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Interfacial shear stress, heat transfer and bubble appearance in falling film evaporation

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ABSTRACT

In the falling film evaporation of dairy products, the phase change process occurs via two major phenomena: surface convective evaporation and boiling evaporation. Previous studies have shown that under certain conditions, the heat transfer mechanism can be greatly improved when the evaporation is dominated by the presence of bubbles or foam clusters. In the present work, the influence of the surface bubbling phenomenon on the heat transfer coefficient has been studied. The effect of the co-flowing vapor rate inside the evaporative tube has been experimentally related to the presence of the surface bubbles for dairy products characterized by different dry solid contents ($DC = 0\%$, 13%, 30%, 40%, 51%). The results show that at low dry solid contents ($DC \leqslant 30\%$), the co-flowing vapor negatively affects the heat transfer when the structure and the dimension of the bubbles are modified or inhibited by the action of the co-flow. At high dry solid contents ($DC = 40\%$, 51%), the sweeping effect of the co-flow plays a positive role on the heat transfer coefficient by promoting a more even circumferential distribution of the falling film and by increasing its velocity.

1. Introduction

Falling film evaporation is a process used to concentrate a product by removing its solvent, increasing its dry solid content by the removal of the solvent. The fluid product falls downward along the inside of tubes (or outside, depending on the application: milk, black liquor) [1–3] driven by the force of gravity, ensuring the wettability of the entire heated surface. The heat for the evaporative process is provided by film condensation of saturated steam on the opposite side of the tube. The difference in temperature between the product and steam is the thermal driving force of the process. At the free surface of the film, the solvent will evaporate via two major phenomena: surface convective evaporation and nucleate boiling evaporation [4]. At a low thermal driving force (ΔT), the evaporation occurs solely through convective evaporation at the vapor-liquid interface. When a higher ΔT is applied, the temperature is sufficient to support the formation of stable nuclei of vapor underneath the free surface, leading to the formation of bubbles.

Previous experimental studies on falling film evaporation [5] have shown that under certain conditions, the heat transfer mechanism can be greatly improved by the presence of bubbles. In addition, under the action of an external shear rate, the accumulation of bubbles in complex structures, such as macrocluster foams, leads to an increase in the velocity of the free surface. Recently, Gylys et al. [6] demonstrated that when bubbles grow until they form a macrocluster foam structure in a vertical flat plate, the heat transfer rate increases with increasing foam velocity. Furthermore, the presence of bubbles improves the wettability of the heated surface, avoiding the formation of dry patches that dramatically reduce the heat transfer coefficient. In this sense, it is important to understand the phenomena affecting the existence of the bubbles during the evaporative process. The life of a bubble is a transient phenomenon that starts with the nucleation of a vapor embryo. After the nucleus has exceeded a specific critical dimension, the volume of the bubble will grow dramatically. For this specific case, the vapor forming the bubble is enclosed between two free surfaces: the free surfaces of the film and a thin external fluid layer that separates the bubble vapor from the surrounding atmosphere [7]. On the interface of a biphasic flow, such as in evaporative films, the life of the bubble will end with a disruption that is often followed by the formation of small droplets (bursting) that are detached from the film [8,9]. The lifespan of the bubble is conditioned by two main mechanisms: the first concerns the effect of drainage that the external thin film undergoes because of the effect of gravity and the surface tension. When the film is relatively thin, then the intermolecular forces (van der Waals) will dominate, and the film will break up. This mechanism is dominant in a quiescent atmosphere. The second mechanism is more closely related to the environmental

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Nomenclature

A	area [m^2]
D	diameter [m]
DC	dry solids content [%]
h	heat transfer coefficient [W m^{-2} K^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
K	consistency factor [Pa s^n]
L	length [m]
$\dot{m}$	mass flow rate [kg s^{-1}]
n	power law index [–]
Nu	Nusselt number [–]
Pr	Prandtl number [–]
q	heat flux [W m^{-2}]
Q	heat load [W]
Re	Reynolds number [–]
T	temperature [°C]
v	velocity [m s^{-1}]
U	overall heat transfer coeff. [W m^{-2} K^{-1}]

Greek letters

$\dot{\gamma}$	shear rate [s^{-1}]
Γ	wetting rate [kg m^{-1} h^{-1}]
δ	thickness [m]
ΔH_{vap}	latent heat of vaporization [J kg^{-1}]
ΔT	temperature difference [°C]
μ	dynamic viscosity [Pa s]
ρ	density [kg m^{-3}]
τ	shear stress [Pa]
τ_y	yield stress [Pa]

Subscripts

avg	average
cond	condensate
co-flow	co-flowing vapor
exp	experimental
g	gas
j	index
i	inlet
inside	inside
l	liquid
la	laminar
o	outlet
outside	outside
m	mean
sat	saturation
steam	steam
t	turbulent
tot	total
tube	tube
vap	vapor
w	wall

conditions surrounding the bubble. In the falling film process, the free surface is exposed to a vapor atmosphere generated by the evaporation. The vapor that is produced will flow in parallel with the fluid, and the flow rate of the vapor will progressively increase, i.e., the flow is continuous, accelerating in the same direction as the film (co-flowing vapor). The momentum shear between the co-flowing vapor and evaporating surface [3] can affect the mechanical equilibrium of the bubble. In industrial applications, such as in the dairy industry, the evaporator tube can be up to 18 m long. Under these circumstances, the co-flow velocity can reach relatively high values of up to 30–50 m/s in the outlet.

There is a lack of knowledge concerning the influence of the bubbles on the falling film evaporation process. This paper makes an experimental contribution to the understanding of the effect of the presence of the surface bubbles on the heat transfer. The experimental approach consisted of the observation of the phenomenon using a high-speed camera and by the measurement of the heat transfer under different co-flow conditions.

2. Experimental setup

The experimental setup consists of an evaporative vertical tube system (see Fig. 1). The tube is 4.125 m long (L_{tube}) with an internal diameter (D_{tube}) of 48.6 mm, a wall thickness (δ_w) of 1.2 mm and a total outside heat transfer area ($A_{outside}$) of 0.66 m^2. Three sight glasses have been installed to observe the process: one on the top (product inlet) and two on the bottom (product outlet) section of the evaporator. The inlet product is fed on the top and evenly distributed before starting to fall down inside the tube. The design was based on previous experience [10] and will ensure an even distribution of the product under all experimental conditions (Fig. 1). The product outlet has been designed to satisfy the experimental requirements in terms of visualization of both: (a) the characteristics of the fluid film inside the tube by a special “half shape” pipe; and (b) the behavior of the product during a conventional process by a normal “straight” outlet pipe. Below the outlet of the tube, a

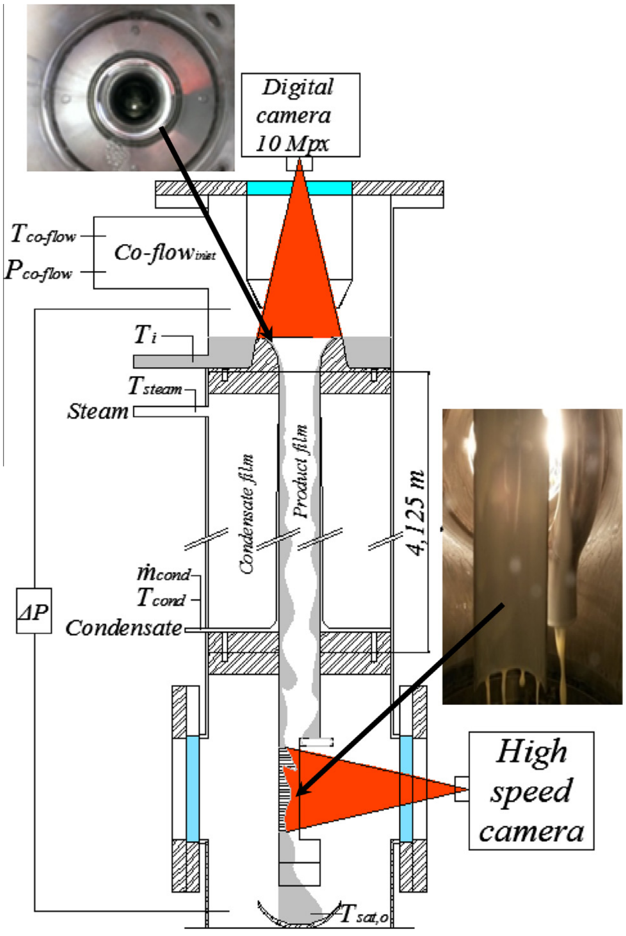

Fig. 1. Experimental setup.