ASPECTS OF FOULING IN DAIRY PROCESSING

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HAYDEN ALBERT EDWARD BENNETT

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ABSTRACT

Fouling of heat treatment equipment in the dairy processing industry is an expensive and persistent problem. The objective of this work was to develop a better understanding of the mechanisms of dairy fouling in heat exchangers and identify methods to control this build-up. This was part of a larger project investigating the interaction between spore-forming thermophilic bacilli (thermophiles) contamination and fouling deposits on internal surfaces of equipment.

Two systems were developed to monitor the onset and build-up of fouling on the internal surfaces of two research heat exchangers. The first used a commercial sensor to measure the local heat flux and the temperature on the hot side of a plate type heat exchanger. The heat transfer coefficient was calculated and normalised with its value at the start of the run to reflect the contribution of fouling deposits to the thermal resistance, thus giving a real-time estimate of the rate of fouling. The second system used an energy balance over a tubular type heat exchanger and measured inlet and outlet temperatures to estimate the overall heat transfer coefficient thus giving a global measurement of fouling over the tubular heat exchanger.

In both systems the plot of normalised heat transfer coefficient over time often stayed constant over an induction period, which was followed by a falling period indicative of growth in the fouling layer thickness and/or mass. Each system was validated by comparing the final value of the normalised heat transfer coefficient with direct measurements of fouling made at the end of a run namely: fouling deposit height for the local measurement and fouling deposit mass for the global measurement. The normalised heat transfer coefficient reported by each system correlated well with the corresponding direct measurement of the fouling layer.

An important factor identified in this study was the effect of air bubble nucleation on fouling deposits. It was shown that bubbles that formed on the heated surface greatly reduced the length of the induction period to a matter of seconds rather than...
Abstract

hours, as found in previous studies of fouling in the absence of surface bubbles. The rate of fouling was also enhanced while the bubbles remained at the surface. The structure of bubble type fouling layers was linked to the behaviour of the bubbles at the heated surface. Visual observations of these bubbles showed evidence of growth, vibration and coalescence during their period of attachment to the heated surface.

Deposits from bubble type fouling consisted of all solid components found in the original milk solution, except lactose, in approximately the same ratio. By contrast fouling deposits reported in the literature with systems operating under the traditional protein denaturation mechanism were reported to consist mainly of whey proteins.

Bubble induced fouling can be limited in a number of ways, the most effective being to maintain a high operating pressure in the equipment to ensure nucleation does not occur. Experiments conducted in this study showed that a pressure of 130 kPa.g was sufficient to suppress all bubble nucleation at the heated surface at a temperature of 90°C.

Another method identified was the use of high linear fluid velocities to entrain any surface bubbles into the processing stream immediately upon nucleation. Linear velocities above 1.0 m/s were shown to achieve this goal in the miniature plate heat exchanger tested. However, this method is only partially successful because the local linear velocity varies with position in heat exchange equipment of complex geometries and can drop below the mainstream average velocity causing surface bubbles to form, especially in recirculation regions behind flow obstacles.

A more reliable method, in situations where high operating pressures could not be used, involved conditioning the heated surface with a thin protein layer during the first few minutes of a run. Conditioning the surface resulted in bubble suppression even at high temperatures and low pressures, thus greatly extending the length of the induction period.

Trials performed in this study showed that the addition of a proteolytic enzyme produced by psychrotrophic microbes greatly increased fouling. The enzyme destabilised the caseins which could attach directly to the heat exchange surface
independently from the bubble fouling mechanism. Thus the quality of the milk is another important factor to consider. However, the addition of enzymes produced by thermophilic bacilli isolated from milk powder plants did not increase fouling.

A theory describing the air bubble induced fouling mechanism is presented along with recommendations on how to reduce this fouling contamination in processing equipment.
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NOMENCLATURE

**Roman**

- \( a \)  gradient constant
- \( A \)  surface area (m\(^2\)) or heat exchange surface area (m\(^2\))
- \( A_p \)  proteinase activity
- \( b \)  y-axis intercept constant
- \( c \)  constant
- \( c_p \)  heat capacity of fluid (J/kg.K)
- \( c_{p,p} \)  heat capacity of the process fluid (J/kg.K)
- \( C_k \)  concentration of para-κ-casein
- \( d_e \)  equal diameter of process fluid cross section (m)
- \( d_i \)  inner diameter of inside tube (m)
- \( d_o \)  outer diameter of inside tube (m)
- \( D \)  hydraulic diameter (m)
- \( D_0 \)  hydraulic diameter at \( t=0 \) (m)
- \( D_i \)  inner diameter of outside tube (m)
- \( D_o \)  outer diameter of outside tube (m)
- \( E \)  activation energy (J/mol)
- \( f \)  friction coefficient
- \( F \)  heat flux calibration factor (Wm\(^2\)/binary unit)
- \( k_a \)  rate constant
- \( k_d \)  deposition rate constant (s\(^{-1}\))
- \( L \)  length of pipe (m) or length of inner tube fouling region (m)
- \( m \)  rate coefficient
- \( \dot{m} \)  mass flow rate of fluid (kg/s)
- \( N_f \)  normalised overall heat transfer coefficient
- \( \Delta P \)  differential pressure (Pa)
- \( q \)  heat transfer flux (W/m\(^2\))
- \( Q \)  flow rate of process fluid (l/h) or (m\(^3\)/h)
- \( R \)  total heat transfer resistance (m\(^2\).K/W)
- \( R_a \)  aluminium tape thermal resistance (m\(^2\).K/W)
R_f  fouling thermal resistance (m².K/W)
R_g  universal gas constant (J/mol.K)
R_hf heat flux sensor thermal resistance (m².K/W)
R_hm heat medium thermal resistance (m².K/W)
R_p  process fluid thermal resistance (m².K/W)
R_ss stainless steel wall thermal resistance (m².K/W)
R_w  wall and its attachment thermal resistance (m².K/W)
R_a  relative surface roughness (μm)
Re  Reynolds number = dv/ρ/μ (dimensionless)
S  cross sectional area of process fluid (m²)
T  solid-liquid interface temperature (°C)
U  heat transfer coefficient (W/m².K)
U_0 heat transfer coefficient at t=0 (W/m².K)
U_i  internal overall heat transfer coefficient (W/m².K)
U_i0 initial internal heat transfer coefficient (W/m².K)
v  flow velocity (m/s)
V  milk velocity (m/s)

Greek
α  fouling parameter
Φ  fouling rate (s⁻¹)
Δθ  temperature difference (°C)
Δθ₁ temperature difference of side 1 (°C)
Δθ₂ temperature difference of side 2 (°C)
Δθ_LMTD log mean temperature difference (°C)
Δθ_m  mean temperature difference (°C)
θ_c  correct temperature (°C)
θ_hf outer temperature of heat flux sensor (°C)
θ_hm temperature of heating medium (°C)
θ_i  inlet temperature of test fluid (°C)
θ_o  outlet temperature of test fluid (°C)
θ_p  temperature of process fluid (°C)
θ_r  recorded temperature (°C)
θ_hm outlet temperature of the heating medium (°C)
θ_p  outlet temperature of the process fluid (°C)
Nomenclature

\begin{align*}
\mu & \quad \text{dynamic fluid viscosity (kg/m.s)} \\
\mu_p & \quad \text{viscosity of process fluid (Pa.s)} \\
\rho & \quad \text{density of fluid (kg/m}^3) \\
\rho_p & \quad \text{density of process fluid (kg/m}^3) \\
\phi & \quad \text{heat transfer rate (W)} \\
\phi_{hm} & \quad \text{rate of heat lost by the heating medium (W)} \\
\phi_p & \quad \text{rate of heat gained by the process fluid (W)} \\
\end{align*}