Available online at www.sciencedirect.com

ScienceDirect

International Journal of Heat and Mass Transfer 50 (2007) 4999–5016

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Flow boiling of liquid nitrogen in micro-tubes: Part I – The onset of nucleate boiling, two-phase flow instability and two-phase flow pressure drop

S.L. Qi [a], P. Zhang [a,*], R.Z. Wang [a], L.X. Xu [b]

[a] *Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China*
[b] *School of Life Sciences and Technology, Shanghai Jiao Tong University, Shanghai 200240, China*

Received 29 January 2007; received in revised form 27 June 2007
Available online 23 October 2007

Abstract

This paper is the first portion of a two-part study concerning the flow boiling of liquid nitrogen in the micro-tubes with the diameters of 0.531, 0.834, 1.042 and 1.931 mm. The contents mainly include the onset of nucleate boiling (ONB), two-phase flow instability and two-phase flow pressure drop. At ONB, mass flux drops suddenly while pressure drop increases, and apparent wall temperature hysteresis in the range of 1.0–5.0 K occurs. Modified Thom model can predict the wall superheat and heat flux at ONB. Moreover, stable long-period (50–60 s) and large-amplitude oscillations of mass flux, pressure drop and wall temperatures are observed at ONB for the 1.042 and 1.931 mm micro-tubes. Block phenomenon at ONB is also observed in the cases of high mass flux. The regions for the oscillations, block and stable flow boiling are classified. A physical model of vapor patch coalesced at the outlet is proposed to explain the ONB oscillations and block. Vapor generation caused by the flash evaporation is so large that it should be taken into account to precisely depict the variation of mass quality along the micro-tube. The adiabatic and diabatic two-phase flow pressure drop characteristics in micro-tubes are investigated and compared with four models including homogeneous model and three classical separated flow models. Contrary to the conventional channels, homogeneous model yields better prediction than three separated flow models. It can be explained by the fact that the density ratio of liquid to vapor for nitrogen is comparatively small, and the liquid and vapor phases may mix well in micro-tube at high mass flux due to small viscosity of liquid nitrogen, which leads to a more homogeneous flow. Part II of this study will focus on the heat transfer characteristics and critical heat flux (CHF) of flow boiling of liquid nitrogen in micro-tubes.

Keywords: Micro-tube; Flow boiling; ONB; Pressure drop; Liquid nitrogen

1. Introduction

Flow boiling heat transfer in microchannels is widely applied for many advantages such as high heat flux dissipation and good compactness. One group of the applications mainly includes high heat flux electronic chip cooling, microelectromechanical system (MEMS), etc., where both the operation pressure and mass flow rate are small, and the working fluid is usually water. Another group is the high efficiency and compact air-cooled heat exchangers in both residential and automotive air-conditioning. In this case, the operation pressure and mass flow rate are very large, and the used fluids are various kinds of refrigerants, such as R-134a, R-12, R-141b, R-124, FC-82 and CO_2. For the wide applications, there are many studies on the flow boiling in microchannels.

An important research content for the flow boiling in microchannels is to determine the location of the onset of nucleate boiling (ONB), because the ONB marks the boundary between the single-phase and two-phase heat

* Corresponding author. Tel.: +86 21 34205505; fax: +86 21 34206814.
E-mail address: zhangp@sjtu.edu.cn (P. Zhang).

0017-9310/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2007.08.018

Nomenclature

A	cross section area of tube (m^2)
B	Chisholm parameter
c_p	specific heat (J/kg K)
C	constant of L–M model
C_{SF}	shape factor for bubble nucleation
D	hydraulic diameter (m)
e	average surface roughness (μm)
E	Friedel parameter
f	friction factor
F	Friedel parameter
Fr	Friedel number
g	gravitational acceleration (m/s^2)
G	mass flux (kg/m^2 s)
h	heat transfer coefficient (W/m^2 K)
h_{fg}	latent heat of evaporation (J/kg)
H	Friedel parameter
I	electric current through the heater (A)
k	thermal conductivity (W/m K)
L	tube length (mm)
$\dot{m}$	flow rate (kg/s)
Nu	single-phase flow Nusselt number
p	pressure (Pa)
Δp	pressure drop (Pa)
q	average heat flux (W/m^2)
Re	Reynolds number
S	inner surface area of tube (m^2)
T	temperature (K)
ΔT	wall superheat (K)
U	electric voltage across the heater (V)
We	Weber number
x	mass quality
X	Lockhart–Martinelli parameter
z	longitudinal abscissa (m)

Greek symbols

β	contact angle (deg)
ε	void fraction
ϕ	two-phase friction multiplier
Γ	Chisholm parameter
μ	viscosity (kg/m s)
θ	dimensionless temperature
ρ	density (kg/m^3)
σ	surface tension (N/m)
ξ	constant in Thom model

Subscripts

a	acceleration
c	critical point property
crit	critical
eq	equilibrium
exp	experimental
f	friction
flash	flash evaporation
F	fluid
g	gravitation
G	gas
GO	gas only
i	inner surface of tube
in	inlet of tube
L	liquid
LO	liquid only
mea	measured
o	outer surface of tube
out	outlet of tube
pred	predicted
sat	saturation
sc	subcooled
ss	stainless steel
Total	total value
Tp	two-phase
w	wall of tube
z	longitudinal location

transfer regions. Hus [1] was the first to postulate the minimum superheat criterion for the ONB in pool boiling. The criterion declares that the bubble nucleus can grow only if the temperature surrounding the bubble is higher than the saturated temperature corresponding to the pressure inside the bubble. Then Sato and Matasumura [2] and Bergles and Rohsenow [3] extended Hus's criterion to the flow boiling in conventional channels. For the ONB in mini-channels, Hapke et al. [4] studied the ONB in a mini-tube with an internal diameter of 1.5 mm using a thermographic measuring method, and reported that the relatively high wall superheat was necessary to initiate the bubble nucleation. No model could predict the experimental tendency that lower wall superheat is obtained for higher mass flux if the heat flux is kept constant. Hence, they presented a semi-empirical model to predict the heat flux and wall superheat at ONB. Ghiaasiaan and Chedester [5] found that the macroscale models underestimated the heat flux at ONB, and they suggested the thermo-capillary force might suppress the bubble nucleation from the wall cavities. Recently, Liu et al. [6] developed an analytical model to predict the heat flux for ONB of water in the rectangular microchannels which are 275 μm wide by 636 μm deep.

Moreover, complex two-phase flow instabilities, which are undesirable since they can cause problems of system control and lead to thermal fatigue in the heat transfer tubes [7], are usually found in microchannels. Zhang et al. [8] found 4–5 Hz temperature fluctuations with the same frequency to the bubble formation in the flow boiling experiments of deionized water in 113 μm silicon