International Journal of Thermal Sciences 54 (2012) 1–12

Contents lists available at SciVerse ScienceDirect

International Journal of Thermal Sciences

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

Flow boiling of ammonia in vertical small diameter tubes: Two phase frictional pressure drop results and assessment of prediction methods

M.H. Maqbool, B. Palm*, R. Khodabandeh

Royal Institute of Technology, KTH, Dept. Energy Technology, Division of Applied Thermodynamics and Refrigeration, Brinellvägen 68, 100 44 Stockholm, Sweden

ARTICLE INFO

Article history:
Received 24 February 2011
Received in revised form
22 November 2011
Accepted 24 November 2011
Available online 9 January 2012

Keywords:
Two phase
Pressure drop
Ammonia
Experimental study

ABSTRACT

Two phase pressure drops were measured for ammonia at a wide range of test conditions in two sizes of vertical mini channels. The test sections were made of stainless steel (AISI 316) tubes with internal diameter of 1.70 mm and 1.224 mm and a uniformly heated length of 245 mm. Experiments were conducted at three saturation temperatures of 23 °C, 33 °C and 43 °C, the heat flux ranging from 15 to 355 kW/m^2 and the mass flux ranging from 100 to 500 kg/m^{2}s. The effect of the heat flux, the mass flux, the vapour quality, the saturation temperature and the internal diameter on the two phase pressure drop are presented in this article. Some generalized two phase pressure drop correlations suggested for macro and micro scale channels are examined by comparing them with our experimental data. None of the examined correlations agreed well with the test data. A new correlation (modified form of Tran et al. correlation) is proposed which is able to predict the experimental data with MAD of 16% and 86% of the data is within ±30% range.

1. Introduction

The transport phenomena in micro channels have gained importance because micro geometries offer higher cooling capability for micro technologies [1]. The advancement in micro fabrication is also important for the application of mini and micro channels. It enables us to precisely manufacture the flow channels ranging from a few micrometres to several hundred micrometres or more [2]. Mini channels offer higher heat transfer capabilities and higher heat transfer coefficients than macro channels [3]. Mini channels can be used for different applications such as electronic cooling, biomedical engineering, automotive industry and compact refrigeration systems etc. Despite many advantages of using mini channels like reduced size, low fluid inventory, reduced cost due to minimum material requirement and compactness, the disadvantage may be higher pressure drop if the system is not designed properly. To get higher heat transfer without increasing pressure drop is a major research task for micro geometries.

Only few published studies are available for mini and micro channels regarding two phase pressure drop of ammonia, and some of the related studies are mentioned below:

Ungar and Cornwell [4] performed flow boiling experiments to investigate two phase pressure drop of ammonia in mini and micro channels. A range of horizontal test sections of diameter 1.46, 1.78, 2.58 and 3.15 mm respectively were used. The two phase frictional pressure drop data was compared with several macro scale correlations. Apart from the homogeneous model with the viscosity definition of McAdams et al. [5], none of the macro scale correlations predicted the data well.

Two phase adiabatic pressure drop in a micro channel of 148 μm diameter was investigated by Brandon and Hrnjak [6]. A number of refrigerants like ammonia, propane, R410a and R134a were tested in this study. The measured data was compared with several correlations but only Mishima and Hibiki [7] correlation was in good agreement with the experimental data of Ammonia. The authors proposed a new correlation based on Chisholm interaction parameter. The new correlation predicted the data of all refrigerants with a Mean Absolute Deviation (MAD) of 12.6%.

Kabelac and Buhr [8] performed flow boiling experiments with ammonia in smooth and low finned horizontal test sections of 10 mm internal diameter and a length of 450 mm. The test conditions were; mass flux range 50–150 kg/m^{2}s, vapour quality range 0–0.9, saturation temperatures −40 to 4 °C and a heat flux range of 17–75 kW/m^2. It was observed that at the same test conditions, the pressure drop of the finned test section was about 50% higher than for the smooth tubes. They compared their experimental data of smooth and finned tubes with many correlations. Among all the

* Corresponding author. Tel.: +46 0 8 790 7453; fax: +46 0 8 20 41 61.
E-mail addresses: maqbool@kth.se (M.H. Maqbool), bpalm@energy.kth.se (B. Palm), rahmat@energy.kth.se (R. Khodabandeh).

1290-0729/$ – see front matter © 2011 Elsevier Masson SAS. All rights reserved.
doi:10.1016/j.ijthermalsci.2011.11.018

prediction methods used, the Chisholm [9] correlation was found to be in best agreement with their experimental data.

Da Silva Lima et al. [10] performed experiments to investigate flow patterns and two phase pressure drop of ammonia in a 14 mm diameter stainless steel tube. The expected trends were observed, i.e. that the two phase pressure drop increases with increasing mass flux and vapour quality. They also compared two phase frictional pressure drop in diabatic and adiabatic flows and found no noticeable influence on frictional pressure drop. Low accuracy of predicting methods were observed except for the correlation of Grönnerud [11] with 93% of the data within an error band of 30%, and the model of Quibén and Thome [12] which best predicted the data with 89% of all data within 20% error band.

One of the objectives of this study is to add data of ammonia for mini and micro channels because of the lack of published data in the literature. This data is particularly interesting because of the very different thermo physical properties of ammonia compared to other refrigerants commonly tested in mini channels. To include the ammonia data will therefore be valuable in the effort to formulate generalised correlations for the prediction of two phase frictional pressure drop in mini and micro channels. Another reason for understanding the behaviour of two phase flow of the natural working fluid ammonia is due to increased concerns of ozone depletion and global warming, as increased knowledge of the performance of this refrigerant may contribute to its use as a substitute to HCFC and HFC refrigerants.

2. Experimental set up and test procedure

A schematic of the experimental set up is shown in Fig. 1. A magnetic gear pump (ISMATEC, type MCP-Z standard) circulated the refrigerant, and a (MicroMotion DS006) Corioli mass flow meter was used to measure the flow rate. A pre heater adjusted the inlet temperature of the fluid before the test section. A filter of 7 μm was used to restrict any particles from entering the test section.

The test sections consisted of metal (AISI 316 stainless steel) tubes with inner diameters of 1.70 mm and 1.224 mm. The roughness of the test sections were determined by scanning the inner surface using a method called conical stylus profilometry and scanned images of inner surface of both test sections can be seen in Figs. 2 and 3. Five profiles of the inner surface of each test section were obtained. It was observed that the inner surface of the 1.70 mm tube is smoother than that of the 1.224 mm diameter tube. The details of the roughness test results are shown in Table 4 where R_a represents the arithmetic mean roughness, R_v the maximum valley depth and R_p is the maximum peak height. Direct electric heating was applied to the test section using a high current, low voltage DC power supply. This direct heating ensured homogeneous heat flux over the test section. The test loop was insulated by thermal insulation. The wall temperatures of the test section were measured by T-type thermocouples. The tip of each thermocouple was electrically insulated and then attached at the outer wall with special epoxy which was thermally conductive and electrically insulating. To measure the fluid temperature at different points in the test loop, T-type thermocouples were installed at the suction and discharge of the pump, at the condenser outlet and at the inlet and outlet of the test section.

The system pressure was monitored by an absolute pressure transducer (Druck PDCR 4060, 20 bar) and the pressure drop by differential pressure transducers (Druck PDCR 2160, 350 and 700 mbar). The heat flux was calculated from the current and voltage of the power input and the surface area of the test section. The inner

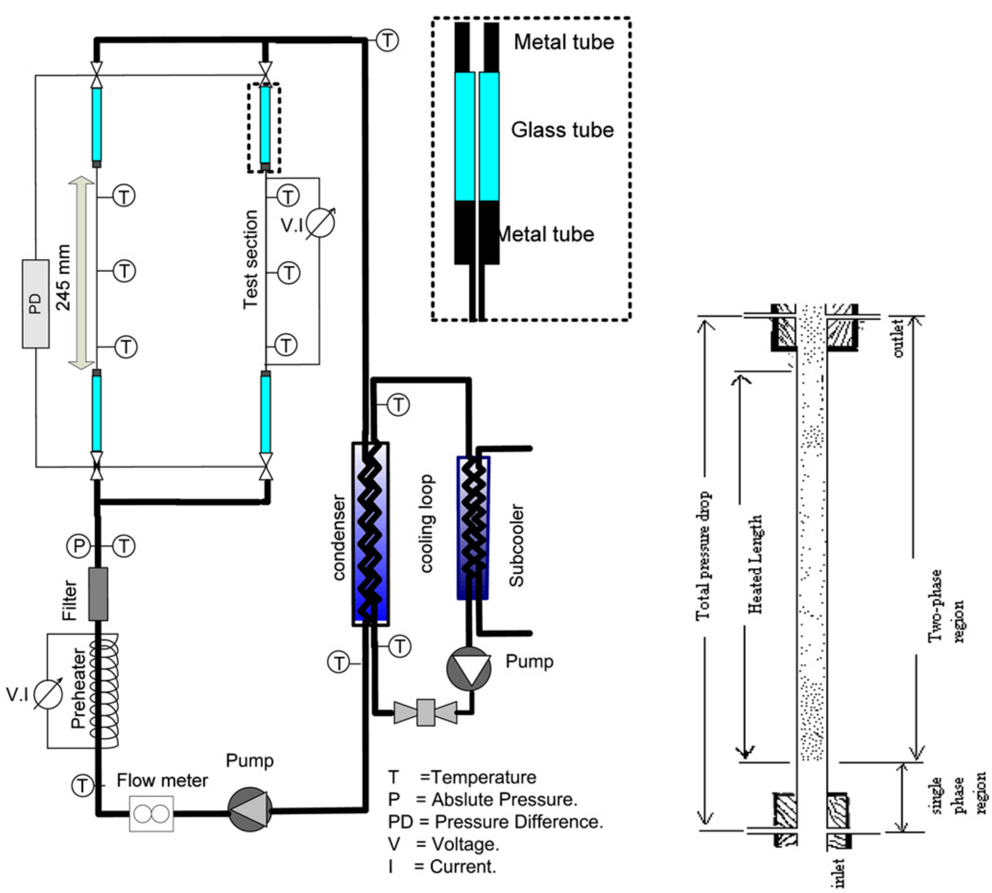

Fig. 1. Schematic diagram of experimental test rig.