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Assessment of body force effects in flow condensation, part II: Criteria for negating influence of gravity

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ABSTRACT

This study concerns the development of a set of mechanistic criteria capable of predicting the flow conditions for which gravity independent flow condensation heat transfer can be achieved. Using FC-72 as working fluid, a control-volume based annular flow model is solved numerically to provide information regarding the magnitude of different forces acting on the liquid film and identify which forces are dominant for different flow conditions. Separating the influence of body force into two components, one parallel to flow direction and one perpendicular, conclusions drawn from the force term comparison are used to model limiting cases, which are interpreted as transition points for gravity independence. Experimental results for vertical upflow, vertical downflow, and horizontal flow condensation heat transfer coefficients are presented, and show that, for the given test section, mass velocities above 425 kg/m^2 s ensure gravity independent heat transfer. Parametric evaluation of the criteria using different assumed values of mass velocity, orientation, local acceleration, and exit quality show that the criteria obey physically verifiable trends in line with those exhibited by the experimental results. As an extension, the separated flow model is utilized to provide a more sophisticated approach to determining whether a given configuration will perform independent of gravity. Results from the model show good qualitative agreement with experimental results. Additionally, analysis of trends indicate use of the separated flow model captures physics missed by simpler approaches, demonstrating that use of the separated flow model with the gravity independence criteria constitute a powerful predictive tool for engineers concerned with ensuring gravity independent flow condensation heat transfer performance.

1. Introduction

1.1. Transitioning from single-phase to two-phase thermal management systems

In recent years, increased heat dissipation from electronic and power devices, coupled with their shrinking size has motivated engineers to develop compact thermal management systems capable of handling the acquisition and rejection of high heat fluxes. These systems are critical to such applications as high performance computers, hybrid vehicle power electronics, directed energy laser and microwave weapons, and avionics for next generation aircraft and spacecraft [1]. Because to their ability to capitalize on a coolant's latent as well as sensible heat, two-phase thermal management systems can yield orders of magnitude enhancement in heat transfer performance over their single phase counterparts, making them ideally suited for thermal management of high heat flux devices and systems.

Many previous studies have been focused on proposed configurations for heat acquisition by boiling, including pool boiling [2], channel flow boiling [3–5], jet [6,7] and spray [8–10], some have investigated mechanisms for heat rejection by condensation, including flow condensation in circular channels [11–13] and rectangular channels [14], but only a select few have focused on ensuring two-phase thermal management systems perform independent of body force effects caused by system orientation and local gravitational acceleration.

The magnitude of body force is an important factor when considering two-phase thermal management, as the orders of magnitude difference between liquid and vapor densities creates significant buoyancy effects relative to those encountered in traditional single-phase thermal management systems. If unmitigated, body force effects can lead to widely varying heat transfer performance with respect to system orientation.

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Nomenclature

a	local acceleration (body force per unit mass); empirical constant
A^+	parameter in eddy diffusivity relation
$A_{f,*}$	flow area of liquid control volume
Bo	Bond number
c	wave speed
c_i	imaginary component of wave speed
c_p	specific heat at constant pressure
c_r	real component of wave speed
D	diameter
D_F	characteristic length scale
D_H	hydraulic diameter
f_i	interfacial friction factor
Fr	Froude number
G	mass velocity
g	gravity
h	heat transfer coefficient
H_f	thickness of liquid layer
H_g	thickness of vapor layer
K	Von-Karman constant
k	wave number
k_c	critical wave number
L_{char}	characteristic length
$\dot{m}$	mass flow rate
n	empirical exponent
P	pressure; perimeter
P_f	friction perimeter
Pr	Prandtl number
Pr_T	turbulent Prandtl number
q''	heat flux
q''_w	wall heat flux
Re_c	vapor core Reynolds number
T	temperature
t	time
T^+	dimensionless temperature
u	velocity
u^*	friction velocity
U_{char}	characteristic velocity
We	Weber number
x_e	thermodynamic equilibrium quality
y	coordinate perpendicular to wall
y^+	dimensionless coordinate perpendicular to wall
z	axial coordinate

Greek symbols

α	void fraction
Γ_{fg}	rate of condensation mass transfer per unit length
δ	mean thickness of liquid film
δ^+	dimensionless mean thickness of liquid film
ε	eddy momentum diffusivity
η	interfacial perturbation
η_0	amplitude of interfacial perturbation
λ	wavelength
λ_c	critical wavelength
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
ρ''	modified density
σ	surface tension
τ	shear stress
θ	channel orientation angle

Subscripts

c	critical
$char$	characteristic
f	liquid
FC	FC-72
g	vapor
i	interfacial
in	inlet to heat transfer measurement length
out	outlet of heat transfer measurement length
sat	saturation
tp	two phase
w	wall; water

1.2. Mitigating body force effects

For flow boiling, a study by Zhang et al. [15] established a set of dimensionless groups capable of predicting at what inlet mass velocities the value of critical heat flux (CHF) would be independent of gravity. His work was later expanded by Konishi et al. [16] to determine gravity independence in cases with finite inlet quality.

Several flow condensation studies have addressed the effects of orientation on condensation heat transfer coefficient [17,18], with a small number focusing on flow condensation in microgravity [19,20], but a systematic approach to mitigating the influence of gravity on flow condensation heat transfer utilizing criteria composed of dimensionless groups is a current deficiency in available literature.

Were such a predictive tool available, it would be highly instrumental in the design of thermal management systems for such important applications as aircraft avionics, spacecraft avionics and power systems, and other applications where a wide range of local accelerations and system orientations are expected. Currently, thermal design engineers are limited in their ability to predict the threshold mass velocity of working fluid required for gravity independent flow condensation heat transfer, leading them to either confirm gravity independence through expensive experiments or utilize unnecessarily high mass velocities and oversized pumps.

1.3. Objectives of study

For the reasons discussed above, it is the primary goal of this second part of a two-part study to develop a set of mechanistic criteria comprised of relevant dimensionless groups that are capable of predicting the onset of gravity independent flow condensation heat transfer. In the first part [21], the influence of gravity on flow condensation was isolated by conducting identical experiments in horizontal flow, vertical downflow, and vertical upflow orientations using FC-72 as working fluid. In this second part, the experimental findings from the first part are used to develop the mechanistic criteria for negating the influence of gravity in condensing flows.

The present study is part of a joint project between the Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL) and NASA Glenn Research Center whose ultimate goal is to develop the Flow Boiling and Condensation Experiment (FBCE) for the International Space Station (ISS). Key goals for the ISS project are to amass flow boiling and condensation databases in microgravity, and to develop mechanistic criteria for negating the influence of gravity

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