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Flow pattern of air–water and two-phase R-134a in small circular tubes

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Abstract

Experimental investigation of two-phase flow patterns for refrigerant R-134a and air–water in horizontal tubes with inside diameter from 1.0 to 3.0 mm was performed. The air–water test results agree very well with previous work. However, R-134a flow leads to a shift in the slug to annular transition to lower value of gas velocity. The locations of bubble to plug and slug flow transition are also significantly affected by the working fluids properties. We concluded that, in addition to buoyant force and turbulent fluctuations, surface tension force is also an important parameter for flow pattern determination in small tubes. Surface tension force causes the system to act to minimize its interfacial area. It tends to keep bubbles retaining its circular shapes and also to keep the liquid holdup between the tube walls to retard the transition from slug to annular. Since the surface tension of air–water is much larger than that of R-134a, it makes the intermittent to bubble flow transition occurs earlier for air–water than for R-134a. And also leads to a shift in the slug to annular transition to lower value of gas velocity for R-134a.

Keywords: Small tube; Two-phase flow; Flow pattern; Surface tension

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1. Introduction

Compact heat exchangers are used extensively in air-condition and refrigeration systems. Because of the enormous progress in manufacturing technology over the past two decades, smaller tubes have been manufactured and used in high performance condenser or evaporators. The tube diameter has been reduced from 15.9 to 6.3 mm. Moreover it is expected to be further reduced in the near future. To provide basic calculation information for designing an optimal compact heat exchanger, the mechanism of heat transfer and friction characteristics in small tubes is necessary. It is known that flow pattern is one of the most important parameters for realizing the transport

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mechanism of two-phase flow. A large amount of data has been published on two-phase flow pattern investigation. However, most of them related to air–water flow in larger tubes. Very limited data are available for two-phase refrigerant system. No experimental results on two-phase refrigerant flow in small tubes are reported in published literature up-to-date. The purpose of the present study is to obtain an appropriate flow pattern of two-phase refrigerant R-134a in small tubes. The flow patterns for air–water in the same size tubes are also investigated for comparison.

2. Previous work

2.1. Flow pattern classification

Studies of two-phase flow patterns in circular tubes cover a period of more than 40 years. The two-phase flow patterns observed in horizontal tubes are complicated asymmetry of the phase resulting from the influence of gravity and liquid shear. The generally accepted flow patterns given by Alves (1954) as described in Collier and Thome (1996) are bubble, slug, plug, stratified, wavy, and annular flow. Manhane et al. (1974) successfully presented a useful map by using the gas and liquid superficial velocities, u_{GS} and u_{LS} as coordinates for fluid properties which do not differ much from air–water in moderate diameter tubes. Taitel and Dukler (1976) use the term intermittent flow to cover slug and plug flows given by Alves (1954). Taitel (1990) reviewed previous flow pattern classification and concluded that the distinction between the various flow patterns is not always clear. A typical problematic zone is the region near the slug, annular and stratified wavy flow. Nicholson et al. (1978) termed this “Proto slug”, Lin and Hanratty (1987) “Pseudo slug”, Taitel and Dukler (1976) “wavy annular flow”. The zone of very high gas and liquid flow is also difficult to define and the distinction among dispersed bubble, slug (or churn) and annular flow is not clear.

2.2. Effect of tube size and fluid properties

In considering the effects of tube size and fluid properties, Taitel and Dukler (1976) provided the first theoretical analysis of two-phase flow pattern transitions. They assumed that stratified flow will prevail unless the interfacial unstable as a result of Kelvin–Holmholtz instability. The theory predicts the effect on transition boundaries of tube size, fluid viscosity and density. Their predictions agree very well with the investigation results by Manhane et al. (1974) of air–water in tubes with inner diameters from 13 to 150 mm. Weisman et al. (1979) concentrated on the effect of fluid properties on the flow pattern, in particular, the effects of density, surface tension and viscosity. They suggested that the stratified-intermittent transition is independent of fluid viscosity whereas Taitel and Dukler (1976) theory predicted a significant effect. Barnea et al. (1983) considered the effect of surface tension in small tubes. They found that surface tension only affects the stratified–slug transition for their test of air–water in tubes with inner diameters of 4–12.3 mm. Reinarts (1993) investigated flow patterns for R-12 in 4.7 and 10.5 mm ID tubes. Only the annular flow region of the gas–liquid parameter space was mapped for the 4.7 mm ID tube. The locations of the flow pattern boundaries are clearly different from those of the previous air–water studies. The annular flow regime occurs at much lower void fraction for R-12 than of air–water. He suggested that the densities of the phases are important factors in flow pattern determination.

Bousman et al. (1996) considered the effect of fluid properties in 12.7 and 25.4 mm ID tubes. The transition from bubble to slug flow was affected by tube diameter for air–water and by changes in liquid viscosity and surface tension. The transition from slug to annular flow was not significantly affected by changes in tube diameter, liquid viscosity or surface tension. This result was obviously conflicted to Barnea et al. (1983) observation.

2.3. Small tube flow pattern maps

Damianides and Westwater (1988) investigated air–water flow pattern for horizontal glass tubes of inner diameters from 1 to 5 mm. They found from their experimental observation that (1) as liquid flow increased, the larger tubes require a larger liquid flow to change from intermittent to dispersed flow; (2) as gas flow increased, the smaller tube require a larger gas flow to change from intermittent to annular; (3) as tube size decreased, the stratified flow regime on the map decreases, until it vanished for the 1 mm tube. Taitel and Dukler (1976) model is good for dispersed bubble-intermittent boundary and annular-intermittent boundary but not for stratified flow boundary. Surface tension is a very important variable for small tubes, but less so for large tubes.

Fukano and Kariyasaki (1993) conducted air–water flow experiment in horizontal and vertical tubes with inner diameter from 1 to 9 mm. They found that the separated flow is hardly seen in the capillary tubes and the critical pipe size at which the surface tension force surpasses the gravitational force is between 5 and 9 mm. Barajas and Panton (1993), Mishima and Hibiki (1996), and Mishima et al. (1993) performed investigation experiment for air–water flow in tubes with similar inner hydraulic diameter range as Fukano and Kariyasaki (1993) did. The transition boundaries from these researches agree well qualitatively with each other. Stratified flow pattern was not found in their investigations.

Triplett et al. (1999) using air and water, conducted experiments in circular micro-channels with 1.1 and 1.45 mm inner diameters, and in micro-channels with semi-triangular cross-sections with hydraulic diameters 1.09 and 1.49 mm. The Taitel and Dukler (1976) models satisfactorily predict their bubbly–slug transition but not for other transition lines. They considered the agreement between their experimental bubbly–slug flow transition and the model of Taitel (1990) should be just coincidental, since the assumptions leading to the deviation of Taitel model do not apply to micro-channels. Their observation is consistent with the results of Fukano and Kariyasaki (1993) and Damianides and Westwater (1988). They concluded that the surface tension is predominant in capillaries and renders the flow characteristics independent of channel orientation with respect to gravity. Since the channel diameters are about equal to or smaller than the Laplace length scale, the hydrodynamic interfacial processes that are governed by Taylor instability do not apply to capillaries.

Coleman and Garimella (1999), the most recently study, investigate air–water flow patterns in circular tubes with diameter from 1.3 to 5.5 mm. Their test results are almost the same as those by Damianides and Westwater (1988) except the transition from intermittent to dispersed regime in tubes smaller than 3.0 mm. Their study shows this transition to occur at higher value of u_{LS} than that by Damianides and Westwater (1988). They also conclude that the surface tension suppress the stratified regime in small diameter tubes and to increase the size of the intermittent regime.

As a result of the previous researches, we may conclude that in addition to gravity and shear forces, surface tension should be another important parameter that predominant the two-phase flow in small tubes. The refrigerant R-134a which popularly used in air-condition and refrigeration systems, has much lower surface tension than air–water has. The flow characteristics may differ from those of air–water. However, there are still no many works on flow pattern investigation for R-134a in small tubes. The present study will provide two-phase flow pattern investigation on both air–water and R-134a in tubes with inner diameter from 1.0 to 3.0 mm.

3. Experimental apparatus

Two test systems were designed for capable investigating two-phase flow patterns of air–water and refrigerant R-134a, respectively. Fig. 1(a) shows the schematic diagram of the air–water test

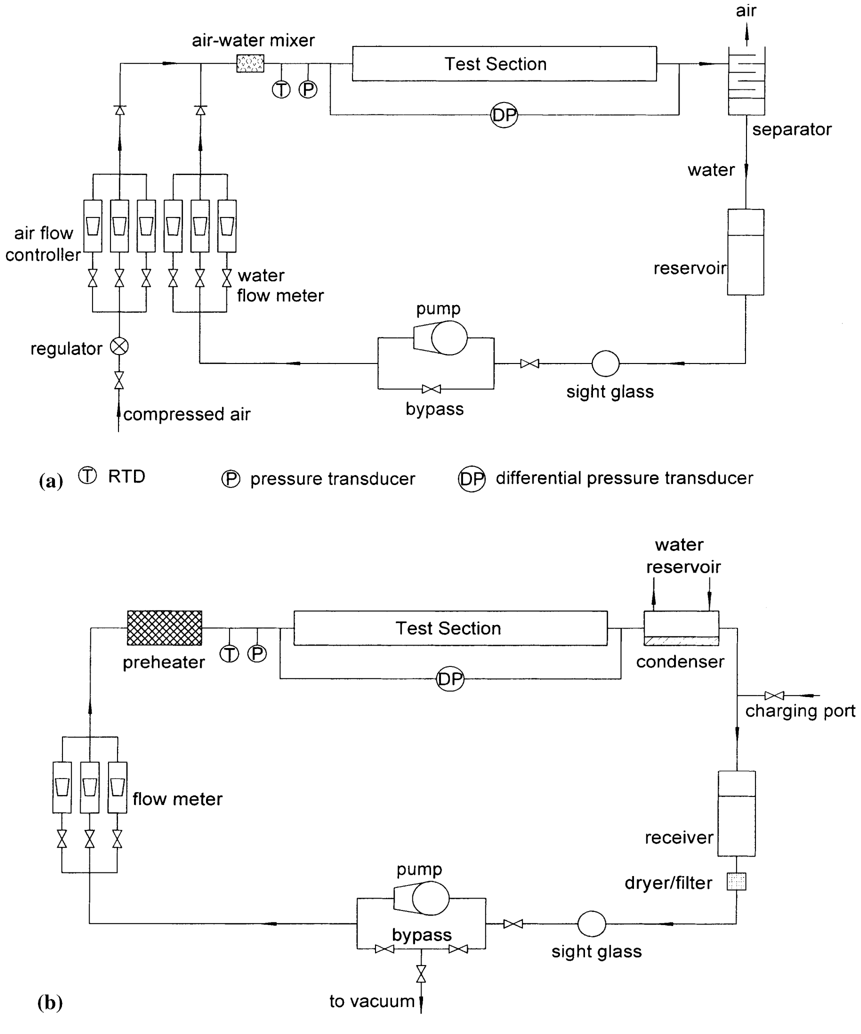

Fig. 1. Schematic diagram of test facility: (a) air–water test system, (b) refrigerant test system.

facility. Air is supplied from a compressed air storage tank at room temperature (25–30°C) and flows through a pressure regulator and a preselected mass flow controller to an air/water mixer. The mixer was made of a cylindrical chamber with inside diameter 12.7 mm and length 50.8 mm. It is filled with stainless steel mesh filter of 40,000 pores per square inch to provide strong agitation and complete mixing of air and water. Water is pumped from a reservoir at 20–25°C by a gear pump through a preselected rotameter to the mixer. The air–water mixture then flows through the transparent Pyrex glass tube test section to an air–water separator. Air is then purged to atmosphere and water comes back to the reservoir to complete a circuit. The estimated uncertainties in air and water flow rate measurement are ±0.6% and ±2%, respectively. Fig. 1(b) is the schematic diagram of refrigerant system. Liquid refrigerant R-134a flows through a positive displacement flow meter and an electrical heater to the test section. The refrigerant is heated to a required vapor quality condition at saturation temperature 30°C in the heater. The flow pattern is observed through the transparent Pyrex glass test section. The two-phase refrigerant is then condensed in a condenser and flows back to a receiver to complete a circuit. The estimated uncertainty in refrigerant flow rate measurement is ±4.8%.

The results presented in this study are from a two-component (air–water) two-phase flow in circular tubes with inner diameters 1.0, 2.0 and 3.0 mm; and a single-component (R-134a) two-phase flow in 2.0 and 3.0 mm circular tubes. R-134a flow patterns in 1.0 mm tube were not observed due to test apparatus limitation. The uncertainty of tube diameter measurement is ±0.02 mm. Detail dimensions of the test tubes are listed in Table 1. Flow patterns were visually observed through the whole range of the test tubes. Some sample flow patterns were photographed at one-third of the tube length prior to the exit of the tubes by using a high-speed camera (Minolta DYNAX 9xi) with a shutter speed of 1/12,000 s. A differential pressure transducer with accuracy of ±0.075% was connected to the inlet and exit of the test section. Mean and dynamic pressure difference was measured to refine transition definition.

4. Experimental results and discussions

Six flow regimes, bubble, slug, plug, wavy stratified, dispersed and annular flow, were observed in this study. But smooth stratified flow was not. Fig. 2 shows the sample photographs of flow patterns observed. The transition boundaries of each flow regime for air–water flow could not be clearly distinguished, especially for slug to annular flow transition. This was also found from the previous studies as stated in Section 2.1. However, this phenomenon was not found for refrigerant flow. The flow regime transitions for two-phase refrigerant R-134a are very sharp and clear. The flow pattern may change from slug to annular by slightly increasing the vapor quality and so that the vapor velocity.

Table 1
Dimensions of tubes tested

Inside diameter d_i (mm)	1.0	2.0	3.0
Outside diameter d_o (mm)	3.0	6.0	8.0
Tube length L (mm)	200	400	600

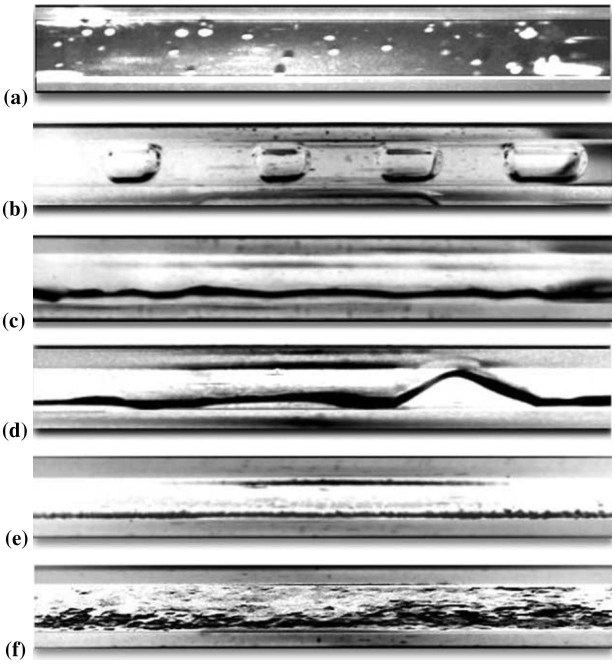

Fig. 2. Photographs of air–water flow patterns in 3.0 mm tube: (a) bubble flow ($u_{LS} = 1.60$ m/s, $u_{GS} = 1.59$ m/s), (b) plug flow ($u_{LS} = 0.12$ m/s, $u_{GS} = 0.043$ m/s), (c) wavy flow ($u_{LS} = 0.0095$ m/s, $u_{GS} = 9.24$ m/s), (d) slug flow ($u_{LS} = 0.017$ m/s, $u_{GS} = 0.71$ m/s), (e) annular flow ($u_{LS} = 0.017$ m/s, $u_{GS} = 71.4$ m/s), (f) dispersed flow ($u_{LS} = 1.52$ m/s, $u_{GS} = 19.0$ m/s).

4.1. Air–water flow maps

Fig. 3 shows air–water two-phase flow patterns observed and their transition lines. Fig. 3(a) is the flow map for the 1.0 mm tube. The superficial water velocity, u_{LS} was from 0.014 to 1.34 m/s, while for the air, u_{GS} was 0.21 to 75 m/s. At low air and water velocity condition, the flow pattern is plug. As air velocity increased, the flow pattern transferred to slug and then to annular. Bubble and dispersed flow was observed at high liquid flow condition. The transition boundary for slug to annular flow regime is not very clear. Within certain air flow velocity range, slug and annular flow dominate the flow regime in the test section alternately. This regime is therefore named the slug–annular flow in current flow maps. The stratified flow was never observed for this tube. This agrees with the previous observation stated in Section 2.3.

Figs. 3(b) and (c) are the flow maps for the 2.0 and 3.0 mm tubes, respectively. The superficial water velocity, u_{LS} was from 0.006 to 2.1 m/s for 2.0 and 3.0 mm tubes, while for the air, u_{GS} was 0.15 to 86.0 m/s and 0.016 to 91.5 m/s for 2.0 and 3.0 mm tubes, respectively. Similar to those presented in Fig. 3(a) for 1.0 mm tube, most of the area of the flow map is occupied by slug and plug flow. However, the stratified wavy flow regime was found in these tubes at high air flow velocity and low water flow velocity conditions. The area of this regime for the 3.0 mm tube flow pattern map is larger than that for the 2.0 mm tube. As the air velocity kept increasing, the wavy liquid layer began to creep up to the tube wall until eventually transition to annular flow. The

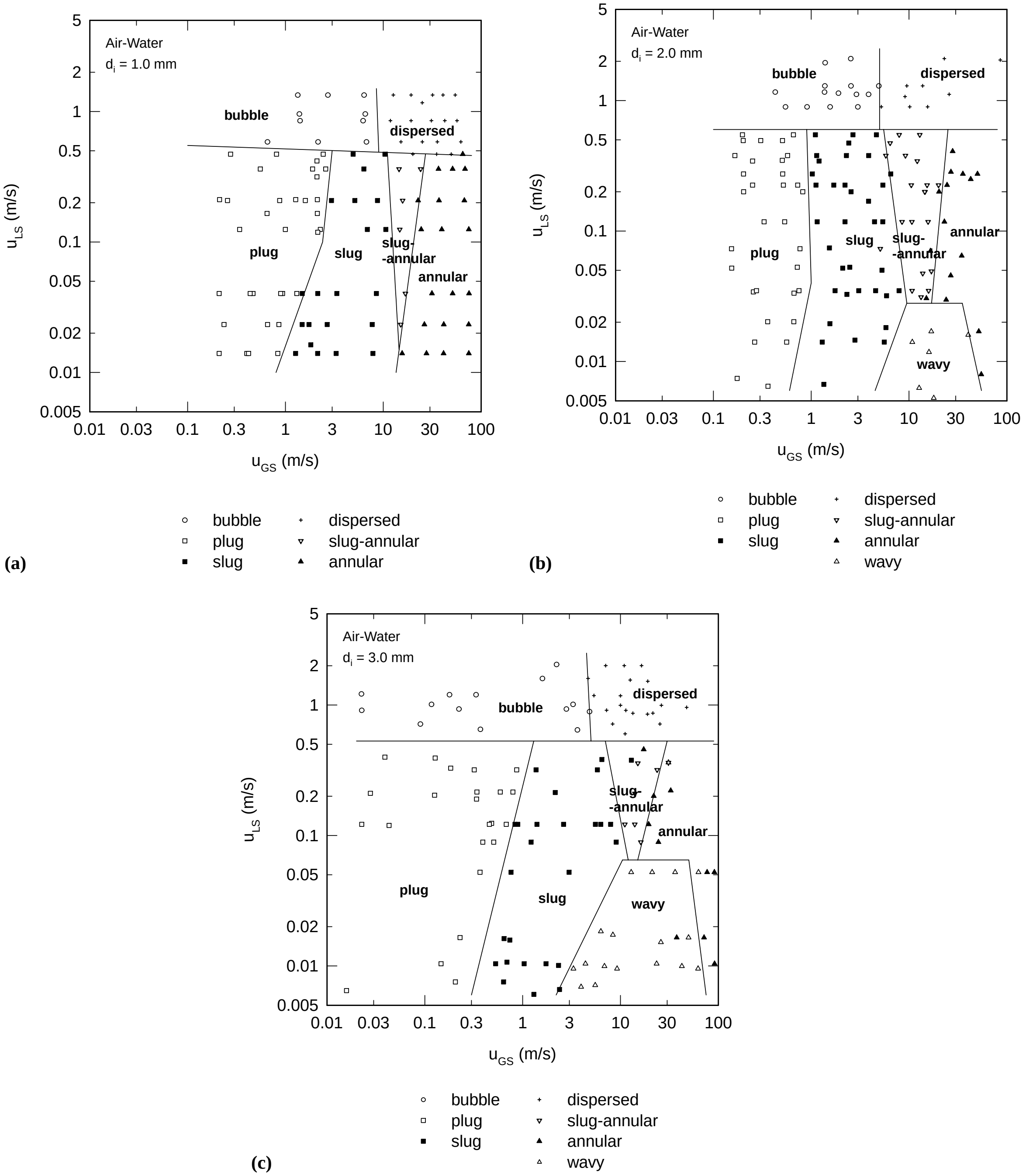

Fig. 3. Air–water two-phase flow patterns and transition lines for: (a) 1.0 mm tube, (b) 2.0 mm tube, (c) 3.0 mm tube.

transition boundary for stratified wavy to annular flow occurred at higher air velocity condition for larger tube. The transition from plug–slug to bubble flow is not significantly affected by changes in tube diameter.

The present developed flow pattern maps are compared with other small tubes observation results and maps developed for larger tubes. The comparisons are presented in Figs. 4 and 5. In Fig. 4, the present maps are compared with the maps proposed by Damianides and Westwater (1988) for the same working fluid and equal diameter tubes. The presently named slug–annular flow regime was also presented in Damianides and Westwater (1988) map, which called the

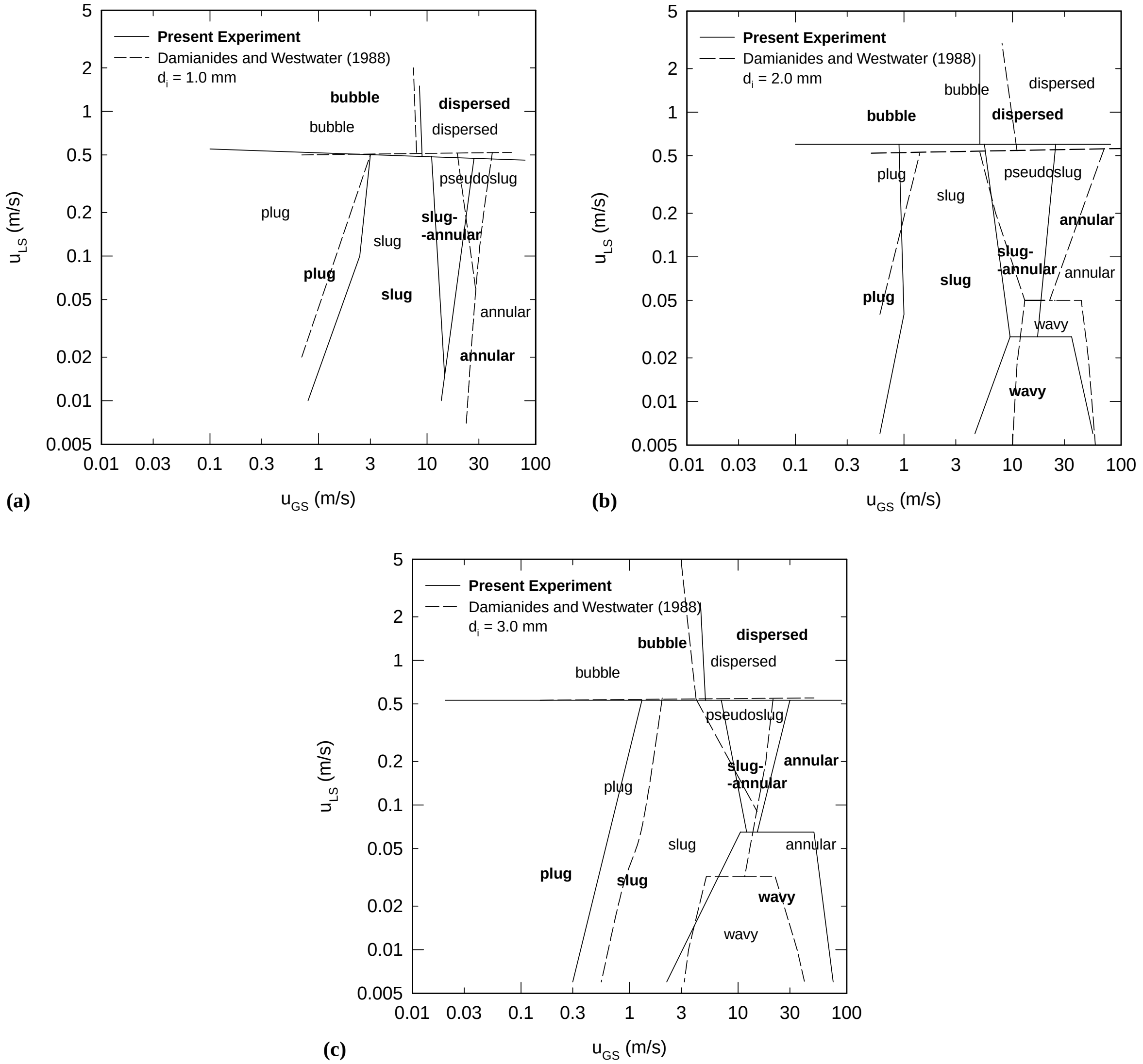

Fig. 4. Comparison of air–water flow maps with Damianides and Westwater (1988) results: (a) 1.0 mm tube, (b) 2.0 mm tube, (c) 3.0 mm tube.

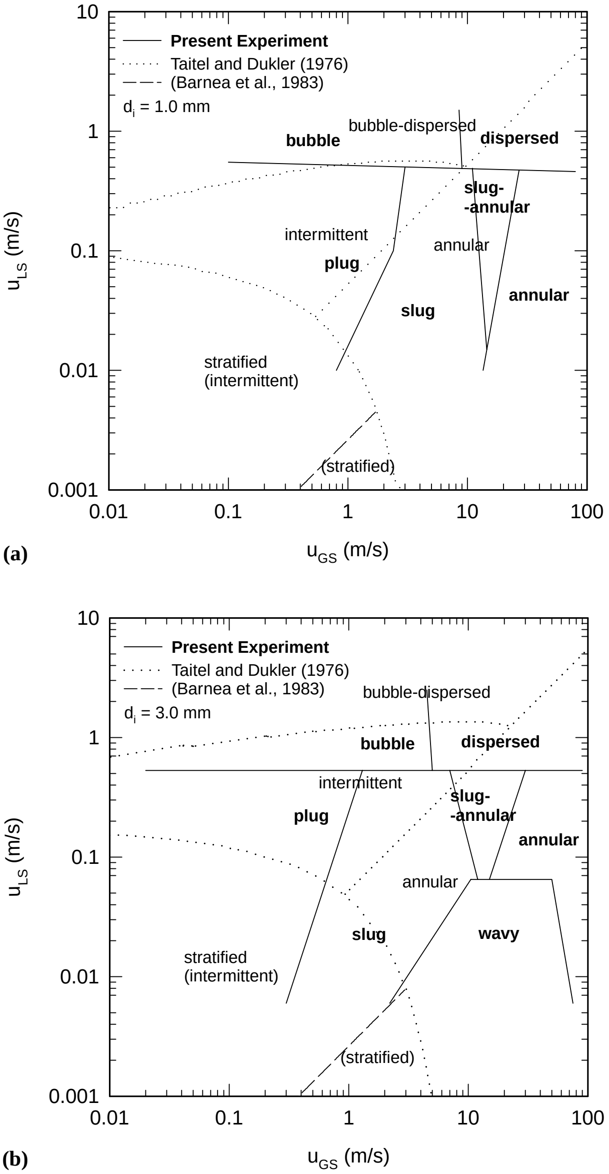

Fig. 5. Comparison of air–water flow maps with the Taitel and Dukler (1976) and Barnea et al. (1983) predictions results: (a) 1.0 mm tube, (b) 3.0 mm tube.

Pseudo slug flow. The comparison shows a very good agreement between the results of these two studies. Fig. 5 compared the present maps with the maps generated by Taitel and Dukler (1976) and Barnea et al. (1983) prediction models. The predicted bubble to intermittent transition boundary agrees well with the present observation result for 1.0 mm tube. But it shifts to higher value of water velocity for that in 3.0 mm tube. The predicted stratified to intermittent transition was not found for both 1.0 and 3.0 mm tubes in current observation, while the test condition for

3.0 mm tube is within the Taitel and Dukler (1976) predictive range. The Barnea et al. (1983) modification provides a better prediction than that by Taitel and Dukler (1976). Taitel and Dukler (1976) suggested that whether intermittent or annular flow will develop depend uniquely on the liquid level in the stratified equilibrium flow. When the equilibrium liquid level in the tube is above the tube centerline, intermittent flow will develop, and if the ratio of liquid level height to tube diameter, $h_L/d_i < 0.5$, annular or annular–dispersed flow will result. This description is not true for the present observation. The transition boundary from slug to annular is dependent mostly on air velocity but not on water velocity.

4.2. R-134a flow maps

Fig. 6 shows two-phase refrigerant R-134a flow patterns observed and their transition lines. Fig. 6(a) is the flow map for the 2.0 mm tube. The mass velocity, G was from 300 to 1600 kg/m^2 s. At $G = 300$ kg/m^2 s, the flow pattern started from plug to slug and to annular with increasing vapor qualities, while at $G = 1600$ kg/m^2 s, the flow pattern transferred from bubble to dispersed. The relative value of vapor qualities and heating paths are also shown in the figure. Since the transitions from one flow regime to others are very clear, the slug–annular flow regime presented for air–water flow was not found for R-134a. The flow pattern for 3.0 mm tube shown in Fig. 6(b) provides the similar result as that for 2.0 mm tube. Since no investigation results for refrigerant flow in comparable size tubes have been found in the published literature, the authors chose Wang et al. (1997) for R-134a in 6.5 mm tube and Hashizume (1983) for R-12 in 10 mm tube flow pattern investigations for comparison. Fig. 7 shows Wang et al. (1997) investigation results agree well with present results for intermittent to annular flow transition. Fig. 8 compares Hashizume (1983) investigation results and the present observed transition boundaries. The slug and semi-annular flow defined by Hashizume (1983) is similar to the plug and slug flow in current study respectively. The Hashizume's transitions from slug to semi-annular and semi-annular to annular flow regime were not much differing from the present observation results. Since both Wang et al. (1997) and Hashizume (1983) works were presented at low mass velocity conditions, only stratified, wavy, plug, slug, and annular but not bubble and dispersed flows were observed.

Fig. 9 compared the present refrigerant test results with Taitel and Dukler (1976) predictions. As those for air–water flow comparison which described preciously, only bubble to intermittent transition can be reasonably predicted.

Figs. 10(a) and (b) compared the flow patterns for air–water and R-134a in 2.0 and 3.0 mm tubes, respectively. It shows the locations of bubble to plug and slug flow transition are significantly affected by the working fluids. The properties that may affect the fluid flow are listed in Table 2. It shows that the surface tension of air–water is much larger than that of R-134a. Taitel and Dukler (1976) suggested that the transition from intermittent to dispersed–bubble flow takes place when the turbulent fluctuations are strong enough to overcome the buoyant forces tending to keep the gas at the top of the tube. However, in small tubes, not only buoyant force and turbulent fluctuations but also surface tension force are important. The main effect of surface tension is that causes the system to act to minimize its interfacial area. It tends to keep bubbles retaining its circular shapes and must be taken into consideration. This makes the intermittent to bubble flow transition occurs earlier for air–water than for R-134a. Since the surface tension also acts to keep the liquid holdup between the tube walls, it tends to retard the transition from slug to annular for high surface tension air–water flow. Therefore, the change in working fluid from air–water to R-134a leads to a shift in the slug to annular transition to lower value of gas velocity. This agrees well with Reinarts (1993) result. However, the exact condition of that how surface tension force, buoyant force and turbulent fluctuation affect the flow pattern transition is still not clear. None of the existing predicting models can be able to well predict those transition boundaries. Further study is necessary for realize the flow pattern transition mechanism in small tubes.

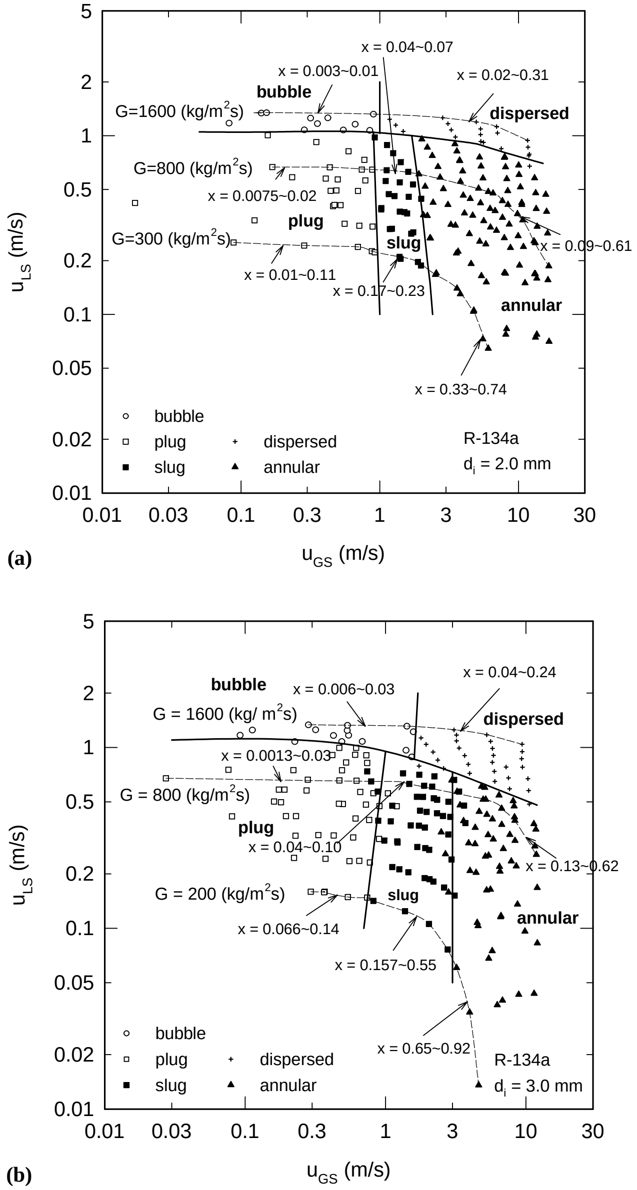

Fig. 6. Two-phase R-134a flow patterns and transition lines for: (a) 2.0 mm tube, (b) 3.0 mm tube.

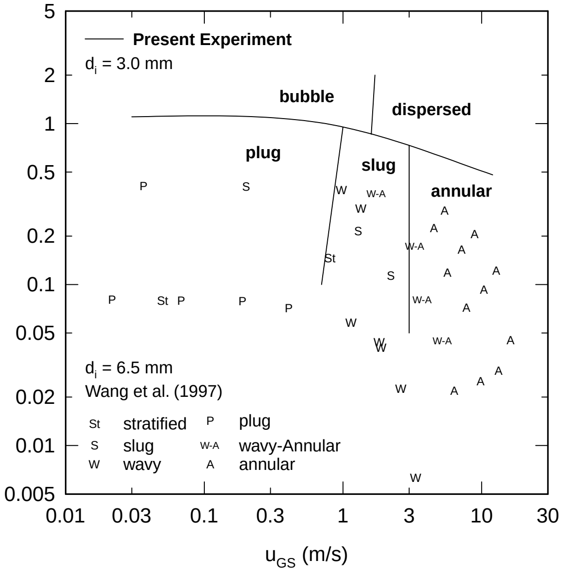

Fig. 7. Comparison of R-134a flow maps for 3.0 mm tube with Wang et al. (1997) for 6.5 mm tube.

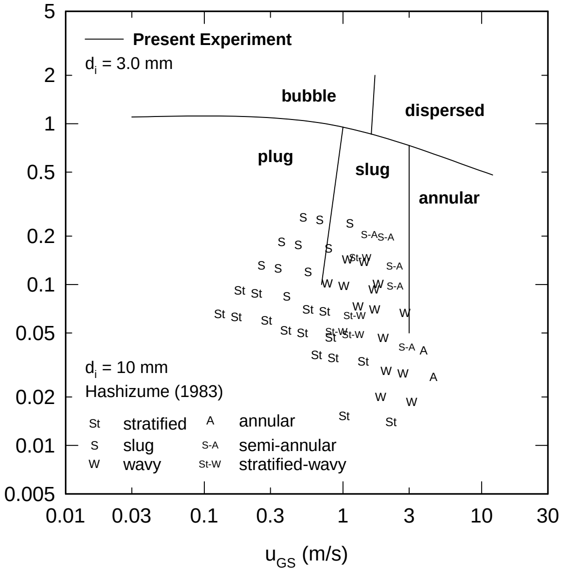

Fig. 8. Comparison of R-134a flow maps for 3.0 mm tube with Hashizume (1983) for R-12 in 10 mm tube.

5. Concluding remarks

Experimental investigation for refrigerant R-134a and air–water two-phase flow in horizontal tubes with inside diameter from 1.0 to 3.0 mm was performed to determine the flow patterns. Six

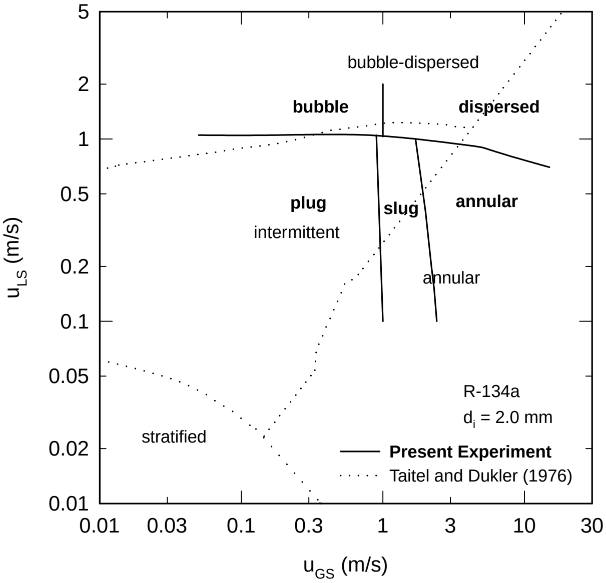

Fig. 9. Comparison of two-phase R-134a flow maps with the predictions by Taitel and Dukler (1976).

flow regimes, bubble, slug, plug, wavy stratified, dispersed and annular flow, were observed in this study. The transition boundaries of each flow regime for air–water flow could not be clearly distinguished, especially for slug to annular flow transition. However, the transitions for refrigerant R-134a is very sharp and clear. The flow pattern may change from slug to annular by slightly increasing the vapor quality and so that the vapor velocity.

In comparing with the previous studies, the present air–water investigation results agree very well with those by Damianides and Westwater (1988). The stratified to intermittent transition predicted by Taitel and Dukler (1976) was not found in the current observation. The transition boundary from slug to annular is dependent mostly on air velocity but not on water velocity as that described by Taitel and Dukler (1976).

The change in working fluid from air–water to R-134a leads to a shift in the slug to annular transition to lower value of gas velocity. The locations of bubble to plug and slug flow transition are also significantly affected by the working fluids properties. In small tubes, in addition to buoyant force and turbulent fluctuations, surface tension force is also an important parameter for flow pattern determination. Surface tension force causes the system to act to minimize its interfacial area. It tends to keep bubbles retaining its circular shapes and also to keep the liquid holdup between the tube walls to retard the transition from slug to annular. Since the surface tension of air–water is much larger than that of R-134a, it makes the intermittent to bubble flow transition occurs earlier for air–water than for R-134a. And also leads to a shift in the slug to annular transition to lower value of gas velocity for R-134a.

None of the existing flow pattern predicting models is able to well predict air–water and refrigerant flow in small tubes. Further study on the effect of tube size and fluid properties should be endeavored for appropriate flow pattern determination.

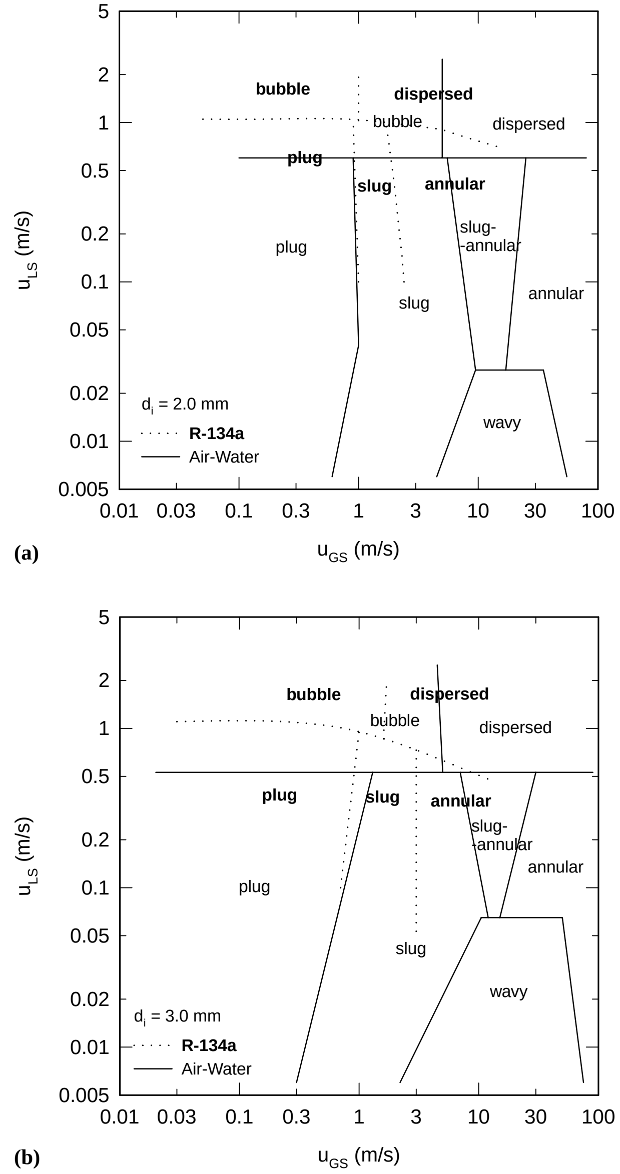

Fig. 10. Comparison of air–water and two-phase R-134a flow maps for: (a) 2.0 mm tube, (b) 3.0 mm tube.

Table 2
Properties of air–water and R-134a

Properties	Air–water at 25°C		R-134a at 30°C	
	Air	Water	Vapor	Liquid
Density (kg/m^3)	1.171	997.4	37.53	1186.7
Viscosity (μN s/m^2)	18.36	896.6	12.6	201
Surface tension (N/m)	0.0721	0.0721	0.0075	0.0075

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