International Journal of Thermal Sciences 50 (2011) 296–308

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Forced flow boiling of carbon dioxide in horizontal mini-channel

Mamoru Ozawa*, Takeyuki Ami, Hisashi Umekawa, Ryosuke Matsumoto, Takashi Hara

Department of Mechanical Engineering, Kansai University, 3-3-35 Yamate-cho, Suita, Osaka 564 8680, Japan

ARTICLE INFO

Article history:
Received 5 January 2010
Received in revised form
24 April 2010
Accepted 25 April 2010
Available online 2 June 2010

Keywords:
Boiling heat transfer
Flow pattern
Pressure drop
Phase stratification
Carbone dioxide
Discrete bubble model
Critical heat flux

ABSTRACT

This paper covers a wide spectrum of thermal flow behavior, including flow patterns, heat transfer, pressure drop, critical heat flux of flow boiling carbon dioxide at high pressure in horizontal mini-channels. The presented experimental data covers relatively wide ranges: tube diameters from 0.51 mm to 3.0 mm, mass flux from 80 kg/m^{2}s to 900 kg/m^{2}s, heat flux from 5 kW/m^2 to 40 kW/m^2, pressure/saturation temperature from 4.0 MPa/5.30 °C to 7.0 MPa/28.7 °C. The carbon dioxide at high pressure has small density difference between vapor and liquid and low surface tension, and shows a slightly different structure of the flow pattern from so far observed conventional two-phase flow with air and water and/or larger diameter tubes. So far proposed transition criteria of flow pattern are as a whole ineffective in the present range of experiment, and the discrete bubble model developed by the authors demonstrates its high potential in predicting flow patterns. The phase mal-distribution in the cross-section becomes rather significant beyond a critical Bond number, while less significant or almost axi-symmetric below the critical Bond number. This significant phase mal-distribution leads to the intermittent dryout at the upper wall of the tube, while below the dryout heat flux the boiling heat transfer is dominated by the nucleate boiling mode, being well predicted with conventional correlations.

1. Introduction

Ammonia and carbon dioxide (CO_2) have been used as refrigerants in refrigeration technologies for over 130 years [1]. Considering the thermo-physical properties, although corrosion and other safety issues have not been solved, ammonia is indeed an ideal substance in refrigeration technologies, while in recent years CO_2 has all the more attracted attention for domestic and small-capacity refrigerators and/or heat pumps for hot water heating, and automobile air-conditioning units. CO_2 ($p_{cr} = 7.38$ MPa, $T_{cr} = 304.1$ K) is non-flammable and non-toxic, and in addition, does not need to be recovered. To develop the compact heat exchanger using CO_2, mini-channel heat exchangers are preferably used because of its high specific heat transfer area. In terms of thermo-physical properties, CO_2 has low viscosity, being preferable in considering the pressure drop, but with high heat transfer coefficient [2]. Aiming at such application, extensive researches have been conducted on flow boiling CO_2, e.g. [3–6], and two-phase flow in mini-channels, e.g. [7–11]. In this paper the discussion is focused on relatively higher pressure region than previously published papers. This is mainly because small density difference between vapor and liquid and low surface tension bring about somewhat different features of boiling two-phase flow from existing literatures [3–11]. Prior to the discussions, important subjects raised in the mini-channel heat exchanger design of CO_2 are listed below:

Two-phase flow pattern of CO_2 in mini-channel and phase mal-distribution,
Pressure drop characteristics in mini-channel,
Flow mal-distribution among parallel channels as well as flow instability,
Heat transfer in rather wide range of pressure, and
Critical heat flux (CHF).

It should be noted here that the flow pattern has close relationship with the pressure drop especially in mini-channels [12], and this pressure drop characteristics essentially affect the flow mal-distribution, if the system consists of multiple channels [13,14]. In this sense, the flow pattern is one of the key issues in discussing two-phase thermal hydraulics. The discussions in this paper are based on a wide range of experiments in tube diameter, pressure, heat flux, mass flux and vapor quality. The critical pressure of CO_2 is rather low compared with e.g. water, and the present results in subcritical pressure region may contribute in understanding flow pattern and flow behavior in subcritical or high pressure region of other fluids.

* Corresponding author. Tel./fax: +81 6 6368 0807.
E-mail address: ozawa@kansai-u.ac.jp (M. Ozawa).

1290-0729/$ – see front matter © 2010 Elsevier Masson SAS. All rights reserved.
doi:10.1016/j.ijthermalsci.2010.04.017