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TWO PHASE FLOW PATTERNS DURING CONDENSATION OF STEAM IN MICRO-TUBES

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ABSTRACT

Flow visualization of two phase flow pattern of steam during condensation process in separate horizontal quartz micro-tubes with inner diameter ranging from 70-675 μ m was conducted. Two main kinds of flow patterns were observed: annular flow and slug flow, which both were nearly symmetrical. The annular flow also can be divided into two kinds: annular flow and annular-wave flow. The effects of tube diameter and mass flux on the two phase flow pattern were discussed and the characteristics of two phase flow in micro-tubes were analyzed. The experimental results were compared with the criteria for two phase flow pattern transition in traditional large diameter tubes and the results indicated that the present data has a good agreement with Mandhane(1974) map, but the ranges of slug flow predicted by Taitel and Dukler(1976) model are obviously narrow and the stratified flow predicted by these three maps was not found at present experiments.

1. INTRODUCTION

With the trend of miniature of various heat transfer equipments, heat transfer in micro-channels has been one of the hot research topics in recent years. Most researches focused on phase change heat transfer deal with boiling heat transfer, however on condensation heat transfer were relatively less in this field. Two phase flow pattern, for boiling or condensation, in micro-channels is of great importance. Different flow patterns maybe correspond to different heat transfer mechanisms. Two phase flow patterns in conventional large diameter tubes have been studied for many years and several important flow regime maps have been developed, such as Baker (1954), Mandhane et al.(1974), Taitel and Dukler(1976), Tandon et al.(1982) and et al. But due to the different importance of the gravity force, interface shear force and surface tension, the two phase flow patterns in micro-channels are great different from those in large diameter tubes.

Researches on two phase flow pattern in small tubes ascend to 1964 when Suo and Griffith (1964) studied the two

phase flow in capillary tubes and developed a correlation for film density and thickness. Barea et al. (1983) studied the two phase flow patterns in horizontal and vertical small diameter tubes and found Taitel and Dukler(1976) model could predict the flow transition well except the transition from stratified to slug flow. Fukano and Kariyasaki(1993) investigated the characteristics of two phase flow in vertical upflow, vertical downflow and horizontal tubes with diameter from 1 to 4.9 mm and found the liquid film more symmetry which depends on the diameter and different from those in large diameter tubes. The difference indicated that surface tension began to play an more important role when the diameter was less than 5mm. Mishima and Hibiki (1996) studied the two phase flow pattern in vertical capillary tubes with diameter ranging from 1 to 4 mm and didn't observe the churn flow in the smallest diameter tube. Coleman and Garimella (1999) investigated the two phase flow pattern of air-water mixtures in round and rectangular tubes with the diameter ranging from 1-5.5 mm systematically and discussed the effect of tube diameter and tube section shape. The comparison results showed Damianides(1998) and Fukano(1989) agrees well with the present results but Taitel and Dukler(1976) fails. Then Coleman and Garimella(2000a, 2000b) studied two phase flow pattern of R134a during condensation processes in small diameter tubes with inner diameter from 1-4.9 mm and developed a new flow regime map for different diameter rectangular tubes which used the G-x coordinate systems to analyze the results. Coleman and Garimella (2003) used the same type tubes to studied the effect of tube section shape and found that the range of intermittent flow in round tube at low mass flux is larger than that in rectangular tubes but nearly the same at high mass flux. Then Tabatabai and Faghri(2001), Yang and Shieh(2001), Chen et al. (2002), Akbar et al.(2003) and Mederic et al.(2005) also studied the two phase flow pattern in micro-channels. Recently Revellin and Thome(2007) studied the two phase flow pattern of R134a and R245fa in 0.5 and 0.8 mm diameter tubes and found that the results agrees well with homogeneous model at low vapor phase velocity but will depart from homogeneous model with increasing vapor velocity.

From the above review of the literature on two phase flow in micro-channels, we can found that many parameters can affect the flow pattern and there was not a relatively general flow regime map for the two phase flow pattern in micro-channels which may limits the researches on the mechanism of phase change heat transfer and pressure drop. And more experimental data were needed. In the present paper, the two phase flow pattern in different quartz glass micro-tubes with the inner diameter ranging from 70-675 μm was observed and the results was compared with some classical map for conventional large diameter tube to evaluate the feasibility for those in micro-tubes. Then the effects of tube diameter and mass flux were discussed.

2. TEST SETUP AND DATA REDUCTION

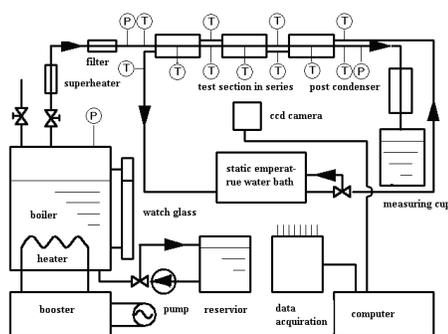


Figure 1. Sketch of test setup

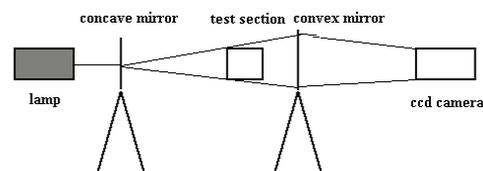


Figure 2. Image acquisition system

2.1 Test Setup

The test setup was described in detail in An (2004) and only some important parts are described here. It contains two main loops: steam loop and cooling water loop as shown in Fig. 1. The water in the boiler was heated by an electric heater to saturation state then the steam was superheated by pre-heater. The steam was filtered and then went into the test section in series. In fact, the test sections in series were tube-in-tube heat exchangers with water as cooling fluid. In the test section, the superheated steam vapor was condensed to moisture vapor and then was post condensed into single phase water. The water in the boiler was compensated by a reservoir which has pump and valve to adjust the flow rate. The cooling water was pumped into the test section and flow back to the bath after the test section.

All the temperature was measured by CuNi-Cu T-type thermal couples whose wire diameter is only 0.1mm and the uncertainty of temperature was 0.1°C. The pressure was measured by high precision pressure gauge with accuracy 0.25%. The mass flow rate of steam was measured indirectly by electronic balance which was used to measure the water which flows into the graduate in given time. All the data of temperature was obtained by KEITHLEY 2700 data acquisition system.

Because of the small diameters of micro-tubes and high velocity of steam, it is very difficult to observe the flow pattern by naked eyes and the magnifier was necessary to obtain clear images. On the other hand, due to the curvature of the wall, the beam may be distorted for the refraction effect so the rectification of the beam was necessary. An image acquisition system was designed to solve this problem as shown in Fig. 2. The beam from the lamp went through a concave mirror, test section, a convex mirror in turn and then arrive the CCD camera which shutter velocity was 1/10000 second. The focus of camera lens could be adjusted from 12.7-75 mm.

2.2 Data Reduction

The heat transfer Q_c of every test section can be computed by Equation (1).

$$Q_c = C_{p,c} m_c \Delta T_c \quad (1)$$

where the $C_{p,c}$ was the isotonic specific heat capacity and m_c was the mass flow rate of cooling water and ΔT_c was the temperature difference between inlet and outlet of every test section.

The vapor quality of every test section was the average value at inlet and outlet of test section and the vapor quality of every test section can be figured out by equation (2).

$$x = \frac{x_{in} + x_{out}}{2} = x_{in} - \frac{Q_c}{m_s r} \quad (2)$$

where x , x_{in} , x_{out} were average quality, inlet quality and outlet quality separately. m_s is the mass flow rate of steam and r was the potential energy at given pressure.

The mass flux of steam could be calculated by mass flow rate and the area of test section as shown in Equation (3).

$$G = \frac{m_s}{A} = \frac{4m_s}{\pi d_i^2} \quad (3)$$

where A and d_i were the area and inner diameter of the test section separately.

Given the vapor quality and mass flux, we can use Equation (4) and Equation (5) to calculate the superficial velocity

of liquid and vapor phase.

$$j_v = \frac{Gx}{\rho_v} \quad (4)$$

$$j_l = \frac{G(1-x)}{\rho_l} \quad (5)$$

Where ρ_l and ρ_v were the density of liquid and vapor phase of steam vapor separately.

The Kline and McClintock(1964) method was use to evaluate the accuracy of the different parameters. The results showed that the accuracy of Q_c was about 11.2% and that of x 12.3%.

3. EXPERIMENTAL RESULT AND DISCUSSION

3.1 Flow Pattern Definition

Due to the complex mechanism, the two phase flow patterns obtained by different researchers often are not consistent, so it is necessary to describe the flow pattern definition adopted in the present work here. We observed five different flow patterns as shown in Fig. 3, namely annular flow, annular-wave flow, slug flow, capillary bubble flow and bubble flow which could be merged into two types: annular flow and slug flow. Annular flow and annular-wave flow are different only at the strength of the wave and the latter three patterns all belong to slug flow. The transition of these two large classes may be due to the change of the magnitude of shear force, gravity and surface tension.

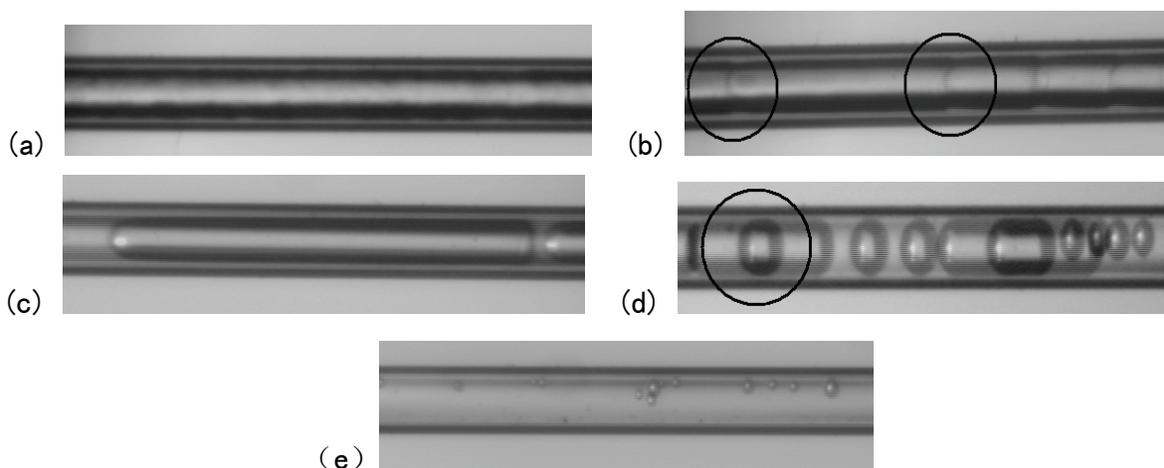


Figure 3. Flow pattern image

a. Annular flow b. Annular-wave flow c. Slug flow d. Capillary bubble flow e. Bubble flow

Annular Flow The vapor phase flows in the core of the tube and the liquid flow encircling the inner wall as shown in Fig. 3a. The waves due to the great difference between the liquid and vapor velocity will appear at the interface as expected but still are very small. Compared with the similar conditions in conventional large diameter tubes, the wave appears more homogenous and the stratified effect of gravity is also very small.

Annular-Wave Flow This flow pattern is very similar to annular flow, only with small vapor quality and thicker

film. But due to the interface waves' mutual interfere, some big film protuberance marked with bold round circle as shown in Fig. 3b appears at different locations. No obvious the stratified role of gravity was observed but the stratified role was of importance in large diameter tubes with thicker film at bottom of the tube than at the top. The effect of gravity on annular flow was small and the shear force and surface tension dominates the condensation process.

Slug Flow The vapor in the core was cut into elongated bubble in series and the thickness between vapor and wall was very fine as shown in Fig. 3c. Slug flow also was called Plug flow in some literatures.

Capillary Bubble Flow Different from Slug flow in which the length of bubble are large than tube diameter, the length of bubble are equivalent to tube diameter and the bubbles became more round as shown in Fig. 3d. Going with the condensation process, more vapor condensed into liquid and lead to smaller fraction of vapor phase. This type may be thought as the mid type between slug flow and bubble flow.

Bubble Flow The diameter of bubble was smaller than the tube diameter as shown in Fig. 3e and small bubbles locates at the top of the tube because of buoyancy which indicated that the effect of gravity depended on the diameter of bubble and more obvious when the tube diameter was larger.

3.2 Experimental Results and Discussion

Two phase flow patterns during condensation process in quartz glass micro-tubes with diameter of 0.675, 0.320, 0.094, 0.070mm were observed. we didn't conduct the experimental at high mass flux larger than 200 kg/m²s for the limitation of test setup, so mist flow was not observed as expected. Three main characteristics can be summarized as follows. Firstly the annular and slug flow are main patterns observed. Then two flow patterns are more symmetry which gravity only has little influence. Thirdly the interface wave exists at all conditions. Despite of small strength, the waves' mutual interfere may be lead to big wave peak. When the peak is large enough to the tube radius, the liquid bridge which cuts the vapor core into discrete elongated bubbles will appear and the transition from annular to slug flow takes place. The interface shear force and surface tension counteract the stratified effect of gravity and make the flow pattern symmetric. But when mass flux and vapor quality are both small, the effect of gravity may becomes relatively obvious and leads to stratification effect. In present experimental conditions, we observed faint stratification effect in the tube with inner diameter of 0.675 and 0.320 mm, relatively larger in present experimental, at low mass flux as shown in Fig. 4a and Fig.4b respectively.

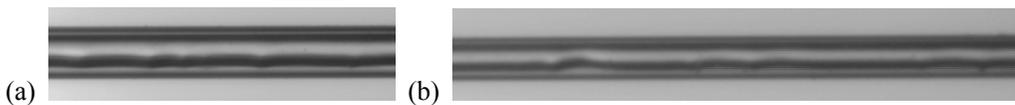


Figure 4. Image with faint effect of stratification

a. $d_i=0.675$ mm, $G=32.5$ kg/m²s, $x=0.332$ b. $d_i=0.320$ mm, $G=39.6$ kg/m²s, $x=0.237$

Fig. 5 shows the effect of tube diameter on the two phase flow pattern. The range of annular and slug flow increases but that of annular-wave flow decreases with decreasing diameter at the same mass flux. This may due to the effect of restraint by surface tension derived from increasing curvature. The quality of the transition from annular flow to annular-wave flow and from annular-wave flow to slug flow decreases with mass flux.

The present experimental results also were compared with Mandhane (1974) map and Taitel and Dukler(1976) model as shown in Fig. 6 and Fig. 7. Mandhane (1974) map was developed predict the two phase flow pattern

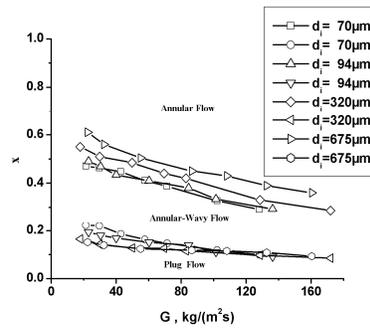


Figure 5. Effect of tube diameter

large diameter tubes which were larger than 12 mm. Annular-wave flow does not exist in Mandhane’s map and but the stratified flow and wave flow were not be observed in present work. The scope of slug flow is larger than that in Mandhane’s map which was called plug flow. The range of annular was well predicted by Mandhane’s map but that of slug flow was under predicted.

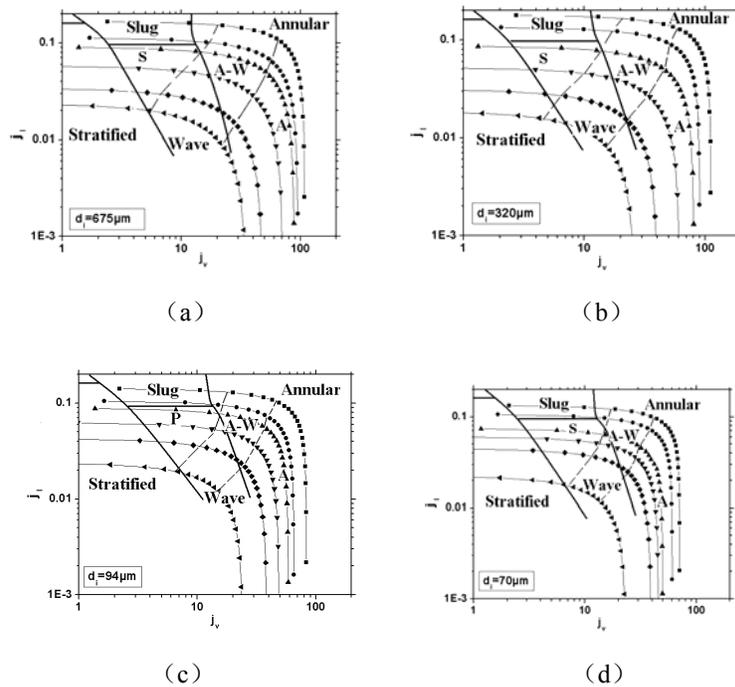


Figure 6 Comparison with Mandhane(1974) map with different tube diameters

A: Annular Flow; A-W: Annular-Wave Flow; S: Slug Flow

Taitel and Dukler(1976) which was developed using pure theoretical method didn’t show the effect of tube diameter. The quality where the transition from annular to slug flow takes place was obviously lower predicted by Taitel and Dukler’s model and the wave flow predicted was not observed but the annular or annular-wave flow were observed at the same conditions. In consideration of annular and annular-wave flow belonging to the same class, the range of slug flow predicted by these correlations is obvious lower and the predicted wave flow was not observed.

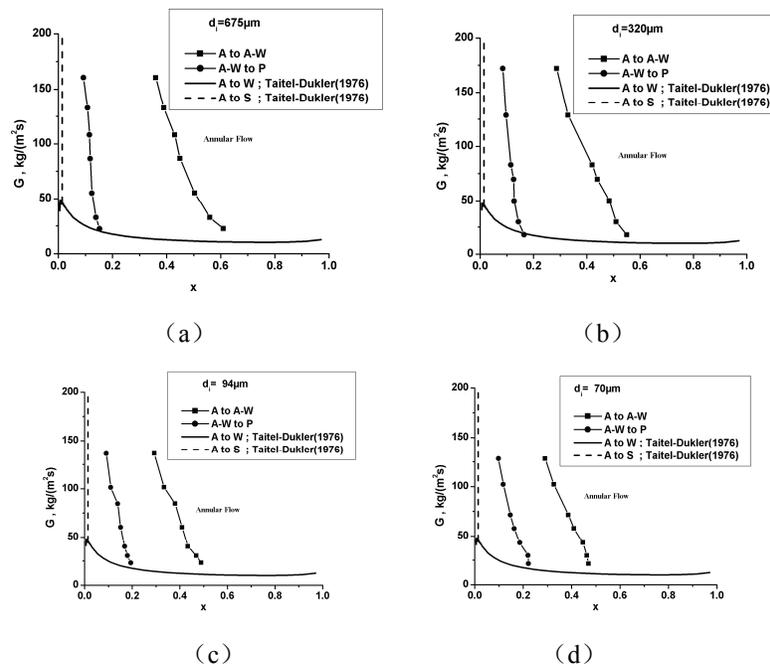


Fig.7 Comparison with Taitel and Dukler (1976) model

A: annular, A-W: Annular-Wave Flow, P: Plug flow, W: Wave flow, S: Slug flow

4. CONCLUSION

1. Annular flow are the main pattern during condensation in micro-tubes and only at the end of the process, slug flow appears. In relatively larger diameter micro-tubes, bubble flow may exist with very small range.
2. Compared with conventional large tubes, the effect of gravity was restricted by interface shear force and surface tension which dominates at micro scale, leading to more symmetry pattern. The effect of stratification of gravity maybe appears in some case.
3. The range of quality occupied by annular and annular-wave flow increases with mass flux at the same conditions and that occupied by annular and slug flow increases with decreasing tube diameter and decreasing scope of annular-wave flow.

REFERENCES

- An, G., 2004, Study on Flow and Heat Transfer Characteristics for Film Condensation of Steam in Microtubes, Ph.D Dissertation, Department of Thermal Engineering, Tsinghua University. (in Chinese)
- Akbar, M. K., Plummer D. A., Ghiaasiaan S. M., 2003, On Gas-Liquid Two-Phase Flow Regimes in Microchannels, *Int. J. Multiphase Flow*, vol. 29: p. 855-865.
- Baker, O., 1954, Simultaneous flow of Oil and gas, *Oil and Gas*, vol. 53: p. 185-195.
- Barnea, D., Luninski, Y., Taitel, Y., 1983, Flow Pattern in Horizontal and Vertical Two-Phase Flow in Small Diameter Pipes, *the Can J Chem Eng*, vol. 61: p. 617-620.
- Chen, W. L., Twu, M. C., Pan, C., 2002, Gas-Liquid Two-Phase Flow in Micro-channels, *Int. J. Multiphase Flow*,

- vol. 28: p. 1235-1247.
- Coleman, J. W., Garimella, S., 1999, Characteristics of Two-Phase Flow Patterns in Small Round and Rectangular Tubes, *Int. J. Heat Mass Transfer*, vol. 42: p. 2869-2881.
- Coleman, J. W., Garimella, S., 2000a, Visualization of Refrigerant Two-Phase Flow During Condensation. *Proceedings of the 34th National Heat Transfer Conference*, ASME: 1-7.
- Colman, J. W., Garimella, S., 2000b, Two-Phase Flow Regime Transitions in Microchannel Tubes: the Effect of Hydraulic Diameter. *Proceedings of the 2000 International Mechanical Engineering Conference and Exposition*, ASME: 1-13.
- Coleman, J. W., Garimella, S., 2003, Two-Phase Flow Regimes in Round, Square and Rectangular Tubes During Condensation of Refrigerant R134a, *Int. J. Refrigeration*, vol. 26: p. 117-128.
- Damianides, C., Westwater, J. W., 1988, Two Phase Flow Patterns in a Compact Heat Exchanger and in Small Tubes, *Proceedings of 2nd UK National Conference On Heat Transfer*: 1257-1268.
- Fukano, T., Kariyasaki, A., 1989, Flow patterns and pressure drop in isothermal gas-liquid concurrent flow in a horizontal capillary tube, *ANS Proceedings 1989 National Heat Transfer Conference*, vol 3:p. 42-50.
- Fukano, T., 1993. Characteristics of Gas-Liquid Two-Phase Flow in a Capillary Tube, *Nucl. Eng. Des.*, vol. 141: p. 59-68.
- Kline, S. J., McClintock, F. A., 1953, The Description of Uncertainties in Single Sample Experiments. *Mechanical Engineering*, vol. 75: p. 3-9.
- Mandhane, J. M., Gregory, G. A., Aziz, K., 1974, A Flow Map for Gas-Liquid Flow in Horizontal Pipes. *Int. J. Multiphase Flow*, vol. 1: p. 537-553.
- Mederic, B., Miscevic, M., Platel, V., et al., 2004, Experimental Study of Flow Characteristics During Condensation in narrow channels: the Influence of the Diameter Channel on Structure Patterns, *Superlattices and Microstructures*, vol. 35: p. 573-586.
- Mishima, K., Hibiki, T., 1996, Some Characteristics of Air-Water Two-Phase Flow in Small Diameter Vertical Tubes, *Int. J. Multiphase Flow*, vol.22 : p. 703-712.
- Revellin, R., Thome, J. R., 2007, Experimental Investigation of R134a and R245fa Two Phase Flow in Microchannels for Different Flow Conditions, *Int. J. Heat Fluid Flow*, vol. 28: p. 63-71.
- Suo, M., Griffith, P., 1964, Two-phase Flow in Capillary Tube, *J. Basic Engineering*, vol.86, no. 3: p.573-582.
- Tabatabai, A, Faghri, A., 2001, A New Two-Phase Flow Map and Transition Boundary Accounting for Surface Tension Effects in Horizontal Miniature and Micro tubes, *Trans. ASME*, vol. 123: p 958-968.
- Taitel, Y, Dukler, A E. 1976. A Model for Predicting Flow Regime Transition in Horizontal and near Horizontal Gas-Liquid Flow, *AIChE J.*, vol.22, no.11: p.47-53.
- Tandon, T. N., Varma, H. K., Gupta C. P., 1985. An Experimental Investigation of Forced- Condensation During Annular Flow Inside a Horizontal Tube. *ASHRAE Trans.*, vol.91, no.1: p. 343-354.
- Yang, C.Y., Shieh, C. C., 2001, Flow Pattern of Air-Water and Two-Phase R134a in Small Circular Tubes, *Int. J. Multiphase Flow*, vol. 27: p. 1163-1177.

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