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# On-line local thermal pulse analysis sensor to monitor fouling and cleaning: Application to dairy product pasteurisation with an ohmic cell jet heater

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ABSTRACT

In the process industry, fouling is considered as a complex (sometimes partially known and identified) phenomenon. In this paper, a fouling sensor (FS) based on local differential thermal analysis is scrutinized and we report the comparison of two operating modes, steady (STR) and periodic (PTR) thermal regimes. Moreover, the development of alternating technologies like direct Joule effect (ohmic) heating to pasteurise and sterilise liquid food products 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 much more problematic than in conventional heat exchangers. In the present study, a new continuous ohmic heating apparatus (Emmepiemme®, Piacenza, Italy) in which an alternating electrical current is applied directly to a jet falling between two stainless steel electrodes is investigated during pasteurisation of a dairy product. Conventional fouling measurements (pressure drop, heat transfer or electrical parameters) cannot be used in such a heater. Fouling and cleaning phases are monitored with fouling sensor and fouling quantified.



## 1. Introduction

Heat treatment remains the oldest and the most frequently used operation in the food industry notable including heating, pasteurisation, sterilisation, cooking and chilling). To perform these operations, sensors, actuators and heat exchangers are fundamental equipment. In spite of significant improvements in conventional technologies over the last few decades, heat treatment of dairy products remains a complex operation. Firstly, fouling occurs during heat treatment, reduces process performance and alters the duration of the production cycle. Secondly, industrial and legal requirements in terms of sterilisation level involve high temperatures to eliminate even heat-resistant germs (Scheldeman et al., 2006) to ensure safety and security of consumers. In the dairy industry, Milk Hygiene Directive 92/46/EEC defined precisely raw matter quality and processing conditions. For sterilisation, typical time–temperature combinations applied in the dairy industry are holding time of the order of few seconds at temperatures ranging from 135 to 150 °C. In this context, the development of new, alternative or modified technologies to pasteurise or sterilise food in a continuous process by heat treatment (geometrical modification of tubular or plate heat exchanger, indirect or direct joule effect heating) or by non-thermal treatment (cross-flow filtration, high pressure process, high intensity light emission, radiation, cell lysis) is of great scientific and industrial interest.

Meantime, fouling is a complex (sometime partially known and described) phenomenon in most food and bioprocess industries.

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**Nomenclature**

| | |
|---|---|
| $a$ | thermal diffusivity, $m^2/s$ |
| $A$ | amplitude, °C |
| Cp | specific heat capacity, J/(kg K) |
| $d$ | diameter, m |
| $E_A$ | activation energy, J/mol |
| $f$ | frequency, Hz |
| Fo | dimensionless time (Fourier number), / |
| $h$ | convection heat transfer, $W/(m^2 K)$ |
| $I$ | electrical current, A |
| $k$ | kinetics constant, L/(g s) |
| $L$ | length, m |
| $P$ | heat power, W |
| $q$ | volume heat generation, $W/m^3$ |
| $r$ | radial coordinate, m |
| $R$ | electric resistance, Ω |
| $R_{th}$ | deposit thermal resistance K/W |
| $S$ | surface area, $m^2$ |
| $t$ | time, s |
| $T$ | temperature, °C |
| $T^*$ | dimensionless temperature, / |
| th | thickness, m |
| $U$ | overall heat transfer coefficient, $W/(m^2 K)$ |
| $V$ | electrical potential, V |
| $x$, $z$ | dimension variable, m |

*Greek letters*

| | |
|---|---|
| $\alpha$ | angular coordinate, rad |
| $\beta$ | coefficient, 1/°C |
| $\gamma$ | coefficient, $1/°C^2$ |
| $\varphi$ | heat flux, $W/m^2$ |
| $\rho$ | density, $kg/m^3$ |
| $\lambda$ | thermal conductivity, W/(m K) |
| $\sigma$ | specific electrical conductivity, S/m |
| $\psi$ | phase lag, rad |
| $\mu$ | viscosity, Pa s |
| $\varpi$ | angular velocity, rad/s |
| $\Delta T$ | temperature difference, °C |

*Abbreviations*

| | |
|---|---|
| LG | lactoglobulin |
| LOD | limit of detection |
| PTR | periodic thermal regime |
| SD | standard deviation |
| STR | steady thermal regime |

*Indices*

| | |
|---|---|
| 0 | initial/reference |
| $b$ | bulk |
| $d$ | deposit |
| $w$ | wall |

Continuous or batch processes lead to fouling of the equipment at varying rates (from minutes up to years) and propensity (from micrometers up to centimetres). The control and understanding of fouling phenomena is clearly relevant to industry: reduction of process performance, energy consumption and water management. Monitoring fouling during ohmic heating and the consequent cleaning processes can provide useful information for operational decision-makers in food processing plants but is also required for security and consumer safety.

To monitor fouling, various devices have been reported in the literature including rheological, electrical, chemical, mechanical, optical, sonic, ultrasonic, and thermal methods each exhibiting its own specificities, advantages, and disadvantages (Duffau et al., 1991; Withers, 1996; Janknecht and Melo, 2003; Prakash et al., 2005; Wallhäußer et al., 2012). The main laboratory and industrial techniques to monitor fouling or product changes are given in Table 1. Several methods have been proposed to monitor fouling in a heat exchanger based on the measurement of heat transfer resistance (thermal balance with temperature probes and flowmeters, (Corrieu and Lalande, 1986; Delplace, 1995) fluxmeter (Jones et al., 1994; Truong et al., 2002)) and the reduction of cross section due to fouling (pressure drop (Corrieu and Lalande, 1986; Delplace, 1995). However, 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 transfer (Lalande et al., 1989; Bott, 1995) or pressure drop (Burton, 1968a; Delplace, 1995) which in the case of small, local deposits may not be significant enough to allow an operational decision to be made. Alternative methods have been proposed such as the variation of optical properties (turbidimeter (Hardy et al., 1985), diffuse reflectance (Payne et al., 1993; Payne, 1994) and backscattered light (Tamachkiarowa and Flemming, 1999; Schaule et al., 2007)), electrical methods (electric resistance (Chen et al., 2004)), and sonic and ultrasonic methods (Gunasekaran, 1996; Hay and Rose, 2003; Lohr and Rose, 2003; Withers, 1996) up to weighing of fouled equipment (Delplace, 1995). 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 (Fujimori et al., 1987), optical techniques (Withers, 1996), ultrasonic methods (Withers, 1996; Pereira et al., 2006) or flux-meters (Davies et al., 1997a). Unfortunately, most of them (i) require extensive 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 suited to the cleaning requirements encountered in the food industry (Janknecht and Melo, 2003).

Over the last two decades, the hot wire technique has been scrutinised and validated as an accurate method of controlling milk coagulation or the gelation of macromolecular food constituents and several scientific works have been published (Hori, 1985; Bellon et al., 1988; Dulac, 1990; Miyawaki et al., 1990; Shimada et al., 1996; Passos et al., 1999; Auvergne et al., 2002). However, modified hot wire methods (hot wire with temperature measurement) are in use for determining thermal conductivity of solid food products (Gatecel and Weill, 1962; Fukai et al., 1991; Tavman and Tavman, 1999; Shariaty-Niassar et al., 2000; Lahoucine and Khellaf, 2004; Strub et al., 2005).

To sum up, product change (protein denaturation, hydrolysis, texturation, polymerisation, browning, gelation, color loss/gain, loss of vitamins, aroma and flavour loss) and fouling are two different mechanisms that may occur in continuous (flowing fluid) and batch (static fluid) processes under isothermal (holding) or thermal (heating or cooling) conditions. In addition, several factors must be considered with regard to the mechanical design of a sensor: chemical, physical, and thermal resistances; hygienic design and cleanability; as well as limiting factors such as sensitivity and the operating range of the sensor. The literature provides the following information:

- No direct measurement of the wall temperature at the fluid–product interface has been carried out to date.