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Flow boiling and critical heat flux in horizontal channel with one-sided and double-sided heating

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ABSTRACT

This study explores flow boiling of FC-72 along a 5-mm high by 2.5-mm wide rectangular channel that is fitted with top and bottom heating walls. By activating one wall at a time, the opposing influences of gravity are examined for inlet velocities from 0.11 to 2.02 m/s. Results for top wall and bottom wall heating are then compared to those for double-sided heating. For top wall heating, high speed video imaging proves gravity effects are dominant at low velocities, accumulating vapor along the heated wall and resulting in low critical heat flux (CHF) values. For bottom wall heating, buoyancy aids in vapor removal and liquid replenishment of the heated wall, resulting in higher CHF values. Higher velocities result in fairly similar interfacial behavior for top wall and bottom wall heating, and double-sided heating exhibiting greater symmetry between interfacial behaviors along the opposite walls. Overall, CHF values for all three configurations converge to one another above 1.5 m/s. This convergence is clearly the result of high inertia negating the influence of gravity. It is shown that interfacial instability theory provides an effective means for assessing the influence of velocity on CHF for top wall versus bottom wall heating. For top wall heating, a stable interface at low velocities causes vapor accumulation against the top wall resulting in very low CHF. Instability theory shows that top wall heating becomes unstable above 1.03 m/s, allowing liquid contact with the wall and improved wall cooling. For bottom wall heating, the interface is always unstable and favorable for liquid contact. Instability theory also shows that inertia dwarfs gravity around 1.5 m/s, where critical wavelengths for top wall and bottom wall heating converge. Convergence of the CHF values for top wall and bottom wall heating also occurred at a similar value.

1. Introduction

1.1. Transitioning from single-phase to two-phase thermal management in future space missions

Subcooled flow boiling is a primary means for thermal management in many applications demanding the dissipation of large heat loads from small surface areas. The merits of flow boiling are derived from reliance on both latent and sensible heat content of a working fluid, which can yield several orders of magnitude enhancement in heat removal compared to single-phase systems. These merits are realized in the nucleate boiling region, provided the heat flux is maintained safely below critical heat flux (CHF). This thermal limit, which is arguably the most important design parameter for a two-phase thermal management system, is associated with interruption of liquid access to the heat dissipating wall, and is known to trigger unsteady escalation in the wall temperature, leading to meltdown, burnout or some other form of catastrophic failure of the heat-dissipating device [1]. This explains the emphasis researchers have placed on determining CHF for a variety of flow boiling configurations, including channel flow [2,3], micro-channel flow [4,5], spray [6,7] and jet [8,9], as well as hybrid micro-channel/jet cooling [10,11].

The merits of subcooled phase change are especially significant for thermal management in space systems, where high two-phase heat transfer coefficients can play a key role in reducing the size and weight of thermal management hardware. In fact, space agencies worldwide are aggressively exploring the implementation of two-phase thermal management to support astronaut life in both space vehicles and planetary bases. The reductions in weight and

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Nomenclature

c_p	specific heat at constant pressure
g	gravity
g_e	Earth gravity
H	height of flow channel's cross-section
h	heat transfer coefficient
$H1$	top heated wall 1
$H2$	bottom heated wall 2
k_c	critical wave number
L_d	development length of flow channel
L_e	exit length of flow channel
L_h	heated length of flow channel
$\dot{m}$	mass flow rate
P	pressure
P_{in}	pressure at inlet to heated portion of channel
q''_w	wall heat flux
T	temperature
t	time
T_{in}	temperature at inlet to heated portion of channel
T_{sat}	saturation temperature
$\Delta T_{sub,in}$	subcooling at inlet to heated portion of channel, $T_{sat} - T_{in}$
T_w	wall temperature
U	mean inlet velocity
W	width of flow channel's cross-section
x_e	thermodynamic equilibrium quality
z	axial coordinate

Greek symbols

δ	mean thickness of liquid or vapor layer
λ_c	critical wavelength
ρ	density
ρ''	modified density
σ	surface tension

Subscripts

avg	average
c	critical
d	developing
e	exit
f	saturated liquid; bulk liquid
g	saturated vapor
h	heated wall
in	inlet to heated portion of channel
n	normal to heated wall; thermocouple location along heated wall
o	outlet from heated portion of channel
sat	saturation
sub	subcooling
w	wall designation ($H1$ or $H2$)

volume amount to appreciable gains in power efficiency. Prime targets for implementation of phase change include Thermal Control Systems (TCSs), which are responsible for controlling the temperature and humidity of the operating environment, and Fission Power Systems (FPSs), which are projected to provide both very high power and very low mass to power ratios [12,13].

But one of the key challenges in adopting phase-change in space applications is limited understanding of the influence of different gravitational environments on two-phase fluid physics and heat transfer, especially on flow boiling CHF.

1.2. Body force effects in flow boiling

Body force can have a strong influence in two-phase flow and heat transfer, especially at low flow velocities. The influence of body force is measured by buoyancy, which is the product of density difference between liquid and vapor, and gravity. Buoyancy influences both vapor removal from the heated wall and liquid replenishment of the wall, thereby impacting both nucleate boiling and CHF.

Many terrestrial two-phase applications capitalize upon the merits of vertical upflow, where buoyancy aids vapor removal from the heated wall in the same direction as the liquid flow. Efficient vapor removal also serves to facilitate liquid replenishment of the wall and enhance both flow stability and CHF. The popularity of vertical upflow explains why the majority of mechanistic models for flow boiling CHF [14–19] are intended for this flow orientation.

However, different applications impose orientations other than vertical upflow. Researchers have attempted to tackle flows in different orientations in pursuit of a mechanistic understanding of the influence of gravity components parallel to the flow and perpendicular to the heated wall on CHF, as well as to develop minimum flow criteria where variations in flow orientation cease to influence CHF, and where the ill effects of certain orientations may be negated.

The horizontal orientation, with gravity perpendicular to the flow direction, is a common flow configuration. Horizontal flow with a bottom heated wall was studied in detail by Zhang et al. [20] for subcooled inlet conditions and Kharangate et al. [21] for saturated inlet conditions. Here, buoyancy aids in vapor removal and liquid replenishment of the heated wall. The opposite is true for horizontal flow with a top heated wall, where buoyancy accumulates the vapor along the heated wall, leading to unusually low CHF values for low velocities [22,23]. Isolating the effects of buoyancy in horizontal flows is achieved with a rectangular channel containing heated walls running parallel to one another. Fig. 1(a) and (b) depict the idealized flow boiling behavior adapted from high speed images for top wall heating and bottom wall heating, respectively. Notice the tendency of vapor for top wall heating, Fig. 1(a), to accumulate into a rather continuous layer, with minimal opportunity for liquid to replenish the heated wall. On the other hand, bottom wall heating, Fig. 1(b), provides greater opportunity for the denser liquid to reach the heated wall, which explains the effectiveness of horizontal flow with bottom wall compared to top wall heating. Fig. 1(c) depicts horizontal two-phase flow in a rectangular channel that is fitted with both top and bottom heating walls. This double-sided heating configuration is far more complex than those depicted in Fig. 1(a) and (b) because the merits of bottom wall heating and detriments of top wall heating are encountered simultaneously in the same flow channel. The benefits or drawbacks of double-sided heating in Earth's gravity are not easily identifiable.

However, double-sided heating was recently examined in microgravity that was simulated by Konishi et al. [24] in parabolic flight experiments. In the absence of gravity for the configuration depicted in Fig. 1(c), equal heat fluxes along the two heated walls produce fairly symmetrical interfacial behavior. With twice the amount of heat supplied to the flow, increased vapor production yielded appreciable acceleration of the flow and a higher CHF compared to one-sided heating in microgravity. However, it is