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THE EFFECT OF RHEOLOGICAL PROPERTIES OF CONCENTRATED MILK ON FOULING OF FALLING FILM EVAPORATORS

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ABSTRACT

A key operational requirement of falling film evaporators is that a complete product film is maintained on the evaporator tubes. Failure to do so leads to excessive evaporator fouling and the need for additional production downtime for more regular and comprehensive cleaning. Preventing excessive fouling is achieved by controlling the product mass flow rates per unit circumference of evaporator tubes to avoid film break-up. This is referred to as the minimum wetting rate.

Prior research has calculated the minimum wetting rate as the balance between the fluid pressures acting downwards and the opposing combined upward forces. The balance of forces is strongly influenced by the viscosity of liquid. Models proposed in literature have tended to utilize constant Newtonian viscosity, however this is not applicable for many foods including concentrated milk where the fluid behaviour is non- Newtonian at higher solid contents. To address this challenge, this study focuses on non-Newtonian fluids using concentrated milk exhibiting pseudo-plastic behaviour as a case study. A relationship between the viscous force and flow behaviour index were shown to be pivotal for establishing the minimum wetting rate for such fluids. By integrating across the thickness of liquid film, an expression predicting stable film thickness was derived and the minimum wetting rate was calculated. The predictions from these calculations were experimentally evaluated using a pilot scale evaporator apparatus where heat transfer data was used to infer the evidence of evaporator fouling. No excessive evaporator fouling was observed over 7.5 hours of operation suggesting that the evaporator tube was completely covered when the wetting rate exceeded the calculated minimum threshold from our model.

INTRODUCTION

Falling-film evaporators are widely used for the concentration of liquid foods. Significant energy saving can be made by having several stages in series whereby the vapour produced by one stage is used to heat a subsequent stage which is operating at a lower temperature and pressure. This advantage makes falling-film evaporators the first choice for concentrating of liquids in in various industrial fields, from the food to pulping industries [1, 2].

Given that an evaporator is a heat exchanger, it is often incorrectly assumed that fouling is similar to heat exchangers. Morison [3] reviewed features of falling-film evaporators and concluded that fouling is typically because the evaporator tube is not completely covered due to poor liquid distribution on the surface of the tubes. Maintaining a complete and continuous product film on evaporator tubes has been well established in literature reviews as a key operational requirement of falling film evaporators, and that failure to do so leads to excessive fouling rates which is detrimental to many production processes [4, 5]. Aside from the reduction in heat transfer from fouling, a subsequent serious problem for many food producers is the growth of heat-resistant micro-organisms on fouled surfaces.

The lowest mass flow rate per unit circumference of falling film evaporator tubes needed to ensure that surfaces of tubes remain completely covered by a liquid film is known as the minimum wetting rate. Hartley and Murgatroyd presented a method to predict the formation of dry patches [6]. The model presented was constructed by balancing surface tension forces and the opposing combined downward forces to estimate minimum film thickness to rewet a dry patch. They calculated the minimum wetting rate for a uniform laminar film moving steadily under gravity over a vertical flat surface as,

$$\Gamma_c = 1.69 \left(\frac{\mu\rho}{g}\right)^{1/5} \left[\sigma(1-\cos\Theta)\right]^{3/5} \quad (1)$$

Hartley and Murgatroyd’s work was extended by many others including Hoke and Chen [7] who combined Hartley and Murgatroyd`s model with an analysis on thermocapillary breakdown of liquid films to provide a better prediction of the initiation of dry patches. More recent investigations employed experimental measurements to propose correlations to improve the models [8, 9]. Regardless of the literature source the minimum wetting rate is strongly influenced by the viscosity of liquid. Models proposed in literature have tended to utilize constant Newtonian viscosity, however this is not applicable for many foods including concentrated

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milk where the fluid behaviour is non-Newtonian at higher solids content.

To address this challenge, this study extended the previous work to apply for non-Newtonian fluids. The predictions from model were evaluated using concentrated milk exhibiting pseudo-plastic behaviour as a case study. A relationship between the viscous force and flow behaviour index were shown to be pivotal to establishing the minimum wetting rate concentrated milk.

MODEL DEVELOPMENT

For a stable dry patch to exist, the surface tension forces must balance the fluid pressure over the outer surface of the boundary of the dry patch. As shown in Figure 1, the kinetic energy is gradually converted to static pressure on the inner surface. The total dynamic pressure (P_d) along the film thickness (δ) will be,

$$P_d = \int_0^{\delta} \frac{1}{2}\, \rho u_{(y)}^2 . dy \qquad (2)$$

and the restraining force (R) due to surface tension will be,

$$R = \sigma(1 - \cos\Theta) \qquad (3)$$

Thus, the forces will be in neutral equilibrium if:

$$\sigma(1 - \cos\Theta) = \int_0^{\delta} \frac{1}{2}\, \rho u_{(y)}^2 . dy \qquad (4)$$

In a uniform laminar film of a pseudo-plastic fluid moving steadily under gravity over a vertical surface, the shear stress at a distance of dy from the wall is given by,

$$\frac{d\tau}{dy} = \rho g \qquad (5)$$

By substituting the power law expression for shear rate Eq. 5 will become,

$$\frac{du}{dy} = -\left(\frac{\rho g y}{K}\right)^{1/n} \qquad (6)$$

and integrating across the thickness of fluid film will give the velocity is given as,

$$u_{(y)} = \frac{n}{n+1}\,\frac{K}{\rho g}\left[\left(\frac{\rho g \delta}{K}\right)^{\frac{n+1}{n}} - \left(\frac{\rho g y}{K}\right)^{\frac{n+1}{n}}\right] \qquad (7)$$

Using Eq. 7 and 4 we find the critical thickness to avoid dry patch formation:

$$\delta_c = \left[\frac{\sigma(1-\cos\Theta)}{a + \frac{a.n}{3n+2} - \frac{2a.n}{2n+1}}\right]^{\frac{n}{3n+2}} \qquad (8)$$

Where "a" is

$$a = \frac{\rho}{2}\left(\frac{n^2}{n^2+2n+1}\right)\left(\frac{\rho g}{K}\right)^{2/n} \qquad (9)$$

The minimum wetting rate is given by:

$$\Gamma_c = \rho\,\frac{n}{n+1}\,\frac{K}{\rho g}\left[\delta_c\left(\frac{\rho g \delta_c}{K}\right)^{\frac{n+1}{n}} - \frac{n}{2n+1}\,\frac{K}{\rho g}\left(\frac{\rho g \delta_c}{K}\right)^{\frac{2n+1}{n}}\right] \qquad (10)$$

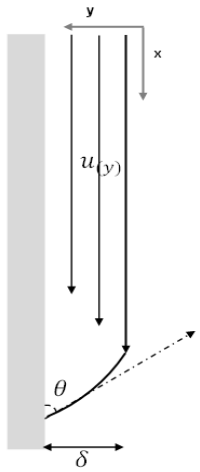

Fig. 1. A uniform laminar fluid film moving steadily under gravity over a vertical surface.

EXPERIMENTAL METHODS

All experiments were conducted on a typical pilot scale single effect evaporator which is illustrated in Figure 2. The effect consisted of one stainless-steel tube with diameter of 0.023 m and length of 15 m equipped with the flowmeters at the inlet and outlet of the product side to measure the flow rates and control the feed pump. The steam temperature (T_{steam}) and saturation temperature of product (T_{sat}) were independently controlled using a series of pressure transmitters. The details of flow rates and temperatures set points for the experimental evaporation test are tabulated in Table 1.

Evidence of fouling was evaluated based on the reduction of the overall heat transfer coefficient (U), the value of which was calculated as,

$$U = \frac{Q}{A(T_{steam} - T_{sat})} \qquad (11)$$

where A is the surface area of the evaporator tube and Q is heat flux which could be calculated from the change in mass flow of feed product (m_{in}) versus produced concentrate (m_{out}) and latent heat of water evaporation as shown in Eq. 12. The uncertainty of the flow rate measurements was calibrated by simultaneously measuring the solid content (SC) of the concentrate.

$$Q = (\dot{m}_{in} - \dot{m}_{out}) \times h_{fg} \qquad (12)$$

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The SC was obtained by comparing the mass of an oven-dried sample, at temperature of 105°C for 24 h, with the original total wet mass. The measurement was performed twice for each sample and an averaged value was used, with solid content defined as,

$$SC(\%) = \frac{mass\ of\ dry\ powder}{mass\ of\ wet\ sample}\ (\frac{kg}{kg}) \times 100 \qquad (13)$$

The shear stress was measured using an Anton Paar MCR 302 (Anton Paar, Germany) rheometer. The temperature of measurements was kept at the same temperature as the evaporative process (50°C). These tests carried out using concentric cylinder (CC27) geometry as a function of the shear rate, which varied from 10 to 1,000 s^{-1}, provided the evolution of the shear stress (in Pa). The rheometer measurements revealed that this product can be identified by power law model.

The product tested in this study was like whole milk, and its properties at measured range were similar to concentrated whole milk. Density and surface tension of concentrated whole milk from literature [10] were used for calculations at this study.

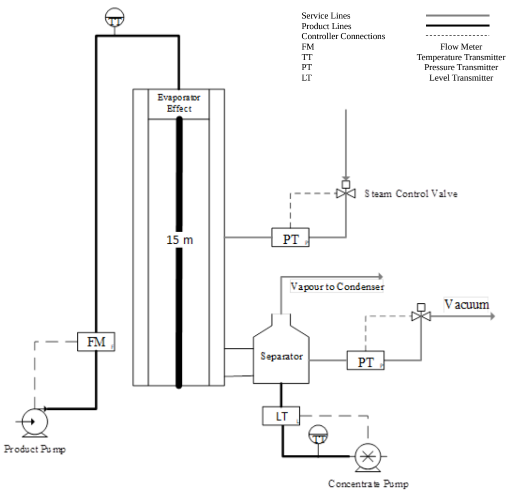

Fig. 2. Schematic diagram of the pilot-scale evaporator setup.

RESULTS AND DISCUSION

The measured shear stress as function of the shear rate for the produced concentrate is shown in Figure 3. The measurements revealed pseudo-plastic behaviour that fits the power law model as,

$$\tau = 0.68\ (\gamma)^{0.75} \qquad (14)$$

Where 0.68 and 0.75 are consistency factor (K) and power-law index (n), respectively.

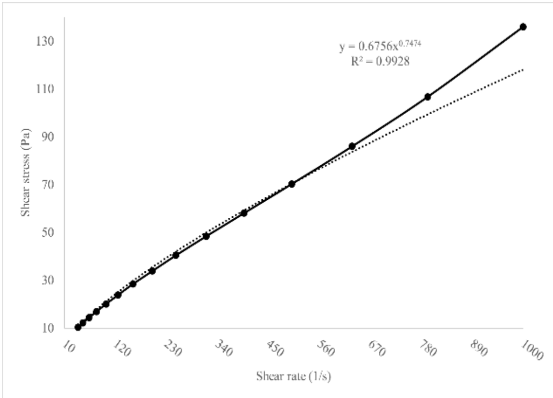

Fig. 3. The evolution of the shear stress (Pa) as a function of the shear rate (s^{-1}). The solid line represents the measured data points, and the dotted line is the fit of equation.

Substituting of flow behaviour index (K and n) to Eq. 8 and 10 gives the minimum wetting rate of 0.30 $kgm^{-1}s^{-1}$. The details of evaporation test are listed in Table 1. The product was pre-concentrated up to a calculated SC to achieve the required concentrate mass flow rate per unit circumference of the tube at the target concentration. The wetting rate exceeded the calculated minimum threshold from our model so the evaporator tube was expected to be completely covered.

Table 1 Evaporation set up for the fouling evaluation test.

m_{in} (kg/hr)	m_{out} (kg/hr)	T_{steam} (°K)	T_{sat} (°K)	Wetting rate ($kgm^{-1}s^{-1}$)
86	80	329.15	323.65	0.31

Figure 4 shows the calculated overall heat transfer coefficient over time during an evaporation run. It could be observed that no reduction of U was recorded after 7.5 hours of evaporation. The absence of excessive fouling is aligned with the expectation from our developed model. This finding is in agreement with previous studies [3, 5] reporting that breakdown of liquid film is main contributor to excessive fouling of falling film evaporators due to burning of product on the edge of dry patches. If there had been excessive reduction of U in Figure 2, this would have been because of stable dry patches. When the tube surface exposes to the vapor atmosphere, the temperature of the wall will increase due to the low heat transfer coefficient of gas phase at these points and the milk will continue to concentrate and foul if the dry patches persist.

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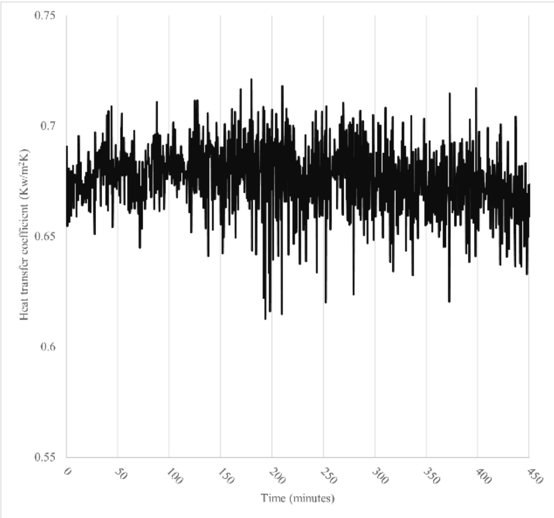

Fig. 4. Calculated overall heat transfer coefficient from the mass flow rates of feed product and produced concentrate.

CONCLUSION

This study extended the previous works to predict minimum wetting rates for falling films of non-Newtonian fluids using a relationship between the viscous force and flow behaviour index. The expectations were experimentally evaluated by concentrated milk exhibiting pseudo-plastic behaviour as a case study. Heat transfer data from a pilot scale evaporator apparatus was analyzed to infer the evidence of fouling. No excessive evaporator fouling was observed over 7.5 hours of operation suggesting that the evaporator tube was completely covered when the wetting rate exceeded the calculated minimum threshold from our model.

The findings of this research emphasize the importance of accounting for non-Newtonian behavior in designing evaporator systems for food processing. Ensuring that a complete product film is maintained on the evaporator tubes is a key requirement for efficient operation and reduced downtime for cleaning not just within the dairy industry but potentially in other sectors using falling film evaporators. The product tested in this study exhibited pseudo-plastic behaviour consistent with the power law model, but yield stress could be present for some food products so extending the model for Hershel-Bulkey equation will broaden its applicability and implications.

NOMENCLATURE

A Heat transfer surface area, m^2
g Gravity acceleration, ms^{-2}
h_{fg} latent heat of water vaporization, Jkg^{-1}
K Consistency factor, Pas^n
$\dot{m}$ Mass flow rate, kgs^{-1}
n Power-law index
P_d Dynamic pressure, Pa
Q Heat flux, W
R Restraining force, Pa
T Temperature, °K
u Velocity, ms^{-1}
U Overall heat transfer coefficient, $Wm^{-2}K^{-1}$
Γ Mass flow rate per unit width, $kgm^{-1}s^{-1}$
δ Thickness of liquid film, m
Θ Angle of contact between liquid and tube, °
μ Dynamic viscosity, Pas
ρ Liquid density, kgm^{-3}
τ Shear stress, Pa
σ Surface tension, Nm^{-1}

Subscript
c minimum critical
in Inlet of the evaporator
out Outlet of the evaporator
sat Saturation

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