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Mechanistic model to predict frequency and amplitude of Density Wave Oscillations in vertical upflow boiling

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ABSTRACT

Modeling of two-phase flow transient behavior and instabilities has traditionally been one of the more challenging endeavors in heat transfer research due to the need to distinguish between a wide range of instability modes systems can manifest depending on differences in operating conditions, as well as the difficulty in experimentally determining key characteristics of these phenomena. This study presents a new mechanistic model for Density Wave Oscillations (DWOs) in vertical upflow boiling using conclusions drawn from analysis of flow visualization images and transient experimental results as a basis from which to begin modeling. Counter to many prior studies attributing DWOs to feedback effects between flow rate, pressure drop, and flow enthalpy causing oscillations in position of the bulk boiling boundary, the present instability mode stems primarily from body force acting on liquid and vapor phases in a separated flow regime leading to liquid accumulation in the near-inlet region of the test section, which eventually departs and moves along the channel, acting to re-wet liquid film along the channel walls and re-establish annular, co-current flow. This process was modeled by dividing the test section into three distinct control volumes and solving transient conservation equations for each, yielding predictions of frequencies at which this process occurs as well as amplitude of associated pressure oscillations. Values for these parameters were validated against an experimental database of 236 FC-72 points and show the model provides good predictive accuracy and capably captures the influence of parametric changes to operating conditions.

1. Introduction

1.1. Importance of flow boiling dynamic behavior in space-based applications

To meet increasingly stringent thermal design constraints posed by dual trends of miniaturization and increased performance across multiple industries, thermal design engineers are considering two-phase flow thermal management systems which capitalize on both sensible and latent heat to offer orders of magnitude improvements in heat transfer performance [1]. Researchers at the Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL) and other organizations have investigated many different configurations to best utilize phase change heat transfer for varying applications, including capillary-driven devices [2–4], pool boiling thermosyphons [5–7], falling film [8,9], channel flow boiling [10,11], micro-channel boiling [12–16], jet impingement [17–20], and spray [21–27], as well as hybrid configurations [28–31] involving two or more of these schemes.

Thermal management systems utilizing phase change heat transfer are particularly attractive options for utilization in aerospace thermal-fluid systems where their high heat transfer coefficients allow significant reductions in size and weight of hardware, both critical design parameters in aerospace applications. This has led space agencies worldwide to fund further development of the technology to allow implementation in both space vehicles and planetary bases. Current targets for adoption of phase change technologies include Thermal Control Systems (TCSs), which control temperature and humidity of the operating environment, heat receiver and heat rejection systems for power generating units, and Fission Power Systems (FPSs), which are projected to provide high power as well as low mass to power ratio [32–34].

Limiting the adoption rate of phase-change heat transfer for these technologies is the presence of complex phenomena related to buoyancy and surface tension present in multiphase flows which can affect critical aspects such as flow regime, phase distribution, and even the nucleation process itself. Many design tools for phase change thermal management rely on empirically

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Nomenclature

A	amplitude, area
D_H	hydraulic diameter
F	force
f	frequency, friction factor
G	mass velocity
g_e	gravitational constant
H	height of flow channel's cross-section; digital filter transfer function
h_{fg}	latent heat of vaporization
L	length
l	length
L_d	development length of flow channel
L_e	exit length of flow channel
L_h	heated length of flow channel
M	momentum
m	mass
$\dot{m}$	mass flow rate
MAE	mean absolute error
N	number of data points
N_{pch}	phase change number
N_{sub}	subcooling number
P	pressure
p	perimeter
P_{in}	pressure at inlet to heated portion of channel
ΔP	pressure drop
Q	total heat input to channel
q''	heat flux on heated perimeter of channel
r	radius
Re	Reynolds number
t	time
u	velocity
v	specific volume
W	width of flow channel's cross-section
x	quality
x_e	thermodynamic equilibrium quality
x_f	flow quality
z	stream-wise position; digital domain variable

Greek symbols

α	void fraction
Γ	mass transfer rate
μ	dynamic viscosity
ρ	density
τ	shear stress
θ	percentage of predictions within 30% of experimental value
ζ	percentage of predictions within 50% of experimental value

Subscripts

12	evaluated between regions 1 and 2
23	evaluated between regions 2 and 3
A	accelerational
a	adiabatic
ave	average
c	cross-section; core
d	diabatic (heated)
DWO	property of Density Wave Oscillation (such as amplitude or frequency)
exp	experimental (measured)
F	friction
f	saturated liquid
FBM	flow boiling module
G	gravitational
g	saturated vapor
HDF	property of HDF
in	inlet to channel
interface	evaluated at the interface (such as shear stress or perimeter)
k	phase indictor
m	heated wall identifier (*a* for heater H_a or *b* for heater H_b)
PC	phase change
pred	predicted
SE	single event
tot	total (indicates parameter is evaluated over the total length of Region 3)
w	wetted
wall	evaluated for the channel wall (such as shear stress or perimeter)
z	stream-wise position
Zivi	evaluated using Zivi void fraction correlation
2φ	two-phase

Superscripts

0	value at initial time (equal to Region 1 value for all Region 3 parameters)
n	indicates current time step

Abbreviations

CHF	Critical Heat Flux
DWO	Density Wave Oscillation
FBM	Flow Boiling Module
HDF	High Density Front
LDV	Laser Doppler Velocimetry
PCI	Parallel Channel Instability
PDO	Pressure Drop Oscillation

correlated expressions for key parameters that were developed based on testing in a certain orientation in Earth's gravity. From the hyper-gravity associated with launch, to the micro-gravity of orbit and/or deep space, to the varying gravitational fields associated with operation on various extra-terrestrial bodies, any system designed for aerospace applications will need to be robust to drastic changes in operating conditions which fall outside the intended range of existing empiric and semi-empiric design tools. Prior studies conducted with the aid of parabolic flight have shown changes in local acceleration lead to dynamic changes in flow boiling behavior, with similar operating conditions tested in micro-gravity and hyper-gravity environments yielding significant difference in flow boiling heat transfer [35,36]. It is likely more sophisticated design tools, such as mechanistic models and computational schemes, could better predict this behavior as they are based less on prior experimental results, which may or may not apply, and more on the dominant underlying physical processes.

In addition to changes in system performance due to varying local acceleration across a mission's lifecycle, continuous changes to ambient thermal environment of the system often necessitate changes in operation mode. Whether due to cyclical solar exposure in orbiting vehicles, differences in ambient temperature between operations in space (transit) and some terrestrial environment (Moon, Mars, *etc.*), or changes in thermal loading associated with periodic operation of high-energy instruments, it is likely any dedicated space-based two-phase flow thermal management system will need to operate across a range of flow rates, heat fluxes, and pressures. Many studies have shown how changes to these param-