

FOULING IN A CENTRITHERM EVAPORATOR WITH WHEY SOLUTIONS

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ABSTRACT

Fouling caused by sweet cheese whey and reconstituted whey powder solutions was studied in a Centritherm evaporator, the behaviour being estimated by measuring the change in the overall heat transfer coefficients with the time. It was found that there was no fouling detectable for the reconstituted whey powder solution. For sweet cheese whey, the fouling rate was linked strongly with the evaporating temperature and temperature difference. Visual observation showed that the deposit layer on the evaporator surface was very thin and soft, and like the type A milk deposit described by other investigators. A high velocity of liquid film delayed the formation of deposit on the surface. Some interactions between the evaporation temperature, feed flow rate, rotating speed and temperature difference are discussed.

The fouling is caused by denaturation of bovine serum albumin in a second order rate reaction.

INTRODUCTION

Deposition of materials on heat transfer surfaces causes an increase in the thermal resistance, known as fouling. In all industrial heat treatment of liquid foods the fouling of such surfaces is a serious problem, which causes loss of production (due to reduced capacity), increases in capital costs (increased heating surface), energy losses, maintenance costs, pollution (due to cleaning agents), and affects the quality of products (e.g. scorched particles in the final products) (Hallström, *et al* 1988). The prevention of deposit formation on heating surfaces has become increasingly important in the dairy industry as the volume of milk processed in a dairy plant has steadily increased. Therefore special consideration has been given to the reduction in energy consumption, amounts of cleaning material used and time spent in cleaning (Hege and Kessler, 1986) as a result of fouling.

Although a large number of investigations have been carried out on heat exchangers (either

plate and tubular) and ultra high temperature (UHT) plants, very few studies have concentrated on fouling during the evaporation process (Kessler, 1989). In a review, Fryer *et al.* (1995) pointed out that fouling in the evaporation process had not been thoroughly studied and the mechanism of fouling is not yet known. More work is needed in this area.

The Centritherm evaporator is a type of thin-film evaporator with rotating heating surfaces, which has very high heat transfer coefficients and short product's residence time. This type of evaporator has found many applications in the industry and provides a good choice (for small to medium capacities) for concentration of food, chemical and pharmaceutical heat sensitive materials.

The objective of this work was to investigate the fouling phenomena occurring in the Centritherm evaporator using reconstituted whey powder solution and sweet cheese whey. In this paper, the effects of evaporating temperature, temperature difference between the evaporating and the steam condensing temperatures and rotating speed of the heating surface, together with the interactions of the experimental variables on fouling of the evaporator surface, are discussed.

MATERIALS AND METHODS

Powdered whey protein concentrate (ALACEN 134) from the Fonterra Cooperative Group Ltd was used to make up a reconstituted whey powder solution at 25% TS. This concentration was used to enhance any effect of concentration on fouling. Many protein denaturation reactions are second order, Dannenberg and Kessler, (1988) and hence fouling will be faster at higher concentrations.

Sweet Cheddar cheese whey (total solids 6.5-7.5%, pH = 4.4-4.8) from the Longburn Cheese factory of the Fonterra Cooperative Group Ltd was used.

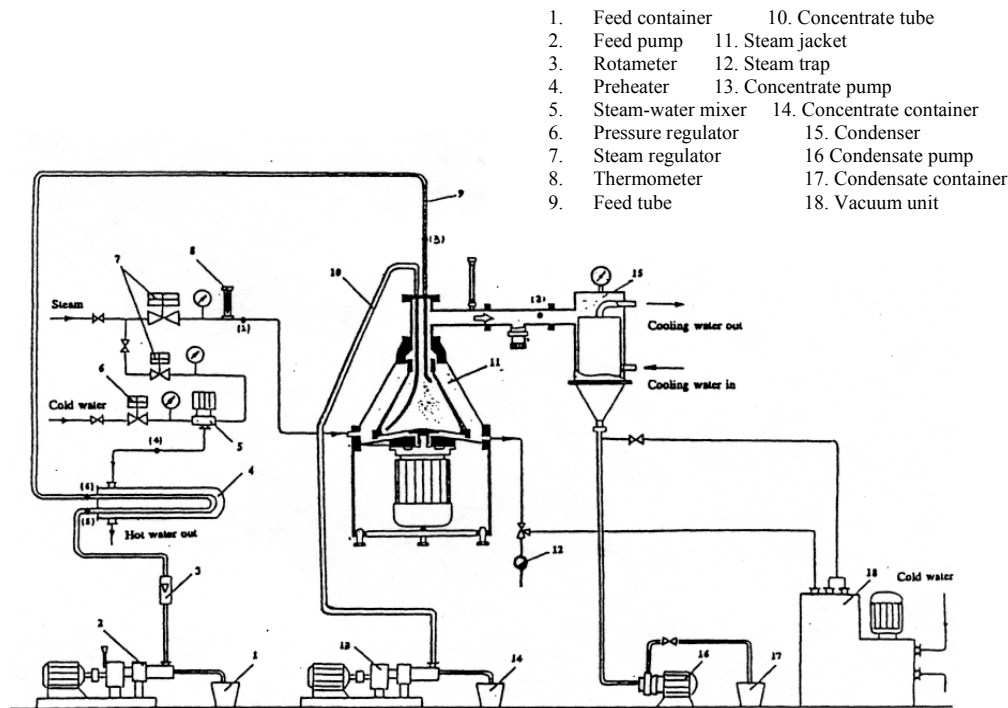


Fig. 1 Diagram of the Centritherm evaporator.

Table 1. Ranges of experimental variables

Evaporating Temperature (°C)	60, 70
Temperature difference (°C)	10, 20
Rotating speed (rpm)	1000, 1780
Feed flow (l/s)	0.04, 0.17

A Centritherm evaporator was used to carry out the experiments. A diagram of the evaporation system is shown in Figure 1. The whey solution was pumped by a variable speed pump through a Spiraflo heat exchanger, where the solution was heated to the evaporating temperature, and then into the feed tube. After passing through the feed tube, the solution was fed onto the inside surface of the cone, close to the axis, and flowed down the surface as an extremely thin, fast-moving, evaporating liquid film, under the centrifugal force caused by the rotation of the cone. The concentrated solution was pumped out by a mono pump and the vapour passed through a vapour chamber to the condenser, from which the condensate was pumped out by a centrifugal pump. To make a recycle of the whey solution in the system and maintain the constant concentration of the feed, the concentrated solution and the vapour condensate were fed back to the feed container. About 40 litres of whey solution were used for each run.

The levels of experimental variables used are shown in Table 1. The temperatures were selected as they are in the range used commercially and are

at the lower level of temperatures that could cause protein denaturation.

Polyacrylamide Gel Electrophoresis (PAGE) was used to determine the extent of whey protein denaturation during processing in the Centritherm.

THEORY

The equation for the overall heat transfer coefficient in an evaporator with a clean surface can be written as:

$$\frac{1}{U_o} = \frac{1}{h_o} \frac{A_m}{A_o} + \frac{1}{h_i} \frac{A_m}{A_i} + \frac{\delta_w}{\lambda_w} \quad (1)$$

If the effect of fouling is taken into account, a fouling resistance (R_f) can be included in the equation as:

$$\frac{1}{U} = \frac{1}{h_o} \frac{A_m}{A_o} + \frac{1}{h_i} \frac{A_m}{A_i} + \frac{\delta_w}{\lambda_w} + \frac{\delta_d}{\lambda_d} \quad (2)$$

or

$$\frac{1}{U} = \frac{1}{U_o} + \frac{\delta_d}{\lambda_d} = \frac{1}{U_o} + R_f \quad (3)$$

Thus the fouling resistance can be calculated from the overall heat transfer coefficients using the following equation:

$$R_f = \frac{1}{U} - \frac{1}{U_o} \quad (4)$$

The overall heat transfer coefficients (U_o and U) are computed by using the measured flow rate of vapour condensate and the temperature difference

between the steam temperature and the evaporating temperature to compute the heat flow. The overall heat transfer coefficient was then calculated from the equation:

$$U = \frac{Wh_{fg}}{A_m \Delta T} \quad (5)$$

The fouling behaviour in the evaporator can then be estimated by measuring the change in the overall heat transfer coefficients with time. The possible mechanisms for milk fouling involve several steps, Burton, (1988):

- (1) **Converting.** One or more of the constituents in the product are converted into a form capable of being deposited on the surface;
- (2) **Transporting.** The depositable material is transferred to a surface;
- (3) **Adsorption.** Fouling materials are attached to the surface to form an initial layer;
- (4) **Build-up.** Deposition of further fouling material on the initial layer
- (5) **Balance.** Balance between deposition and removal through the shear forces caused by the flow of the products across the deposit-liquid interface.

One major reaction involved in fouling is the denaturation of whey protein, which can be described as a consecutive reaction of unfolding and aggregation, de Jong, *et al.*, (1992). The fouling behaviour of whey in the Centritherm evaporator is complex. Under the experimental conditions, only the initial stage of fouling from whey solutions on the rotating surface was studied.

RESULTS AND DISCUSSION

Reconstituted Whey Solutions

Initially, a reconstituted whey powder solution (25%TS) was used. It was found that there was no fouling detectable after running for 6 hours at an evaporating temperature of 60°C, temperature difference of 20°C, rotating speed of 1780 rpm, and a feed flow rate of 0.04 liters per second. Jeurnink (1995a), similarly found that reconstituted milk gave much less fouling than fresh milk in tubular heat exchangers.

The possible reason for this finding is that materials which are responsible for forming the deposits on the surface have been removed (inactivated) or reduced during the manufacture of powders. The depositable materials included some minor constituents in their native form, minerals and denatured whey protein. It has been found that aggregated whey proteins are less active for fouling (Jeurnink, 1995b). Jeurnink (1995a) also suspected that the process of reconstitution presumably

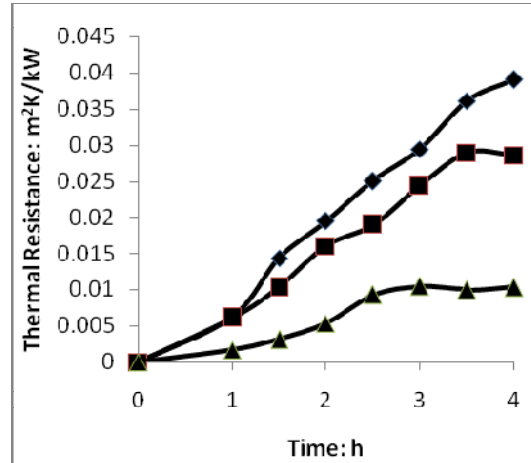


Fig. 2 Plot of thermal resistance against time for recycled sweet cheese whey in a Centritherm evaporator .

- ◆ Evaporating temperature (ET) 60°C rotating speed(rpm) 1000 ΔT 20°C Feed Flow (FF) 0.017 l/s
- ET 60°C rpm 1000 ΔT 20°C FF 0.042 l/s
- ▲ ET 60°C rpm 1000 ΔT 10°C FF 0.017 l/s

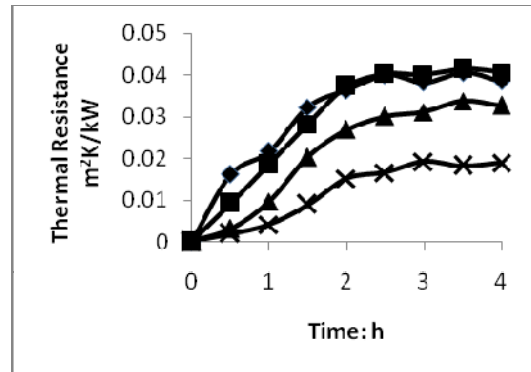


Fig.3 Plot of thermal resistance against time for recycled sweet cheese whey in a Centritherm evaporator at an evaporating temperature of 70°C and a rotating speed of 1000 rpm.

- ◆ ET 70°C ΔT 20°C FF 0.017 l/s
- ▲ ET 70°C ΔT 20°C FF 0.42 l/s
- ET 70°C ΔT 10°C FF 0.017 l/s
- × ET 70°C ΔT 10°C FF 0.42 l/s

caused other changes affecting the fouling behaviour.

The Effects of Evaporation Temperature, Temperature Difference, and Flow Rate

Figs. 2 and 3 show that the fouling resistance increases with time for cheese whey at evaporation temperatures of 60°C and 70°C.

Table 2. The Percentage Loss of Native Whey Protein during Evaporation at a Temperature of 70°C and a Temperature Difference of 20°C.

Time: h	1	2	3	4	6
α -lactalbumin	0	0	0	0	0
β -lactoglobulin	0	0	0	0	0
B.S.A.	44	50	61	72	72

It is confirmed that both the evaporation temperature and temperature difference strongly influence fouling on the heating surface. The higher the levels of these factors the greater is the rate of fouling on the surface. This can be attributed to the fact that depositable materials adsorb on the surface more quickly at a high temperature than at a low temperature, Roscoe, and Fuller, (1994). The evaporation temperature has a greater effect the temperature difference. This is because with the latter effect the increase is on the steam side of the metal, and the temperature drop through the metal will lower the difference on the evaporation side. The effect of the temperature difference diminishes as the thickness of the fouled layer increases. The heat flow through the metal will diminish, and the evaporating side metal temperature increase as a result. However there will then be a temperature drop through the fouling layer, and with the reduced heat flow a lower temperature drop through the laminar liquid layer. Hence the temperature of the liquid against this layer will be lower and the fouling rate reduced.

It can be seen in the fouling curves that an induction period of about one hour exists for an evaporating temperature of 60°C but there is no observable induction period for evaporating temperature of 70°C and a temperature difference of 20°C. An induction period of about a half hour was, however, observed for an evaporating temperature of 70°C, and a temperature difference of 10°C. These results show that the rate of protein denaturation from whey protein is slower at 60°C than at 70°C. It was demonstrated by other investigators (Jeurink, 1995a, 1995b, de Jong et al. 1992, Hege & Kessler, 1986), that the denaturation of the whey protein is strongly associated with milk fouling.

The change of the protein's state in cheese whey solutions after running (recycled) in the evaporator at 60°C and 70°C for 6 hours was determined using PAGE. There was no detectable level of denatured whey proteins at 60°C, and only loss of bovine serum albumin (BSA) was found at 70°C. Results for the more severe conditions are presented in table 2.

By using the equation proposed by Chen *et al.* (1994) the inner surface temperature of the rotating cone was calculated to be about 77°C, when the evaporation temperature was 70°C and the temperature difference was 20°C (rotating

speed of the cone: 1780 rpm, feed flow 0.041/s). At this temperature only BSA would be expected to denature. This explains why the BSA only was 72% denatured but the other whey proteins were undenatured after running the evaporator at 70°C for 6 hours.

Although the content of BSA in whey is small, this amount of denatured BSA could easily be attached to the surface, and be associated with the other depositable materials existing in the whey.

After the run was completed the evaporator was disassembled, and the fouled cone surface examined. The deposit layer was very thin and soft, resembling the type A deposit described by other investigators (Burton, 1968, Lalande *et al.*, and Tissier *et al.*, 1984). From a theoretical calculation if the thermal conductivity λ_d is taken 1984, as 0.3 W/m.K (Wood, 1982) the thickness of deposit on the cone surface, assuming fouling resistance of 0.04 m²K/kW, can be determined as 12 μ m. Obviously the low conductivity of the fouling layer makes such a thin deposit produce a significant reduction in the overall heat transfer coefficient.

It can be seen from Figs. 2 and 3 that the fouling rate is lower at higher flow rates, although the effect of evaporation temperature is more marked. As the film is soft it is likely that there is more scouring effect at higher flow rates, and hence the net deposition rate is lower.

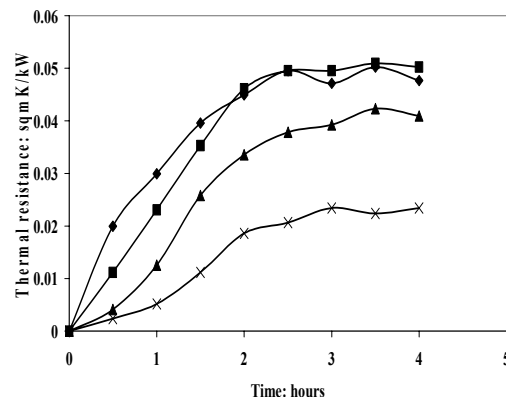


Fig. 4. Plot of thermal resistance vs time for recycled sweet cheese whey in a Centritherm evaporator at different rotating speeds. Evaporating temperature 70°C.

- ◆ ΔT : 20°C, FF: 0.17 l/s, RS (rotating speed): 1000 rpm
- ΔT : 20°C, FF: 0.17 l/s, RS: 1780 rpm
- ▲ ΔT : 10°C FF: 0.017 l/s RS 1000 rpm
- × ΔT : 10°C FF: 0.017 l/s, RS: 1780 rpm

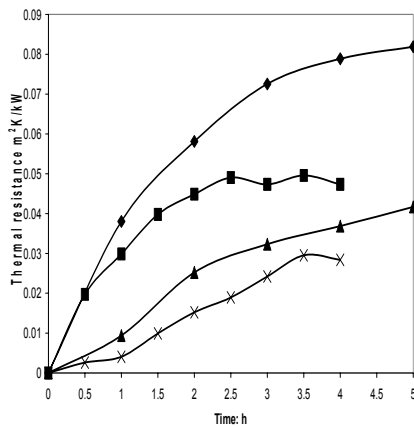


Fig. 5. Comparison of the thermal resistance in a falling film evaporator and a Centritherm evaporator.

- ◆ ET 70°C, FF 0.04 l/s Falling film evaporator
- ET 70°C, FF 0.04 l/s, Centritherm evaporator.
- ▲ ET 60°C, FF 0.017 l/s, Falling film evaporator
- × ET 60°C, FF 0.017 l/s, Falling film evaporator

Rotating Speed

The effect of the rotating speed of the cone on the thermal resistance can be observed in Fig. 4. There is a tendency for the amount of fouling to be lowered with an increase in rotating speed at a low temperature difference. However the effect of the rotating speed on the thermal resistance is not significant at higher temperature differences.

Comparison Between the Centritherm and a Falling Film Evaporator

Figure 5 shows a comparison between the fouling on a falling film evaporator and the Centritherm evaporator. It can be seen that the fouling rate is higher in the falling film evaporator than that in Centritherm. This shows that the high velocity of the liquid film delays the formation of the deposit on the heat transfer surface. In theory, the higher the rotating speed, the higher the centrifugal force applied on the liquid film, then the deposition rate would be reduced and the rate of increase of thermal resistance with time will be lower. Taborek *et al* (1972) also found that increased flow velocity results not only in higher heat transfer coefficients, but in a decreased tendency toward fouling

The Interaction of Variables on the Fouling Resistance

The fouling process is a transient process. To find out the interaction of the variables, the values of

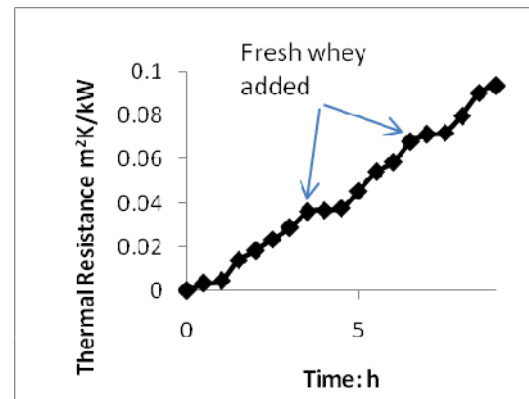


Fig. 6 Plot of thermal resistance vs time for recycled sweet cheese whey, when fresh whey was introduced after recycling for some hours. ET: 60°C, ΔT :20°C, RS:1000 rpm, FF:0.04 l/s.

fouling resistance after 4 hours operation were loaded into a regression analysis program (Quattro Pro). The following equation was obtained:

$$R_f = 3.4 E^{-3} T - 3. E^{-5} \Omega + 0.052 Q - 7.5 E^{-4} TQ + 1.4 E^{-6} \Delta T \Omega$$

There is a negative interaction between the evaporation temperature and flow rate. This means that at higher flow rates the effect of the temperature is smaller. A possible explanation may be that the higher evaporating temperature causes a reduction in the viscosity of the evaporating solution, which in turn increases the flow velocity and decreases the fouling rate (Taborek *et al.* 1972).

It was also found that the interaction between temperature difference and rotating speed causes the fouling resistance to increase. A possible explanation may be that although the rotating speed has a negative effect on the fouling rate, the positive effect of the temperature difference is greater at a higher temperature.

Build-up of the Deposits

Figure 6 shows that the fouling resistances increased with time after new whey solutions were introduced into the system. That is, the whey solution was run for the first four hours and then new whey solutions were introduced and the evaporator run for another three hours. The curve in Figure 6 indicates that the depositable materials in the whey would be used up or inactive after running for some time and that the deposition rate

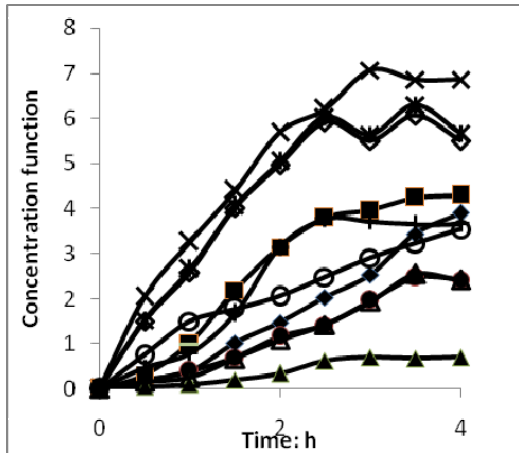


Fig. 7. Effect of flow rate, temperature difference and evaporating temperature on evaporator fouling resistance using $\frac{1}{2}$ order rate equations.

□ ET 60°C rpm 1000 ΔT 20°C FF 0.14 l/s
 □ ET 60°C rpm 1000 ΔT 20°C FF 0.017 l/s
 □ ET 60°C rpm 1000 ΔT 10°C FF 0.017 l/s
 X ET 70°C rpm 1000 ΔT 20°C FF 0.017 l/s
 * ET 70°C rpm 1000 ΔT 20°C FF 0.14 l/s
 □ ET 70°C rpm 1000 ΔT 10°C FF 0.017 l/s
 + ET 70°C rpm 1000 ΔT 10°C FF 0.14 l/s
 ~ ET 70°C, FF 0.04 l/s, Centritherm evaporator
 O ET 60°C, FF 0.017 l/s, Falling film evaporator
 □ ET 60°C, FF 0.017 l/s, Centritherm evaporator

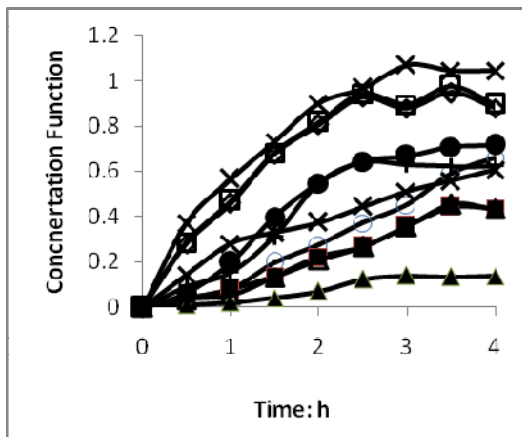


Fig. 8. Effect of flow rate, temperature difference and evaporating temperature on evaporator fouling resistance using 1st order rate equations. The legend is the same as for Fig. 7.

largely depends on the concentration of the depositable materials. The result agrees with the fouling model proposed by Jeurnink (1995b). He found the fouling rate is related to concentration

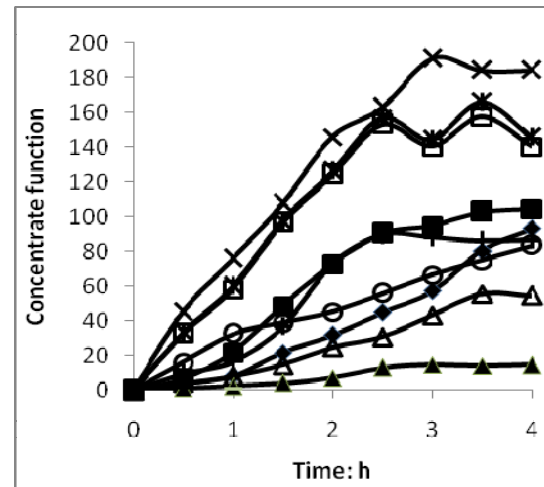


Fig. 9. The effect of flow rate, temperature difference and evaporating temperature on evaporator fouling. The legend is the same as for Fig. 7. at 70°C is not shown on the graphs.

of activated molecules (e.g. unfolded whey protein) in the solutions.

It can be seen that there is an induction period when a new whey solution is introduced. However, the induction period decreased, i.e. it was about one hour for the first introduced solution and about half hour for the following introduced solution. This may be due to the fact that it takes less time for depositable materials to be adsorbed on the fouled or unclean surface than on the clean surface Burton, (1988). So the first induction period is longer than the following induction periods.

Reaction Order

This fouling is caused by denaturation of BSA. To determine the order of this reaction under the conditions used, the data in Figs. 2 to 5 was plotted for half order (Fig. 7), first order (Fig. 8), and second order (Fig. 9), reactions. The concentrations were calculated by assuming that a fouling resistance of $0.1 \text{ m}^2\text{K/kW}$ represented complete denaturation of the BSA, and that the concentration estimated from the calculated thickness of the deposited layer, and that the thickness was inversely proportional to the fouling resistance. The curve for the falling film evaporator evaporation temperature 70°C, flow rate 0.04 l/s, was not used for the reaction order analysis. Under the conditions of this experiment the surface temperature of the wall was at a maximum; the rate of fouling was high and the concentration of BSA after running for some time was very low. The reaction rate numbers were so large that to include these results would have made the rest of the graph

unreadable. Under these conditions other fouling reactions may have commenced, and this would mean that these results are in error and should be disregarded.

For a half- order reaction the equation:

$$k\theta = C_0 - C_\theta \tag{6}$$

and for the first order the equation:

$$k\theta = \ln \frac{C_0}{C_\theta} \tag{7}$$

and for second order the equation

$$k\theta = \frac{1}{C_\theta} - \frac{1}{C_0} \tag{8}$$

Under conditions where the fouling rate is high, after some time the concentration of BSA in the whey is very low. As the concentration is determined by subtracting the amount of deposited material from the initial concentration, it is obtained by subtracting two numbers of similar sizes, and hence is very inaccurate, as can be seen from the graphs. Especially at lower temperatures, there is a lag phase, which will influence the shape of the curves in the early stages. The results in these areas have been ignored in assessing the likely reaction order.

The major portions of the 1/2 order reaction curves, Fig. 7, are distinctly curved indicating that this order of reaction is unlikely. The 1st order curves, Fig. 8, are also curved, but the curvature is less pronounced, particularly at lower fouling rates. The major portions of the 2nd order reaction curves, Fig. 9, are approximately straight, although there is clearly some experimental error.

Using the Mathcad 2000 computer program the standard errors for linear regressions of the significant portions of the curves in Figs. 7 to 9 were determined. (The lag phase at the lower end and the inaccurate portion at the upper end were omitted). The results are shown in table 3. The averages of the errors for each order of reaction were used with a Student's "t" test to determine the significance of the differences. The results are shown in table 4, and indicate the reaction is probably of second order. The curves for the experiment with an evaporating temperature of 70° C, a temperature difference of 20° C and a flow rate 0.17l/s. (curve 7) were not used for the analysis of the reaction order, as no part of these curves (in Fig. 7) was straight. The metal surface temperature was higher and the boundary layer thickness was lower for this experiment than any other, and it is likely that other fouling reactions were commencing under these conditions.

During the lag phase it is thought that a layer of denatured BSA is being built up on the metal surface. The BSA molecules in this layer are much closer together than they would be in

Table 3. Means of standard errors of linearity tests for different orders of reaction.

Order	Mean standard error	Standard Deviation
1/2	0.18	0.085
1 st	0.34	0.13
2 nd	0.035	0.035

Table 4. Results of a Student's t test for the linearity of different orders of reaction.

Comparison	"t" value	Significance level
1/2 - 1 st	1.45	10%
1 st - 2 nd	2.67	1%
1/2 - 2 nd	1.4	10%

solution. If the reaction is second order between two BSA molecules it would proceed more quickly once the layer formation was completed and would be taking place both in solution, and between molecules in solution, and deposited molecules.

In the analysis of reaction order the assumption is made that the reactants are in solution. This is partly true during the lag phase, but once there is a film of denatured BSA on the surface the concentration there, for BSA molecules close to the surface, is high and does not change with time, but molecules in solution may react with denatured molecules on the surface. If this is true, in the region close to the surface only the concentration of the molecules in solution will change with time. Hence in this region the rate equation will be first order and:

$$\frac{dC_s}{d\theta} = kC_s \tag{9}$$

where Cs is the concentration near the surface. There will be a laminar layer close to the surface, so the rate of transfer of BSA molecules to the surface will be diffusion controlled and proportional to the concentration. Therefore:

$$\frac{dC_s}{d\theta} = k_d(C_s - a^{k\theta}) \tag{10}$$

or

$$\ln(k_d C - dC/d\theta) = k\theta - \ln(k_d a) \tag{11}$$

For each of the curves the significant portion was fitted to an exponential relation. The equation thus obtained was used to determine the value of the differential in equation 11. Mathcad was used to perform a regression analysis of the data and determine the constants in equation 11. In the absence of other information, kd was assumed to be 1. The results are shown in tables 5 and 6.

Table 5. Properties of smoothed curves from the results.

Curve	Intercept	Slope	Std Error
1	-2.341	-0.185	0.021
2	-2.364	-0.13	0.026
3	-2.452	-0.04	0.018
4	-2.733	-1.07	0.307
5	-2.698	-0.98	0.101
6	-2.741	-0.561	0.064
7	-2.884	-0.168	0.028
8	-2.818	-1.053	0.435
9	-2.991	-0.44	0.176
10	-2.987	-0.162	0.084

Table 6. Properties of lines obtained by correlating the function $(dC/d\theta - k_d C)$ with time.

Curve	Intercept	Slope	Std Error
1	2.34	0.185	.000327
2	2.363	0.145	.0003654
3	2.353	-.00154	.000706
4	2.731	1.074	.000750
5	2.696	0.981	.000719
6	2.772	0.55	.0320
7	2.881	0.169	3.27E-04
8	2.816	1.054	8.90E-04
9	2.99	0.44	6.55E-04
10	2.985	0.162	2.93E-04

The curves are clearly straight lines, and are evidence that the reaction is a second order one, and that the deposited BSA is still reactive for its denaturation.

There is little in the literature on the reaction kinetics of the denaturation of BSA, but Dannenberg and Kessler, (1988) state that the denaturation of α -lactalbumin and β -lactoglobulin are second order reactions.

CONCLUSIONS

For reconstituted whey powder solution, no fouling was detected. For sweet cheese whey, fouling is strongly linked with the evaporation temperature and temperature difference and is mainly due to the whey protein denaturation. The fouling rate was presumably related to the concentration of the depositable materials in the solutions. Even a small amount of denatured whey protein could reduce the heat transfer coefficients significantly. In this type of evaporator with a very low temperature range, and a very high liquid velocity, the deposit formation

would be smaller than that of a falling film evaporator.

The fouling reaction is a denaturation of BSA and is probably of second order.

NOMENCLATURE

A_m	Average heat transfer area [$A_m = 2\pi L(r_0 - r_i) / \ln(r_0/r_i)$] (m^2)
A_i	Inside heat transfer area (m^2)
A_o	Outside heat transfer area (m^2)
C	Initial concentration of BSA
C_θ	Concentration of BSA after time θ
C_s	Concentration of BSA in solution near the fouled surface
h_{fg}	Latent heat of vapour condensation (kJ/kg)
h_i	Film heat transfer coefficient on inside of cone (kW/m^2K)
h_o	Film heat transfer coefficient on outside of cone (kW/m^2K)
k	Constant in rate equations
k_d	Diffusion Constant
Q	Flow rate m^3/s
R_f	Fouling resistance (m^2K/kW)
ΔT	Temperature difference between the liquid evaporating and the steam condensing temperatures (K)
U	Overall heat transfer coefficient at time t (kW/m^2K)
U_o	Clean overall heat transfer coefficient at time zero (kW/m^2K)
W	Flow rate of vapour condensate (kg/s)

Greek symbols

δ_d	Thickness of the deposit at time t (m)
δ_w	Thickness of the heat transfer wall (m)
λ_d	Thermal conductivity of the deposit (kW/mK)
λ_w	Thermal conductivity of the heat transfer wall (kW/mK)
θ	Time of reaction (h)
Ω	Angular velocity rad/s

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