A LABORATORY INVESTIGATION OF MILK FOULING UNDER THE INFLUENCE OF ULTRASOUND

S. X. Q. Lin and X. D. Chen*

Food and Bioproduct Processing Cluster, Department of Chemical and Materials Engineering, The University of Auckland, Auckland, New Zealand

Abstract: In this study, a lab scale device was constructed to conduct an initial investigation of milk fouling under the influence of ultrasound. Milk fouling was prevented in some circumstances over 2 h of heating. For similar heating conditions and in the absence of ultrasound in heat transfer, serious fouling was developed within only 1 h. The enhancement caused by the ultrasound (up to 62%) reduced the solid–liquid interface temperature for the same heating duty, leading to considerable reduction in fouling. The ultrasonically induced movement of the depositing species in the near wall region is also thought to be responsible for fouling reduction as it does not allow the molecules to stay at the wall longer than the time needed for them to form a firm deposit. The observations reported in this study form a good basis for a more detailed and systematic investigation in the near future.

Keywords: milk fouling; fouling mitigation; ultrasound.

*Correspondence to: Professor X. D. Chen, Department of Chemical Engineering, Monash University, Building 36, Clayton Campus, VIC 3800, Australia. E-mail: dong.chen@eng.monash.edu.au

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INTRODUCTION

In the dairy industry, thermal processing is a widely used energy intensive unit operation (de Jong, 1997). Milk fouling of heat exchangers is a serious problem as it increases resistance to heat transfer and pressure drop. As a result of fouling, the temperature of the heating medium must be increased in order to achieve the required heating duty and the pumping power must be increased to maintain the production rate. These result in increased energy costs, cleaning costs and loss of production time. In New Zealand alone, 13 billion litres of milk are processed each year (Fonterra Co-operative Group, 2004). Improving heat transfer efficiency could generate significant savings. Milk protein molecules have been shown to adsorb on the surface even at room temperature, so it is a matter of time before the processing should be stopped for cleaning.

A significant amount of research has been done on milk fouling. Changani *et al.* (1997) have summarized that milk fouling involves bulk processes rather than surface reactions. The process of whey protein fouling in a tubular heat exchanger has been modeled based on both surface and bulk reaction mechanisms along with the transport of foulant towards the wall (Toyoda *et al.*, 1994; Chen *et al.*, 1998, 2001). The following sequence of events was suggested (Changani *et al.*, 1997):

(1) reaction in the liquid;
(2) mass transfer to the surface;
(3) surface reaction into the deposit; and
(4) possible transfer back to the bulk; or re-entrainment.

It is envisaged that ultrasonic treatment may affect all the steps involved in the transport processes. The sub-layer reactor model suggested by Paterson and Fryer (1988) indicated that the temperature and the size of the sub-layer are the two key factors that promote milk fouling. Ultrasound can enhance heat transfer by thinning the boundary layer (easier exchange of molecules between bulk and surface region).

A series of studies have been performed to investigate the role of protein denaturation (Burton, 1968; Kessler and Beyer, 1991; Belmar-Beiny *et al.*, 1993; Toyoda *et al.*, 1994; Chen *et al.*, 2004; Santos *et al.*, 2005). Increasing the temperature of the fluid usually results in a higher fouling rate. The nature of the fouling changes from Type A (soft and voluminous) to Type B (hard and granular) if the processing temperature is greater than beyond 120°C (Changani *et al.*, 1997).

The application of ultrasound in the food industry has been a subject of research and development for many years (Mason *et al.*, 1996), where the physical and mechanical effects of ultrasound, i.e., strong shear forces, particle fragmentation, increased heat and mass transfer, increased nucleation sites. Ultrasound has been investigated in extraction, crystallization, freeze, emulsification, filtration, defoaming, drying and biofilms removal (Ensminger, 1988; Suslick, 1988; Mason *et al.*, 1996; Oulahal *et al.*, 2004).

Ultrasound has been shown to enhance heat transfer between a heated solid surface and the liquid being heated in drying processes (Ensminger, 1988; Mason *et al.*, 1996). The ultrasound can either be introduced to the liquid itself or by vibrating the heated solid surface. It is usually argued that the cavitations induced by ultrasound aid in the disruption of fluid boundary layers. Heat transfer enhancement of 30–60% was also reported in drying experiments (Mason *et al.*, 1996).

Kim *et al.* (2004) described heat transfer enhancement in natural convection and pool boiling induced by ultrasonic vibration. Cavitations and acoustic streaming are the major factors in enhancing the heat transfer rate. Heat transfer enhancement as high as 70% has been reported (Kim *et al.*, 2004).

The temperature–time profile is the most important factor influencing fouling behaviour. For the same heating duty, the heat transfer enhancement will reduce the surface temperature and the average temperature of the thermal boundary layer. This aspect alone should give an opportunity to reduce/prevent fouling. In this study, a laboratory scale system for studying milk fouling under the influence of ultrasound has been constructed and the extent of heat transfer enhancement measured. Fouling profiles were recorded for different ultrasound power levels and the mechanisms responsible for the reduction in fouling rate are discussed.

EXPERIMENTAL

Figure 1 shows the experimental setup for studying the heat transfer measurement with the ultrasonic power effects. A U-shape electrical heater (stainless 316 finish; 8 mm diameter and 230 mm heating length) was immersed in 10 litres of milk solution, which is held in an ultrasonic cleaning bath (Elma T840DH; working frequency; 40 kHz; waveform; double half-wave; ultrasound intensity of the transducer; 2.25 W cm^{-2} at 100% output; bath dimensions; 300 mm width and 327 mm depth; total transducer area; 80 cm^2). Four ultrasonic transducers are distributed at the bottom of the bath and the distance between the bath bottom and heater was set to be 65 mm.

Twelve thermocouples (type K, 0.3 mm diameter) were welded on the surface of the heater, six on the top and the other six at the bottom. The thermocouple positions are illustrated in Figure 1. Another thermocouple (Type T, 0.3 mm diameter) located at about 15 mm above and between the two legs of the U-shape heater was used to measure the bulk temperature. All thermocouples were calibrated with an accuracy of $\pm 0.2^{\circ}$C.

The temperature of the liquid in the ultrasonic cleaning bath was controlled by a water bath controller/heater. During each experiment, energy was released into the bath from the heating element (maximum power 800 W) and the ultrasound transducer. In order to maintain the bath temperature constant, a cooling coil (6 mm diameter copper tube, total length 3 m) removed the excess heat. Mixing/agitation was provided by a water bath stirrer. The intensity of the agitation

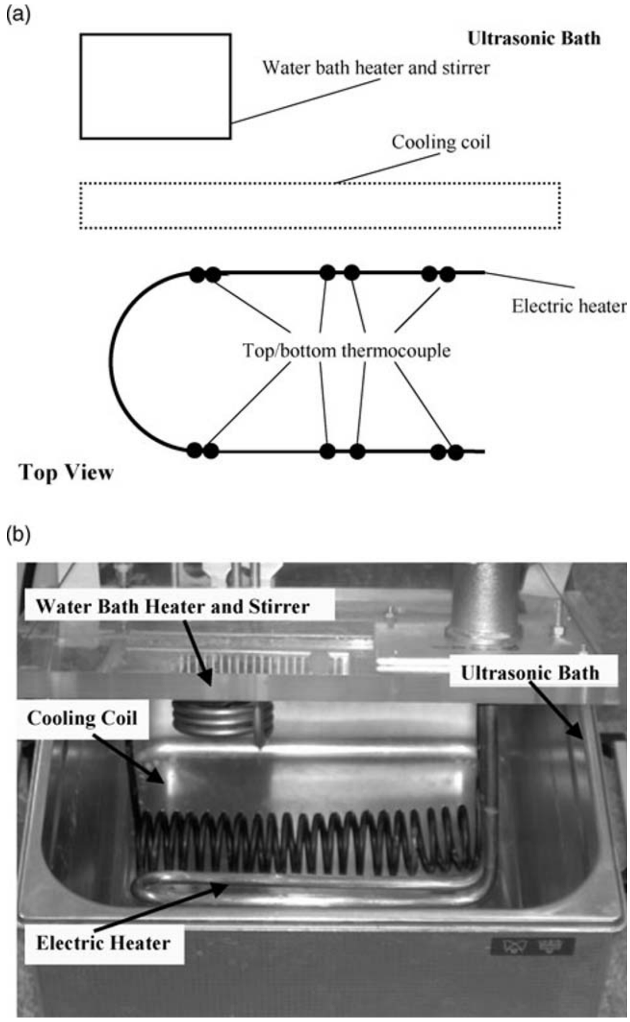

Figure 1. Ultrasound aided milk fouling set-up.

was benchmarked using the following heat transfer equation (Incropera and DeWitt, 1996):

$$Nu = \frac{hD}{k} = CRe^m Pr^{1/3} \quad (1)$$

where Nu is Nusselt number, h the average heat transfer coefficient (W m^{-2} K^{-1}), D the diameter of the heating tube (m), k the thermal conductivity (W m^{-1} K^{-1}), Re the Reynolds number, Pr the Prandtl number and C and m are constants with values of 0.193 and 0.168, respectively. Pr is estimated to be about 0.92. In the heat transfer experiments, the temperature difference and the heat flux were measured in the absence of ultrasound and the heat transfer coefficient calculated from equation (1), the mixing/agitation equivalent Reynolds number was estimated to be $\sim 1.2 \times 10^4$. All experiments were conducted under this mixing intensity by operating the stirrer at the same mixing speed though this equation does not represent the true physical situation, it gives a 'feel' of the kind of mixing intensity in a turbulent regime.

The temperatures of the heating surface and the bulk temperature were recorded using a data acquisition system (Picolog TC-08) and the power of the electric heater was