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Criteria for negating the influence of gravity on flow boiling critical heat flux with two-phase inlet conditions

Christopher Konishi [a], Issam Mudawar [a,*], Mohammad M. Hasan [b]

[a] *Boiling and Two-Phase Flow Laboratory (BTPFL), School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907, USA*
[b] *NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, OH 44135, USA*

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ABSTRACT

This study explores the complex flow boiling CHF mechanisms encountered at different orientations relative to Earth's gravity when the fluid is supplied as a two-phase mixture. Using FC-72 as working fluid, different CHF regimes are identified for different orientations, mass velocities and inlet qualities. Low mass velocities are shown to produce the greatest sensitivity to orientation, while high mass velocities greatly reduce this influence, especially for high inlet qualities. It is also shown that the influence of orientation can be negated by simultaneously satisfying three separate criteria: overcoming the influence of gravity perpendicular to the heated wall, overcoming the influence of gravity parallel to the heated wall, and ensuring that the heated wall is sufficiently long to ensure liquid contact. These criteria are combined to determine the minimum mass velocity required to negate gravity effects in both terrestrial and space applications. Exceeding this minimum is of paramount importance to space systems since it enables the implementation of the vast body of published CHF data, correlations and models developed from terrestrial studies for design of thermal management systems for space applications.

1. Introduction

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

Space systems are increasing in complexity, size and power requirements. A key emphasis of space agencies is to increase the efficiency of power utilization for both space vehicles and future planetary bases by reducing system weight [1,2]. Among the various subsystems comprising any space vehicle or planetary base are several thermal management systems that are crucial to supporting astronaut life and operation of mechanical and electronic hardware. Key among those is the Thermal Control System (TCS), which is responsible for controlling the temperature and humidity of the operating environment. The TCS is responsible for acquiring heat from a number of heat-producing sources, transporting the heat, and rejecting it to deep space by radiation.

While previous space systems, such as NASA's space shuttles, employed a single-phase liquid TCS, weight reduction for future space systems will require transitioning from single-phase liquid to two-phase thermal management [1,2]. The key reason behind this transition is to capitalize on the merits of latent heat of the working fluid rather than sensible heat alone. With this transition, the TCS can take advantage of orders of magnitude enhancement in evaporation and condensation heat transfer coefficients compared to the heat transfer coefficients realized in single-phase liquid systems. For a given total heat load, this transition translates into drastic reductions in weight and volume of the thermal management hardware.

1.2. Gravity effects in boiling systems

Large density difference between liquid and vapor is the primary reason for the strong influence of gravity on two-phase fluid flow and heat transfer. This influence is manifest in the form of a buoyancy force proportional to the product of density difference and gravity. Critical heat flux (CHF) is arguably the most important design parameter for heat-flux-controlled two-phase systems. This explains the great emphasis researchers have placed on measuring, correlating and/or predicting CHF for virtually every two-phase flow configuration, including pool boiling [3,4], channel flow boiling [5–10], jets [11–14], sprays [15–17], and enhanced surfaces [18–20]. The present study concerns CHF in channel flow boiling.

1.3. Influence of orientation on flow boiling CHF

Vertical upflow is a preferred orientation for flow boiling systems because it enables buoyancy to move vapor in the same

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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

A	cross-sectional area of flow channel
A_h	heated area of flow channel
A_w	area of wetting front
b	ratio of wetting front length to wavelength
Bo	Bond number
D_h	hydraulic diameter
Fr	Froude number
G	mass velocity
g	gravity
g_e	earth gravity
H	height of flow channel
H_f	mean thickness of liquid layer
h_{fg}	latent heat of vaporization
H_g	mean thickness of vapor layer
L	heated length
P	pressure
q''_m	critical heat flux
U_f	mean velocity of liquid layer
U_g	mean velocity of vapor layer
U_∞	rise velocity of slug bubble
We	Weber number
x_e	thermodynamic equilibrium quality
z	axial distance
z_0	axial location where vapor layer velocity just exceeds liquid layer velocity
z^*	axial location for determining vapor layer thickness and critical wavelength in Interfacial Lift-off Model

Greek symbols

δ	vapor layer thickness
θ	flow orientation angle
λ_c	critical wavelength
ρ	density
σ	surface tension

Subscripts

f	saturated liquid
g	saturated vapor
in	inlet to heated portion of flow channel.

direction as the liquid flow. This imparts flow stability to the system and helps achieve relative high CHF values by aiding vapor removal from, and liquid replenishment of the heated wall. This explains why the majority of published studies on flow boiling CHF are conducted in the vertical upflow orientation. While different mechanisms have been proposed for flow boiling CHF [21–25], photographic evidence points to a dominant *Wavy Vapor Layer Regime* commencing along the heated wall as CHF is approached, and CHF being triggered by an *Interfacial Lift-off Mechanism* [26–31], which will be discussed later.

Flow boiling CHF for all other orientations can be highly complicated by the manner in which buoyancy influences the vapor and liquid flows both along the flow channel and perpendicular to the heated wall. Fig. 1(a) is used as a guide to explain the influence of flow orientation on CHF for a flow channel that is heated along one side. Shown are eight channel flow orientations, with the flow radiating outwards, and the placement of the heated wall, indicated by a black rectangular strip.

1.4. Influence of buoyancy along the flow channel

The influence of buoyancy *along* the channel is especially problematic for vertical downflow, $\theta = 270°$. Here, buoyancy opposes the liquid forces – both drag and shear – and flow behavior is therefore a function of the relative magnitude of buoyancy and liquid forces. Zhang et al. [28,29] showed that the vertical downflow orientation results in one of three possible CHF regimes. At very low flow rates, buoyancy exceeds liquid forces, causing the vapor to flow backwards (vertically upwards) along the channel with CHF associated with a *Vapor Counterflow Regime* and *Flooding* and CHF values are quite small. Increasing the flow rate increases the relative magnitude of the liquid forces, and a particular flow rate is reached that causes a balance between the two opposing forces, causing the vapor to stagnate along the channel. Here, CHF is associated with a *Stagnation Regime*, and corresponding CHF values are vanishingly small. A further increase in flow rate causes the liquid forces to exceed buoyancy, and the vapor to flow concurrently with the liquid. CHF for these conditions is associated with a *Separated Concurrent Vapor Flow Regime*, and CHF values are appreciably greater than those for the *Vapor Counterflow* or *Stagnation Regimes*. In the limit of a very high flow rate, the liquid forces render any buoyancy effects negligible, and CHF values for vertical upflow and vertical downflow converge. Clearly, high flow rate is an effective means to negating the influence of buoyancy on both flow behavior along the channel and CHF magnitude.

1.5. Influence of buoyancy perpendicular to the heated wall

The influence of buoyancy perpendicular to the heated wall is most noticeable for horizontal flow orientations with the heated wall pointing upwards, $\theta = 0°$, and downwards, $\theta = 180°$ [28,29]. For $\theta = 0°$ and small flow rates, small bubbles that nucleate along the heated wall tend to coalesce together to form larger vapor bubbles, which are driven by buoyancy across the channel to the opposite adiabatic wall. Here, CHF is associated with a *Pool Boiling Regime*. For $\theta = 180°$ and small flow rates, buoyancy causes the vapor to stratify above the liquid and adjacent to the heated wall. Clearly, this *Stratification Regime* impedes liquid access to the heated wall, resulting in very low CHF values. By greatly increasing the flow rate for both horizontal orientations, the flow behavior at CHF begins to resemble that for vertical upflow, $\theta = 90°$. Furthermore, CHF values for $\theta = 0°$ and 180° at high flow rates converge with those for vertical upflow, $\theta = 90°$. The convergence of CHF values for different orientations at high flow rates has been confirmed in several prior studies [32–35].

1.6. Importance of wavy layer regime

Fig. 1(b) shows CHF data for FC-72 measured by Zhang et al. [29] in a flow velocity–orientation plane. The data are grouped into the six aforementioned CHF regimes for which representative photographs are also depicted in Fig. 1(b). Notice that all CHF regimes other than the *Wavy Vapor Layer Regime* are encountered at low velocities, while the *Wavy Vapor Layer Regime* is dominant at high velocities regardless of orientation. Interestingly, the *Wavy Vapor Layer Regime* is prevalent in the vertical and near-vertical upflow orientations, $\theta = 90°$ and 135°, respectively, even at low velocities.

In a subsequent study, Zhang et al. [36] performed similar flow boiling experiments in parabolic flight to simulate microgravity. In the absence of buoyancy, the *Wavy Vapor Layer Regime* was