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APPLICATION OF THE HOT WIRE METHOD TO MONITOR FOULING PHENOMENA IN FOOD PROCESS

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Abstract : A thermal sensor, based on the hot wire technique, was studied in order to monitor fouling phenomena or product change in food process. An experimental device has been devised with additional temperature probes, electrical parameters and generated heat measured. An experimental investigation and a theoretical analysis (heat transfer phenomena) highlight the potential application in food processes as well as its accuracy as a function of deposit properties.

Key-words: *hot wire method, fouling, food process, heat transfer.*

INTRODUCTION

In the food industry, heating, holding and cooling operations are carried out in continuous or batch processes. During these operations, the products evolve (biochemical reactions, rheology, colour, pH) due to heating or maturation and fouling phenomena may occur in the equipment. The control and monitoring of fluid properties constitutes a major subject of investigation and is of evident industrial interest [1-14]. Various methods have been reported including rheological, chemical and optical methods [6] and thermal methods [2, 5, 10].

Fouling detection and quantification in the food industry could provide an efficient and cost effective solution for controlling and optimising a treatment. Several methods have been proposed to monitor a fouling in a heat exchanger : (i) the measurement of a heat transfer resistance (temperature probe, fluxmeter) [3, 7, 14], (ii) the reduction of cross-section due to fouling (pressure drop) [3] and the ultrasonic detection [8]. To sum-up, product change and fouling are two different mechanisms, which may occur in continuous (flowing fluid) and batch (static fluid) processes under isothermal (holding) or thermal (heating or cooling) conditions.

In the present work, a thermal sensor based on the hot wire method associated with wall temperature measurement, was investigated in order to monitor fouling phenomena and fluid change in a continuous thermal process. Firstly, a bibliographic overview presents similar experimental devices and theoretical considerations are described. Secondly, material and methods are described before presenting our results and a discussion dealing with sensor sensitivity to fouling (deposit elimination) and product change (starch suspension, milk coagulation). Finally, the temperature profile and sensitivity are modelled for the existing sensor geometry.

BIBLIOGRAPHY

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 on this subject such as Hori (1985), Bellon *et al.* (1988), Dulac (1990), Miyawaki *et al.* (1990), Shimada *et al.* (1996), Passos *et al.* (1999) and Auvergne *et al.* (2002). Most of the experimental devices were similar and have been employed to monitor or control physical changes during a reaction (gelation, coagulation) in food process (dairy industry, gel-melting or gel-setting temperatures). However they are not appropriate for continuous and/or on-line monitoring of viscosity [9], yet modified hot wire methods (hot wire with temperature measurement) are already in use for thermal conductivity determination with solid food products [11, 13].

Industrial devices [1, 2, 4] are dedicated to process control and an electrical signal issued by the hot wire is used as information. This signal is usually the electrical potential of a platinum wire submitted to a constant direct electric current, whose resistance evolves with temperature and heat dissipation efficiency. Obviously this limited information may indicate a heat transfer change from natural convection into conduction phenomena, but could hardly be used to appreciate or to estimate physical properties (viscosity, thermal conductivity). Dulac (1990) reported that a thermal sensor was constituted of a platinum probe (wire and glass sheath, $L=14\text{mm}$, $\varnothing=2\text{mm}$) and that a second temperature gauge measured the bulk temperature.

Laboratory devices [5, 9] were scrutinised from a heat transfer point of view in order to monitor the physical properties of a fluid. The hot wire sensor was composed of a platinum wire ($L=106\text{mm}$, $\varnothing=0.1\text{mm}$) immersed axially and in contact with the sample. The authors assumed that the surface temperature of the hot wire (θ_w) to be equal to the average temperature of the hot wire, whose temperature is calculated from the electric resistance (R). Unfortunately, hot wire is subject to the Joule effect (a stationary thermal regime with heat generation). Thus, the temperature profile versus radius follows a parabolic curve in a cylindrical wire, even if for a low power this point may be negligible. This statement becomes more important if we investigate the heat transfer at the interface between the sensor and the product. Free and forced convection heat transfer are described by semi-empirical correlations between dimensionless numbers : $Nu=f(Gr, Pr)$ for natural convection and $Nu=f(Re, Pr)$ for forced convection. The correlations are restricted to operating conditions and geometrical systems. Dimensionless numbers (Re , Nu , Pr , Gr) require the determination of physical properties (density, viscosity, heat capacity, thermal conductivity) at an accurate temperature (wall, bulk or film temperature) in order to estimate the heat transfer coefficient with a low precision ($\pm 10\text{-}20\%$) in specific conditions. The use of a relationship to determine a physical property like viscosity appears hazardous as a heat transfer mechanism should be perfectly identified (conduction, natural, mixed or forced convection), an accurate correlation needs to be used and the wall temperature precisely measured.

Passos *et al.*, 1999 developed an original system using a heated thermistor instead of platinum wire in order to increase sensitivity. This thermistor (heated wire, $\varnothing=0.08\text{mm}$) was placed in a hypodermic needle ($L=30\text{mm}$, $\varnothing=0.55\text{mm}$) and its voltage drop indicated product change. In addition, a type T thermocouple was in contact with the hot wire inside the needle. This sensor was validated to monitor thermal conductivity during milk coagulation.

Reported publications provide the following information:

- No direct measurement of the wall temperature at the fluid-product interface has been carried out,
- Investigations have been limited to static fluids (batch process) under isothermal conditions,
- Most of the applications concern dairy product.

Furthermore, we note that the hot wire method is mainly used for thermal conductivity measurements in solid food products, whereas no investigation has yet been carried out in continuous and thermal process.

MATERIALS & METHODS

Thermal sensor and Measuring system

The concept of the experimental device came from two specific food applications : (i) the use of the hot wire method to monitor milk coagulation in static and isothermal conditions [1, 2, 4, 5, 10] and (ii) the wall temperature measurement in tubular Joule effect heaters (JEH) to quantify the heat transfer coefficient and fouling mechanism in a continuous heating process. The thermal sensor was made of two platinum probes (Sté Heraeus, probe UE go2327, class B, $L=25\text{mm}$, $\varnothing=3\text{mm}$) and one thermocouple (Sté Thermo-Electric, Type K, ref. MTS-56025-2500-1500, $\varnothing=0.25\text{mm}$).

One platinum probe acted as a sheathed hot wire sensor. A platinum wire with ceramic and stainless steel sheathes was used, as shown in Figure 1. The ceramic sheath ensured the electrical insulation between the stainless steel and the platinum wire. The platinum wire (hot wire) was connected to a direct current generator (0-50mA) built by LEIMA laboratory. The

electric current (I) and potential (U) applied to the standard resistance were recorded and the heat power (P , 0-500mW), the flux (ϕ , 0-2 kW/m²) and the electric resistance (R) calculated. The electric resistance enabled us to determine the average temperature of the platinum hot wire, following the relationship between θ and R for a standard platinum probe (R_0 , A and B are constant).

$$R = R_0 \cdot (1 + A \cdot \theta + B \cdot \theta^2)$$

The thermocouple was stuck half way along the platinum probe and measured the wall temperature (θ_w) at the sensor – product or deposit interface. The second platinum probe measured the bulk temperature (θ_b).

Each sensor signal (I , U , θ_w , θ_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.

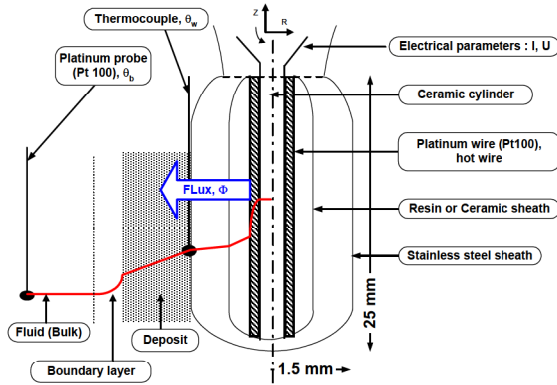


Figure 1 : Thermal sensor structure, interface with deposit or product and schematic temperature profile.

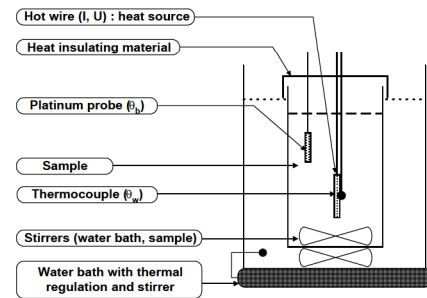


Figure 2 : Experimental system to test the thermal sensor.

Theoretical considerations

In the platinum probe, we consider the heat transfer balance in cylindrical coordinates with the following equations:

$$\rho \cdot C \cdot \frac{d\theta}{dt} = \lambda \cdot \nabla \theta + q \quad \text{with} \quad \nabla \theta = \frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial \theta}{\partial r} + \frac{\partial^2 \theta}{\partial z^2} + \frac{1}{r} \cdot \frac{\partial^2 \theta}{\partial \alpha^2} \quad \text{Eq. 1, Eq. 2}$$

Geometric and thermal simplifications lead to the simplification of this formula in the platinum wire submitted to the Joule effect and in the ceramic and stainless steel sheathes. We made the following assumptions:

- Permanent thermal regime, $d\theta/dt=0$,
- Heat generation was limited to the platinum hot wire, $q \neq 0$,
- In the central cylinder (ceramic) flux was equal to zero, $\phi=0$,
- Geometric simplification with $L \gg r$.

Flux (ϕ) and power (P) were determined with electrical parameters (I , U) and the wall temperature (θ_w) was measured at the sensor – product or deposit interface. Knowledge of the bulk temperature allows the description of heat transfer by different modes (conduction, natural or forced convection). Thus, heat transfer may be formulated for a constant flux, and in a system in which a deposit layer may exist.

$$P = K \cdot 2 \cdot \pi \cdot L \cdot (\theta_w - \theta_b) \quad \text{with} \quad \frac{1}{K} = \frac{1}{h \cdot (r + e)} + \frac{\ln(1 + e)}{\lambda_d} \quad \text{Eq. 3, Eq. 4}$$

We note that $\Delta\theta$, equal to $(\theta_w - \theta_b)$, is a consequence of the flux and global heat transfer coefficient (K). At constant flux, if the product structure evolves (fusion, gelation, cooking) or a deposit layer increases or disappears (fouling, cleaning) then the global heat transfer coefficient will change as well as $\Delta\theta$. In consequence, if our knowledge of the product is reliable, heat transfer analysis (conduction, convection) may lead to interesting information

about the product or process. An overview of the heat transfer in the probe and the product leads to a calculation of the temperature profile versus the radius in permanent regime.

Experimental device and protocol

Our experimental device is described in Figure 2. This system was composed of a water bath equipped with a thermal regulation and a stirrer. The sample was immersed in the water bath and could be stirred with a magnetic stirrer, in order to simulate a continuous process with fluid flow. The thermal sensor was plunged vertically into the test fluid and a thermal insulator placed at the top. In a first instance, sensor response was studied versus heat power with model solutions (water, polysaccharide solutions and glycerol) in isothermal (20 to 80°C) and static conditions. These preliminary results were in agreement with previous scientific publications and enabled us to define a constant electric current equal to 40mA (equivalent to $P \approx 0.2 \text{ W}$) as a working condition.

For isothermal experiments, we analysed milk coagulation and a standardised milk (Sté Lactel, Grand Lait Frais) was used. A solution of active chymosin (Sté Rhone Poulenc Rorer, Cooper, 500mg/l) was added to the milk maintained at 30°C under static or stirred conditions. For thermal experiments, a starch suspension (Sté Arnaud, Amidon Purity W Waxy Maize Starch E1442) with varying concentrations (1.5, 3.0 and 5.0%w/w) was used as a test fluid. Starch disruption occurred for temperatures close to 60°C, thereby inducing an important viscosity change in the solution. During the experiments, the temperature increase of $+0.9^\circ\text{C}/\text{min}$ ($\pm 10\%$) was maintained between 40 and 80°C, while the sample was constantly stirred.

For the fouling study, a model deposit was simulated by a wax layer of different thicknesses. Wax provides the advantages of being easily shaped around the sensor, of fusing at 57°C, simulating a deposit layer elimination with rising temperature and of exhibiting a low thermal conductivity ($\lambda = 0.1 \text{ W.m}^{-1}.\text{K}^{-1}$).

RESULTS & DISCUSSION

Sensitivity to product evolution in batch and continuous processes

Previous publications [1, 5, 10] have demonstrated the accuracy of the hot wire method to monitor milk coagulation under constant temperature and in static conditions. In a first step, we evaluated the sensitivity of the thermal sensor to product change, under isothermal conditions and discuss the effect of product flow. In figure 3, the temperature gradient ($\Delta\theta$) is plotted against time for milk coagulation at 30°C with the addition of active chymosin.

In static conditions, a widely recognised S curve was observed with an increase of the temperature gradient due to coagulation. Then the passage from natural convection (in liquid) to conduction (coagulated milk) heat transfer became noticeable.

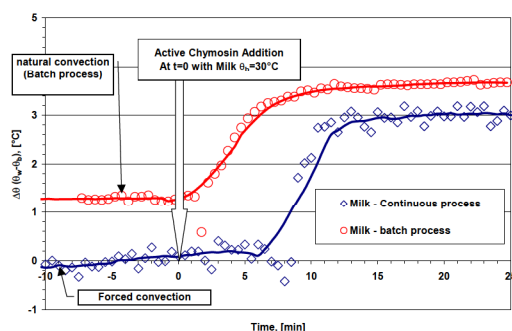


Figure 3 : Temperature gradient ($\Delta\theta$) versus time (t) during milk coagulation at 30°C under static and dynamic (stirred) condition.

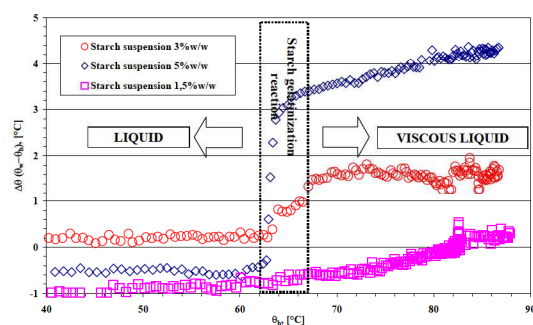


Figure 4 : Temperature gradient ($\Delta\theta$) versus bulk temperature (θ_b) during the heating of starch suspensions under dynamic condition.

In dynamic conditions, our observations were identical, except that we noted a transition from forced convection to conduction. Before active chymosin was added, the temperature gradient were very different for static and dynamic conditions, in agreement with eq.4. Strong stirring induced a high convection coefficient resulting in an initial temperature gradient close to zero. After coagulation, the magnetic stirrer was immobilised in the coagulated milk. Then,

the product properties (structure, thermal conductivity) appeared to be similar, as indicated by an identical temperature gradient ($\Delta\theta \approx 3 - 3.5^\circ\text{C}$) after 20min. In a second step, we investigated the sensor response in a transitory thermal regime for a constant heating kinetic ($+0.9^\circ\text{C}/\text{min}$ between 40 and 80°C) with thermo-dependant products. Figure 4 represents the temperature gradient versus the bulk temperature for starch solutions of varying concentration under stirred conditions. An increasing temperature gradient step was observed against starch concentrations at temperature exceeding 65°C . During starch disruption, the apparent viscosity increased. For 3%w/w concentration, viscosity was close to 0.1 and 0.32 Pa.s at 30°C and 70°C respectively. As defined in eq. 3 and 4, a reduction of convection coefficient resulting from higher viscosity and less efficient stirring induced an increase in the temperature gradient. At the lowest temperature, we remarked that the temperature gradient was different for each suspension. This fact is probably due to the low precision (for $\Delta\theta$: $\pm 1^\circ\text{C}$) of our experimental conditions, as well as the flexible position of the sensor inside the sample. In this part, we draw conclusions to the thermal sensor efficiency in monitoring product change under dynamic conditions (product flow) and a transitory thermal regime. However the strong change of the global heat transfer coefficient requires an important product modification. If only small changes in properties (viscosity, thermal conductivity) occur during the process, then the global heat transfer coefficient is not affected and measurements are almost impossible (i.e. 1.5%w/w starch suspension). If gel formation is observed, then heat transfer is strongly modified (natural or forced convection to conduction) and the thermal sensor would be suitable.

Sensitivity to fouling and detection limits.

Fouling control in continuous food processes is a fundamental parameter. Fouling may occurs in heaters (compound denaturation, hot surface) or coolers (gelation or solidification at wall) and even in holding sections (product maturation).

In the present work, we used a fouling model to evaluate the sensor sensitivity to deposit thickness and elimination. Fouling layers were created at the sensor surface and the temperature gradient versus bulk temperature was monitored as the sensor was immersed in stirred water (Figure 5). For bulk temperatures below the fusion temperature of wax (57°C), we observed an increase in the temperature gradient against the deposit thickness. If we consider eq. 3 and 4, the temperature gradient led to a constant value when deposit thickness increased. This point was experimentally observed and explained by the asymptotic value of the global heat transfer coefficient when the deposit increased (eq. 4).

At temperatures exceeding 55°C , the deposit elimination was monitored without problem. For temperatures above 60°C , a complete removal of the deposit was visible and the temperature gradients reached a common value close to zero.

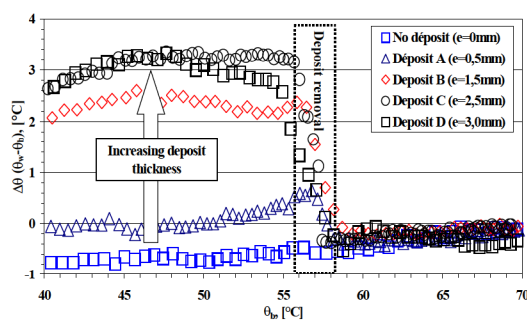


Figure 5 : Temperature gradient ($\Delta\theta$) versus bulk temperature (θ_b) impact of deposit layer and sensitivity to fouling elimination.

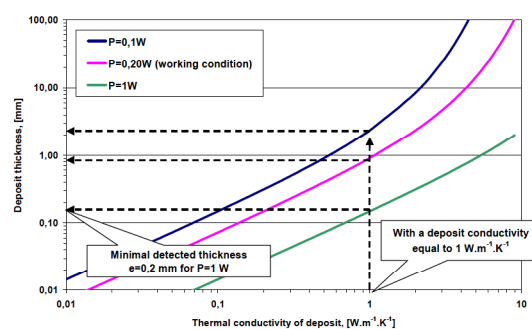


Figure 6 : Minimal deposit quantified (e) versus deposit thermal conductivity (λ_d) and heat power (P) for a temperature gradient increase of 0.5°C .

Finally, we focussed on the limits of fouling detection for the thermal sensor. We considered Fourier's law in an annular cylinder. Internal (θ_w) and external (θ_b) temperatures were controlled, and a heat flux was imposed. Our system was limited by wall and bulk temperature precision ($\pm 0.5^\circ\text{C}$) and we assumed a variation of 0.5°C as the minimal temperature gradient required to detect a significant deposit. In figure 6, the minimal deposit quantified is plotted against the thermal conductivity of the deposit and heat power. We observed that in our

experimental conditions (sensor geometry, heat power equal to 0.20W) for food products (thermal conductivity ranging between 0.1 to 0.6 W.m⁻¹.K⁻¹), the thermal sensor may detect a fouling of 0.1 to 0.5 mm in thickness.

CONCLUSIONS

In this study, a thermal sensor based on the hot wire technique has been scrutinised and validated as an accurate method of monitoring fouling phenomena or product changes in food process (cooling, heating or holding section). The heat dissipated by the sensor in the process is negligible and could not affect the product. Minor sensor modifications need to be integrated such as geometry (length, diameter) and temperature precision. In the future, the thermal sensor used for on-line measurements in continuous processes should be investigated.

NOMENCLATURE & REFERENCES

Latin letters		t	Time, [s]
e	Thickness of deposit, [m]	U	Potential, [V]
C	Heat capacity, [J.K ⁻¹ .Kg ⁻¹]	Greek letters	
Gr	Grashoff number, [I]	α	Angle, [rad]
h	Convection heat transfer, [W.m ⁻² .K ⁻¹]	φ	Flux, [W.m ⁻²]
I	Electric current, [A]	λ	Thermal conductivity, [W.m ⁻¹ .K ⁻¹]
K	Heat transfer coefficient, [W.m ⁻¹ .K ⁻¹]	θ	Temperature, [K]
L	Length, [m]	ρ	Volume mass, [Kg.m ⁻³]
Nu	Nusselt number, [I]	Δθ	Temperature gradient, [K]
P	Heat power, [W]	Φ	Power, [W]
Pr	Prandtl number, [I]	Indices	
r	Radius sensor, [m]	b	Bulk
R	Electric resistance, [Ω]	d	Deposit
Re	Reynolds number, [I]	w	Wall

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