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Climbing film, flooding and falling film behavior in upflow condensation in tubes

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ABSTRACT

Upflow condensation in vertical tubes is complicated by the relative magnitude of the opposing vapor shear and gravity. This study examines the different flow regimes for condensation of FC-72 in a vertical tube using both high-speed video imaging and detailed heat transfer measurements. Four regimes are identified, falling film, where the condensing film drains downwards by gravity opposite to low velocity vapor flow, oscillating film, corresponding to film flow oscillating between upwards and downwards, flooding, where film begins to be sheared upwards by the vapor core, and climbing film, where high vapor velocity causes the film to be sheared upwards. The four flow regimes are well segregated in a flow regime map based on dimensionless superficial velocities of the vapor and liquid. The condensation heat transfer coefficient is shown to decrease axially because of gradual thickening of the film, except for high mass velocities, where turbulence and intensified interfacial waviness cause downstream heat transfer enhancement. An annular flow model is constructed, which shows fair predictions for the climbing film regime. The predictive accuracy of the model is influenced by flow oscillations occurring downstream of the climbing film region and inability of the model to account for interfacial waves.

1. Introduction

The recent increase in heat dissipation in electronic and power devices and systems has spurred interest in the development of compact, high-power-density phase-change thermal management systems that tackle both the heat acquisition from the device by boiling or evaporation, and the heat rejection to the ambient by condensation. These systems are becoming increasingly important to the development of high performance computers, electric vehicle power electronics, avionics, and directed energy laser and microwave weapon systems [1]. Different configurations have been proposed for heat acquisition by boiling, including pool boiling [2,3], channel flow boiling [4,5], jet [6–8] and spray [9,10], as well as enhanced surfaces [11,12] and hybrid cooling configurations [13,14]. However, far less emphasis has been placed on the condensation, or heat rejection part of these systems.

Much of the condensation knowhow and design models come from early research related to condensers found in power generation, chemical, and refrigeration and air conditioning industries. These condensers come in a variety of configurations, including falling film condensation on the outside of horizontal tubes in shell-and-tube heat exchangers, and inside horizontal, vertical and inclined tubes. The present study concerns internal upflow condensation in vertical tubes.

Condensation inside tubes takes the form of a number of flow regimes, which, in the order of decreasing quality, include pure vapor, annular, slug, bubbly and pure liquid [15]. Drastic differences in flow structure between these regimes have led investigators to construct flow regime maps and develop flow regime transition relations [16–21] that enable identification of regimes based on measurable parameters, and to develop models that are specific to individuals regimes. The annular regime, which consists of a thin film surrounding a vapor core, has been the focus of most studies on condensation in tubes because of its prevalence over a large fraction of the tube length and its ability to deliver very large heat transfer coefficients.

Vertical upflow condensation is encountered when the vapor is supplied upwards from the bottom of a vertical tube. At low vapor velocities, a *falling film* regime is encountered, where the condensing liquid film is driven downwards by gravity, opposite to the direction of the vapor flow. This regime is highly complicated by the role of interfacial waves, and is reminiscent of the complex interfacial behavior encountered in flow boiling at low velocities in vertical downflow [22–25]. Increasing the vapor velocity increases the vapor shear exerted on the film interface, which begins to slow the downward motion of the liquid film. A particular vapor velocity is reached that causes the interfacial portion of the film to be carried upwards rather than drain to the bottom. This condition

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Nomenclature

A	area
A^+	constant in eddy diffusivity function
$A_{f,*}$	flow area in liquid control volume
C	flooding constant
c_p	specific heat at constant pressure
D	diameter
f_i	interfacial friction factor
G	mass velocity
g	gravitational acceleration
h	condensation heat transfer coefficient
$\bar{h}$	condensation heat transfer coefficient averaged over region where $x < 1$
h_{fg}	latent heat of vaporization
j	superficial velocity
j^*	dimensionless superficial velocity
K	Von-Karman constant
k	thermal conductivity
$\dot{m}_f$	mass flow rate of FC-72 liquid film
$\dot{m}_{FC}$	total mass flow rate of FC-72
$\dot{m}_g$	mass flow rate of FC-72 vapor core
$\dot{m}_w$	mass flow rate of cooling water
P	pressure
P_f	perimeter
Pr	Prandtl number
Pr_T	turbulent Prandtl number
q	heat transfer rate
q''	heat flux at distance y from inner wall of inner stainless steel tube
q''_w	heat flux at inner wall of inner stainless steel tube
q_w	heat transfer rate from FC-72 to cooling water
Re_f	FC-72 film Reynolds number, $Re_f = G\,(1-x)\,D_h/\mu_f$
T	temperature
t	time
T^+	dimensionless temperature
u	velocity
u^+	dimensionless liquid film velocity
u^*	friction velocity
u_f	local liquid film velocity
$\bar{u}_g$	mean vapor core velocity
x	mass quality
x_e	thermodynamic equilibrium quality
y	distance perpendicular to inner wall of inner stainless steel tube
y^+	dimensionless distance perpendicular to inner wall of inner stainless steel tube
z	stream-wise distance

Greek Symbols

Γ_{fg}	rate of mass transfer due to condensation per unit distance
δ	thickness of condensing film
δ^+	dimensionless film thickness
ε_m	eddy momentum diffusivity
ε_h	eddy heat diffusivity
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension
τ	shear stress

Subscripts

c	vapor core
exp	experimental, measured
f	saturated liquid; liquid film
FC	FC-72
g	saturated vapor; vapor core
i	interfacial; inner wall of inner stainless steel tube
in	inlet
o	outer wall of inner stainless steel tube
out	outlet
$pred$	predicted
sat	saturation
ss	inner stainless steel tube
w	water; wall
$wall$	wall of inner stainless steel tube

is termed the *onset of flooding*, or simply the *flooding* point [26]. There is a finite vapor velocity range between the onset of flooding and the condition where the entire liquid film begins to be carried upwards. Above the latter condition, *climbing film* flow is achieved, as the vapor shear begins to dwarf the influence of gravity.

The ability to predict flooding is crucial to the design and operation of condensers in which vapor flows upward. However, a survey of the flooding literature by Bankoff and Lee [26] (i) points to most findings being based on experiments performed in relatively large diameter tubes, and (ii) reveals a dearth of reliable predictive tools. The most popular predictive tool for flooding is a relation by Wallis [27] that is based on the densities and superficial velocities of the vapor and liquid, and the tube diameter. Various attempts were made to improve the Wallis relation by incorporating the influences of additional parameters such as inlet and exit geometries, inclination angle, and other fluid properties [28–37]. However, the complexity of the flooding mechanism has led some to the conclusion that no reliable correlations or models are available that can accurately predict the onset of flooding with reasonable accuracy for different geometries and fluid types [38]. In general, the vapor velocity corresponding to the onset of flooding increases with increasing tube diameter [36,39], decreasing liquid viscosity [29] and increasing surface tension [35,40]. Attempts have been made to ascertain the effects of tube inclination for tubes with small diameters [41] and larger ones [42,43]. It is recommended that the use of empirical correlations for flooding be limited to the ranges of flow rates, fluid properties, and tube geometries of the databases these correlations are based upon [33].

A few theoretical models have been based on the notion that flooding is related to the interaction of vapor flow with a wavy liquid film interface. Several attempts were made to model the flooding mechanism theoretically by exploring wave growth using stability analysis [44–48]. Other models are based on vapor shear as the primary means for momentum transfer [49–51]. A few studies involved the use of commercial computational fluid dynamics (CFD) codes [52] to estimate the forces acting on a standing wave just before flooding is initiated.

The concurrent motion of the vapor and liquid film renders *climbing film* flow more easily predictable using popular models and correlations for annular flow condensation, especially where the effects of gravity are negligible compared to those of vapor shear.

The primary objective of the present study is to explore the various flow regimes that are encountered in upflow condensation of FC-72 in tubes. High-speed video imaging is used to investigate the interfacial interactions within each regime, and to construct a