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Time-averaged and transient pressure drop for flow boiling with saturated inlet conditions

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ABSTRACT

This study explores flow boiling pressure drop of FC-72 in a rectangular channel subjected to single-side and double-sided heating for vertical upflow, vertical downflow, and horizontal flow with positive inlet quality. Analysis of temporal records of pressure transducer signals is used to assess the influences of orientation, mass velocity, inlet quality, heat flux, and single-sided versus double-sided heating on magnitude of pressure drop oscillations, while fast Fourier transforms of the same records are used to capture dominant frequencies of oscillations. Time-averaged pressure drop results are also presented, with trends focusing on the competing influences of body force and flow inertia, and particular attention paid to the impact of vapor content at the test section inlet and the rate of vapor generation within the test section on pressure drop. Several popular pressure drop correlations are evaluated against the present pressure drop database. Predictions are presented for subsets of the database corresponding to low and high ranges of inlet quality and mass velocity. The correlations are ranked based on mean absolute error, overall data trends, and data spread. While most show general success in capturing the data trends, they do so with varying degrees of accuracy.

1. Introduction

1.1. Utilizing two-phase thermal management in next generation space missions

Two-phase thermal management systems offer vast improvements over their single-phase counterparts due to their utilization of both latent and sensible heat of the working fluid. With electronics across all industries trending towards smaller sizes and higher power consumption, the orders of magnitude enhancement in heat transfer offered by two-phase thermal management systems makes them ideal for cooling the next generation of high flux devices [1].

One area in which phase change systems show great promise is space, where their high heat transfer coefficients can play a significant role in reducing the size and weight of thermal management hardware. Because of this potential, space agencies worldwide are exploring the benefits and challenges associated with implementation of two-phase thermal management systems to support astronauts in both space vehicles and planetary bases. Current targets for implementation of phase change include Thermal Control Systems (TCSs), which control the temperature and humidity of the operating environment, and Fission Power Systems (FPSs), which are projected to provide high power as well as low mass to power ratio [2–4].

Unlike thermal management of stationary Earth-based systems, use of two-phase cooling schemes for space applications entails the added complication of variable body force across missions. From hyper-gravity associated with launch, to microgravity encountered in orbit and interplanetary transit, to unique planetary gravitational environments associated with specific missions, thermal management systems designed to operate in space must be capable of performing in a broad range of gravitational accelerations. This greatly complicates the use of two-phase thermal management systems, where the orders of magnitude difference between phase densities causes body force (buoyancy) effects to affect flow behavior significantly.

Many previous studies have focused on different schemes for heat acquisition through boiling, including pool boiling thermosyphons [5,6], falling film [7–9], channel flow boiling [10], micro-channel boiling [11,12], jet impingement [13–15], and spray [16–18], as well as hybrid configurations [19] involving two or more of these schemes. While each possesses unique pros and cons, all suffer from a lack of understanding regarding the precise influence of body force on system heat transfer and pressure drop.

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Nomenclature

A	amplitude
Bd	bond number
Bo	boiling number, q''/Gh_{fg}
C	parameter in Lockhart–Martinelli correlation; empirical parameter
D	tube diameter
D_h	hydraulic diameter
f	Fanning friction factor; frequency
G	mass velocity
g, g_e	gravitational acceleration
H	height of flow channel's cross-section
H_a	heated wall a
H_b	heated wall b
h_{fg}	latent heat of vaporization
L_d	development length of flow channel
L_e	exit length of flow channel
L_h	heated length of flow channel
MAE	mean absolute error
N	number of data points
N_{conf}	Confinement number
P	pressure; perimeter
ΔP_{tp}	pressure drop across heated portion of channel
q''	wall heat flux
q''_H	heat flux based on heated perimeter of channel
Re	Reynolds number
Re_f	superficial liquid Reynolds number, $\mathrm{Re}_f = G(1-x)D_h/\mu_f$
Re_{fo}	liquid-only Reynolds number, $\mathrm{Re}_{fo} = GD_h/\mu_f$
Re_g	superficial vapor Reynolds number, $\mathrm{Re}_g = GxD_h/\mu_g$
Re_{go}	vapor-only Reynolds number, $\mathrm{Re}_{go} = GD_h/\mu_g$
Re_{tp}	two-phase Reynolds number, $\mathrm{Re}_{tp} = GD_h/\mu_{tp}$
Su	Suratman number
T	temperature
t	time
T_{sat}	saturation temperature
$T_{w,ave}$	average wall temperature
v	specific volume
v_{fg}	specific volume difference between saturated vapor and saturated liquid
W	width of flow channel's cross-section
We	Weber number
X	Lockhart–Martinelli parameter
x, x_e	thermodynamic equilibrium quality
z	axial coordinate measured from inlet to heated portion of channel

Greek symbols

α	void fraction
β	channel's aspect ratio ($\beta < 1$)
ζ	percentage predicted within 50% of data
θ	percentage predicted within 30% of data
μ	dynamic viscosity
ρ	density
σ	surface tension
φ	two-phase multiplier
ψ	flow orientation angle
ω	parameter is Beattie and Whalley viscosity relation

Subscripts

A	accelerational
ave	spatial average
eq	equivalent
exp	experimental (measured)
F	frictional
f	saturated liquid
fo	liquid only
G	gravitational
g	saturated vapor
go	vapor only
H	heated
in	inlet to heated portion of channel
k	liquid (f) or vapor (g)
m	wall identifier (a for heater H_a or b for heater H_b)
n	axial thermocouple location
out	outlet from heated portion of channel
$pred$	predicted
sat	saturation
tp	two-phase
tt	turbulent liquid–turbulent vapor
tv	turbulent liquid–laminar vapor
vt	laminar liquid–turbulent vapor
vv	laminar liquid–laminar vapor
w	wall

The expenses associated with experimentation in space render repeated prototyping infeasible, making accurate predictive tools capable of accounting for variable gravitational environments a necessity for adoption of two-phase thermal management schemes in space-based systems.

1.2. Quantifying pressure effects in two-phase systems

Despite many decades of research, accurate determination of pressure in two-phase systems remains quite illusive. Different types of models have been proposed to tackle different fluids, flow geometries, and operating conditions. The simplest of these is the Homogeneous Equilibrium Model (HEM) [20], which is based on the assumptions of equal phase velocities and fluid mixture maintaining saturation temperature in the two-phase region. Several variations of HEM exist in the form of different formulations of two-phase friction factor or mixture viscosity. Overall, HEM reduces reliance on empiricism and, in some cases, allows the derivation of analytical relations for pressure drop.

The Separated Flow Model (SFM) [20] provides more realistic depiction of two-phase flows by allowing for differences in phase velocities. The Slip Flow Model is the simplest of SFMs, where the vapor and liquid phases are assumed to possess uniform flow velocities. Pressure drop predictions based on the Slip Flow Model commonly require numeric solutions, as it is difficult to achieve model closure based only on available experimental results. Many researchers turn instead to semi-empirical correlations based on the Slip Flow Model to eliminate the difficulty of achieving closure while maintaining some of the physical attributes of the model.

The assumption of uniform phase velocities is relaxed in more advanced models, such as the Drift Flux Model [21], which allows for local radial variations in flow velocity and void fraction, making it one of the most physically sound models, albeit with successful predictions limited mostly to vertical upflow and vertical downflow. Similar to the Slip Flow Model, however, it suffers from an inability to achieve closure without detailed velocity measurements provided by micro-PIV or other advanced measurement techniques, meaning pressure drop calculations based on the Drift Flux Model are often tedious and of questionable applicability.

In an attempt to alleviate many of the shortcomings associated with pressure drop calculations based on physical models, researchers have turned to empirical and semi-empirical