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FOULING OF STAINLESS STEEL SURFACES BY HEATED WHOLE MILK

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SUMMARY

The formation of fouling deposits in heat treatment equipment such as pasteurisers and evaporators used in milk processing plants reduces heat transfer and is a source of economic loss as a result of more frequent shut-down of the equipment for cleaning. Measurement of the kinetics and mechanisms of such fouling will enable an improved understanding of the design and operation of heat treatment equipment and allow improved control of fouling.

The present study was carried out to investigate the fouling behaviour of heated whole milk on to non-heated stainless steel surfaces and to determine the effects of mass flow rate and flow disturbance on the fouling of these surfaces.

A pilot-scale fouling rig was designed and built to mimic the heat treatment methods and conditions that are currently used in large-scale processing plants. Whole milk was first heated from about 6 to 75 °C in a plate heat exchanger and then heat treated to 95°C via a direct steam injection (DSI) heater. Custom built tubular and sudden expansion fouling test sections of different sizes were placed at different locations downstream of the DSI heater. These test sections were easily disassembled to access the fouling layers. Milk flow in these test sections was in the range of 80-120 kg/h and Reynolds numbers ranged between 2500 and 3800.

A system to monitor fouling at different locations on the internal surfaces of the fouling test sections was developed. This included the use of a calibrated sensor to measure the local heat flux and temperature at the outer surfaces of the test section. The fouling rate was calculated and expressed as the rate of decrease of the internal heat transfer

coefficient during the deposit growth, normalised using the internal heat transfer coefficient determined at the start of a run. A plot of the fouling rate versus run time exhibited a delay period during which the normalised internal heat transfer coefficient was either constant (*i.e.* the ratio = 1) or slightly increased (*i.e.* the ratio > 1) followed by a decrease period during which it gradually decreased (*i.e.* the ratio < 1). The decrease period started when the deposit thickness reached about 0.5 mm, at which stage the sensor began to respond to the changes in the heat flux and surface temperature.

To investigate the effects of local flow disturbance on the fouling behaviour of whole milk heated to 95°C, three tubular sudden expansion geometries, ratios of upstream-to-downstream diameter of 0.2, 0.43 and 0.74, were used. Fouling in the area beyond the step of the expansion coincided with the recirculation flow zone characterised by the rapid change of the fluid shear rates, as shown by the results of the computational fluid dynamics (CFD) modelling. The local fouling rate in this zone increased when the fluid velocity was increased and when the ratio of upstream-to-downstream diameter was decreased (*i.e.* the step height was increased). These results indicate that flow disturbance, which in turn causes the fluid velocity to change its direction and/or magnitude, can induce fouling.

Fully denatured and aggregated β-lactoglobulin or the casein proteins were found to play a minor role in the fouling of whole milk heated to 95°C in the fouling rig. It is therefore hypothesised that, during heating, the native β-lactoglobulin unfolds to form an ‘active species’ and this ‘species’ is responsible for the fouling of non-heated surfaces. The concentration of the ‘active species’ formed during heating is directly related to the concentration of residual native β-lactoglobulin. The local fouling rate in various areas downstream of the DSI heater, which was found to relate to the local concentration of residual native β-lactoglobulin confirms this hypothesis.

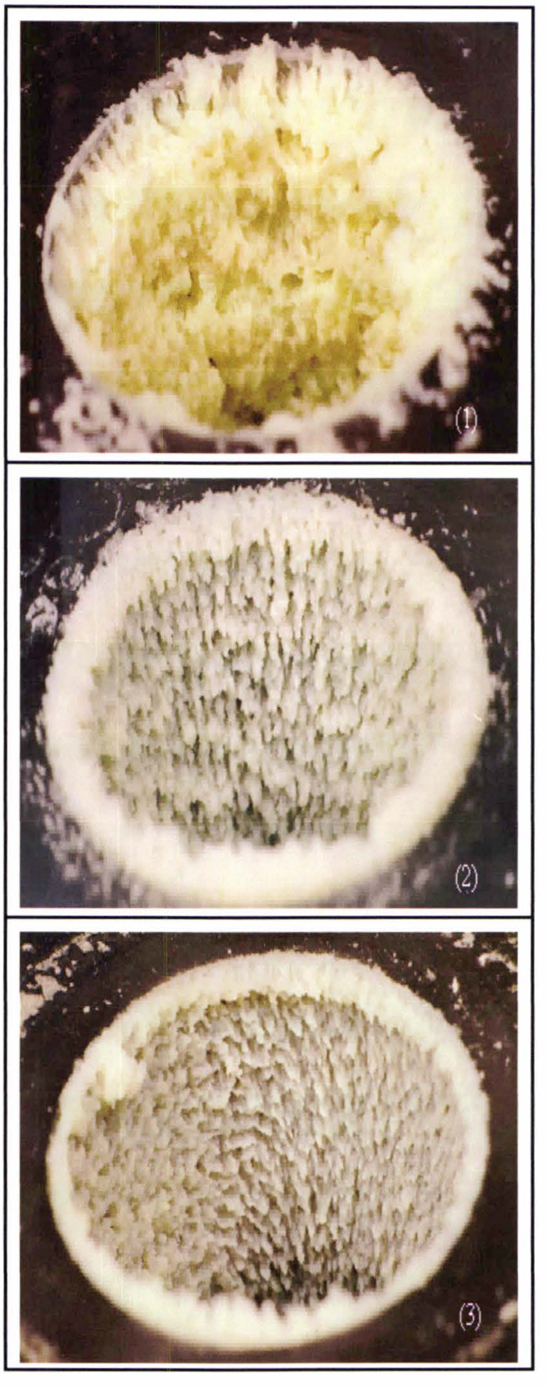
Relationships between local and average fouling rates to account for the effects of flow geometry were determined.

Fouling by heated milk fluids in the downstream areas of the DSI heater in industrial-scale milk evaporators was monitored with heat flux sensors. The fouling behaviour matched very well the pattern obtained in the fouling rig although the milk was heated to a higher temperature, *i.e.* 105°C, at a higher flow rate, *i.e.* Reynolds number > 10^5, and the processing run time of up to 24 hrs was considerably longer than in the pilot-plant runs.

The rate and extent of fouling in large-scale plant were found to vary with the types of milk product, such as skim milk, whole milk, modified skim milk and modified whole milk, and with treatment temperatures. Local equipment geometry in the section downstream of the DSI, such as flow disturbed by an orifice, was also found to have a strong effect on local fouling.

Recommendations for improving the design and operation of the DSI heater to reduce fouling of unheated surfaces by whole milk heated 95°C are suggested.

FRONTISPIECES



Photographs (3 x enlargement) of deposits formed inside tubular fouling test pieces: (1) placed near the direct steam injection (DSI) heater; (2) placed further downstream from the DSI heater; (3) placed farthest from the DSI heater.

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Lastly, I wish to dedicate this thesis to my parents and to the memory of my younger brother, Second-Lieutenant Truong Ho Vy.

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LIST OF PRESENTATIONS

This study has been presented in part at the following scientific conferences:

1. Truong, T. (1997). Design and development of a pilot-scale fouling rig for the study of fouling of unheated stainless steel surfaces by dairy fluids. *Chemeca '97 Conference*, Rotorua, September 1997.

2. Truong, T., Anema, S., Kirkpatrick, K. & Trinh, K. T. (1998). In-line measurement of fouling and CIP in milk powder plants. *Fouling and Cleaning in Food Processing '98 Conference*, Cambridge, April 1998.

3. Truong, T., Anema, S. & Kirkpatrick, K. (2000). A novel local fouling monitoring system. *Chemeca '2000 Conference*, Perth, July 2000.

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NOMENCLATURE

Roman

a	constant
A	heat transfer area (m^2)
b	constant
C	concentration (kg m^{-3})
Cf	heat flux calibration factor
Cp	heat capacity (J kg^{-1} K^{-1})
D	pipe, hydraulic diameter (m) or diffusion coefficient (m^2 s^{-1})
d	thickness or small pipe and orifice diameter (m)
E	activation energy (J mol^{-1})
f	friction factor
h	convective heat transfer coefficient (W m^{-2} K^{-1}) or step height (m)
H	enthalpy (kJ kg^{-1})
I_I	Normalised internal heat transfer coefficient
k	thermal conductivity (W m^{-1} K^{-1})
Kd	deposition coefficient (m s^{-1})
L	length (m)
m	mass flow rate (kg s^{-1}) or weight (kg)
M	weight (kg)
n	number of sensor
N	mass transfer rate (kg s^{-1})
P	pressure (Pa)
q	heat flux (W m^{-2})
Q	heat transfer (W)
r	flow ratio
R	thermal resistance (m K W^{-1}) or universal gas constant (8.314 J mol^{-1})
r	pipe radius (m)
t	reaction, elapsed, transit, fouling and run time (s)

T temperature ($^\circ$C) or absolute temperature (K)
Tf heat flux sensor temperature correction factor
U overall heat transfer coefficient (W m^{-2} K^{-1})
v average velocity (m s^{-1})
V volumetric flow rate (m^3 s^{-1}) or voltage (mV)
W weight (kg)

Greek

α fouled fraction of hydraulic channel diameter
δ thickness of boundary layer (m)
ε turbulence energy dispersion (J $kg^{-1}s^{-1}$)
k turbulence kinetic energy (J kg^{-1})
μ dynamic viscosity (kg m^{-1} s^{-1})
ρ density (kg m^{-3})
τ shear stress (N m^{-2})

Dimensionless Group

Re Reynolds number = $dv\rho / \mu$

Subscript

a ambient properties
agg aggregated
b bulk properties
c critical conditions
den denatured
f fouling deposit properties, liquid properties
hf heat flux sensor properties
i internal, inlet condition
LMTD log mean temperature difference
m milk, molecular properties
nat native
o outlet, initial condition

s	sealant properties
ss	stainless steel properties
t	total, turbulent conditions
v	vapour properties
w	wall conditions
wt	weight

Superscript

n	reaction order