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FOULING OF HEAT EXCHANGERS BY DAIRY FLUIDS – A REVIEW

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ABSTRACT

Fouling of heat exchangers in the dairy industry has been investigated extensively and a large number of studies are reported in literature. This review focuses on the mechanisms of milk fouling, detailing the role of protein denaturation and aggregation reactions as well as mass transfer. It has also been endeavoured to review the effect of a number of different factors on milk fouling. These factors have been divided into five major categories: milk composition, operating conditions, heat exchanger characteristics, presence of micro-organisms, and location of fouling.

INTRODUCTION

In the dairy industry, thermal processing is an energy intensive process since every product is heated at least once (de Jong 1997). Processing over 13 billion litres of milk every year in New Zealand (Fonterra 2004) means the efficiency of the heating process is of paramount importance. Fouling of heat exchangers is a serious issue as it reduces heat transfer efficiency and increases pressure drop and hence affects the economy of processing plant (Müller-steinhagen 1993, Toyoda et al. 1994). As a result of fouling, there is a possibility of deterioration in product quality since the process fluid cannot be heated up to the required temperature (say for pasteurisation or sterilization). The deposits dislodged by the flowing fluid can also cause contamination.

Fouling related costs are: additional energy, lost productivity, additional equipment, manpower, chemicals, environmental impact (Gillham et al. 2000). Generally milk fouling is so rapid that heat exchangers need to be cleaned every day to maintain production capability and efficiency and meet strict hygiene standards. In comparison, the heat exchangers in other major processing plants like petroleum, petrochemical etc need to be cleaned only once or twice a year. According to Georgiadis et al. (1998), in the dairy industry the cost due to the interruption in production can be dominant compared with the cost due to reduction in performance efficiency. Along with the cost, quality issues are equally important and in fact many times a shut down is required due to the concerns of product quality/contamination instead of performance of the heat exchanger.

Milk is a complicated biological fluid and contains a number of species. Its average composition in weight % is: water – 87.5, total solids - 13.0, fat – 3.9, lactose – 4.8, proteins – 3.4 (casein – 2.6, β-lactoglobulin (β-Lg) – 0.32, α-lactalbumin (α-La) – 0.12), minerals – 0.8, and small quantities of other miscellaneous species (Bylund 1995). Thermal response of these constituents generally differs from each other. β-Lg has high heat sensitivity and figures prominently in the fouling process (Lyster 1970, Lalande et al 1985, Gotham et al. 1992, Delplace et al. 1994, Bylund 1995). Milk fouling can be classified into two categories (Burton 1968, Lund and Bixby 1975, Visser and Jeurnink 1997, Changani et al. 1997): i) Type A (protein) fouling takes place for temperatures between 75°C and 110°C. The deposits are white, soft, and spongy (milk film) and their composition is 50-70% proteins (mainly β-Lg), 30-40% minerals, and 4-8% fat, ii) Type B (mineral) fouling takes place at temperatures above 110°C. The deposits are hard, compact, granular in structure, and grey in colour (milk stone) and their composition is 70-80% minerals (mainly calcium phosphate), 15-20% proteins, and 4-8% fat.

MECHANISMS OF MILK FOULING

Whey proteins constitute just around 5% of the milk solids but they account for more than 50% of the fouling deposits in type A fouling. β-Lg and α-La are the two major whey proteins in the milk. Both are of globular nature and heat sensitive, however, β-Lg is the dominant protein in heat induced fouling (Lyster 1970, Lalande et al 1985, Bylund 1995). The caseins are resistant to thermal processing but do precipitate upon acidification (Visser and Jeurnink 1997). Although the exact mechanisms and reactions between different milk components are not yet fully understood, a relationship between the denaturation of native β-Lg and fouling of heat exchangers has been established (Dalgleish 1990). Upon heating of milk, the native proteins (β-Lg) first denature (unfold) and expose the core containing reactive sulphydryl groups. The denatured protein molecules then react with the similar or other types

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of protein molecules like casein, α-lactalbumin (α-La) and form aggregates. The rate of fouling may be different for the denatured and aggregated proteins. Being larger in size, the transport of the aggregated proteins from the bulk to the heat transfer surfaces may be more difficult compared with the denatured proteins (Treybal 1981, Chen 2000). According to Changani et al. (1997), fouling occurs when the aggregation takes place next to the heated surfaces. Delplace et al. (1994) experimentally observed that only 3.6% of denatured β-Lg was involved in deposit formation. Lalande et al. (1985) found the figure to be around 5%. However, it is not clear whether fouling was primarily caused by the aggregated proteins or the denatured proteins deposited first on the heat transfer surfaces and the aggregation took place subsequently. Toyoda et al. (1994) modelled the milk fouling process based on the assumption that only aggregated proteins resulted in fouling. According to Delplace et al. (1997), fouling is controlled by the aggregation reaction of protein molecules. de Jong et al. (1992) found that the formation of protein aggregates reduces fouling. van Asselt et al. (2005) believe that β-Lg aggregates are not involved in fouling reactions. Chen et al. (1998a, 2001) in their mathematical modelling considered that along with aggregated proteins, denatured proteins also took part in deposit formation.

Usually an induction period is required for the formation of the protein aggregates or insoluble mineral complexes before noticeable amount of deposits are formed (Elofsson et al. 1996, Visser and Jeurnink 1997, de Jong et al. 1998). This time period varies between 1 and 60 minutes for tubular heat exchangers (de Jong 1997) but is much shorter or even instantaneous in plate heat exchangers where intense mixing of fluid takes place due to higher turbulence (Belmar-Beiny et al. 1993). Activation energies of deposition reactions for both types of heat exchangers are reported to be similar, which suggests that the underlying processes are the same in both cases (Fryer and Belmar-Beiny 1991).

The native proteins may adsorb on the heat transfer surface at low temperatures i.e. below 70°C with coverage of less than 5 mg/m^2 but this does not result in any fouling. According to Fryer and Belmar-Beiny (1991), protein denaturation in heat exchangers starts only at temperatures above 70-74°C. They also reported that the first deposit layer (usually < 5μm) is largely mineral. According to Visser and Jeurnink (1997) mainly the proteins form the first layer. Analysis of deposits after fouling for an extended period usually shows that the deposits near the surface contain a higher proportion of minerals. This is caused by the diffusion of minerals through the deposits to the surface rather than minerals forming firstly on the surface (Belmar-Beiny et al. 1993). Belmar-Beiny and Fryer (1993) analysed deposits with contact heating times down to 4 s and found that the first layer was made of proteinaceous material.

Fouling in a heat exchanger depends on bulk and surface processes. The deposition is a result of a number of stages (Belmar-Beiny and Fryer 1993):

i) denaturation and aggregation of proteins in the bulk
ii) transport of the aggregated proteins to the surface
iii) surface reactions resulting in incorporation of protein into the deposit layer and
iv) possible re-entrainment or removal of deposits.

The step controlling the overall fouling hence may either be related to physical/chemical changes in the proteins or the mass transfer of the proteins between the fluid and the heat transfer surface. In some cases, it may be a combination of both. Belmar-Beiny et al. (1993) and Schreier and Fryer (1995) proposed that fouling was dependent on the bulk and surface reactions and not on the mass transfer. It was also proposed that the fouling rate was independent of the concentration of foulant in the liquid (Schreier and Fryer 1995).

According to Lalande et al. (1985), Hege and Kessler (1986), Arnebrant et al. (1987), and Kessler and Beyer (1991), protein denaturation is the governing reaction. On the other hand, Lalande and René (1988) and Gotham et al. (1992) have observed that protein aggregation is the governing reaction. de Jong et al. (1992) observed that the deposition of milk constituents in heat exchangers is a reaction-controlled adsorption of denatured proteins. Toyoda et al. (1994) suggested that mass transfer between bulk fluid and thermal boundary layer was also important along with the bulk and surface reactions. Also only aggregated proteins in the thermal boundary layer were able to cause deposition. Changani et al. (1997), Anema and McKenna (1996), and Chen et al. (1998a) suggested that the protein unfolding or denaturation step is reversible whereas Ruegg et al. (1977), Lalande et al. (1985), Arnebrant et al (1987), and Roefs and de Kruif (1994), and Karlsson et al. (1996) have found evidence that the denaturation step is irreversible. In comparison, the protein aggregation step has been reported to be always irreversible (Mulvihill and Donovan 1987, Changani et al 1997, Anema and McKenna 1996, and Chen et al 1998a).

Chen et al. (2001) proposed, based on their experimental data, that fouling was caused by both denatured and aggregated whey proteins and perhaps primarily influenced by the presence of the denatured (but not the aggregated) proteins in the bulk. They also included the mechanism of the reversible formulation in the protein denaturation process. Their simulated results showed that similar accuracy of the fouling predictions was achieved with different combinations of unfolded and aggregated proteins for hot surface – cold fluid scenario. However, different mechanisms may lead to quite different predictions for cold surface – hot fluid scenario. This illustrates the need to study the cold surface effect for better understanding.

Factors Affecting Milk Fouling

Milk fouling may be unavoidable practically and continuous efforts are required to minimise it. Fouling in a heat exchanger depends on various parameters like heat transfer method, hydraulic and thermal conditions, heat transfer surface characteristics, type and quality of milk along with its processing history etc. The factors affecting milk fouling in heat exchangers can be broadly classified into five major categories:

- Milk composition
- Operating conditions in heat exchangers
- Type and characteristics of heat exchangers
- Presence of micro-organisms
- Location of fouling

Milk composition

The composition of milk depends on its source and hence may not be possible to change. A seasonal variation in milk fouling depends on differences in its composition (Butron 1967, Belmar-Beiny et al. 1993, de Jong 1997). Increasing the protein concentration results in higher fouling (Toyoda et al. 1994, Changani et al. 1997).

The heat stability of milk proteins decreases with a reduction in pH (Foster et al. 1989, Xiong 1992, Corredig and Dalgleish 1996, de Jong et al. 1998). The calcium ions present in the milk decrease the denaturation temperature of β-Lg, promote aggregation by attaching to β-Lg, and enhance the deposition by forming bridges between the proteins adsorbed on the heat transfer surface and aggregates formed in the bulk (Changani et al. 1997, Christian et al. 2002). It has also been reported that increasing or decreasing the calcium content of milk compared with normal milk lowers the heat stability and caused more fouling (Roefs and de Kruif 1994). The fat present in milk has little effect on fouling (Visser and Jeurnink 1997). Additives may reduce fouling by enhancing heat stability of milk but they may not be permitted in many countries (Lyster 1970, Skudder et al. 1981, Changani et al. 1997).

Holding milk for 24 hours before processing results in less fouling although further ageing increases fouling (Burton 1968, Changani et al. 1997). Prolonged storage of milk for a few days at 5°C may enhance fouling due to the action of proteolytic enzymes (Burton 1968, de Jong 1997). Preheating of milk in holding tubes causes denaturation and aggregation of proteins before the heating section, which then leads to lower fouling in the heat exchangers (Bell and Sanders 1944, Burton 1968, Mottar and Moermans 1988, Foster et al. 1989).

Reconstituted milk gives much less fouling since around 25% of β-Lg is denatured during the production of milk powders (Changani et al. 1997, Visser and Jeurnink 1997). The concentration of calcium is reported to be 9% less in the reconstituted milk, which would result in less fouling (Changani et al. 1997). In contrast, Newstead et al. (1998) found that UHT fouling rates of the recombined milk increased with increasing preheat treatment (preheating temperature x preheating time). The fouling deposits also had high levels of fat (up to 60% or more) compared with the deposits formed during fresh milk processing (10% or less). The difference is attributed to changes in fat-globule membranes. Fung et al. (1998) studied the effect of damage to milk fat globule membrane by a cavitating pump on fouling of whole milk. The fouling rate was enhanced and the argument was that the damage to the membranes results in the fat globules to coalesce, which then tend to migrate faster towards the heated wall.

Operating conditions in heat exchangers

Important operating parameters that can be varied in a heat exchanger are: air content, velocity/turbulence, and temperature.

The presence of air in milk enhances fouling (Burton 1968, de Jong 1997, de Jong et al. 1998). However, fouling is enhanced only when air bubbles are formed on heat transfer surfaces, which then act as nuclei for deposit formation (Burton 1968, de Jong 1997). The solubility of air in milk decreases with heating as well as a reduction in the pressure (de Jong 1997, de Jong et al. 1998). Also the formation of air bubbles is enhanced by mechanical forces induced by valves, expansion vessels, free-falling streams etc. (de Jong 1997).

Fouling decreased with increasing turbulence (Belmar-Beiny et al. 1993, Santos et al. 2003). According to Paterson and Fryer (1988) and Changani et al. (1997) the thickness and subsequently the volume of laminar sublayer decrease with increasing velocity and as a result the amount of foulant depositing on the heat transfer surface decreases. Higher flow velocities also promote deposit re-entrainment through increased fluid shear stresses (Rakes et al. 1986). Higher turbulence and different flow characteristics are in fact found to result in smaller induction period in plate heat exchangers compared with tubular heat exchangers (Belmar-Beiny et al. 1993). The reason for this may be the presence of low velocity zones near the contact points between the adjacent plates. The use of pulsatile flow was found to mitigate fouling when only the wall region near the heat transfer surface was hot enough to cause the protein denaturation and aggregation reactions. The reason was that the fluid spent less time near the wall due to higher mixing (Bradley and Fryer 1992). The pulsations however, enhanced fouling when the bulk fluid was also hot enough for the protein reactions to take place.

Temperature of milk in a heat exchanger is probably the single most important factor controlling fouling (Burton 1968, Kessler and Beyer 1991, Belmar-Beiny et al. 1993, Toyoda et al. 1994, Elofsson et al. 1996, Jeurnink et al. 1996, Corredig and Dalgleish 1996, Santos et al. 2003). Increasing the temperature results in higher fouling. Beyond 110^{o}C, the nature of fouling will change from type A to type B (Burton 1968). It is worth mentioning that both the absolute temperature and temperature difference are important for fouling. This means that it is feasible to have fouling in coolers where the wall temperature is lower than the bulk temperature. Chen and Bala (1998) investigated the effect of surface and bulk temperatures on the fouling of whole milk, skim milk, and whey protein and found that the surface temperature was the most important factor in initiating fouling. When the surface temperature was less than 68^{o}C, no fouling was observed even though the bulk temperature was up to 84^{o}C. Chen et al. (2001) predicted that mixing caused by in-line mixers can reduce fouling substantially.

Type and characteristics of heat exchangers

Plate heat exchangers are commonly used in dairy industry as they offer advantages of superior heat transfer performance, lower temperature gradient, higher turbulence, ease of maintenance, and compactness over tubular heat exchangers. However, plate heat exchangers are prone to fouling due to their narrow flow channels (Delplace et al. 1994). Also milk fouling in a heat exchanger is difficult to completely eliminate, simply due to the fact that the temperature of the heat transfer surface needs to be considerably higher than the bulk temperature in order to have efficient heat transfer. Complex hydraulic and thermal characteristics in plate heat exchangers make it very difficult to analyze milk fouling. The use of co-current and counter-current flow passages within the same heat exchanger further complicates the problem.

The heat transfer surface to which the deposits stick also affects fouling. However, the surface characteristics are important only until the surface gets covered with the deposits. The surface treatment may be of great benefit for fouling removal as fouling would occur after a time delay and the strength of the adhesion of the deposits onto the metal surfaces may be weaker, giving way to an easier cleaning process. Stainless steel is the standard material used in the dairy industry. Factors that may affect fouling of a stainless steel surface are: presence of a chromium oxide or passive layer, surface charge, surface energy, surface microstructure (roughness and other irregularities), presence of active sites, residual materials from previous processing conditions, and type of stainless steel used (Jeurnink et al. 1996, Visser and Jeurnink 1997). The modifications of the heat transfer surface characteristics through electro-polishing, surface coatings etc. may help reduce fouling by altering the surface roughness and wettability (changing the polarisation from a hydrophilic into a hydrophobic state) (Yoon and Lund 1994, Pießlinger-Schweiger 2001, Beuf et al. 2003, Santos et al. 2001, Rosmaninho et al. 2003). Increasing the surface roughness provides a larger effective surface area and results in a higher effective surface energy than a smooth surface (Yoon and Lund 1994). As a result, the adhesion of deposits with a rough surface would be comparatively stronger. The affect of different surface coatings tend to be less on the deposit formation but more on their adhesion strength (Britten et al. 1988). Magnetic field treatment was observed to have no effect on the milk fouling rate (Yoon and Lund 1994).

There has been an increasing use of heat exchangers that foul comparatively less e.g. fluidised bed heat exchangers (Klaren 2003), Helixchanger heat exchangers (Master et al. 2003), heat exchangers equipped with turbulence promoters (Gough and Rogers 1987) etc., however there is little information available about their use in thermal processing of dairy fluids. The use of pulsatile flow exchanger results in higher mass transfer that may enhance fouling in case the deposition process is mass transfer controlled (Bradley and Fryer 1992). The use of fluid bed heat exchanger was found to reduce the amount of fouling and increase the rate of heat transfer as well (Bradley and Fryer 1992).

Direct heating methods like steam injection and steam infusion allow to have an optimal selectivity between desired (nutritional value) and undesired (surviving micro-organisms) product transformations (de Jong et al. 1998). These methods result in low fouling rate because the desired temperatures are achieved within a very short time due to high heating rates (de Jong 1997). Also high viscous fluids can be handled more easily (de Jong et al. 1998). The absence of heat transfer surface in such a case is also an advantage. The resulting dilution however may not be desirable. The direct injection of hot air/nitrogen was found to give satisfactory performance in concentrating milk through evaporation of water (Zaida et al. 1987)

Microwave heating has been used in numerous industrial applications for several years due to its advantages like faster throughput, better quality, energy saving, less space requirement etc. over conventional heating methods (Metaxas and Meredith 1988). However, limited lifespan of a microwave system can raise doubts over its economic viability. A number of studies have been reported on heat treatment of milk using microwaves, however these are based on general quality issues like nutrients, micro-organisms etc. instead of fouling (Kindle et al. 1996, Villamiel et al. 1996, Sieber et al. 1996, Thompson and Thompson 1990).

In induction heating, heat is generated by placing food material inside electric coils. These coils generate oscillating magnetic fields, send electric current through the food material, and thus cause heating. Induction heating produces high local temperatures very quickly but its use has been limited to materials industry only.

Ohmic heating or direct resistance heating is a novel heat treatment process where an electrical current is passed through the milk and heat is generated within the milk to achieve pasteurization or sterilization (Quarini 1995). This technique offers the potential of thermal processing of materials without relying on an inefficient mechanism like conduction of heat from a surface into the fluid. The resistance heating technique was used for milk pasteurization in the early 20th century (de Alwis and Fryer 1990). In recent years this technology has been in use again, after being abandoned for a major part of the 20th century. APV International Ltd. (England) developed commercial ohmic heating units for continuous sterilization of food products (Skudder and Biss 1997). Ayadi et al. (2003a, b, 2004)) have investigated the performance of a plate type ohmic heater for the thermal treatment of dairy products.

The major advantages of ohmic heating are: absence of moving parts, non-dependency on thermal conductivity of materials, fast and uniform heating, and ability to start/stop thermal processing instantaneously. The disadvantages are: deposition and corrosion of electrode surfaces and additional safety requirements. Ohmic heating has an advantage over microwave processing where processing can be limited by the depth to which energy can penetrate the food material (Fryer et al. 1993).

Fouling can not be completely eliminated in an ohmic heating process because when milk is heated for the pasteurization/sterilization, it results in protein denaturation, aggregation and deposition. However, since surface temperature is lower due to the generation of heat in the bulk, less fouling should take place. However, the temperature profile changes dramatically when the deposits start attaching to the electrode surfaces (Ayadi et al. 2003b, Bansal et al. 2005). In conventional indirect heating methods like shell and tube or plate heat exchangers the deposit formation lowers the deposit/fluid interface temperature. In an ohmic heating process some heat is generated in the deposit layer as well due to its own electrical resistance. Also the deposits prevent the outward flow of heat from the bulk fluid. As a result, the deposit/fluid interface temperature increases and promotes fouling (Bansal et al. 2005).

There are two other issues that may be important in an ohmic heating process. Better mixing of the fluid may be required to overcome the wall effect and result in uniform heating but it may also promote fouling as the foulant is transferred easily from the bulk to the surface. Cooling may be employed to reduce the temperatures of electrode surfaces that would help control fouling.

Presence of Micro-organisms

The formation of deposits promotes the adhesion of micro-organisms to the surface resulting in bio-fouling. Furthermore, the deposits provide nutrients to micro-organisms ensuring their growth. It is worth mentioning here that most of the processes in industry are carried out at temperatures below 100°C. For example, pasteurisation is generally achieved by heating of milk at 72°C for 15 seconds in a continuous flow system. At this temperature only the pathogenic bacteria along with some vegetative cells are killed. A higher temperature of 85°C is required to kill the remaining vegetative cells. Spores are much more heat-resistant and remain active well beyond this temperature. However, their inactivation is important for the products with longer shelf life.

Bio-fouling, either micro-organisms deposition or bio-film formation, in a heat exchanger raises serious quality concerns. Flint and co-workers have investigated the effect of bio-fouling in dairy manufacturing plants (Flint and Hartley 1996, Flint et al. 1997, 1999, 2000). According to Bott (1993), bio-fouling takes place through two different mechanisms: deposition of micro-organisms directly on the heat transfer surfaces of the heat exchanger, and deposition/attachment/entrapment of micro-organisms on/in the deposit layer forming on the heat transfer surfaces. With the supply of nutrients by the deposits, bacteria multiply. The presence of micro-organisms in the process stream and/or deposit layer does not only affect the product quality, it influences the fouling process as well (Yoo et al. 2004). Also bacteria can get released into the process fluid due to the hydrodynamic forces and result in increased concentration of bacteria downstream. This may also result in the bacterial growth in areas which otherwise are not conducive to bio-fouling. The release pattern of thermophilic bacteria Bacillus stearothermophilus into the process stream was studied in detail by Chen et al. (1998b) and Yoo and Chen (2002).

Location of fouling

Protein denaturation and aggregation reactions take place as soon as milk is processed thermally. The relative amounts of the denatured and aggregated proteins depend on a number of factors like operating conditions, type and design of heat exchanger, properties of the heat transfer surface etc. The use of an efficient technology may help to mitigate fouling within a heat exchanger; however the processed milk at the exit of the heat exchanger would still have large amounts of the denatured and aggregated proteins. This would result in severe fouling at various locations further downstream. Hence controlling fouling within the heat exchanger may not yield effective results and an overall strategy may need to be developed to study the fouling process over the entire setup (Petermeier et al. 2002).

CONCLUSIONS

Fouling in the dairy industry is affected by a number of parameters that can be classified into five major categories: a) milk quality, b) operating conditions, c) type and characteristics of heat exchangers, d) presence of micro-organisms, and e) transfer of location where fouling takes place. It may not be possible to alter the properties of the milk as they are dependent on the source, collection schedule, season and many other factors. Lower surface temperature and higher flow velocity help to reduce fouling. Lowering the surface roughness as well as wettability is likely to lower the tendency of the proteins to adsorb onto the surface. The presence of micro-organisms causes bio-fouling. Furthermore, the deposits provide nutrients to the micro-organisms ensuring their growth. The situation gets worse if the micro-organisms are released into the process stream due to its interaction with the deposit layer. The use of newer technologies (microwave heating, ohmic heating, steam infusion etc.) is gaining momentum because these result in lower fouling, however further research is required to realise their full potential.

A significant amount of research has been done on fouling; however the underlying fouling mechanisms are not yet fully understood. A part of the problem is the complex nature of milk and the dairy processes. The absence of generalised methodologies and techniques to control fouling worsens the problem. Further, concentrated and joint efforts among industry, research institutes, and academia are required to combat this serious problem.

REFERENCES

Anema S. G. & McKenna A. B. (1996) Reaction kinetics of thermal denaturation of whey proteins in heated reconstituted whole milk. Journal of Agricultural and Food Chemistry 44 422-428.

Arnebrant T., Barton K. & Nylander T. (1987) Adsorption of α-lactalbumin and β-lactoglobulin on metal surfaces versus temperature. Journal of Colloid and Interface Science 119 (2) 383-390.

Ayadi M. A., Bouvier L., Chopard F., Berthou M., Fillaudeau L. & Leuliet J. C. (2003a) Heat treatment improvement of dairy products via ohmic heating processes: thermal and hydrodynamic effect on fouling. Proceedings of Heat Exchanger Fouling and Cleaning - Fundamentals and Applications, Santa Fe, USA.

Ayadi M. A., Chopard F., Berthou M. & Leuliet J. C. (2003b) Ohmic heating unit performance under whey proteins fouling. Proceedings of International Conference Engineering and Food (ICEF9), Montpellier, France.

Ayadi M. A., Leuliet J. C., Chopard F., Berthou M. & Lebouche M. (2004) Continuous ohmic heating unit under whey protein fouling. Innovative Food Science & Emerging Technologies, 5 (4) 465-473.

Bansal B., Chen X. D. & Lin S. X. Q. (2005) Skim milk fouling during ohmic heating, Heat Exchanger Fouling and Cleaning: Challenges and Opportunities, Engineering Conferences International, Kloster Isree, Germany.

Bell R. W. & Sanders C. F. (1944) Prevention of milkstone formation in a high-temperature-short-time heater by preheating milk, skim milk and whey. Journal of Dairy Science 27 499-504.

Belmar-Beiny M. T. & Fryer P. J. (1993) Preliminary stages of fouling from whey protein solutions. Journal of Dairy Research 60 467-483.

Belmar-Beiny M. T., Gotham S. M., Paterson W. R., Fryer P. J. & Pritchard A. M. (1993) The effect of Reynolds number and fluid temperature in whey protein fouling. Journal of Food Engineering 19 119-139.

Beuf M., Rizzo G., Leuliet J. C., Müller-Steinhagen H., Yiantsios S., Karabelas A. & Benezech T. (2003) Potency of stainless steel modifications in reducing fouling and in improving cleaning of plate heat exchangers processing dairy products. Proceedings of Heat Exchanger Fouling and Cleaning - Fundamentals and Applications, Santa Fe, USA.

Bott T. R. (1993) Aspects of biofilm formation and destruction, Corrosion Reviews 11 (1-2) 1-24.

Bradley S. E. & Fryer P. J. (1992) A comparison of two fouling-resistant heat exchangers. Biofouling 5 295-314.

Britten M., Green M. L., Boulet M. & Paquin P. (1988) Deposit formation on heated surfaces: effect of interface energetics. Journal of Dairy Research 55 551-562.

Burton H. (1967) Seasonal variation in deposit formation from whole milk on a heated surface. Journal of Dairy Research 34 137-143.

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

Bylund G. (1995) Dairy Processing Handbook, Tetra Pak Processing Systems AB, Sweden.

Changani S. D., Belmar-Beiny M. T. & Fryer P. J. (1997) Engineering and chemical factors associated with fouling and cleaning in milk processing. Experimental Thermal and Fluid Science 14 392-406.

Chen J. (2000) Computer Simulation of Whey Protein based Milk Fouling. Master of Engineering Thesis, The University of Auckland, Auckland, New Zealand.

Chen X. D. & Bala P. (1998) Investigation of the influences of surface and bulk temperatures upon fouling of milk components onto a stainless steel probe. Proceedings of Fouling and Cleaning in Food Processing, Jesus College, Cambridge, England, 25-32.

Chen X. D., Chen Z. D., Nguang S. K. & Anema S. (1998a) Exploring the reaction kinetics of whey protein denaturation/aggregation by assuming the denaturation step is reversible. Biochemical Engineering Journal, 2 (1) 63-69.

Chen X. D., Yoo J., Benjamin A. & Turner M. (1998b) Study of bacteria 'transportation' in model milk foulant and bacteria emission from milk fouling layer into streams of rinse water, Milk and Cleaning Chemical Solutions, Proceedings of Conference on Fouling and Cleaning in Food Processing '98, Edited by D. I. Wilson, P. J. Fryer, and A. P. M. Hasting, Jesus College, Cambridge, England 79-96.

Chen X. D., Chen J. & Wilson D. I. (2001) Modelling whey protein based fouling of heat exchangers – further examining the deposition mechanisms. Proceedings of Heat Exchanger Fouling – Fundamental Approaches & Technical Solutions, Davos, Switzerland.

Christian G. K., Changani S. D. & Fryer P. J. (2002) The effect of adding minerals on fouling from whey protein concentrate – development of a model fouling fluid for a plate heat exchanger. Transactions of IChemE (part C) 80 231-239.

Corredig M. & Dalgleish D. G. (1996) Effect of temperature and pH on the interactions of whey proteins with casein micelles in skim milk. Food Research International 29 (1) 49-55.

Dalgleish, D. G. (1990) Denaturation and aggregation of serum proteins and caseins in heated milk. Journal of Agricultural and Food Chemistry 38 (11) 1995-1999.

de Alwis A. A. P. & Fryer P. J. (1990) The use of direct resistance heating in the food industry. Journal of Food Engineering 11 3-27.

de Jong P., Bouman, S. & van der Linden, H. J. L. J. (1992) Fouling of heat transfer equipment in relation to the denaturation of β-lactoglobulin. Journal of the Society of Dairy Technology 45 3-8.

de Jong P. (1997) Impact and control of fouling in milk processing. Trends in Food Science and Technology 8 401-405.

de Jong P., van der Horst H. C. & Waalewijn R. (1998) Reduction of protein and mineral fouling. Fouling and Cleaning in Food Processing '98, Jesus College, Cambridge, UK 39-46.

Delplace F., Leuliet J. C. & Tissier J. P. (1994) Fouling experiments of a plate heat exchanger by whey proteins solutions. Transactions of IChemE (Part C) 72 163-169.

Delplace F., Leuliet J. C. & Levieux D. (1997) A reaction engineering approach to the analysis of fouling by whey proteins of a six-channel-per-pass plate heat exchanger. Journal of Food Engineering 34 91-108.

Elofsson U. M., Paulsson M. A., Sellers P. & Arnebrant T. (1996) Adsorption during heat treatment related to the thermal unfolding/aggregation of β-lactoglobulin A and B. Journal of Colloid and Interface Science 183 408-415.

Flint S. & Hartley, N. (1996) A modified selective medium for the detection of pseudomonas species that cause spoilage of milk and dairy products. International Dairy Journal 6 (2) 223-230.

Flint S. H., Brook J. D., van den Elzen H. & Bremer P. J. (1997) Biofilms in dairy manufacturing plant – a threat to product quality. The Food Technologist (New Zealand) 27 (2) 61-64.

Flint S. H., van den Elzen H., Brooks J. D. & Bremer P. J. (1999) Removal and inactivation of thermo-resistant streptococci colonising stainless steel, International Dairy Journal 9 (7) 429-436.

Flint S. H., Brooks J. D. & Bremer P. J. (2000) Properties of the stainless steel substrate influencing the adhesion of thermo-resistant streptococci, Journal of Food Engineering 43 (4) 235-242.

Fonterra Co-Operative Group (www.fonterra.com) (2004) New Zealand.

Foster, C. L., Britten M. & Green M. L. (1989) A model heat-exchanger apparatus for the investigation of fouling of stainless steel surfaces by milk I. deposit formation at 100°C. Journal of Dairy Research 56 201-209.

Fryer P. J. & Belmar-Beiny M. T. (1991) Fouling of heat exchangers in the food industry: a chemical engineering perspective. Trends in Food Science & Technology 33-37.

Fryer P. J., de Alwis A. A. P., Koury E., Stapley A. G. F. & Zhang L. (1993) Ohmic processing of solid-liquid mixtures: heat generation and convection effects. Journal of Food Engineering 18 101-125.

Fung L., McCarthy O. J. & Tuoc T. K. (1998) The effect of fat globule membrane damage on fouling of whole milk. Fouling and Cleaning in Food Processing '98, Jesus College, Cambridge, UK 33-38.

Georgiadis M. C., Rotstein G. E. & Macchietto S. (1998) Optimal design and operation of heat exchangers under milk fouling. AIChE Journal 44 (9) 2099-2111.

Gillham C. R., Fryer P. J., Hasting A. P. M. & Wilson D. I. (2000) Enhanced cleaning of whey protein soils using pulsed flows. Journal of Food Engineering 46 199-209.

Gotham S. M., Fryer P. J. & Pritchard A. M. (1992) β-lactoglobulin denaturation and aggregation reactions and fouling deposit formation: a DSC study. International Journal of Food Science and Technology 27 313-327.

Gough M. J. & Rogers J. V. (1987) Reduced fouling by enhanced heat transfer using wire matrix radial mixing elements. AIChE Symposium Series - 257 16-21.

Hege W. U. & Kessler H.-G. (1986) Deposit formation of protein containing dairy liquids. Milchwissenschaft 41 356-360.

Jeurnink T., Verheul M., Stuart M. C. & de Kruif C. G. (1996) Deposition of heated whey proteins on a chromium oxide surface. Colloids and Surfaces B: Biointerfaces 6 291-307.

Karlsson C. A.-C., Wahlgren M. C. & Trägårdh A. C. (1996) β-Lactoglobulin fouling and its removal upon rinsing and by SDS as influenced by surface characteristics, temperature and adsorption time. Journal of Food Engineering 30 43-60.

Kessler H.-G. & Beyer, H.-J. (1991) Thermal denaturation of whey proteins and its effect in dairy technology. International Journal of biological macromolecules 13 165-173.

Kindle G., Busse A., Kampa D., Meyer-Konig U. & Daschner F. D. (1996) Killing activity of microwaves in milk. Journal of Hospital Infection 33 (4) 273-278.

Klaren D. G. (2003) Improvements and new developments in self-cleaning heat transfer leading to new applications. Heat Exchanger Fouling and Cleaning: Fundamentals and Applications, Santa Fe, New Mexico, USA.

Lalande, M. & René F. (1988) Fouling by milk and dairy product and cleaning of heat exchanger surfaces. Fouling Science and Technology, L. F. Melo, T. R. Bott, and C. A. Bernardo, eds., Kluwer, Amsterdam, Netherlands 557-573.

Lalande M., Tissier J.-P. & Corrieu G. (1985) Fouling of heat transfer surfaces related to β-lactoglobulin denaturation during heat processing of milk. Biotechnology Progress 1 (2) 131-139.

Lund D. B. & Bixby B. (1975) Fouling of heat exchanger surfaces by milk. Process Biochemistry 10 52-55.

Lyster R. L. J. (1970) The denaturation of α-lactalbumin and β-lactoglobulin in heated milk. Journal of Dairy Research 37 233-243.

Master B. I., Chunangad K. S. & Pushpanathan V. (2003) Fouling mitigation using helixchanger heat exchangers. Heat Exchanger Fouling and Cleaning: Fundamentals and Applications, Santa Fe, New Mexico, USA.

Metaxas A. C. & Meredith R. J. (1988) Industrial Microwave Heating, Published by Peter Peregrinus Ltd., London, United Kingdom 296-321.

Mottar J. & Moermans R. (1988) Optimization of the forewarming process with respect to deposit formation in indirect ultra high temperature plants and the quality of milk. Journal of Dairy Research 55 563-568.

Müller-Steinhagen H. (1993) Fouling: the ultimate challenge for heat exchanger design. Proceedings of the Sixth International Symposium on Transport Phenomena in Thermal Engineering, Seoul, Korea 811-823.

Mulvihill D. M. & Donovan M. (1987) Whey proteins and their thermal denaturation - a review. Irish Journal of Food Science and Technology 11 43-75.

Newstead D. F., Groube G. F., Smith A. F. & Eiger R. N. (1998) Fouling of UHT plants by recombined and fresh milk: some effects of preheat treatment. Fouling and Cleaning in Food Processing '98, Jesus College, Cambridge, UK 17-24.

Paterson W. R. & Fryer P. J. (1988) A reaction engineering approach to the analysis of fouling. Chemical Engineering Science 43 (7) 1714-1717.

Petermeier H., Benning R., Delgado A., Kulozik U., Hinrichs J. & Becker T. (2002) Hybrid model of the fouling process in tubular heat exchangers for the dairy industry. Journal of Food Engineering 55 9-17.

Pießlinger-Schweiger S. (2001) Electrochemical and chemical polishing of heat exchangers. Proceedings of Heat Exchanger Fouling – Fundamental Approaches & Technical Solutions, Davos, Switzerland.

Quarini G. L. (1995) Thermalhydraulic aspects of the ohmic heating process. Journal of Food Engineering 24 561-574.

Rakes P. A., Swartzel K. R. & Jones V. A. (1986) Deposition of dairy protein-containing fluids on heat exchanger surfaces. Biotechnology Progress 2 (4) 210-217.

Roefs S. P. F. M. & de Kruif K. G. (1994) A model for the denaturation and aggregation of β-lactoglobulin. European Journal of Biochemistry 226 883-889.

Rosmaninho R., Rizzo G., Müller-Steinhagen H. & Melo L. F. (2003) The influence of bulk properties and surface characteristics on the deposition process of calcium phosphate on stainless steel. Proceedings of Heat Exchanger Fouling and Cleaning - Fundamentals and Applications, Santa Fe, USA.

Ruegg M., Moor U. & Blanc B. (1977) A calorimetric study of the thermal denaturation of whey proteins in simulated milk ultrafiltrates. Journal of Dairy Research 44 509-520.

Santos O., Nylander T., Paulsson M. & Trägårdh C. (2001) Adsorption behaviour of β-Lactoglobulin on different types of stainless steel surfaces. Proceedings of

Heat Exchanger Fouling – Fundamental Approaches & Technical Solutions, Davos, Switzerland.

Santos O., Nylander T., Rizzo G., Müller-Steinhagen H., Trägårdh C. & Paulsson M. (2003) Study of whey protein adsorption under turbulent flow rate. Proceedings of Heat Exchanger Fouling and Cleaning - Fundamentals and Applications, Santa Fe, USA.

Schreier P. J. R. & Fryer P. J. (1995) Heat exchanger fouling: a model study of the scaleup of laboratory data. Chemical Engineering Science 50 (8) 1311-1321.

Sieber R., Eberhard P. & Gallmann P. U. (1996) Heat treatment of milk in domestic microwave ovens. International Dairy Journal 6 (3) 231-246.

Skudder P. J., Thomas E. L., Pavey J. A. & Perkin A. G. (1981) Effects of adding potassium iodate to milk before UHT treatment. I. Reduction in the amount of deposit on the heated surfaces. Journal of Dairy Research 48 99-113.

Skudder P. & Biss C. (1987) Aseptic processing of food products using ohmic heating. The Chemical Engineer 26-28.

Thompson J. S. & Thompson A. (1990) In-home pasteurization of raw goat's milk by microwave treatment. International Journal of Food Microbiology 10 (1) 59-64.

Toyoda I., Schreier P. J. R. & Fryer P. J. (1994) A computational model for reaction fouling from whey protein solutions. Proceedings of Fouling Cleaning in Food Processing, Cambridge, England 222-229.

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

van Asselt A. J., Vissers M. M. M., Smit F. & de Jong P. (2005) In-line control of fouling. Proceedings of Heat Exchanger Fouling and Cleaning - Challenges and Opportunities, Engineering Conferences International, Kloster Irsee, Germany.

Villamiel M., Corzo N., Martinez-Castro I. & Olano, A. (1996) Chemical changes during microwave treatment of milk. Food Chemistry 56 (4) 385-388.

Visser J. & Jeurnink Th. J. M. (1997) Fouling of heat exchangers in the dairy industry. Experimental Thermal and Fluid Science 14 407-424.

Xiong Y. L. (1992) Influence of pH and ionic environment on thermal aggregation of whey proteins. Journal of Agricultural and Food Chemistry 40 380-384.

Yoo J. & Chen X. D. (2002) An emission pattern of a thermophilic bacteria attached to or imbedded in porous catalyst, International Journal of Food Microbiology 72 11-21.

Yoo J., Hardin M. T. & Chen X. D. (2004) The influence of milk composition on the growth of bacillus stearothermophilus, Biotechnology and Biological Engineering (Accepted).

Yoon J. & Lund D. B. (1994) Magnetic treatment of milk and surface treatment of plate heat exchangers: effect on milk fouling. Journal of Food Science 59 (5) 964-969, 980.

Zaida A. H., Sarma S. C., Grover P. D. & Heldman D. R. (1987) Milk concentration by direct contact heat exchange, Journal of Food Process Engineering 9 (1) 63-79.