SKIM MILK FOULING DURING OHMIC HEATING

B. Bansal[1]*, X. D. Chen[2] and S. X. Q. Lin[3]

Department of Chemical and Materials Engineering
The University of Auckland, Auckland, New Zealand
[1]b.bansal@auckland.ac.nz
[2]d.chen@auckland.ac.nz
[3]xlin004@ec.auckland.ac.nz

ABSTRACT

This study deals with the investigation of deposition from reconstituted skim milk solution in an ohmic heater. The heater was made of two concentric cylinders acting as two separate electrodes. The heating of the milk solution resulted in deposit formation on both electrodes. These deposits provided additional electrical resistance and the current passing through the milk solution dropped by up to 45% within 4 hours of operation. The applied voltage increased slightly during this time period. The deposit formation was reasonably uniform at any cross-section. Lowering the milk temperature at the inlet of the ohmic heater enhanced the rate of fouling. In contrast, increasing the milk solution flow rate by a factor of two was found to have almost no effect on the fouling rate. A mathematical model was developed to simulate the fouling process and investigate the effect of different parameters in detail.

INTRODUCTION

Fouling of heat transfer equipment during thermal processing of food materials like milk is a serious industrial problem. Lower heat transfer and flow efficiencies, product contamination, production loss etc. are some of the major drawbacks of fouling and costs related to fouling are millions of dollars per year in New Zealand. Ohmic heating technology, based on Joule's heating effect, is considered to be an alternate for the indirect heating methods like shell and tube and plate heat exchangers where heating of milk is done through a surface. Heat is generated directly within milk in an ohmic heater and hence the problems associated with heat transfer surfaces are eliminated.

The ohmic heating technology is not new and has been used for over 100 years (Jones 1897; de Alwis and Fryer 1990). After its successful use during the earlier part of the 20th century, this technology was abandoned for several years. Product contamination, uneven heating at electrode surfaces, electrolysis etc. were some of the practical difficulties that prevented the widespread use of this technology (de Alwis and Fryer 1990). Efforts by several researchers over the past two decades have initiated the revival of this technology (Skudder and Biss 1987; Stirling 1987).

Research is being carried out in our laboratory to investigate skim milk fouling during ohmic heating (Bansal and Chen 2005). The main objective of this study was to investigate the effect of milk flow rate and temperature through experimental work as well as mathematical modelling.

EXPERIMENTAL SETUP

5 wt % skim milk solution was prepared by dissolving appropriate amount of skim milk powder (New Zealand Milk Products Limited, New Zealand) in ordinary tap water. A simple schematic of the experimental setup used is shown in Figure 1. The milk solution was pumped to the ohmic heater using a peristaltic pump. The details of the ohmic heater are shown in part b of Figure 1. The heater consisted of two concentric cylinders (stainless steel) acting as the two electrodes and the solution flowed in the annulus (length - 115 mm and gap – 7 mm between the electrodes). By having a set voltage difference across the two electrodes, a current was allowed to pass through and heat the milk. The hot milk leaving the ohmic heater was returned to holding tank which was kept at a constant temperature with the help of a temperature controlled electric heater and a stirrer. A large, 40 L tank was used to minimise the impact of reduction in protein concentration through deposit formation.

A computer controlled data acquisition system was used to record the experimental data. The inlet and outlet temperatures of the milk were measured and recorded continuously throughout the experiment using K-type thermocouples. The current and voltage values were recorded using a current transducer and a voltage transducer respectively. The fouling process was monitored by observing the drop in the current passing through the ohmic heater, caused by the formation of the fouling deposits on the electrode surfaces. Type A (protein) fouling (Lyster 1965; Burton 1968) was observed in all the experiments since the maximum operating temperature in the heater was always below 90°C.

* Current address: Fonterra Co-operative Group Ltd, Private Bag 11029, Palmerston North, New Zealand
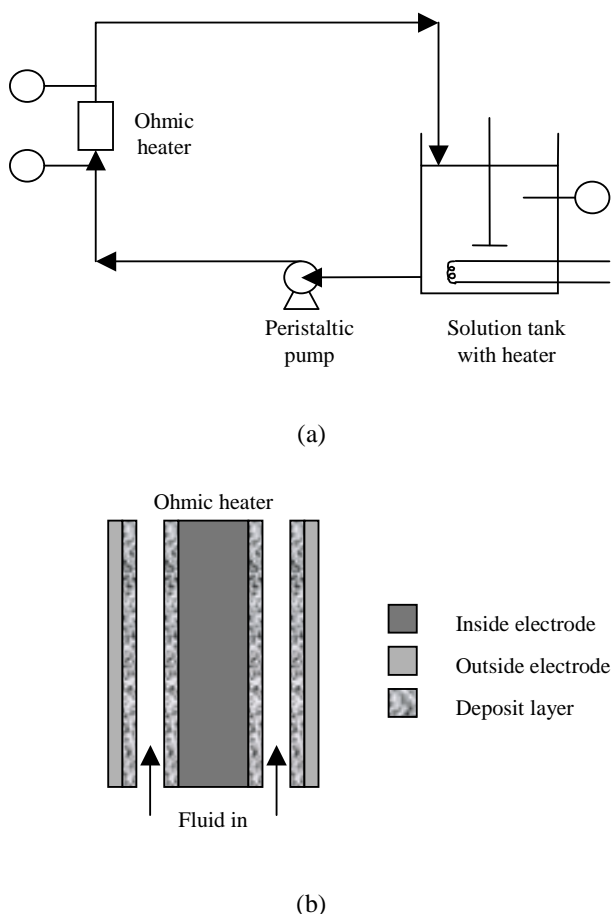Email: bipan.bansal@fonterra.com

(a)

(b)

Fig. 1   a) Experimental set up, b) ohmic heater

At the end of each experiment, the ohmic heater was unassembled and the deposit pattern was observed.

MILK FOULING AND OHMIC HEATING

Milk fouling is affected by a number of factors: seasonal variations, entrapped air, pH, age of milk, flow rate, bulk and heat transfer surface temperatures, type of heat exchanger, type and nature of heat transfer surface and many more (Lund and Bixby 1975; Changani et al. 1997; Visser and Jeurnink 1997).

Ohmic heating process is basically a bulk heating process where heat is produced directly within milk by virtue of its electrical resistance when a current is passed through it.   This not only overcomes the limitations of slower heat transfer based on thermal conduction (Fryer 2003) but also improves the product quality due to higher sterilisation rates (Fryer et al. 1993).   The added advantage is the absence of hot surfaces.   The electrode surface temperatures are generally below the milk temperature because the resistivity of the electrode material is

comparatively lower.   The absence of the hot surfaces is considered to reduce the fouling problems which sometimes limit the operation of conventional plants (Fryer et al. 1993).

Fouling can not be completely eliminated in an ohmic heating unit simply because milk has to be heated to a certain temperature for the pasteurization or sterilization to take place and this would still result in denaturation and aggregation of the milk proteins.   However, there are differences between milk fouling processes in a conventional heat exchanger (indirect heating) and an ohmic heater (direct heating) as shown in Figure 2.   At the start, less fouling is observed in the ohmic heater, simply due to the absence of hotter heat transfer surfaces.   However, the situation becomes vastly different once the deposition starts. The deposits lower the deposit/fluid interface temperature in the conventional indirect heating method.   In the ohmic heating unit, however there is an additional generation of heat with in the deposit layer due to its own electrical resistance.   Also the deposits restrict the outward flow of heat from the bulk fluid.   As a result, the deposit/fluid interface temperature is raised.   The increasing thickness of the deposit layer also reduces the efficiency of the heating process by consuming more power.   Similar results have been reported by Ayadi et al. (2004).
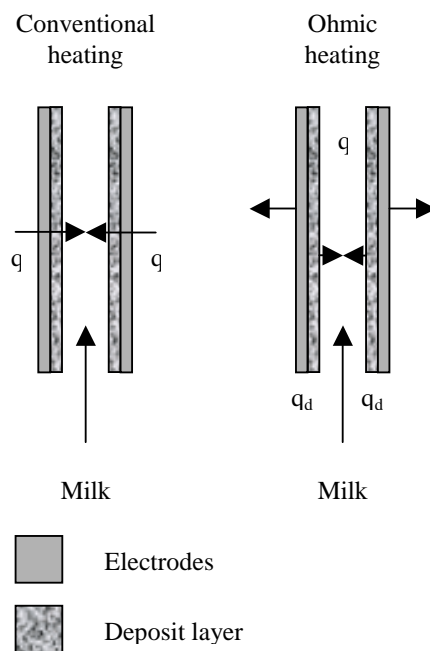

Fig. 2   Conventional (indirect) heating Vs ohmic (direct) heating

RESULTS AND DICUSSION

A series of fouling experiments was performed over a range of operating conditions. Typical fouling curve is shown in Figure 3. The effect of fouling is represented in terms of reduction in the overall current passing through the ohmic heater with time. The milk flow rate in this trial was 15.5 kg/hr that corresponded to an average velocity of 0.45 cm/s (laminar flow, Re ~ 80). The milk temperature in the tank was set at 78°C and the corresponding temperature at the inlet of the ohmic heater was slightly lower i.e. 75.6°C. At the start, the amount of current passing through milk was 27.8 A (average current density = 1225 A/m^2) for a voltage difference of 10.15 V, resulting in an initial power input of around 280 W (mains power, electric frequency 50 Hz). Under these conditions, the outlet temperature of milk was around 88.3°C. The fouling process started instantly and no induction period was observed. The entire fouling period could be divided into two separate stages. In the first stage i.e. within first 15 minutes, the overall current dropped linearly to around 23 A; representing a reduction of over 17% (power input ~ 240 W). In the second stage, the rate of reduction was much less with the current value settling to around 17 A after 4 hours of operation. During the course of this fouling experiment, the voltage increased by around 12%. At the end of 4 hours, the power input into the ohmic heater was around 190 W and the outlet temperature decreased to around 84.5°C.
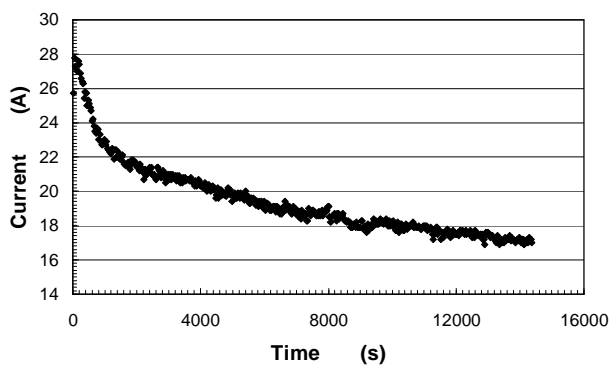

Fig. 3 Typical skim milk (5 wt %) fouling curve in the ohmic heater

Visual observation of the ohmic heater after the fouling experiment showed that there was substantial fouling of the electrode surfaces. The inner electrode had comparatively more fouling than the outer electrode. This trend could be attributed to comparatively higher current density (due to lower surface area) and different flow characteristics (Bird et al. 2002) at the inner electrode. Generally, the deposition was uniform across a cross-section but there was a mixture of layer-wise and spot-wise

deposition. The deposit layer was up to several mm thick at places. The deposits were compact, hard and difficult to remove. Chemical cleaning using 0.5 wt % sodium hydroxide solution was not enough to completely clean the fouled surfaces and some mechanical cleaning was required in addition.

Based on these observations, it can be seen that protein denaturation and aggregation processes started in the solution tank. These processes intensified when milk was pumped to the ohmic heater. Hence deposits were formed on the electrode surfaces despite having lower temperatures. The deposition rate was highest at the beginning of the trial due to the highest heating rate as well as solution concentration. As the time progressed, the formation of the deposit layers provided additional electrical resistance and lowered the heat generated within milk. In addition, some heat was generated within the deposit layers. Changing temperature distribution (decreasing bulk temperature and increasing deposit/milk interface temperature) resulted in lower fouling rates. Gradual reduction in the solution concentration also had some effect.

The effect of milk temperature at the inlet of the ohmic heater is illustrated in Figure 4. A reduction in the inlet temperature of around 7°C, corresponding to the tank temperature of 70°C, was expected to result in lower fouling. In contrast, the rate and amount of fouling were observed to be higher. The initial power input for this trial was around 290 W (28.1 A, 10.3 V). The operating conditions after 4 hours of operation were: power – 185 W, current 16 A, voltage – 11.65 V.
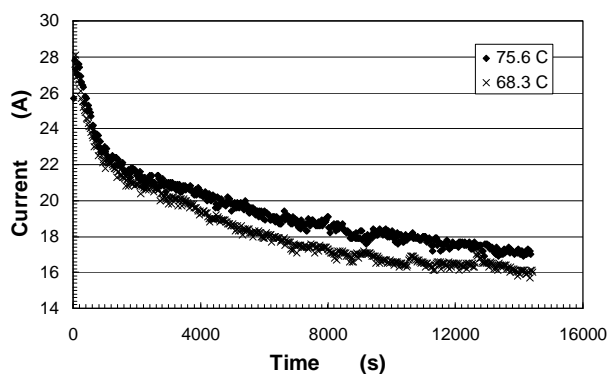

Fig. 4 Effect of milk inlet temperature on fouling

According to the Visser and Jeurnink (1997), the effect of temperature on the deposition of whey proteins is quite complex. In their experimental study on deposition of whey proteins, they observed that the deposition increased with the increasing temperature, up to 77-78°C. Any further increase in the temperature resulted in a dramatic drop in the deposition rate and finally it settled to a lower value at

around 82°C. It is also worth noting that during heat induced fouling of whey proteins (primarily β-lactoglobulin) (Lyster 1970; Lalande et al. 1985; Bylund 1995), denatured and aggregated proteins represent the intermediate and final states respectively. An increase in the milk temperature is bound to result in the higher concentration of the aggregated proteins. However, being larger in size, the convection of the aggregated proteins to the electrode surfaces may be difficult compared with the denatured proteins (Treybal 1981; Chen 2000). Based on the experimental information available in the current study, it is not possible to evaluate the effect of the operating temperature inside the ohmic heater in any further detail.

The effect of milk flow rate on fouling is shown in Figure 5. Over 100% increase in the flow rate (from 15.5 kg/hr to 31.5 kg/hr) seemed to have little effect on the fouling rate. The power input at the higher flow rate was observed to be similar, around 275 W (28.5 A, 9.6 V), since the flow rate should have had a minimal effect on the electrical resistance of the milk solution. Increasing the flow rate resulted in a lower temperature gain (outlet temperature = 81.4°C) and allowed faster convection of the proteins to the electrode surfaces. These effects may have been counteracted by the increasing fluid hydrodynamic forces at the electrode surfaces that would allow lower settling rates.
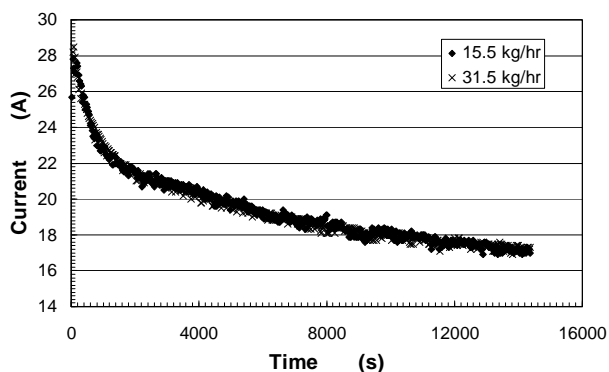

Fig. 5   Effect of milk flow rate on fouling

Significant pit corrosion of both electrode surfaces was observed. The use of mains power supply with frequency of 50 Hz meant that apparently each cycle was long enough (1/50 s) to promote electrolysis of the stainless steel surfaces. A number of examples can be cited in the literature where mains power supply has been used (frequency 50 or 60 Hz) during ohmic heating, however the corrosion issues have not been discussed (Skudder and Biss 1987; Qihua et al. 1993; Assiry et al. 2003; Ayadi et al. 2004). Assiry and co-workers (Assiry et al. 2003) studied degradation kinetics of ascorbic acid during ohmic heating (electric frequency 60 Hz) and found that uncoated stainless

electrodes were corroded. The corrosion reactions were considered to affect the degradation kinetics of ascorbic acid. In general, the corrosions reactions not only affect the local pH but they also degrade the surface characteristics resulting in the availability of sheltered places for the fouling deposits. The corresponding changes in the hydraulic and thermal conditions promote fouling. In the current study as well, it is likely that the corrosion of the stainless steel electrodes had an effect on the localised fouling rates. Further experiments are required to study this effect. A number of methods are available to control the corrosion effects. The use of different surface materials with lower corrosion tendencies or the coating of the existing surfaces with less corroding materials may be one possibility (Ibrahim 1999; Samaranayake and Sastry 2005). The use of higher frequency power supply is another method where lower cycle times would slow down the electrolysis process (Ibrahim 1999).

MODELLING OF FOULING PROCESS

A mathematical model has been developed based on the approach suggested by Fryer and Slater (1985) and further refined by Toyoda et al. (1994) and Chen et al. (2001). This model is based on the basic principles of transport phenomena and reaction kinetics and takes into account local thermal and hydraulic conditions. The denaturation and aggregation reactions of β-lactoglobulin considered are modelled in elementary steps, as given below (Chen et al. 1998; Chen et al. 2001):

$$i) -\frac{dC_N}{dt} = k_1 C_N^a - k_2 C_D^b$$

$$ii) \frac{dC_D}{dt} = k_1 C_N^a - k_2 C_D^b - k_3 C_D^c \qquad (1)$$

$$iii) \frac{dC_A}{dt} = k_3 C_D^c$$

where a, b, and c are orders of reactions (a = 1, b = 1, c = 2, (Chen et al. 1998)) and k_1, k_2, and k_3 are rate constants that depend on the temperature T as per the Arrhenius law:

$$k_i = A_i e^{-\frac{E_i}{RT}} \qquad (2)$$

where A_i is Arrhenius constant, E is activation energy, R is gas constant, and i = 1, 2, 3.

The fouling process is assumed to be based on the following conditions:

- Protein denaturation and aggregation reactions take place in bulk fluid as well as thermal boundary layers.
- The denaturation step is considered to be reversible (see equation 1).
- Mass transfer takes place for all three forms of the proteins (i.e. native, denatured, and aggregated) between bulk fluid and thermal boundary layers.
- Only denatured and aggregated proteins present in thermal boundary layers are able to cause deposition at the electrode surfaces.
- The reaction kinetics parameters (Arrhenius constant and activation energy) for all the reactions steps are taken from (Chen et al. 1998) and are given in Table 1 below:

Table 1. Reaction kinetics parameters (Chen et al. 1998)

Reaction step	Arrhenius constant	Activation energy
1	7.7×10^{27} 1/s	202.0 kJ/mol
2	7.7×10^{7} 1/s	72.5 kJ/mol
3	7.1×10^{6} m³/kg.s	55.0 kJ/mol

Various equations developed to describe the fouling process in the ohmic heater are given below.

Mass balance (bulk fluid):
Native protein:

$$\frac{\partial C_N}{\partial t} + u_L \frac{\partial C_N}{\partial x} = -\left(A_1 e^{\frac{-E_1}{RT_L}}\right) C_N + \left(A_2 e^{\frac{-E_2}{RT_L}}\right) C_D$$

$$+ \frac{A^*_{HIN2}}{A_{cb}\delta x} k_{mN2}\left(C^*_{N2} - C_N\right) - \frac{A^*_{HIN1}}{A_{cb}\delta x} k_{mN1}\left(C_N - C^*_{N1}\right) \quad (3)$$

Denatured protein:

$$\frac{\partial C_D}{\partial t} + u_L \frac{\partial C_D}{\partial x} = +\left(A_1 e^{\frac{-E_1}{RT_L}}\right) C_N - \left(A_2 e^{\frac{-E_2}{RT_L}}\right) C_D$$

$$-\left(A_3 e^{\frac{-E_3}{RT_L}}\right) C_D^2 - \frac{A^*_{HIN2}}{A_{cb}\delta x} k_{mD2}\left(C_D - C^*_{D2}\right) \quad (4)$$

$$- \frac{A^*_{HIN1}}{A_{cb}\delta x} k_{mD1}\left(C^*_{D1} - C_D\right)$$

Aggregated protein:

$$\frac{\partial C_A}{\partial t} + u_L \frac{\partial C_A}{\partial x} = +\left(A_3 e^{\frac{-E_3}{RT_L}}\right) C_D^2$$

$$- \frac{A^*_{HIN2}}{A_{cb}\delta x} k_{mA2}\left(C_A - C^*_{A2}\right) - \frac{A^*_{HIN1}}{A_{cb}\delta x} k_{mA1}\left(C^*_{A1} - C_A\right) \quad (5)$$

Similar equations can be developed for all forms of proteins for the thermal boundary layers at the inside and outside electrode surfaces.

Energy balance:
Bulk fluid:

$$\frac{\partial T_L}{\partial t} + u_L \frac{\partial T_L}{\partial x} = \frac{4k_{d1}}{\delta_{d1}} \frac{A_{HIN1}}{A_c \delta x \rho_L C_{PL}}\left(\overline{T}_{d1} - T_{s1}\right)$$

$$- \frac{4k_{d2}}{\delta_{d2}} \frac{A_{HIN2}}{A_c \delta x \rho_L C_{PL}}\left(T_{s2} - \overline{T}_{d2}\right) \quad (6)$$

$$+ \frac{\left(\frac{I}{N_x}\right)^2 \sigma_{RL}}{\left(\frac{A_{HIN1} + A_{HIN2}}{2}\right)} \frac{\delta_L}{A_c \delta x \rho_L C_{PL}}$$

Inside thermal boundary layer:

$$\frac{\partial \overline{T}_{d1}}{\partial t} = -\frac{4k_{d1}}{\delta_{d1}} \frac{1}{A_{cd1}\delta x \rho_{d1} C_{Pd1}} \begin{bmatrix} \left(\overline{T}_{d1} - T_{s1}\right)A_{HIN1} \\ -\left(\overline{T}_{d1} - T_{s0}\right)A_{HOT1} \end{bmatrix}$$

$$+ \frac{\left(\frac{I}{N_x}\right)^2 \sigma_{Rd1}}{\left(\frac{A_{HIN1} + A_{HOT1}}{2}\right)} \frac{\delta_{d1}}{A_{cd1}\delta x \rho_{d1} C_{Pd1}} \quad (7)$$

Outside thermal boundary layer:

$$\frac{\partial \overline{T}_{d2}}{\partial t} = +\frac{4k_{d2}}{\delta_{d2}} \frac{1}{A_{cd2}\delta x \rho_{d2} C_{Pd2}} \begin{bmatrix} \left(T_{s2} - \overline{T}_{d2}\right)A_{HIN2} \\ -\left(\overline{T}_{d2} - T_{s3}\right)A_{HOT2} \end{bmatrix}$$

$$+ \frac{\left(\frac{I}{N_x}\right)^2 \sigma_{Rd2}}{\left(\frac{A_{HIN2} + A_{HOT2}}{2}\right)} \frac{\delta_{d2}}{A_{cd2}\delta x \rho_{d2} C_{Pd2}} \quad (8)$$

The thicknesses of the deposits layers on both electrode surfaces can be determined using the following equations:

$$\frac{\partial \delta_{d1}}{\partial t} = \frac{k_{d1}}{h} \beta\left(K_{wD}C^*_{D1} + K_{wA}C^*_{A1}\right) \quad (9)$$

$$\frac{\partial \delta_{d2}}{\partial t} = \frac{k_{d2}}{h} \beta\left(K_{wD}C^*_{D2} + K_{wA}C^*_{A2}\right) \quad (10)$$

Standard equations available in the literature have been used to determine heat transfer coefficient, mass

transfer coefficient, diffusion coefficient, thicknesses of laminar sublayer and thermal boundary layer, and flow velocity in laminar sublayer (Treybal 1981; Perry and Green 1997; McCabe et al. 2001; Bird et al. 2002; Holman 2002; Incropera and De Witt 2002) and are not shown here due to space limitations.

For simulation purposes, the entire ohmic heater was subdivided into ten segments along the flow path. For a given time iteration, initially the program was solved for all the segments one by one. Following that, the entire procedure was repeated for subsequent time iterations till the end of the total fouling period.

Figure 6 shows the simulation results for a typical fouling trial. The measured experimental data is also plotted for comparison purposes. Based on the results, it can be seen that the model is able to predict correct fouling trend and there is a reasonable agreement with the experimental data.
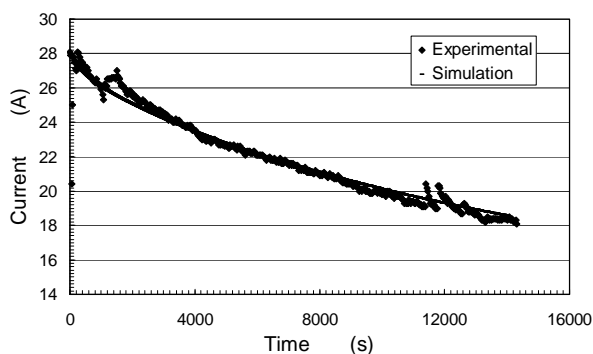
Fig. 6   Numerically simulated Vs experimental results

An interesting observation needed to be made using the model was to check the changing temperature profile inside the ohmic heater as fouling progressed since this information was not available from the experimental data. Figure 7 illustrates the simulated bulk temperature profiles at different times during the fouling process. As expected, the milk temperature was lowest at the inlet and increased rapidly due to heating as it moved along the heater. Under the given conditions, the bulk temperature at the exit was estimated to be slightly over 90°C, a slight over-prediction compared with the experimental data. With the formation of the fouling deposits, electrical resistance inside the ohmic heater increased and as a result less heat was generated. Some heat was generated in the deposit layer as well. Consequently, the temperature rise of the fluid decreased significantly and the exit temperature after 4 hours of operation was less than 85°C, very similar to the experimentally measured temperature.
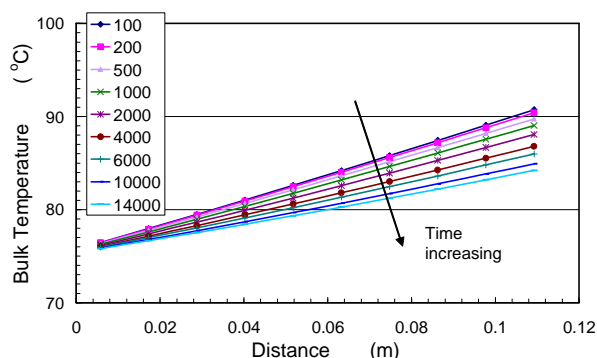
Fig. 7   Bulk fluid temperature profile at different times (s) during the fouling process

Figure 8 illustrates the simulated deposit/fluid interface (at the inside electrode) temperature profiles. Build-up of the deposit layer with time and corresponding generation of heat, aided by its comparatively lower thermal conductivity, allowed the temperature to rise significantly along the flow path. These results clearly demonstrate a unique nature of the ohmic heating process and how the temperature profiles can be significantly different from standard heat exchangers with indirect heating. These temperature profiles are bound to have a significant impact on the overall fouling process.
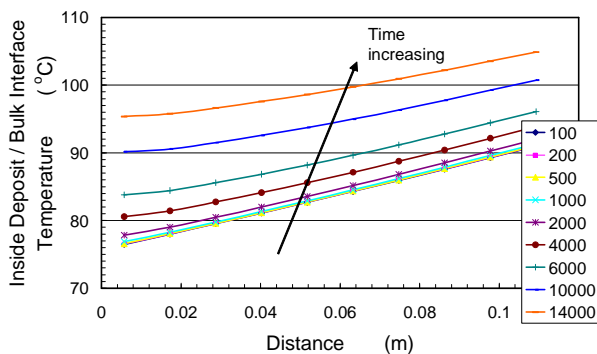
Fig. 8   Deposit/fluid interface (inside electrode) temperature profile at different times (s) during the fouling process

Currently efforts are being made to simulate the effect of different variables and their interrelationships on the overall fouling process. The main variables being investigated are temperature, flow rate, and solution concentration. Another variable is the design of the ohmic heater.

CONCLUSIONS

Fouling of skim milk flowing in the annulus of a cylindrical ohmic heater, with two stainless steel concentric cylinders acting as the electrodes, was investigated. Fouling was found to enhance when the milk temperature at the inlet was reduced. Also increasing the milk flow rate by a factor of two was observed to have a minimal effect on the fouling rate. The effect of temperature on the extent of protein reactions, different deposition rates for denatured and aggregated proteins, and fluid hydrodynamic forces are among the important variables that influence the overall fouling rate. Significant corrosion of the electrode surfaces was observed during the experiments which may have affected the fouling rate. The corrosion was probably caused by the use of low frequency (50 Hz) power supply.

A mathematical model based on the principles of transport phenomena and reaction kinetics of whey protein based fouling process was developed to simulate the fouling process during the ohmic heating. According to the simulated results, the formation of deposits on the electrode surfaces not only introduced additional resistance, some heat was generated within the deposits as well. As a result, the electrode surface/fluid interface temperature increased and the bulk temperature reduced with deposition. This rather unique temperature profile, substantially different from indirect heat exchangers, would affect the fouling process differently. Further experiments and simulations are currently being carried out to study this fouling process in detail.

NOMENCLATURE

A_1	Arrhenius constant for protein denaturation reaction (forward step), 1/s
A_2	Arrhenius constant for protein denaturation reaction (backward step), 1/s
A_3	Arrhenius constant for protein aggregation reaction, m^3/kg.s
A_c	Cross-sectional area, m^2
A_H	Area of heat transfer, m^2
C	Protein concentration, kg/m^3
C_P	Specific heat, J/kg.K
E	Activation energy for protein reaction, J/mol
h	Heat transfer coefficient, J/m^2.s.k
I	Total current in the ohmic heater, amp
k	Thermal conductivity, J/m.s.K
k_m	Mass transfer coefficient of protein (between bulk and thermal boundary layer), m/s
K_w	Deposit rate constant, m/s
N_x	Number of computational segments in the ohmic heater (along the flow length)
t	Processing time, s

T	Average temperature (averaged over a single segment of length δx), ^oC
u_L	Average velocity of liquid, m/s

Subscripts

b	Bulk
c	Cross-sectional
d	Deposit
N, D, A	Native / denatured / aggregated
IN	Inside boundary layer
L	Liquid
OUT	Outside boundary layer
s	Surface
1, 2	Inside / outside electrode

Superscripts

*	Thermal boundary layer

Greek Symbols

ρ	Density, kg/m^3
δ_d	Thickness of deposit layer, m
δ_L	Thickness of liquid in the bulk (including thermal boundary layers), m
δx	Length of a computational segment along the flow length), m
σ_R	Resistivity, ohm.m
β	Fouling proportionality constant, m^2/kg

REFERENCES

A. Assiry, S. K. Sastry, and C. Samaranayake, 2003, Degradation kinetics of ascorbic acid during ohmic heating with stainless steel electrodes, *Journal of Applied Electrochemistry*, Vol. 33, pp. 187-196.

M. A. Ayadi, J. C. Leuliet, F. Chopard, M. Berthou, and M. Lebouche, 2004, Continuous ohmic heating unit under whey protein fouling, *Innovative Food Science & Emerging Technologies*, Vol. 5, No. 4, pp. 465-473.

B. Bansal and X. D. Chen, 2005, Modelling of milk fouling during ohmic heating, CHEMECA Conference, Brisbane, Australia, September 25-28 (on CD-ROM).

R. B. Bird, W. E. Stewart, and E. N. Lightfoot, 2002, *Transport Phenomena*, John Wiley & Sons, New York.

H. Burton, 1968, Deposits from whole milk in heat treatment plant - a review and discussion, *Journal of Dairy Research*, Vol. 35, pp. 317-330.

G. Bylund, 1995, *Dairy Processing Handbook*, Tetra Pak Processing Systems AB, Lund, Sweden.

S. D. Changani, M. T. Belmar-Beiny, and P. J. Fryer, 1997, Engineering and chemical factors associated with

fouling and cleaning in milk processing, *Experimental Thermal and Fluid Science*, Vol. 14, No. 4, pp. 392-406.

J. Chen, 2000, Computer Simulation of Whey Protein based Milk Fouling, Master of Engineering, The University of Auckland, Auckland.

X. D. Chen, J. Chen, and D. I. Wilson, 2001, Modelling whey protein based fouling of heat exchangers - further examining the deposition mechanisms, *Heat Exchanger Fouling: Fundamental Approaches and Technical Solutions*, Davos, Switzerland.

X. D. Chen, Z. D. Chen, S. K. Nguang, and S. Anema, 1998, Exploring the reaction kinetics of whey protein denaturation/aggregation by assuming the denaturation step is reversible, *Biochemical Engineering Journal*, Vol. 2, No. 1, pp. 63-69.

A. A. P. de Alwis and P. J. Fryer, 1990, The use of direct resistance heating in the food industry, *Journal of Food Engineering*, Vol. 11, No. 1, pp. 3-27.

P. J. Fryer, 2003, Electrical Process Heating, Encyclopedia of Food Sciences and Nutrition. Elsevier Science Ltd, Oxford, pp. 3044-3049.

P. J. Fryer, A. A. P. de Alwis, E. Koury, A. G. F. Stapley, and L. Zhang, 1993, Ohmic processing of solid-liquid mixtures: Heat generation and convection effects, *Journal of Food Engineering*, Vol. 18, No. 2, pp. 101-125.

P. J. Fryer and N. K. H. Slater, 1985, A direct simulation procedure for chemical reaction fouling in heat exchangers, *The Chemical Engineering Journal*, Vol. 31, No. 2, pp. 97-107.

J. P. Holman, 2002, *Heat Transfer*, McHraw-Hill, New York.

E. S. Ibrahim, 1999, Corrosion control in electric power systems, *Electric Power Systems Research*, Vol. 52, No. 1, pp. 9-17.

F. P. Incropera and D. P. De Witt, 2002, *Fundamentals of Heat and Mass Transfer*, John Wiley & Sons, New York, 5th edition.

F. Jones, 1897, Apparatus for Electrically Treating Liquids, US Patent No. 592735, USA.

M. Lalande, J.-P. Tissier, and G. Corrieu, 1985, Fouling of heat transfer surfaces related to b-lactoglobulin denaturation during heat processing of milk, *Biotechnology Progress*, Vol. 1, No. 2, pp. 131-139.

D. B. Lund and B. Bixby, 1975, Fouling of heat exchanger surfaces by milk, *Process Biochemistry*, Vol. 10, pp. 52-55.

R. L. J. Lyster, 1965, The composition of milk deposits in an ultra-high-temperature plant, *Journal of Dairy Research*, Vol. 32, pp. 203-208.

R. L. J. Lyster, 1970, The denaturation of a-lactalbumin and b-lactoglobulin in heated milk, *Journal of Dairy Research*, Vol. 37, pp. 233-243.

W. L. McCabe, J. C. Smith, and P. Harriott, 2001, *Unit Operations of Chemical Engineering*, McGraw-Hill, New York, 6th edition.

R. H. Perry and D. W. Green, 1997, *Perry's Chemical Engineers' Handbook*, McGraw Hill, 7th edition.

T. Qihua, V. K. Jindal, and J. van Winden, 1993, Design and performance evaluation of an ohmic heating unit for liquid foods, *Computers and Electronics in Agriculture*, Vol. 9, No. 3, pp. 243-253.

C. P. Samaranayake and S. K. Sastry, 2005, Electrode and pH effects on electrochemical reactions during ohmic heating, *Journal of Electroanalytical Chemistry*, Vol. 577, pp. 125-135.

P. Skudder and C. Biss, 1987, Aseptic processing of food products using ohmic heating, *The Chemical Engineer*, February, pp. 26-28.

R. Stirling, 1987, Ohmic heating - a new process for the food industry, *Power Engineering Journal*, Vol. 6, pp. 365-371.

I. Toyoda, P. J. R. Schreier, and P. J. Fryer, 1994, A computational model for reaction fouling from whey protein solutions, *Fouling and Cleaning in Food Processing*, Cambridge, England, pp. 222-229.

R. E. Treybal, 1981, *Mass Transfer Operations*, McGraw-Hill Book Company, 3rd edition.

J. Visser and T. J. M. Jeurnink, 1997, Fouling of heat exchangers in the dairy industry, *Experimental Thermal and Fluid Science*, Vol. 14, No. 4, pp. 407-424.