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Experimental and computational investigation of vertical upflow condensation in a circular tube

Chirag R. Kharangate, Hyoungsoon Lee, Ilchung Park, Issam Mudawar *

Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL), School of Mechanical Engineering, 585 Purdue Mall, West Lafayette, IN 47907, USA

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ABSTRACT

This study explores the condensation of FC-72 in vertical upflow both experimentally and computationally. An axisymmetric 2-D computational model is used to predict variations of void fraction, condensation heat transfer coefficient, wall temperature and temperature profile across the liquid film. The computed results are shown to effectively capture the observed complex flow characteristics during flooding and climbing film conditions, including the annular film's interfacial waviness, formation of liquid ligaments along the film's interface, and breakup of liquid masses from these ligaments that are either re-deposited onto the film or entrained in the vapor core before moving towards the centerline. The model also shows good agreement with measured spatially averaged condensation heat transfer coefficients and wall temperatures. The predicted temperature profiles across the flow area successfully capture an appreciable temperature gradient at the liquid–vapor interface and saturation temperature in the vapor core.

1. Introduction

1.1. Phase change methods for thermal management applications

The past three decades have witnessed unprecedented increases in the amount of the heat that must be removed from heat dissipating devices and systems, including computer data centers, electric vehicle power electronics, avionics, and directed energy laser and microwave weapon systems [1]. Coupled with stringent weight and volume constraints, the increased rate of heat dissipation meant that conventional single-phase air-cooled or liquid-cooled thermal management systems could no longer safely achieve the heat removal requirements. Through their ability to capitalize upon latent heat content in addition to sensible heat, phase change thermal management systems are ideally suited for high heat density applications. With their ability to increase boiling and condensation heat transfer coefficients by orders of magnitude compared to liquid-cooled systems, phase change systems greatly reduce surface temperatures, and therefore increase the life of both device and system.

The vast majority of recent studies concerning two-phase thermal management have been focused on heat acquisition through evaporation or boiling, while the number of studies addressing heat rejection by condensation is relatively small. And most of the published condensation studies concern vertical downflow, a flow orientation that provides fairly stable condensate film motion aided by gravity. This configuration was explored in great detail by Park et al. [2] both experimentally and theoretically. However, because of volume and packaging constraints, it is impractical to design condensers utilizing the vertical downflow orientation alone. Most condensers adopt a serpentine design, with flow often alternating between vertical downflow and vertical upflow. Therefore, understanding vertical upflow condensation is crucial for the design of condensers used in two-phase thermal management systems.

Vertical upflow condensation is substantially more complicated than vertical downflow because of the opposing influences of vapor shear and gravity on the motion of the condensate film. As indicated in [3], several distinct flow regimes are encountered in vertical upflow condensation. At low inlet flow rates, the liquid film is driven downwards by gravity as the upward vapor shear is too weak to influence the film's motion; this flow behavior is categorized as the *falling film* regime. Increasing the flow rate causes the flow to transition to an *oscillating film* regime, corresponding to the liquid film alternating between upflow and downflow. A further increase in flow rate results in *flooding*, where vapor shear becomes strong enough to just balance the weight of the liquid film, causing the film to begin its ascent. Further flow rate

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* Corresponding author. Tel.: +1 (765) 494 5705; fax: +1 (765) 494 0539.
E-mail address: mudawar@ecn.purdue.edu (I. Mudawar).
URL: https://engineering.purdue.edu/BTPFL (I. Mudawar).

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Nomenclature

Δc	mesh (cell) size
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
D	diameter
$e_{i,j}$	strain rate tensor
E	specific internal energy (J/kg)
F	force
G	mass velocity (kg/m^2 s)
g	gravitational acceleration
h	heat transfer coefficient
h_{fg}	latent heat of vaporization
I	turbulence intensity
k	thermal conductivity
L	condensation length used in computational model
M	molecular weight
$\dot{m}$	mass flow rate
$\dot{m}''$	interfacial mass flux
$\vec{n}$	unit vector normal to interface
p	pressure
Q	energy source term (W/m^3)
q''	heat flux
R	universal gas constant (=8.314 J/mol K)
R_1, R_2	radii of curvature at free interface
Re	Reynolds number
r_i	mass transfer intensity (s^{-1})
S	volumetric mass source (kg/m^3 s)
T	temperature
t	time
t_i	unit tangential vector on free interface
U	velocity
u	velocity
x_e	thermodynamic equilibrium quality
y	distance perpendicular to the wall
y^+	dimensionless distance perpendicular to the wall
z	stream-wise coordinate
z_0	axial location where $x_e = 1$

Greek symbols

α	volume fraction; void fraction
γ	molecules transfer fraction in Schrage model [48]
δ_i	initial assumed liquid film thickness
μ	dynamic viscosity
ρ	density
σ	surface tension
τ	time period ($L/U_{g,in}$)

Superscripts

–	time average
→	vector
‘	fluctuating component
+	dimensionless

Subscripts

avg	spatial average
c	condensation
e	evaporation, thermodynamic equilibrium
eff	effective
f	liquid
g	vapor
h	hydraulic
i	initial, interfacial, thermocouple location, direction index
in	inlet
j	direction index
k	phase
sat	saturation
vol	volume
w	water
wall	wall

increases cause the vapor shear to overcome gravity effects and the liquid film to flow upwards; this behavior is categorized as the *climbing film* regime.

1.2. Predictive methods for condensation

In general, condensing flows encompass a variety of regimes including pure vapor, annular, slug, bubbly and pure liquid [4], which occur in order of decreasing quality. Given the vast differences in interfacial behavior among these regimes, it is quite difficult to construct universal models for flow condensation. This is why flow regime maps and/or models are constructed for condensing flows [5–8], which serve as a logical starting point for constructing models that are specific to individual regimes.

Of the aforementioned regimes, annular flow has received the most attention by researchers because of its prevalence over the largest fraction of the length of a condensation tube. Such studies include semi-empirical correlations, which are limited in validity to the ranges of parameters used in the database upon which a correlation is based [9–20]. A second approach to predicting annular condensation in tubes is the predominantly theoretical control-volume-based method [21]. The third, and rather more recent approach, is computational modeling [22–25]. Numerical simulations can be used to predict flow behavior with velocity profiles and turbulence structures, as well as parameters that can be measured experimentally, such as heat transfer coefficient. A key advantage of computational models is their ability to predict transient behavior, which is absent from correlations or theoretical models.

1.3. Numerical methods for multi-phase flows

Numerical approaches for multiphase system can be grouped into three general categories: Lagrangian, Eulerian, and Eulerian–Lagrangian. The Lagrangian approach involves tracking a portion of the fluid or interface and observing how it behaves. Smoothed-Particle Hydrodynamics (SPH) [26,27] and Particle-in-Cell (PIC) [28] methods have been adopted in conjunction with the Lagrangian approach. Due to the need for complicated grip topologies, the Lagrangian approach has been limited to rather simple flow situations.

The Eulerian approach is simpler and easier to implement, which explains its popularity relative to the Lagrangian approach. The Level-set Method (LSM) [29] and Volume of Fluid (VOF) method [30] are two schemes that have been developed in conjunction with the Eulerian approach. The LSM is capable of capturing curvatures and sharp interfaces accurately, but has issues preserving mass conservation. The VOF method [30] is based on the phase volume fraction, α, of each phase, which has a value between 0 and 1. While this method preserves mass conservation along the interface, it is less accurate than the LSM in determining interface topology. The Coupled Level-Set/Volume of Fluid (CLSVOF) method is based on the LSM, but also employs the VOF method to conserve mass when the interface is advected [31–33].