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Flow behaviour of drop and jet modes of a laminar falling film on horizontal tubes

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ABSTRACT

The flow behaviour of a falling film on horizontal tubes has significant impacts on the efficiency of heat and mass transfer for the horizontal tubular evaporators and absorbers. Thus it is crucial to investigate the effect of contact angle and specific flow rate on the hydrodynamics of films and droplets in the drop and jet modes, which are the most important modes for evaporators and absorbers. A three-dimensional CFD model, using the volume of fluid (VOF) method, has been built to capture the gas-liquid interface. By employing mesh refinement and independence tests, the film spreading and droplet formation, liquid bridge breakup, droplet detachment, impact and fluctuation waviness of the simulations at the completely wetting condition are found to be in good agreement with experimental data and theory. In the drop mode, the behaviours of the droplets alternately falling from neighboring sites, including unstable slender liquid bridge and complex saddle waves were observed. This indicates that the wave propagation speed at first is higher than the impaction speed. In the in-line jet mode, the flow pattern is almost stationary but it is perturbed weakly by the impaction wave. The circumferential ring film has its maximum thickness located at the middle of the two-column in-line jet due to the wave interaction. In addition, the wetting area, spreading speed and instability time of the falling film are reduced with an increase in the contact angle, while the first two parameters increase at higher specific flow rates. In particular, an overshoot occurred at the larger contact angle. Finally, the results showed that the falling film flow pattern is sensitive to the initial wetting condition. Further, it reveals that the final steady wetted region depends on the receding contact angle, thus the introduction of the dynamic contact angle is the best approach for accurately determining the behaviour of falling films.

1. Introduction

The horizontal tube falling film heat/mass exchangers, including absorbers and evaporators, have been widely utilized in the energy and environment, desalination, refrigeration, HVAC (heating, ventilation and air conditioning), chemical engineering, petroleum refining and food industries, due to their high heat/mass transfer coefficients and they operate with smaller liquid inventories than flooded exchangers [1]. The falling film horizontal tubular absorber, that contains a bundle of horizontal tubes and sprayed drippers, have been used to absorb species from a surrounding vapour due to their potential for high heat transfer rates and low pressure drops, such as the LiBr/water by Hosseinna [2], R-134a-DMAC (dimethyl-acetamide) solution by Harikrishnan [3], and other greenhouse gases (GHG) [4]. On the other hand, since the 1970s, the falling film evaporators, which use a similar technology, have also been studied by many investigators, especially the heat and mass transfer characteristics of the evaporation process, see, Parken [5], Xu [6], Mu [7], Zheng [8], and Fiorentino [9–11]. In most industrial absorbers/evaporators, the mass flow rate of the solution is usually maintained such that a droplet flow exists between each of the tubes [12]. For the purpose of improving the absorption/evaporation, the available mass transfer area can be enhanced by increasing the exposed surface area of the liquid due to the formation process of the droplets [13].

Actually, the flow pattern around the horizontal tube reflects the state of the flow of the falling film and it dominates the heat and mass transfer [14]. However, the flow mechanics of the falling film is not fully understood due to the combined effect of several important parameters, such as density, surface tension, viscosity, tube diameter and their spacing, liquid flow rate and gravity [1] and contact angle of the wall [8]. Thus, the accurate prediction of the film and droplet behaviours, mass and heat transfers in the

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Nomenclature

d	diameter, mm
Ga	modified Galileo number = $\rho\sigma^3/\mu^4 g$, –
g	gravitational acceleration, m s^{-2}
L	length, m
m	mass, kg
$\dot{m}$	mass flow rate, kg s^{-1}
N_d	number of dripping sites, –
P	pressure, Pa
r	radius, m
R	gas constant, J mol^{-1} K^{-1}
Re	Reynolds number = $4\Gamma/\mu$
s	spacing between tubes, m
t	time, s
t_{fall}	drop fall time, s
t_{form}	drop formation time, s
u	flow direction velocity, m s^{-1}
v	velocity in film thickness direction, m s^{-1}
V	volume, m^3
x	flow direction (tangential), m
y	coordinate perpendicular to flow direction (normal axis), m
x', y', z'	Cartesian coordinate system, m

Greek

α	volume fraction, –
Γ	specific film flow rate, kg m^{-1} s^{-1}
γ	kinematic viscosity, m^2 s^{-1}
δ	film thickness, m
θ	angle, radian
τ	period of unsteady flow, s
λ	average distance between drop formation sites or departure-site spacing, m
μ	dynamic viscosity, Pa s
ρ	density, kg m^{-3}
σ	Surface tension, N m^{-1}

Subscripts

$*$	dimensionless
A,R	Advancing/receding contact angle
d	drop
G	gas
i	inlet or inner
L	liquid
o	outer
t	tube

gas-liquid interface are quite complicated. In recent decades, many researchers have investigated the hydrodynamics of the falling film both experimentally and numerically.

In the experiments, it is worth mentioning that Hu [1] observed that the flow patterns of the falling films of water, ethylene glycol, water/glycol, oil and alcohol, and then they divided patterns into five mode types, namely drop, droplet-jet, in-line/staggered jet, jet-sheet and sheet modes. The results showed that the transition *Re* is related with the *Ga* number and the predicted different mode transitions are given by:

$$\begin{aligned}
&\text{Droplet to droplet/jet}: \quad Re_f = 0.074Ga^{0.302}\\
&\text{Droplet/jet to jet}: \quad Re_f = 0.096Ga^{0.301}\\
&\text{Jet to jet/sheet}: \quad Re_f = 1.414Ga^{0.233}\\
&\text{Jet/sheet to sheet}: \quad Re_f = 1.448Ga^{0.236}
\end{aligned} \tag{1}$$

where the *Ga* and Re_f are define as follows:

$$Ga = \frac{\rho\sigma^3}{\mu^4 g}, \quad Re_f = \frac{d_{eff}\rho u}{\mu} = \frac{4\Gamma}{\mu} \tag{2}$$

where $d_{eff} = 4S_{half}/L_t$. L_t is the tube length and Γ is the inlet specific film flow rate, which is the mass flow on one side of the tube, and it is calculated by:

$$\Gamma_i = \frac{\dot{m}_i}{2L_t}\rho u\delta \tag{3}$$

where δ is the film thickness. Hu [15] found that the liquid falls from the tube at sites which are at a fixed distance apart, λ, called the departure-site spacing. This behaviour appears to the related to the Taylor instability. For an inviscid incompressible fluid, Bellman [16] firstly found the so-called critical and most dangerous Taylor wavelengths and they represent the wavelength of the shortest unstable disturbance and the disturbance length that grows most rapidly. Then, Zuber [17], Lienhard [18], Yung [19] and Taghavi [20] provided several correlations for the jet/droplet spacing by employing theoretical and experimental approaches. However, all the above researchers ignored the effect of the film Reynolds number and Galileo number on the length of the instability. Recently, Armbruster [21] proposed a more accurate correlation based on data from two fluids, namely water and isopropyl alcohol, and with an uncertainty of ±7.5%. This may be expressed as [15,21]:

$$\lambda = \frac{2\pi\sqrt{2}}{\sqrt{\frac{\rho g}{\sigma}\left(1 + \left(\frac{Re_f/2}{G_a^{1/4}}\right)^{0.8}\right) + \frac{2}{d_o^2}}} \tag{4}$$

In addition, several analytical models for the flow characteristics for the falling film, drop formation and fall flow regimes in the drop mode on horizontal tubes, based on the falling film Nusselt solution [2], Taylor instability and semi-empirical droplet sizes [19], have been developed by Kirby [12], Jeong [22], and Kyung [23] in order to analytically evaluate the mass and heat transfer. Nevertheless, most of these investigations have no experimental validation, thus the accuracy of the analytical model is unknown.

For details of the flow pattern, Killion [24] conducted a number of experiments and provided identification and visual droplet evolution, including the axial elongation along the tube, droplet formation, impact and interaction phenomena. Corresponding simulations were later reported [25]. However, some important parameters, namely, film thickness, droplet sizes and unsteady period of the drop mode were not provided. Xu [26] measured the wall film thickness at the circumferential angles 45°, 90° and 135° along the horizontal using the capacitance method. They found that the film thickness increases with the increasing spray density, but it is independent of the tube diameter although a reduction in the diameter enhances the film fluctuations. However, as the limitations of the accuracy and resolution of the sensors, the details of the film behaviour cannot be deduced. Lazcano-Véliz [27] concluded experimentally that the distribution of the film and droplets in the drop mode was more favourable for a better efficiency in the values of the falling film exchangers. Chen [14] experimentally measured the film thickness around 19 mm and 25.4 mm outside diameter tubes by employing laser-induced fluorescence technology where the range of Reynolds number is from 184 to