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Characterization of Diabatic Air-Water Flow in a Vertical Micro-Channel

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Abstract

Two-phase gas-liquid flow experiment was conducted to study fluid flow and heat transfer characteristics in a vertical micro-channel. Air-water mixture was used as working fluid which was forced to flow in a stainless steel tube having a diameter of 1 mm. The heat transfer results were obtained based on constant surface heat flux condition, provided by a DC power supply. Flow pattern data, including slug flow and churn flow, are presented at superficial velocities of gas and liquid ranging between 2-40 m/s and 0.2-2 m/s, respectively. It is found from this study that the churn flow yields higher heat transfer performance in comparison to the slug flow. However, pressure drop becomes lower when the slug flow is developed in the micro-channel.

Keywords: micro-channel, two-phase flow, flow pattern

1. Introduction

During the present time, the microtechnology dealing with two-phase flow has been rapidly developed for many engineering applications, such as micro-channel heat sinks [1], microreactors [2], micro fuel-cells [3], micro heat-exchangers [4], and so on. The understanding of the trends and parameters dominating two-phase flow behaviors in micro-channels is essential for optimum design and process control of miniature systems. In micro-channels, capillary force is likely to play an important role for two-phase flow mechanisms, resulting in flow phenomena which are significantly different from those observed in ordinary-sized channels. The discrepancies between micro-scale and macro-scale flows were reported in the literature [5-11]. The studies of two-phase gas-liquid flow in micro-channels have been mainly reported for horizontal flow as discussed in Saisorn and Wongwises [12]. Regarding the literature survey, there is very little data available for heat transfer characteristics in two-phase flow in vertical micro-channel. In this study, hence, flow pattern, heat transfer and pressure drop data are presented for a vertical upward flow micro-channel.

2. Experimental apparatus and procedure

The experimental apparatus includes the water flow loop, air-flow supply, and measuring instruments. Fig. 1 shows a schematic diagram of the experimental apparatus. A peristaltic pump with adjustable flow rate was used to supply liquid flow through the test section. The liquid mass flow rates were obtained by using an electronic balance (320 ± 0.001 g) to measure weight of the liquid flowing from the test section outlet over a sufficient time, whereas the flow rates of gases were measured by four rotameters within the range of 5-50 sccm, 0.05-0.5, 0.2-2.0, and 1-10 SCFH, respectively. Cross-junction mixing chamber was used to allow the air-water mixture to flow along the upward direction. The mixture flows freely from the channel outlet. The test section used in this work is a stainless steel tube with inner diameter of 1 mm. The gas-liquid flow in the test section was carried out under constant heat flux condition provided by DC power supply (120 A, 15 V). The single-phase and two-phase pressure drops across the test section were determined by two pressure transducers installed at the channel inlet. The low-range pressure transducer was calibrated from 0 to 250 kPa with a ± 0.5 kPa accuracy, and the high range one was calibrated from 0 to 1000 kPa with a ± 2 kPa accuracy. A set of 12 T-type thermocouples were used to measure tube surface and fluid temperatures.

The detailed formation of each flow pattern is registered by a camera system having shutter speeds of 1/15 to 1/10,000 s and a frame rate of 30 frames per second. In this study, the magnification is adjusted so that the appropriate view field (L/D = 10) is obtained. The region near the channel outlet is always selected as the viewing window available for the captured image. An adjustable LED light source is placed perpendicular to the viewing section.

The single-phase flow experiments were the first to be performed and the results were well agreed with the theory based on laminar fully developed flow with uniform surface heat flux condition (Nu = 4.36). Following this, the two-phase flow experiments were conducted at various gas and liquid flow rates. In this work with a constant heat flux of 52 kW/m^2, the gas flow rate was increased by small increments, while the liquid flow rate was kept constant at a pre-selected value. The system was allowed to approach steady conditions before the

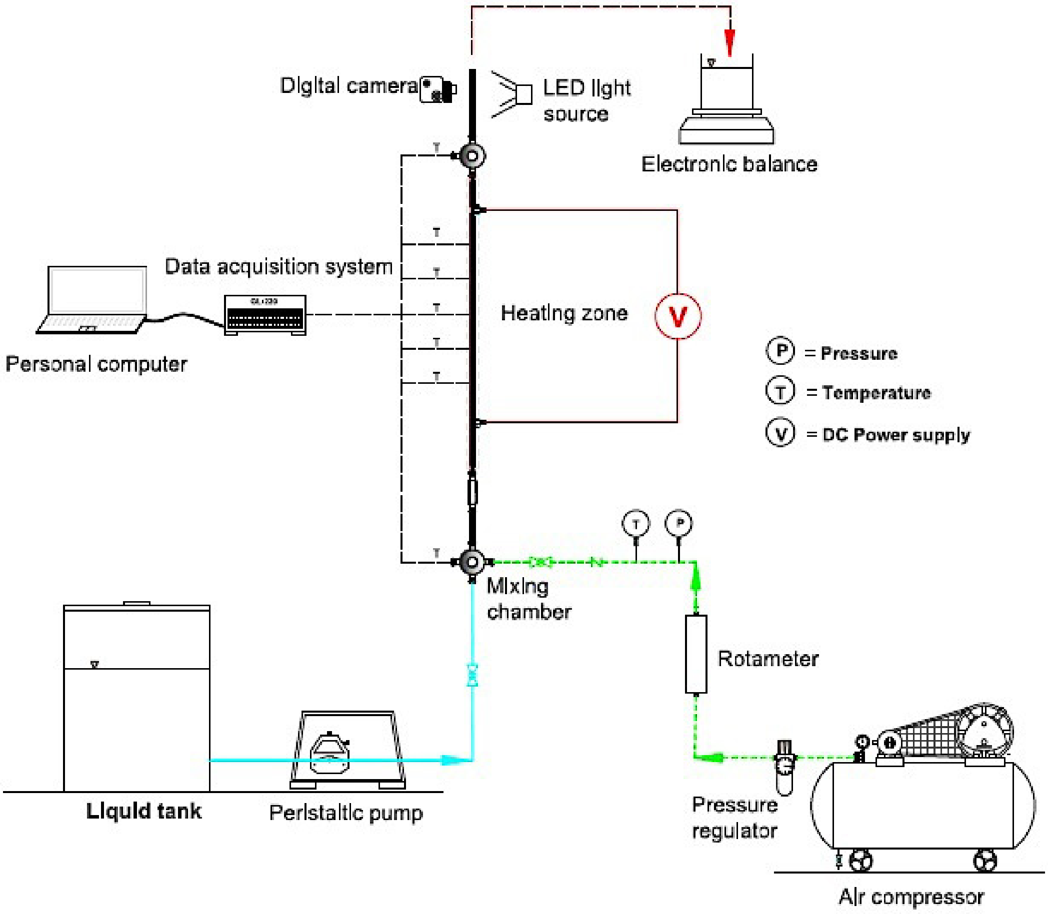

Fig. 1. Schematic diagram of experimental apparatus.

temperatures, fluid flow rates, flow patterns, and pressure drops were recorded.

3. Data Reduction

The 10 T-type thermocouples are installed on the top and bottom sides at equal distances along the tube to measure the tube surface temperature. For each position where the thermocouple is installed on the tube surface, the inner wall temperature at a given position is determined using the equations for steady-state one-dimensional heat conduction through the tube wall with internal heat generation. At a given distance, hence, the average temperature of the inner wall at the top and bottom sides stands for the local temperature on the inner wall, $T_{wall,in,loc}$. Finally, the local heat transfer coefficient, h_{loc}, for two-phase flow along the test section is determined using the following equation.

$$h_{loc} = \frac{q}{\left(T_{wall,in,loc} - T_{fluid}(z)\right)} \quad (1)$$

Regarding the constant surface heat flux condition, the local fluid temperatures, T_{fluid} (z) can be obtained by

$$T_{fluid}(z) = T_{fluid,in} + \frac{q\pi D}{\dot{m}c_p} z \quad (2)$$

Heat flux, q, based on joule heating method can be determined as shown below.

$$q = \frac{IV}{\pi DL} \quad (3)$$

As shown in the above equations, D refers to tube diameter, L is channel length, z is local distance along the tube length, $\dot{m}$ is mass flow rate of air-water mixture, and c_p represents specific heat. Heat loss estimation obtained from energy balance was less than 5%, which can be negligible.

4. Results and Discussion

4.1 Flow Pattern

Visual observation shows that different flow patterns may occur with gas-liquid co-current flow in a vertical micro-tube. For vertical upward flow, the effects of surface tension, gravitational, inertia, and viscous shear forces on two-phase flow mechanisms can result in a formation of a specific flow pattern. The observations were carried out using a visualization system. By keeping the water flow rate constant at a pre-selected value and increasing the air flow rate by small increments under constant heat flux condition, typical photographs were obtained from the viewing window located downstream of the test section as shown in Fig. 2.

4.2 Heat Transfer

Two-phase heat transfer characteristics are presented based on local Nusselt number for different superficial Reynolds numbers as illustrated in Fig. 4. The heat transfer results showed that for a given liquid superficial Reynolds number, the Nusselt number increases with gas superficial Reynolds number. It was also found that the highest heat transfer performance takes place during churn flow regime. The improved heat transfer performance may result from the strong agitation near the tube wall, which is induced by churn flow pattern. For rectangular channels, however, Saisorn et al. [13] found that good heat transfer results corresponded to slug flow regime.

4.3 Pressure drop

Prior to obtaining data for the frictional pressure drop, measurements of the total pressure drop are

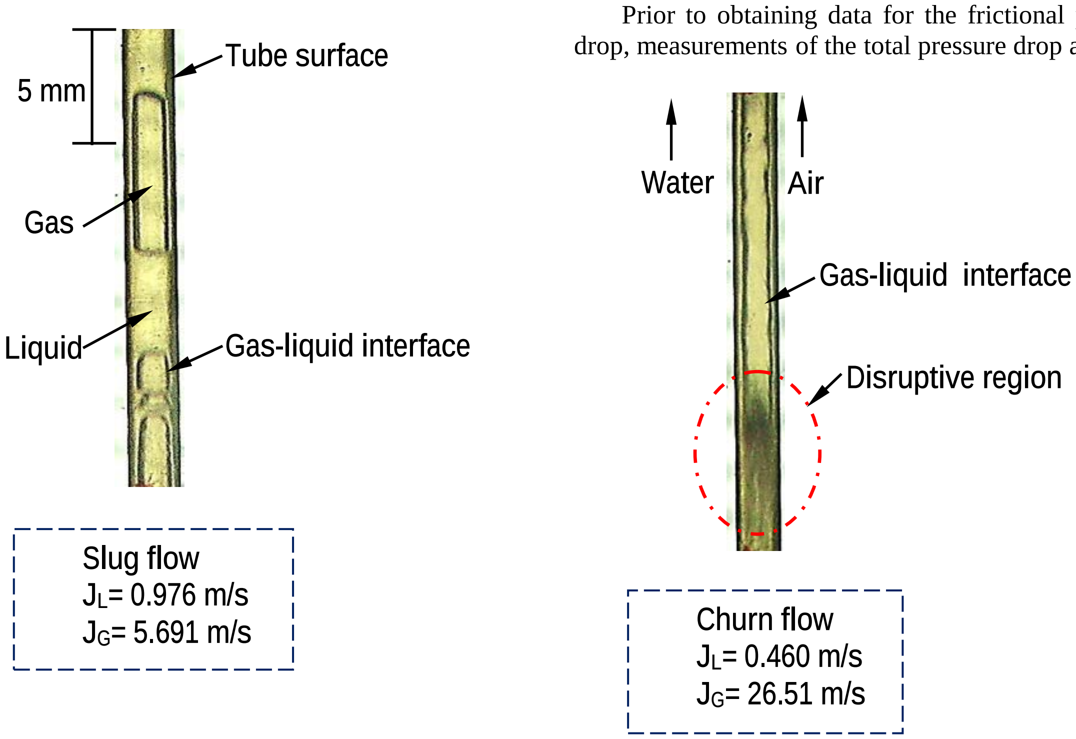

Fig. 2. Photographs of slug flow and churn flow patterns.

Slug flow occurs at low gas flow rate and is characterized by elongated bubbles that are larger in length than the channel diameter.

Churn flow: In the region of high liquid flow rates, sufficiently high gas flow rate can lead to the appearance of churn flow, which is characterized by a disruptive region developed due to the distortion of the elongated bubbles.

The flow pattern data for vertical upward flow is also presented in Fig. 3, which is the flow regime map established with the coordinates of superficial liquid and gas velocities. It should be noted that superficial velocity is defined as the rate of volumetric flow divided by the flow area.

taken under various different conditions. In this work, the total pressure drop of a two-phase flow in vertical channel is composed of frictional pressure drop, gravitational pressure drop and accelerational pressure drop, and is expressed by the following balance equation:

$$\Delta P_{exp} = \Delta P_f + \Delta P_g + \Delta P_a \tag{4}$$

where ΔP_g and ΔP_a stand respectively for gravitational pressure drop and accelerational pressure drop, which can be evaluated by the following two expressions:

$$\Delta P_g = gL\sin\theta\left[\alpha\rho_G + (1-\alpha)\rho_L\right] \tag{5}$$

$$\Delta P_a = G^2\left\{\left[\frac{x^2}{\alpha\rho_G}+\frac{(1-x)^2}{(1-\alpha)\rho_L}\right]_{outlet}-\left[\frac{x^2}{\alpha\rho_G}+\frac{(1-x)^2}{(1-\alpha)\rho_L}\right]_{inlet}\right\} \quad (6)$$

where G is mass velocity, α is void fraction, L is channel length, θ is angle of inclination of the tube and x is mass quality. The details can be seen in Saisorn and Wongwises [12].

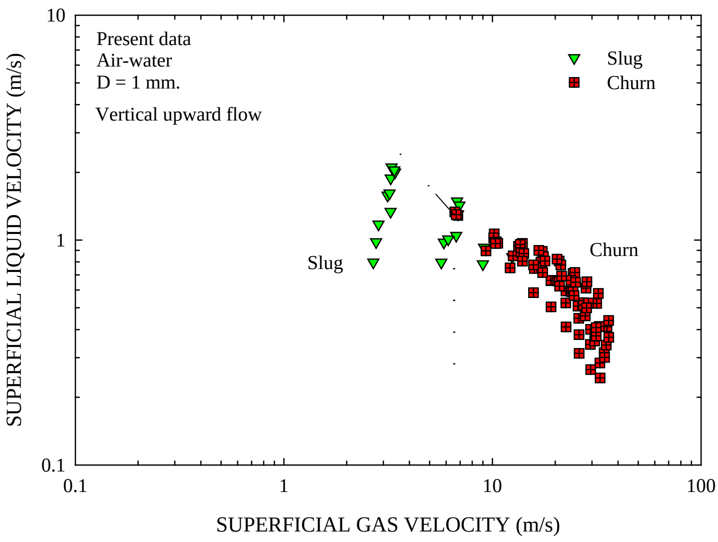

Fig. 3. Flow pattern map.

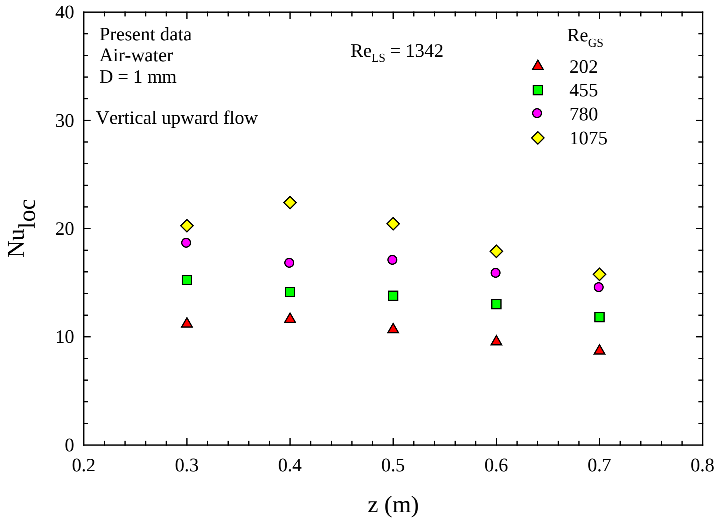

Fig. 4. Heat transfer data for different superficial Reynolds numbers.

The frictional pressure drop, ΔP_f, can be obtained through the above equations. Based on the present flow conditions, it is found that the gravitational pressure drop and accelerational pressure drop possess the values of less than 10% of the total pressure drop, and the two terms are negligibly small. In general, as expected, the frictional pressure drop dominates the other two components.

The frictional pressure drop data are presented in Fig. 5. The frictional pressure drop was obtained by subtracting the gravitational term and accelerational term from the total pressure drop. The figure illustrates that the higher the superficial velocity, the higher is the frictional pressure drop. It was found from the experiments that the churn flow causes the frictional pressure drop to be higher than that corresponding to slug flow regime. Such high pressure drop for churn flow is mainly due to the disruptive region and unstable liquid film near the tube wall.

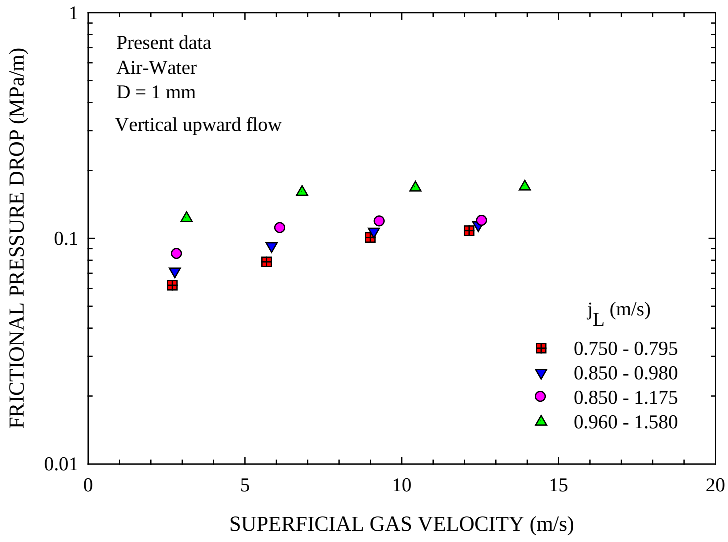

Fig. 5. Frictional pressure drop vs. superficial velocity

5. Conclusions

In this work, the non-boiling gas-liquid flow in vertical upward micro-channel is studied to explore fluid flow and heat transfer phenomena. The test section is a stainless steel tube with inner diameter of 1 mm. The air-water flow in the test section is carried out under constant heat flux condition. Flow visualization, heat transfer and pressure drop data for vertical upward micro-channel is obtained. The conclusions from this study can be presented as follows.

1. Slug flow and churn flow are observed during the present experiment.
2. The Nusselt number increases with the increase in superficial Reynolds numbers, especially during churn flow pattern.
3. The pressure drop penalty can be reduced by forming slug flow pattern in the vertical micro-channel.

6. Acknowledgement

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7. References

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