Applied Thermal Engineering 88 (2015) 185–191

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Condensation heat transfer of steam on vertical micro-tubes

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HIGHLIGHTS

- Condensation heat transfer of steam on micro-tubes was studied experimentally.
- The effect of tube diameters on heat transfer for micro-tubes was presented.
- A new correlation for condensation heat transfer of steam was proposed.

ARTICLE INFO

Article history:
Received 14 June 2014
Received in revised form
4 August 2014
Accepted 26 August 2014
Available online 16 September 2014

Keywords:
Condensation heat transfer
Micro-tubes
Steam
Correlation

ABSTRACT

In this paper the condensation heat transfer of steam on vertical micro-tubes was investigated. Experiments were carried out under various vapour pressures and vapour velocities. Four tubes with different diameters, 0.608 mm, 0.793 mm, 1.032 mm and 1.221 mm, were included. The results showed that, with the increase in vapour-to-surface temperature difference, condensation heat transfer coefficient decreased monotonously, as well as that by Nusselt's Equation on vertical surface. With the decrease in tube diameter, the condensation heat transfer coefficient decreased monotonously. As the curvature effect on heat transfer, the experimental values of condensation heat transfer coefficients were higher than the predicted values by Nusselt's Equation. The difference of condensation heat transfer coefficients between different tubes was obvious. It indicated that the effect of tube diameters on condensation heat transfer for micro-tubes was significant, and should be attached great importance. With the increase in vapour pressure and vapour velocity, the condensation heat transfer coefficient increased. A new correlation for condensation heat transfer of steam was proposed considering the effect of tube diameter and vapour velocity. For 95% of the data, the deviation between the predicted values and the experimental data is in the range of ±20%.

1. Introduction

With the development and progress of high technology, compact and effective heat exchangers are required in many applications, such as space vehicle, automotive air-conditioning, micro-machine, etc. Smaller tube diameter and phase-change heat transfer are usually demanded in these devices. Thus, efficient phase-change heat transfer with micro-scale attracted much attention in recent years. The condensation heat transfer in micro-channels has been the focus of many researchers. The heat transfer characteristic of condensation in micro-channels is apparently different from that in macro-channels. Several influencing factors, such as viscous dissipation, thermal diffusion, slip effect, compressibility, etc, which can be neglected in macro-channels, may be the major factors in micro-channels. So far there is no unified standard for the boundary between the macro-channels and micro-channels. In Ref. [1] Palm discussed the current situation of the definition for micro-channels. The author pointed out that, simple definition is that a micro-channel is any channel with a (hydraulic) diameter in the micrometer range, i.e., less than 1 mm. The simple definition seems to be widely used in the case of single-phase flow. In the case of two-phase flow, it is appropriate to have a wider definition of the term "micro-channel".

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http://dx.doi.org/10.1016/j.applthermaleng.2014.08.058
1359-4311/

In the case of condensation inside micro-tubes, Kim et al. [2] conducted an experimental study on the condensation of R134a in a single tube with 0.691 mm inner diameter. They found that the experimental results were inconsistent with those predicted by the correlation in conventional channel. Yan and Lin [3] also performed an experimental study on the condensation of R134a in a single tube with 2.0 mm inner diameter. They observed that the condensation heat transfer coefficient decreased as the heat flux increased, particularly when the heat flux was high. The comparison between the present data and the data in existing references showed that the scale effect on heat transfer coefficient was weak. Webb and Ermis [4] experimentally studied the condensation heat transfer characteristic of R134a in tubes with 0.4–2.6 mm inner diameters at high mass flux (300–1400 kg m^{-2} s^{-1}) and low heat flux (4–12 W m^{-2}). They pointed out that the heat transfer coefficient increased with the decrease in tube diameter and the increase in mass flux, and it was proportional to the heat flux with a power of 0.2. The experimental results were in good agreement with those calculated by the equivalent Reynolds model for smooth tube condensation proposed by Moser et al. [5]. Wang and Rose [6] investigated the film condensation of R134a in horizontal micro-channels with different shapes. They reported that the entrance effect and channel shape significantly influenced the condensation heat transfer. Al-Jarrah et al. [7] theoretically explored the film condensation of steam on a vertical micro-channel. They found that velocity slip and temperature slip appeared due to the micro-scale effect, and it was obvious when the condensate film became thinner. With the increase in velocity slip, the temperature slip caused by micro-scale effect increased, and the condensate mass flux increased accordingly. Wang and Du [8] theoretically examined the flow condensation characteristic in a horizontal mini-tube and compared it with that in a vertical mini-tube. It was found that, when the mini-tube was changed from vertical to horizontal, the heat transfer was enhanced. With the decrease in tube diameter, the effect of gravity became weak, and the heat transfer increased, but the degree of enhancement weakened. The studies mentioned above were all about condensation inside tubes. In the case of condensation occurred outside of tubes with small diameter, Rohsenow [9] pointed out that, when the tube diameter was larger than 3 mm, the effect of the tube diameter on condensation heat transfer could be neglected. Wang and Yu [10] theoretically and experimentally investigated condensation heat transfer for vapour flow outside along a vertical tube of small diameter. They found that, their experimental data was much higher than their theoretical predicted results and other correlations for turbulent flow. They pointed that, due to the different materials between the test tube and the connecting pipe, the chatter phenomenon occurred during their experiments and enhanced condensation heat transfer.

Although many works have been carried out on condensation for micro-tubes, investigations of condensation heat transfer characteristic on the outside of micro-tubes were not sufficient yet, and particularly the effect of tube diameter in micro-scale on condensation heat transfer was not clear. The main purpose of the present work was to investigate the condensation heat transfer characteristics of steam on vertical micro-tubes at various tube diameters, vapour velocities and pressures. Moreover, an experimental correlation was also proposed to predict the heat transfer characteristics.

2. Experiment setup and methods

2.1. Experiment setup

The experiment system built in this paper is shown schematically in Fig. 1. It is a closed cycle system and consists of four parts:

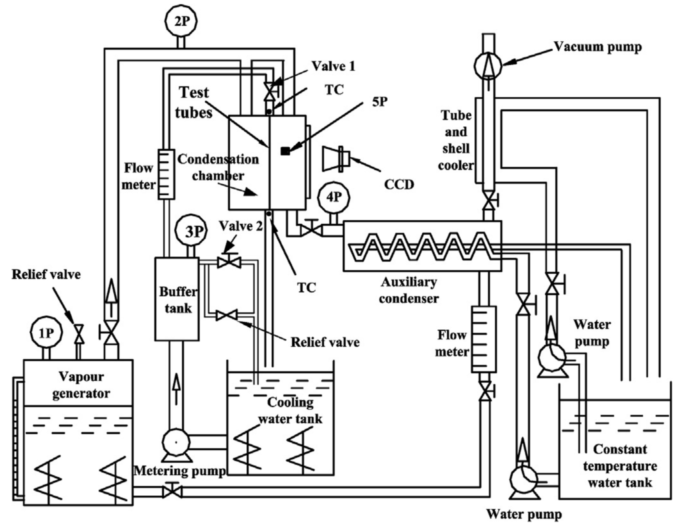

Fig. 1. The schematic diagram of experimental apparatus.

the vapour loop, the cooling water loop, the auxiliary cooling water loop and the vacuum loop. The former two parts are the main loop while the latter two are the auxiliary loop. Each part is described in detail below.

The vapour loop consists of a vapour generator, a condensation chamber, an auxiliary condenser, measuring instruments, associated pipes and valves. Water was heated in the vapour generator and the saturated vapour entered the condensation chamber through the pipes. Then, a small portion of vapour condensed on the vertical micro-tube surface, and the condensate and the rest vapour went through the lower part of the condensation chamber into the auxiliary condenser where the latter condensed completely. The total condensate passed through the flow meter with the help of gravity, returned to the vapour generator.

The cooling water loop consists of a water tank with an electric heater, a metering pump, a buffer tank, a flow meter, test tubes, associated pipes and valves. The cooling water was transported from the water tank to the buffer tank by the metering pump. The buffer tank connected a regulator valve which made the cooling water flow stably and a relief valve which had a 2 MPa rated pressure. The cooling water with stable pressure entered the test tubes from the buffer tank and flown down vertically to cool the vapour. After cooling the test tubes, the cooling water returned to the water tank. The inlet and outlet temperatures of the cooling water were measured by a couple of thermocouples with an accuracy of 0.05 K. The cooling water in the water tank was heated slowly by the electric heater to change the temperature of the micro-tube surface.

The auxiliary cooling water loop consists of a constant temperature water tank, a pump and an auxiliary condenser, associated pipes and valves. The rest vapour was completely condensed in the auxiliary condenser. The desired vapour pressure was achieved by adjusting the flow rate of cooling water in the auxiliary condenser.

The vacuum loop consists of a water pump, a tube and shell cooler, a vacuum pump, associated pipes and valves. As the effect of non-condensable gas on heat transfer was great, a vacuum pump continuously work to extract the non-condensable gas from the outlet of the auxiliary condenser. In addition, the tube and shell cooler was installed to avoid the loss of the vapour.

The condensation chamber is shown in Fig. 2. It was made of stainless steel, and was rectangular in cross-section with an internal sectional area of 100 × 20 mm. Four test micro-tubes were installed vertically in the chamber. The vapour entered the