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Experimental and numerical study of heat transfer in a large-scale vertical falling film pilot unit

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ABSTRACT

Heat transfer in a large-scale vertical falling film pilot unit is investigated experimentally and numerically. We study a broad range of operating conditions with Kapitza and Reynolds numbers ranging from $Ka = 167–7010$ and Re 18–1854, respectively. We compare local heat transfer measurements, conducted over a vertical length of 4 m, with those obtained by directly solving the full Navier-Stokes equations in two dimensions and using the volume of fluid (VOF) numerical framework. We examine the development region along with the one in which we assume statistically steady conditions. In both our experiments and simulations we see significant differences between the two regions in terms of the magnitude of the heat transfer coefficient. We show how this is a result of the temperature gradient within the liquid film, along with the thickness of the liquid film. The degree of bulk mixing, introduced by the waves, has a profound influence on the thermal boundary layer and depends strongly on the fluid properties and the operating conditions.

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1. Introduction

Falling liquid film is a technology suitable for heat transfer operations [1]. The thin film gives the units high heat transfer at relatively low mass flow rates and small temperature differences. For that reason, falling films are utilized in a wide range of engineering and technological applications. These industrial units are typically large and the heat transfer surfaces are constructed of long plates or tubes. In addition, the falling film heat transfer is, as are several other thermal operation techniques, inherently energy intensive. Thus, improving the energy efficiency of the technique can substantially improve the overall energy economy of the plant. Hence, detailed knowledge is needed about the heat transfer in these units. Since heat transfer is heavily influenced by the hydrodynamics [1], it is important to gain detailed knowledge on the flow characteristics as the flow progresses downwards.

At the top of a falling film unit, i.e. at the liquid inlet, the film is smooth [2]. As the film flows downwards, there is a simultaneous development of the hydrodynamic and thermal profiles [3,4]. The present instabilities within the fluid will, if sufficiently large, grow into waves since they are influenced by gravity. The fluid temperature will also change as the heating causes a temperature gradient to develop within the thin film. Many studies argue that, after sufficient length denoted an entrance region, the flow can be considered *statistically steady* [2,5,6]. This means that, after this distance, the flow characteristics, such as the film thickness and the heat transfer coefficient (HTC), do not develop any further but instead are constant, in the time averaged perspective, for the remaining section of the unit.

The magnitude of the heat transfer, once the flow is statistically steady, is strongly dependent on the flow regime that is in turn connected to the working fluid and the operating conditions. Al-Sibai [6] developed models for statistically steady regimes under non-evaporative conditions. In that study, the models depend on the Kapitza (Ka) and Reynolds (Re) numbers and the flow was mapped into five different regimes: Laminar (L), Sinusoidal (S), Wavy-Laminar (WL), Transition (TR) and Turbulent (T).

The Laminar regime exists for small Re numbers and it is characterized by a calm liquid film without the presence of waves. Under these conditions, the Nusselt analytical solution [7] is considered valid. In the Turbulent regime, the flow becomes fully turbulent. The flow is entirely shear- governed and individual waves cannot be detected [5]. For the Sinusoidal and Wavy-Laminar

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Nomenclature

Abbreviations

2D	two-dimensional
3D	three-dimensional
CSF	surface force model
HTC	heat transfer coefficient
HV	high viscosity
IV	intermediate viscosity
L	laminar
LV	low viscosity
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
S	sinusoidal
T	turbulent
TR	transition
VOF	volume of fluid
WL	wavy-laminar

Symbols

C_p	heat capacity, J/kg K
d_{tube}	tube diameter, m
F	disturbance frequency, Hz
F_σ	surface tension force, N/m^3
g	gravitational acceleration, m/s^2
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
L_H	heated length, m
$\dot{m}$	mass flow rate, kg/s
p	pressure, Pa
q	heat flux, W/m^2
T	temperature, K
t	time, s
u	film velocity, m/s
$\boldsymbol{V}$	velocity, m/s

Greek letters

α	volume fraction
Γ	wetting rate, kg/(m·s)
δ	film thickness, m
ε	disturbance amplitude
κ	curvature of the interface
μ	dynamic viscosity, Pas
ν	kinematic viscosity, m^2/s
π	pi
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

b	bulk
g	gas
l	liquid
N	nusselt
w	wall
x	x-direction
y	y-direction

regimes the film is partly laminar in the substrate and partly turbulent in the waves [8]. In the Transition regime the flow gradually changes from being a wave-governed to a shear-governed one [5]. This causes the Transition regime to become a complex mixture of the adjacent regimes.

Extensive experimental work was done in order to map the subcooled heat transfer in falling films [3,9,10]. These studies were performed on different types of equipment, with respect to size and operating conditions, and both inlet phenomena and statistically steady conditions were investigated. Two definitions of the thermal entry length can be found in the literature: *i)* it is defined as the average distance between the beginning of a heated plate and the point where the thermal boundary layer arrives at the film surface, or *ii)* as the length between the beginning of the heated section and the point from which the heat transfer coefficient (HTC) remains constant [11]. The first interpretation was suggested by several authors [12–14]. Lel et al. [13] used thermal cameras to detect a vertical position at the surface when the temperature started to change. The same authors developed correlations that estimate the length of this region to be in the range of 0–0.5 m. The second interpretation is less straightforward to use, since the heat transfer coefficients need to be measured at multiple locations over a large length. Ishigai et al. [3], Wilke [9], and Mitrovic [12] made an attempt to determine the length of this zone. However, their results varied significantly, in the range of 0–1.5 m. It is interesting to note that Wilke [9] did not find any significant fluid influence, but instead mainly a dependence on the flow rates. In the same time, other authors claimed to have observed a pronounced fluid dependence. The relation between the thermal entrance length and hydrodynamics is not discussed in much detail in these publications. Further studies are therefore needed to better understand the length of this region and how it is related to the hydrodynamics and fluid properties. In this study, we will focus on the second definition as it is more interesting for industrial applications.

Correlations for statistically steady conditions were developed based on the above-mentioned studies. One commonly used correlation was developed by Schnabel and Palen [15]. Here, the heat transfer coefficient depends on the Reynolds (*Re*) and Prandtl (*Pr*) numbers and can be used to estimate the magnitude of heat transfer in different regimes. The highest heat transfer is usually achieved in the Laminar regime for very low flow rates due to the thin liquid film, or for very high flow rates in the Turbulent regime, because of the increased bulk mixing due to turbulence. However, large-scale units are often operated in the Transition regime, since low flow rates lead to wetting problems (dry spots) and high flow rates increase the pressure drop and give high pumping costs. Even if the value of the HTC can be estimated in the Transition regime, little is known about the flow structure beneath the surface of the film. Hence the Transition regime is a key focus area in our study. Also, the transient behavior for falling film needs to be captured in order to fully understand the system of interest [16].

The presence of the surface tension gradients, also known as the Bénard-Marangoni effect or the thermo-capillary convection, can sometimes cause interfacial instabilities in falling film if the surface temperature varies significantly. This phenomenon has been studied both experimentally [17,18], and mathematically [19,20].

In recent years, it has become possible to directly numerically solve the Navier–Stokes equations for falling films. Such studies utilize, for example, the Volume of Fluid (VOF) numerical framework [21] to reproduce the evolution of the film and examine in detail the flow structure beneath the gas-liquid interface e.g. [22]. These studies revealed the importance of the wave formation,

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