International Journal of Heat and Mass Transfer 120 (2018) 144–166

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental investigation into the impact of density wave oscillations on flow boiling system dynamic behavior and stability

Lucas E. O'Neill [a], Issam Mudawar [a,*], Mohammad M. Hasan [b], Henry K. Nahra [b], R. Balasubramaniam [b], Nancy R. Hall [b], Aubrey Lokey [b], Jeffery R. Mackey [c]

[a] Purdue University Boiling and Two-Phase Flow Laboratory (PU-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
[c] Vantage Partners, 3000 Aerospace Parkway, Brook Park, OH 44142, USA

ARTICLE INFO

Article history:
Received 5 April 2017
Received in revised form 29 November 2017
Accepted 1 December 2017

Keywords:
Flow boiling
System dynamics
Transients
Stability maps
Density wave oscillations

ABSTRACT

In order to better understand and quantify the effect of instabilities in systems utilizing flow boiling heat transfer, the present study explores dynamic results for pressure drop, mass velocity, thermodynamic equilibrium quality, and heated wall temperature to ascertain and analyze the dominant modes in which they oscillate. Flow boiling experiments are conducted for a range of mass velocities with both subcooled and saturated inlet conditions in vertical upflow, vertical downflow, and horizontal flow orientations. High frequency pressure measurements are used to investigate the influence of individual flow loop components (flow boiling module, pump, pre-heater, condenser, *etc.*) on dynamic behavior of the fluid, with fast Fourier transforms of the same used to provide critical frequency domain information. Conclusions from this analysis are used to isolate instabilities present within the system due to physical interplay between thermodynamic and hydrodynamic effects. Parametric analysis is undertaken to better understand the conditions under which these instabilities form and their impact on system performance. Several prior stability maps are presented, with new stability maps provided to better address contextual trends discovered in the present study.

1. Introduction

1.1. Challenges limiting the adoption of two-phase thermal management systems

Across industries worldwide, thermal design engineers are turning to phase change energy transfer methods to meet increasingly difficult thermal management requirements posed by successive generations of products [1]. By using boiling for device cooling and condensation for heat rejection, both latent and sensible heat of the fluid can be utilized, allowing achievement of orders of magnitude improvement in heat transfer compared to traditional single-phase alternatives.

Although useful for any application involving thermal management of high energy density devices, phase change systems show particular promise in the field of space thermal-fluid systems, where their high heat transfer coefficients can allow an appreciable reduction in size and weight of hardware. Because of this potential, space agencies worldwide are investigating the benefits and drawbacks accompanying implementation of two-phase systems in both space vehicles and planetary bases. Current targets for adoption of phase change technologies include Thermal Control Systems (TCSs), which control temperature and humidity of the operating environment, heat receiver and heat rejection systems for power generating units, and Fission Power Systems (FPSs), which are projected to provide high power as well as low mass to power ratio [2–4].

Unlike their Earth-based counterparts, however, use of two-phase cooling schemes for space missions entails the added complication of variable body force across missions or even across mission duration. From hyper-gravity associated with launch, to microgravity encountered in interplanetary transit and orbit, to unique planetary gravitational accelerations, thermal management systems designed to operate in space must be robust enough to perform in a broad range of gravitational accelerations. This greatly complicates the use of two-phase thermal management systems, where the orders of magnitude density difference between phases causes body force (buoyancy) effects to impact flow behavior significantly. To adequately mitigate the risks associated with operation in space, accurate, robust design tools for a wide array of boiling configurations is a necessity.

* Corresponding author.
E-mail address: mudawar@ecn.purdue.edu (I. Mudawar).
URL: https://engineering.purdue.edu/BTPFL (I. Mudawar).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.011
0017-9310/© 2017 Published by Elsevier Ltd.

Nomenclature

A	amplitude
c_p	specific heat at constant pressure
D_h	hydraulic diameter
f	frequency
f_r	resonant frequency
G	mass velocity
H	height of flow channel's cross-section
h_{fg}	latent heat of vaporization
L	length
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
N_{pch}	phase change number
N_{sub}	subcooling number
P	pressure
ΔP	pressure drop across heated portion of channel
P_{in}	pressure at inlet to heated portion of channel
P_{out}	pressure at outlet to heated portion of channel
Pwr_{PH}	power supplied by pre-heater
Q	total heat input
q''	heat flux on heated perimeter of channel
Re	Reynolds number
Re_f	superficial liquid Reynolds number, $Re_f = G(1-x)D_h/\mu_f$
T	temperature
t	time
T_{in}	temperature at channel inlet
T_{sat}	saturation temperature
$T_{sat,in}$	saturation temperature of fluid at inlet to heated portion of channel
T_{tr}	transport time
U	mean velocity
v	specific volume
W	width of flow channel's cross-section
x	quality
x_e	thermodynamic equilibrium quality

Greek symbol

μ	dynamic viscosity

Subscripts

ave	average
exp	experimental (measured)
f	saturated liquid
FBM	flow boiling module
FC	FC-72 fluid
g	saturated vapor
in	inlet to heated portion of channel
m	heated wall identifier (*a* for heater H_a or *b* for heater H_b)
PH	pre-heater
pred	predicted
sat	saturation
w	wall

Many previous studies have investigated a variety of 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 configuration possesses unique attributes as well as drawbacks, all suffer from a lack of understanding regarding the precise influence of body force on system performance, and transient system performance in particular.

Although most researchers and design engineers are primarily concerned with steady, time-averaged values for key parameters such as heat transfer coefficient, pressure drop, and critical heat flux (CHF), under certain conditions, system transient behavior has the ability to significantly impact performance and drive system design. These include operation near a critical point (*e.g.,* choking, CHF), where fluctuations in operating conditions brought on by instabilities inherent to flow boiling systems have the capacity to push the system into a failure mode, and applications concerned with precise system control (*e.g.,* maintaining science instrument temperature within a small range), where oscillations degrade system performance. Additionally, and of particular interest to the present study, is the case of changing body force (brought on by system utilization in space vehicles). As evidenced by previous studies conducted with the aid of parabolic flight [20,21], rapid changes in local acceleration lead to dynamic changes in flow boiling behavior. Better characterization of flow boiling transient behavior and the effects of body force variations on this behavior are crucial to designing the next generation of space-based thermal management systems.

1.2. Flow boiling instabilities and transient behavior

Due to the complex interplay of fluid and thermal effects, two-phase flows with mass transfer (flow boiling, flow condensation) commonly exhibit flow '*instabilities*', dynamic, transient events that can impact system performance under certain conditions. The study of two-phase flow instabilities originated with Ledinegg [22], who discovered that, under certain operating conditions, two-phase flow systems can experience an excursion from an unstable location to a stable location on the system's internal-external pressure curve, manifest as a change in mass velocity within the system.

It was not until several decades later that researchers began to delve into less noticeable, more persistent transient phenomena found in two-phase flow systems [23–25], with special attention paid to Density Wave Oscillations (DWOs) [26,27]. It was around the same time that Boure et al. published their seminal review of two-phase flow instabilities [28], which contains two facts of particular interest to the present work:

(1) Two-phase flow instabilities can be broadly classified into two groups: (a) '*static instabilities*', indicating a single excursion to a new operating condition (*e.g.,* Ledinegg instability, CHF), and (b) '*dynamic instabilities*', which are continuous, periodic oscillations within the flow (*e.g.,* DWOs, Pressure Drop Oscillations, Parallel Channel Instability).
(2) Instabilities falling into the second category of dynamic instabilities can often be best characterized by analyzing the frequencies at which they occur.

Recently, researchers have continued to focus on characterization of flow boiling transient behavior in a wide range of two-phase flow systems, including systems driven by natural circulation [29], forced flow in single mini-channels [30–32] and micro-channels [33,34], and in parallel micro-channel heat sinks [35–40]. Recent reviews, such as those by Tadrist [41], Kakac and Bon [42], and Ruspini et al. [43], provide updated surveys of literature relating to phenomena first reported by Boure et al. [28], including overviews of analytic, empiric, and numeric approaches adopted in modeling their behavior. From the lack of overlap