International Journal of Heat and Mass Transfer 61 (2013) 176–190

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Investigation of the influence of orientation on critical heat flux for flow boiling with two-phase inlet

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*

ARTICLE INFO

Article history:
Received 13 September 2012
Received in revised form 27 January 2013
Accepted 28 January 2013
Available online 26 February 2013

Keywords:
Flow boiling
Critical heat flux
Flow orientation

ABSTRACT

This study explores the mechanism of flow boiling critical heat flux (CHF) for FC-72 in a rectangular channel fitted along one side with a heated wall. The flow is supplied as a two-phase mixture and the channel is tested at different orientations relative to Earth's gravity. High-speed video imaging is used to identify the CHF trigger mechanism for different orientations, mass velocities and inlet qualities. It is shown that orientation has a significant influence on CHF for low mass velocities and small inlet qualities, with the orientations surrounding horizontal flow with downward-facing heated wall causing stratification of the vapor towards the heated wall and yielding very small CHF values. High mass velocities cause appreciable diminution in the influence of orientation on CHF, which is evidenced by similar flow patterns and CHF trigger mechanism regardless of orientation. The interfacial lift-off model is shown to predict the influence of orientation on CHF with good accuracy. Overall, this study points to the effectiveness of high mass velocities at combating buoyancy effects and helping produce CHF values insensitive to orientation.

1. Introduction

1.1. Importance of two-phase flow and heat transfer to future space missions

As the attention of space agencies worldwide is shifting to more complex and more distant missions, including manned missions to Mars, greater emphasis is being placed on efficiency of power utilization onboard both space vehicles and future planetary bases. A key tactic towards achieving this goal is to reduce the weight and volume of all subsystems. These include several components that are intended specifically for thermal management. One means to achieving this goal is to transition from single-phase to two-phase thermal management. By capitalizing upon the merits of latent heat of the working fluid rather than sensible heat alone, two-phase systems are expected to yield orders of magnitude enhancement in evaporation and condensation heat transfer coefficients compared to single-phase systems, which would result in drastic reductions in the weight and volume of thermal management hardware [1].

Thermal management plays a crucial role in supporting astronaut life onboard space vehicles and planetary bases. Thermal management systems are responsible for controlling the temperature and humidity of the environment using a Thermal Control System (TCS), and fall into three main categories [2]. *Heat acquisition* components acquire energy from a heat-producing source. *Heat transport* components move the energy from the heat acquisition component to heat rejection hardware. *Heat rejection* components reject the heat from the TCS to deep space by radiation. There are also other specialized subsystems, such as *refrigerator/freezer* components that provide cooling for science experiments and food storage, and *water recovery* components that transfer crew and system wastewater into potable water for crew and system reuse.

Understanding the influence of gravity on two-phase flow and heat transfer is crucial to the development of space power for future missions. For example, NASA's Fission Power System (FPS) program aims to develop a fission system for use on advanced science missions, which would provide both very high power and very low mass to power ratio [3]. The Rankine cycle is one example of a high power system (>100 kW) that promises high thermal efficiency and enables high performance nuclear electric propulsion for distant cargo and human missions. But before the Rankine cycle can achieve fruition, the influence of microgravity on fluid physics must be well understood. This includes critical heat flux (CHF) in the boiler, and shear driven condensation heat transfer.

1.2. Influence of gravity

The influence of gravity is exasperated in a two-phase system by the large density difference between liquid and vapor. This difference plays a crucial role in dictating the motion of vapor relative

---

* Corresponding author. Tel.: +1 (765) 494 5705; fax: +1 (765) 494 0539.
E-mail address: mudawar@ecn.purdue.edu (I. Mudawar).
URL: https://www.engineering.purdue.edu/BTPFL (I. Mudawar).

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.01.076

Nomenclature

A	cross-sectional area of flow channel
A_w	area of wetting front
b	ratio of wetting front length to wavelength
c	wave speed
$C_{f,i}$	interfacial friction coefficient
c_p	specific heat at constant pressure
D	diameter
f	friction factor
G	mass velocity
g_e	Earth gravity
H	height of flow channel; layer thickness
h_{fg}	latent heat of vaporization
k	wave number
$\dot{m}$	mass flow rate
$\dot{m}'_{fg}$	liquid evaporation rate between heated wall liquid and vapor layers
p	pressure
P_e	electric power input to second preheater
P_i	interfacial perimeter
P_w	perimeter in contact with channel walls
q''	wall heat flux
q''_m	critical heat flux
Re	Reynolds number
T	temperature
t	time
U	mean axial velocity
u_i	interfacial velocity
W	width of flow channel
x_e	thermodynamic equilibrium quality
x_f	liquid mass flow fraction
y	coordinate normal to heated wall
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

α	vapor (area-based) void fraction
δ	vapor layer thickness
e_f	liquid area fraction
h	interfacial perturbation
q	flow orientation angle
λ_c	critical wavelength
μ	dynamic viscosity
ρ	density
ρ''	modified density
σ	surface tension
τ_i	interfacial shear stress
τ_w	wall shear stress

Subscripts

1	insulated wall liquid layer
2	middle vapor core
3	heated wall liquid layer
4	heated wall wavy vapor layer
exp	experimental (measured)
f	saturated liquid
g	saturated vapor
i	interface
in	inlet to heated portion of flow channel
k	phase k, $k = g$ or f
n	normal to heated wall
pred	predicted
preh	upstream of second preheater
w	wall; wetting front.

to liquid, thereby influencing heat transfer effectiveness. Flow boiling CHF is an important heat transfer design parameter that exhibits complex variations with the magnitude of gravitational field. The challenge in designing a thermal management system is to make certain that the prevailing boiling heat flux is safely below CHF, which explains the importance space system design engineers place on precise determination of the influence of both flow conditions and gravity on CHF. This is especially the case for high-flux, heat-flux-controlled electronic and power devices, where CHF occurrence can lead to device burnout or other forms of permanent damage. This risk explains a recent surge in the number of published articles addressing means to enhance CHF using a variety of configurations, including spray [4–7], jet [8–11], and micro-channel cooling schemes [4,12–15], and surface enhancement techniques [16].

A key strategy in designing two-phase components for space missions is to develop tools that enable the prediction of flow conditions (e.g., coolant flow rate) that would ensure insensitivity of evaporation or condensation to gravity [1,17,18] for the relevant gravity range important to a particular space system or mission, as illustrated in Fig. 1. This would allow existing data, correlations, and models developed from ground-based $1 - g_e$ studies to be employed with confidence for design of reduced gravity and microgravity thermal management systems.

Researchers employ a variety of techniques to assess the important influence of gravity on flow boiling CHF. These include conducting ground-based experiments at different flow orientations relative to Earth's gravity [17,18]. Microgravity is achieved in drop tower and drop shaft experiments, which provide a high degree of control of residual gravity, but are too short (less than 10 s) to achieve steady two-phase flow or to collect sufficient amounts of data for statistical analysis without a significant number of repetitive drops [2]. Aircraft parabolic flight tests offer significant advantages over drop tower and drop shaft tests, including longer test duration (up to 25 s), larger and more complex test packages, and ability of the experimenter to interact with the test [1]. Space Shuttle experiments provided an ideal testing environment because of the ability to accommodate long-duration experiments with good control of residual gravity. Since the recent abandonment of Space Shuttles, the International Space Station (ISS) has become the sole platform for conduction long duration microgravity experiments.

Researchers at the Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL) have been involved in several NASA-supported initiatives to explore the influence of gravity on both flow boiling and condensation. These studies are initiated with ground experiments, by exploring the effects of flow orientation relative to Earth's gravity [17,18]. The same hardware is then tested in parabolic flight experiments [1]. Both types of tests are used to assist the design of test hardware for future experiments onboard the ISS. The present study concerns flow boiling CHF findings from ground-based $1 - g_e$ experiments.

1.3. Mechanisms of flow boiling CHF

Four different mechanisms have been proposed to trigger flow boiling CHF: *Boundary Layer Separation*, *Bubble Crowding*, *Sublayer*