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Qualitative investigation of the flow behaviour during falling film evaporation of a dairy product

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ABSTRACT

Falling film evaporation is an important technology in the dairy industry for producing powders. In this paper, flow details of liquid falling films have qualitatively been investigated using a pilot evaporator, and in particular using a high-speed camera. Variations with different dry solids contents, flow rates and driving temperature differences were investigated. The flow characteristics were seen to be considerably affected by all three variables. Two of the main observations were the formation of bubbles under evaporative conditions and that the flow, bubble formation and evaporative heat transfer coefficient was observed to be heat flux dependent.

1. Introduction

Multistage evaporators are commonly used in the food and chemical process industry to concentrate solutions in an energy efficient way. Examples in the food industry are to produce concentrates of dairy products or juices concentrates, an example in the chemical process industry is black liquor evaporation, which is part of the recovery cycle in a kraft pulp mill. The falling film type evaporator is commonly used in these applications, and it is used in several different configurations; outside vertical tubes, inside vertical tubes, outside dimple plates, and outside horizontal tubes just to mention some.

The demand for dairy powder products in the world is growing and it is expected that this trend will continue. In 2006 more than 9 Mtonnes of dairy powders (including skim milk, wholemilk, casein and whey powders) were produced, this number increased to over 10 Mtonnes in 2012 and is expected to continue to increase [1]. In the dairy industry for producing powders, long vertical tubes are commonly used in a multistage evaporation plant prior to spray drying. The evaporation plant is generally an energy efficient way of concentrating the product as it has low specific steam consumption, in comparison with the spray drying. To design and model falling-film evaporators, knowledge of the flow characteristics and evaporation behaviour is important. It is important for multiple reasons, mainly to determine which factors that control heat transfer and to control the wettability of the surface as to ensure product quality but also for estimating vapour flow pressure drop. Poor wettability can cause fouling, for example by adsorption of a monolayer of proteins onto the surface [2] or by minerals depositing on the surface [3].

In this work, flow characteristics of falling film evaporation on the outside of a tube under various conditions have been investigated qualitatively. The choice of using an external flow instead of the more common internal flow was to enable good visual examinations; however we intend to investigate the internal flow in a subsequent study. The work consists of pilot plant investigations where high-speed imaging has been carried out together with heat transfer measurements. The effect on the evaporation and on the flow behaviour has been investigated, varying the dry solids contents and operating conditions such as mass flow rate and driving temperature difference.

2. Theory

Characterization of the flow in falling films is often described using dimensionless numbers. The most important parameters are: the Nusselt number (Nu), which characterizes the heat transfer and measures the relative importance of convection to conduction in the liquid film, the Reynolds number (Re), which is the flow rate parameter and measures the importance of inertia relative to viscous effects, the Prandtl number (Pr), which gives the ratio of momentum diffusion to thermal diffusion in the liquid film and

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Nomenclature

A	Heat transfer area (m^2)
c_p	specific heat (J/kg K)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
K	constant
Ka	Kapitza number $(\rho^{1/3}\sigma)/(\mu^{4/3}g^{1/3})$
Nu	Nusselt number, h/k $(v^2/g)^{1/3}$
P	parameter
Pr	Prandtl number $(Cp\ \mu)/k$
$\dot{q}$	Heat flux (W/m^2)
$\dot{Q}$	heat load (W)
r_c	critical radius of cavity mouth (m)
Re	Reynolds number, $4\Gamma/\mu$
t	time (s)
T	temperature (°C)
U	Overall heat transfer coefficient (W/m^2 K)
v_{fg}	specific volume difference between liquid and gas phase (m^3/kg)
X	dry solids mass fraction (%)

Greek symbols

Γ	specific mass flow rate per unit circumference (kg/m s)
ΔH_{vap}	latent heat of vaporization (J/kg)
ΔT	temperature difference
δ_w	tube wall thickness (m)
μ	dynamic viscosity (Pa s)
v	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
ρ_g	gas phase density (kg/m^3)
σ	surface tension (N/m)

the Kapitza number (Ka) which compared the surface tension forces to the forces of inertia, all defined as follows:

$$\mathrm{Nu} \equiv \frac{h}{k}\left(\frac{v^2}{g}\right)^{1/3} \tag{1}$$

$$\mathrm{Re} \equiv \frac{4\Gamma}{\mu} \tag{2}$$

$$\mathrm{Pr} \equiv \frac{c_p\mu}{k} \tag{3}$$

$$\mathrm{Ka} \equiv \frac{\rho^{1/3}\sigma}{\mu^{4/3}g^{1/3}} \tag{4}$$

where h is the heat transfer coefficient, k is the thermal conductivity, v is the kinematic viscosity, g is the gravitational acceleration, Γ is the specific mass flow rate per unit circumference, μ is the dynamic viscosity, c_p is the specific heat, ρ is the density, and σ is the surface tension. Regarding the Kapitza and Reynolds numbers, several alternative definitions are found in the literature.

For falling films, the flow patterns are usually characterized by the degree of turbulence in the liquid phase. The flow is usually divided into three regimes, smooth laminar, transition regime and fully turbulent flow [4]. The transition region can in turn be divided into different regions. When the transition occurs is often described as a function of Reynolds number and Kapitza number [5].

For low Reynolds numbers in the transition region, surface tension forces play an important role in the appearance of waves. In this region capillary waves, which are small ripples with high frequency and low amplitude, will occur [6]. At higher Reynolds numbers, inertial waves or roll waves are present. The name comes from that the waves appear as rolling down over a thin substrate film which has a much lower velocity. These waves have longer wavelengths and much lower frequencies than capillary waves [6]. Already at moderate Reynolds numbers, the waves can have amplitudes that are two to five times the substrate thickness [7]. Typically falling films in this region will get covered with a random array of small and large waves that, mainly because of different superficial velocities, will interact in a complex fashion [8]. As the waves have a high amplitude and velocity, most of the flow will be associated with the roll waves and only a small fraction of the fluid will be associated with the substrate film [9,10].

At higher Reynolds numbers the flow will become fully turbulent and the falling films will consist of three regions: a viscous boundary layer near the wall, a turbulent core, and a viscous boundary layer near the free interface [11].

Al-Sibai [5] developed expressions to delimit the different flow regimes for non-evaporative conditions, see Table 1.

Falling film heat transfer is closely linked to the hydrodynamics of the film and the locally obtained heat transfer will vary with film thickness [12]. Numrich [13] divides the flow into only two regions, the laminar and the turbulent, with heat transfer only depending on the Reynolds number in the laminar region and on the Reynolds and Prandtl number in the turbulent region. The general trend is that the Nusselt number decreases with Reynolds in the laminar region and increases in the turbulent one. Numerous heat transfer models for falling film evaporation exist in a general dimensionless form [14–21]:

$$\mathrm{Nu} = K \cdot \mathrm{Re}^a \cdot \mathrm{Pr}^b \tag{5}$$

with one set of parameters for the laminar/wavy laminar region and one for the turbulent. What vary between these are the parameter values and also how the transition from laminar to turbulent is handled. Even if the laminar region is hydrodynamically divided into laminar, wavy laminar, etc., this is usually not influencing the coefficients in the heat transfer correlations recommended. Most correlations are developed using experimental data having Prandtl values up to about 7. There are, however, investigations showing that it is usually possible to extrapolate up to Prandtl values of around 50. An exception to the correlation form in Eq. (5) is Alhusseini et al. [22] who developed a heat transfer correlation on a different form on the basis of theoretical considerations which also includes the Kapitza number.

In recent years, there has been a rapid development of numerical methods that enables detailed calculation of flow and heat transfer of falling films, including the formation of waves. Direct Numerical Simulation (DNS) of Navier–Stokes equations has until recently only been possible to use for very low Reynolds numbers, i.e. outside regions of industrial interest. By using an extremely fine grid and supercomputer capacity, Doro [27] has shown that it is possible to obtain converged results (2D) up to Reynolds numbers

Table 1
Flow regions according to Al-Sibai [5].

Flow region	Delimitation
Laminar (L.)	$\mathrm{Re} < 2.4\ \mathrm{Ka}^{0.3}$
Sinus-shaped waves (S.W.)	$2.4\ \mathrm{Ka}^{0.3} < \mathrm{Re} < 4.0\ \mathrm{Ka}^{0.3}$
Wavy-laminar (W.L.)	$4.0\ \mathrm{Ka}^{0.3} < \mathrm{Re} < 100\ \mathrm{Ka}^{0.27}$
Transition (Tr.)	$100\ \mathrm{Ka}^{0.27} < \mathrm{Re} < 768\ \mathrm{Ka}^{0.18}$
Turbulent (Tu.)	$\mathrm{Re} > 768\ \mathrm{Ka}^{0.18}$