($^\circ\text{C}$)	$62 \pm 0.4^\circ\text{C}$
	Outlet Temperature, ($^\circ\text{C}$)	$91 \pm 0.4^\circ\text{C}$
Electric variables	Tension, (V)	3500 ± 10
	Intensity, (A)	2.15 ± 0.02

Fig. 4 presents the calculated thickness of protein deposit generated by model dairy product. Initial value (with water) is close to zero in agreement with measurement precision. Fouling mechanism started instantly in the ohmic cell and holding tube without induction period in opposition with conventional heat exchangers (Delplace, 1995). The thickness evolved linearly up to 2.2mm within 4 hours. However, such deposit thickness remains negligible in cell system and can not significantly modify hydraulic, electrical and thermal performances of cell apparatus. A

visual observation of ohmic heater showed that there was substantial fouling at mass electrode surface. No protein deposit was observed on phase electrode. This trend was attributed to (i) comparatively higher temperature (91°C) at mass electrode and (ii) strongly different flow pattern between inlet (nozzle) and outlet (conical receptacle). Thereby, fouling and cleaning during ohmic heating of dairy products, even with jet cell, should be evaluated and on-line monitored with an adapted method.

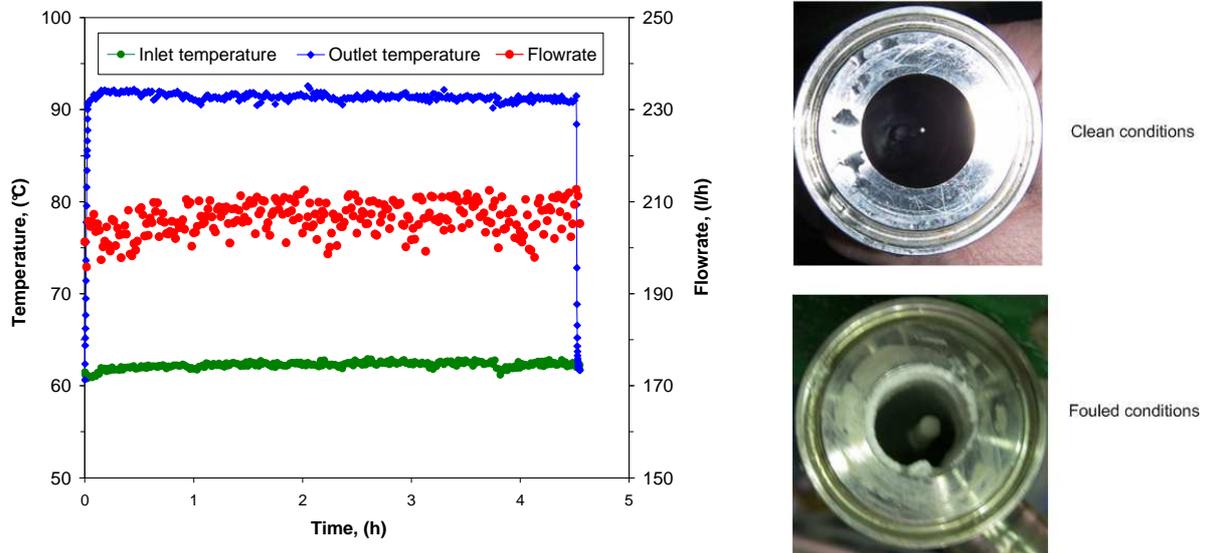


Fig. 3. Evolution of inlet/outlet temperatures and flowrate in the ohmic heating cell versus time - Pictures present the thermal sensor under clean and fouled conditions.

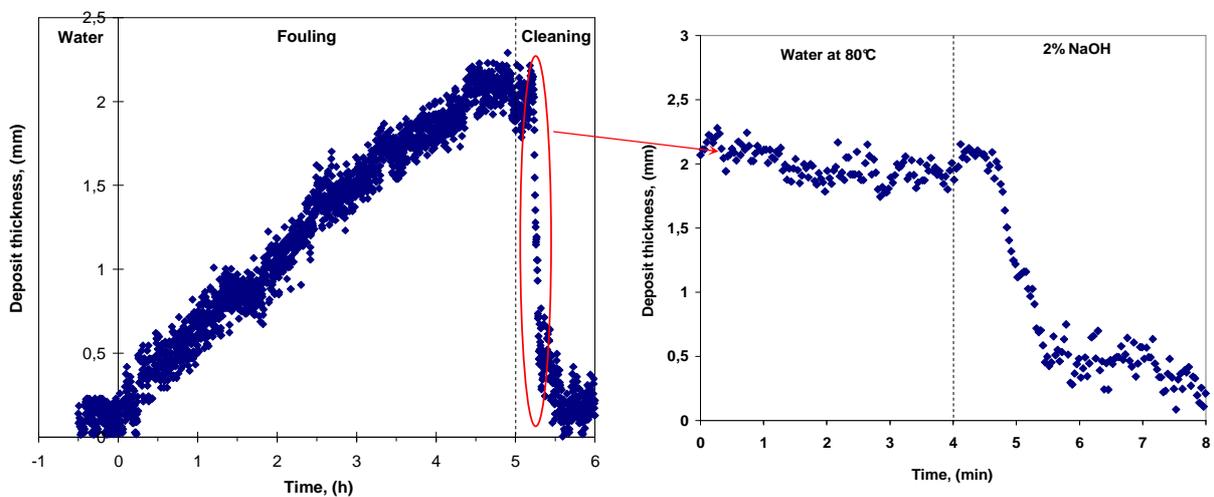


Fig. 4. On-line fouling and cleaning monitoring by hot wire method at the outlet of the continuous ohmic heater.

Although the online monitoring of fouling kinetics through global or local measurement is essential in dairy process industry; the cleaning procedure and therefore the elimination of the deposit formed is just as important. Cleaning in Place (CIP), costly in terms of both money and time (water and chemical consumption, production stop, energy consumption, etc.), should remove foreign substances from equipment surfaces so that they are physically, chemically and biologically cleaned. However, the cleaning mechanisms are poorly understood, modelled and controlled. Fig. 4 illustrates the monitoring of cleaning step (water rinsing and alkaline solution at 80°C) through a local measurement (fouling sensor). The calculated thickness of fouling is plotted versus time. A sharp decrease of

thickness is noticeable which demonstrated a high kinetics of deposit removal. In our investigated condition, a single chemical cleaning using 2%wt/wt caustic solutions was sufficient to completely remove macro-fouling.

4. CONCLUSIONS

The development of alternative (thermal or non-thermal) technologies to pasteurise or sterilise liquid food in a continuous process is of great scientific and industrial interest. Although direct Joule effect technology appears both simple and advantageous, several difficulties are encountered in its application. In fact, if a temperature gradient between bulk and electrode surface or if deposit at electrode surface takes place, electrode temperature starts rising. The Joule effect inside the deposit causes overeating of the wall that makes fouling spiral out of control, because the fouling mechanism undergoes a "snowball effect". The fouling build-up causes an increase in the electric power required due to the fact that the deposit on electrode surfaces acts as an additional electrical resistance. In this study, a fouling sensor based on the hot wire technique was validated as an accurate method of on-line monitoring fouling and cleaning phenomena during continuous ohmic heating by using fluid jet. In addition, this experimental investigation highlights the potential application of this innovated ohmic heating technology for dairy product stabilisation. Further studies must be initiated like analysis of the kinetics of protein deposit formation according to operating conditions such as inlet temperature or flow regime in the ohmic cell.

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