International Journal of Heat and Mass Transfer 81 (2015) 721–736

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Flow boiling in microgravity: Part 2 – Critical heat flux interfacial behavior, experimental data, and model

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ARTICLE INFO

Article history:
Received 9 August 2014
Received in revised form 21 October 2014
Accepted 21 October 2014
Available online 21 November 2014

Keywords:
Microgravity
Flow boiling
Interfacial behavior
Critical heat flux

ABSTRACT

This study is the second part of a two-part investigation of flow boiling critical heat flux (CHF) in microgravity, which is simulated in parabolic flight experiments. Using FC-72 as working fluid, flow boiling experiments are conducted in a rectangular channel fitted with two opposite heated walls, allowing either one or both heated walls to be activated during a test. While the first part explored flow boiling conditions leading to CHF, this part addresses events just before CHF, during the CHF transient, and immediately following CHF. For both single-sided and double-sided heating, interfacial behavior just before CHF is characterized by dominant wavy vapor layers covering the heated walls, where liquid is able to access the walls only in wetting fronts corresponding to the wave troughs. CHF is associated with successive lift-off of wetting fronts from the walls, consistent with the Interfacial Lift-off Model, which has been validated extensively in past studies using single-sided heating in both μg_e and $1 - g_e$. It is shown this model predicts μg_e double-sided flow boiling CHF with excellent accuracy. Additionally, the model points to convergence of CHF values for μg_e and $1 - g_e$ for inlet velocities greater than about 1 m/s. Therefore, by maintaining velocities above this threshold allows designers of space systems to achieve inertia-dominated performance as well as to adopt prior data and correlations developed from terrestrial studies.

1. Introduction

1.1. Implementation of flow boiling and condensation in future space missions

For decades, thermal management onboard manned space vehicles has been tackled by conventional single-phase systems that absorb the heat by raising the sensible heat of an appropriate coolant, and reject it to deep space via a space radiator. This type of system has been used successfully on all of NASA's Space Shuttles. However, there is now specific interest in long duration space missions, especially the manned mission to Mars, which are expected to pose many technological challenges, especially the need to greatly increase energy efficiency and reduce both the weight and volume of the entire systems [1,2], including the Thermal Control System (TCS) responsible for maintaining the temperature and humidity of the operating environment. These benefits will be realized by shifting from present single-phase liquid thermal management to two-phase counterpart. By capitalizing on both sensible and latent heat of the coolant instead of sensible heat alone, two-phase systems can yield orders of magnitude enhancement in flow boiling and condensation heat transfer coefficients while significantly reducing the temperature of the heat dissipating device compared to single-phase systems.

Two-phase thermal management systems utilizing flow boiling and condensation have attracted significant interest in recent years in many applications demanding efficient heat removal from high-power-density devices, including computer data centers, hybrid vehicle power electronics and avionics [3,4]. The effectiveness of these systems has been demonstrated using a variety of boiling configurations, including pool [5,6], macro-channel flow [7,8], micro-channel flow [9], jet [10,11], and spray [12–14], as well as hybrid schemes combining the merits of two or more boiling configurations [15,16].

However, the feasibility of a particular boiling configuration in a space vehicle's TCS is dependent on a number of considerations, which include, aside from reduced weight and volume, low pumping power and the ability to manage phase separation in a closed

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.10.052
0017-9310/

Nomenclature

A	cross-sectional area of flow channel
$A_{w,w}$	area of wetting front
b	ratio of wetting front length to wavelength
$C_{f,i}$	interfacial friction coefficient
c	wave speed
c_i	imaginary component of wave speed
c_p	specific heat at constant pressure
c_r	real component of wave speed
D	hydraulic diameter
f	friction factor
G	mass velocity
g	gravity
g_e	Earth's gravitational acceleration
H	height of flow channel's cross-section
h_{fg}	latent heat of vaporization
k	wave number
L	length
L_d	development length of flow channel
L_e	exit length of channel
L_h	heated length of channel
MAE	mean absolute error
$\dot{m}$	mass flow rate
N	number of data points
p	pressure
P_i	interfacial perimeter
P_w	wall friction perimeter
q''_m	critical heat flux
q''_w	wall heat flux
$q''_{w,w}$	wetting front heat flux
Re	Reynolds number
T	temperature
t	time
T_{in}	inlet temperature
T_{sat}	saturation temperature
T_w	wall temperature
$\Delta T_{sub,in}$	inlet subcooling, $T_{sat} - T_{in}$
U	mean inlet liquid velocity; mean axial velocity
u_i	interfacial velocity
W	width of flow channel's cross-section
x	flow quality
y	coordinate normal to heated wall
z	axial distance
z_o	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 void fraction
Γ_{fg}	evaporation rate per unit distance
δ	mean vapor layer thickness
η	interfacial perturbation
η_0	amplitude of interfacial perturbation
θ	flow orientation angle
λ	wavelength
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

est	estimated
exp	experimental (measured)
f	saturated liquid; bulk liquid
g	saturated vapor
i	interfacial
in	inlet to heated portion of flow channel
k	phase k, $k = g$ or f
m	maximum (CHF); heated wall identifier ($m = 1$ for H_1, $m = 2$ for H_2)
n	normal to heated wall; thermocouple location along heated wall
o	outlet from heated portion of flow channel
$pred$	predicted
sat	saturation
sub	subcooling
w	wall; wetting front

TCS loop in microgravity. These considerations preclude spray and jet configurations as viable options. Pool boiling is also very problematic in microgravity because it has been shown to produce massive bubbles upon the heated wall that significantly decrease critical heat flux (CHF) compared to terrestrial pool boiling [17]. These reasons are why flow boiling, using macro-channels or micro-channels, is presently the configuration most favored for the space vehicle's TCS. Even in microgravity, flow inertia in flow boiling serves to maintain high CHF by flushing bubbles away from the heated wall before they coalesce into insulating blankets, and by maintaining liquid replenishment of the heated wall. This is especially important to heat-flux-controlled devices, such as avionics, where CHF occurrence can lead to physical meltdown, burnout, or catastrophic damage to the heat-dissipating surface and surrounding components.

But, while the merits of flow boiling are well acknowledged, design engineers lack the data and technical knowhow to assess the influence of reduced gravity on flow boiling CHF. Flow boiling is obviously highly influenced by the large density differences between liquid and vapor, which, in the terrestrial environment, yield an appreciable buoyancy force that helps dictate both flow behavior and heat transfer effectiveness. However, in reduced gravity, especially microgravity, body force is much weaker, meaning flow behavior is dictated more by other forces such as inertia and surface tension. This brings into question the applicability of terrestrial flow boiling data, models and correlations to reduced gravity. To correct this knowledge gap, flow boiling experiments must be performed in reduced gravity, aided by flow visualization methods, to facilitate a comprehensive fundamental understanding of interfacial behavior and the roles of dominant forces.

1.2. Postulated mechanisms for flow boiling CHF in Earth gravity

CHF is arguably the most important design parameter for flow boiling systems involving thermal management of heat-flux-controlled surfaces. Most attempts to model flow boiling CHF concern vertical upflow in Earth gravity, which is the orientation that provides both stable two-phase flow and favorable CHF values. The most crucial component of these models is predicting the physical mechanism responsible for initiating – triggering – flow boiling