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Flow regimes for horizontal two-phase flow of CO_2 in a heated narrow rectangular channel

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Abstract

Two-phase flow patterns of CO_2 in a narrow rectangular channel or a small diameter tube are very important in understanding heat transfer characteristics and in developing an appropriate heat transfer correlation. Geometric effects on two-phase flow patterns of CO_2 are very significant in many respects. In the present study, the flow boiling process of CO_2 in a horizontal narrow rectangular channel, having a width of 16 mm and a height of 2 mm, is visualized at various test conditions, and then the effects of mass flux are analyzed. Based on the test results, a flow regime map is developed and then compared with the existing maps and flow regime transition criteria that are selected by considering physical phenomena occurred during the flow regime transition processes of CO_2. In addition, the flow transition criteria for bubbly–slug, slug–annular, and bubbly–annular flow in a horizontal narrow channel are proposed by comparing the test data with existing transition criteria.

Keywords: Flow pattern; Narrow channel; Flow boiling; Transition criteria; Horizontal flow; CO_2; Flow regime map

1. Introduction

CO_2 shows different convective boiling heat transfer characteristics from conventional refrigerants such as CFCs (chlorofluorocarbon) and HCFCs (hydrochlorofluorocarbon) (Yun et al.,

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2003; Pettersen, 2002). To explain boiling characteristics of CO_2, it is necessary to know the two-phase flow patterns of CO_2. As noted, the characteristics of bubble formation can explain the phenomena of nucleate boiling, and the shape of liquid film is closely related with convective boiling heat transfer and dryout. Two-phase flow patterns in a mini tube or a narrow channel show significant differences from those of large diameter tubes (Pettersen, 2002; Mishima et al., 1993). However, most previous studies on two-phase flow patterns have been focused on large diameter tubes. Therefore, it is required to investigate two-phase flow characteristics in a narrow channel, which are important design factors in a cooling system of microelectronics and an atomic reactor with plate type fuels.

Several studies on the characteristics of two-phase flow patterns in a narrow channel have been performed. Fujita et al. (1995) suggested that the influence of surface tension as well as liquid viscosity would be much pronounced in gas–liquid flows moving through narrow flat channels as compared to that in larger channels. Wilmarth and Ishii (1994) investigated the vertical and horizontal two-phase flows of air–water mixture through narrow rectangular channels. They reported that the transition from bubbly to slug flow was well estimated by the Mishima and Ishii model (1984). Xu (1999) studied air–water two-phase flow in vertical rectangular channels with the gaps of 0.3, 0.6, and 1.0 mm. By decreasing the channel gap, the transitions for bubbly–slug, slug–churn, and churn–annular flow shifted toward left in the flow regime map with the superficial vapor velocity as an abscissa and the superficial liquid velocity as an ordinate.

Several researchers proposed flow transition criteria for two-phase flow boiling in a narrow channel. Xu et al. (1999) modified the Mishima and Ishii model (1984) to predict the flow transitions for bubbly–slug and slug–churn flow in a narrow rectangular channel. Hibiki and Mishima (2001) also suggested the flow transition criteria in a narrow rectangular channel by considering the effects of narrow channel geometry on flow patterns. The studies on two-phase flow patterns and transition criteria of CO_2 in a horizontal narrow channel at heating conditions are very limited in open literature. Most flow pattern observations are focused on two-phase flow of air–water mixture under adiabatic conditions.

The objective of this study is to investigate two-phase flow regimes of CO_2 in a horizontal narrow rectangular channel at heating conditions. The flow transitions, such as bubbly to slug, bubbly to annular, and slug to annular flow, are visually and physically studied. The analysis of visualization results and the comparison of the data with the existing flow regime maps and transition criteria will help to understand two-phase heat transfer and pressure drop characteristics of CO_2 in a mini tube.

2. Experimental setup

Fig. 1 shows a schematic diagram of the test loop for flow visualizations. The test loop consists of a magnetic gear pump, a mass flow meter, a preheater, a test section, a control tank, and a condenser. The magnetic gear pump circulates CO_2, and the preheater is used to adjust inlet vapor quality of the test section. The visualization section mainly consists of a camera and a short duration light source, whose specifications are given in Table 1. The light source is located behind the camera, which is installed vertically to the test section. A photograph for two-phase flow in a narrow channel is taken by making short duration light source periodically flash like stroboscope.

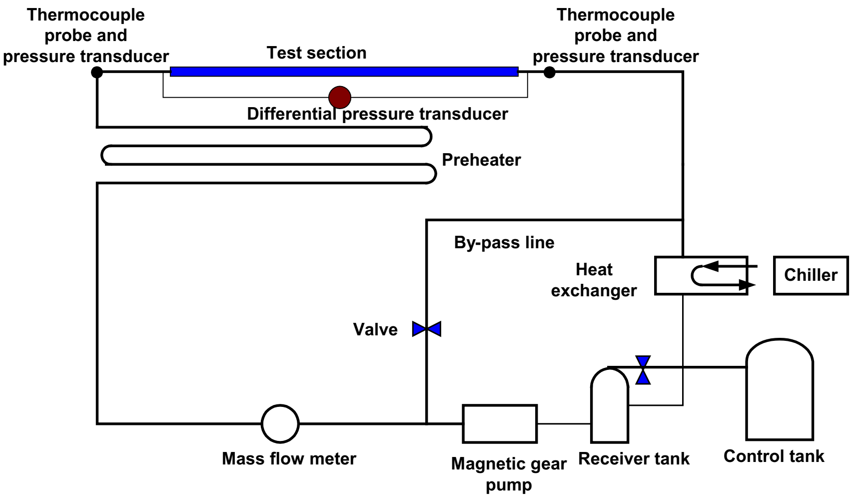

Fig. 1. Schematic diagram of the experimental setup.

Table 1
Specifications of camera and short duration light source

Items	Specifications
CCD	1/1.8-in. high density CCD
Lens	4× Zoom-Nikkor, $f = 8$–32, F2.6-5.1
Shooting distance	0.02 m–∞
Flash lamp	Xenon flash lamp (Max. = 7 W)
Light duration of the flash	0.7 μs

Shooting distance of the camera and light intensity are controlled to capture the clearest image of bubbles. Moving images of bubble or vapor in the camera are magnified and observed by the monitor. To prevent light interruption, the photograph is taken at the environment similar to a dark room.

The test section consists of a thick stainless steel body and a glass. Flow channel having a width of 16 mm and a height of 2 mm is machined on the body, and the glass is covered on that channel. Cartridge heaters with an individual capacity of 100 W are equally placed in the body to supply uniform heat flux to the flow channel. To determine correct vapor quality at the measuring point, it is necessary to know net heat input to the fluid in the channel. The test section is heavily insulated using a rubber with a thermal conductivity of 0.04 W/mK to minimize heat loss to the ambient. The heat loss is measured by comparing electric heat input with actual heat transfer to the fluid in terms of the enthalpy difference between subcooled inlet and outlet fluid of CO_2. The 84% of the electric heat input is transferred to the fluid in the narrow rectangular channel, and it is taken into account in the determination of vapor quality of CO_2.

The flow rate of CO_2 is measured by using a Coriolis effect flow meter with an uncertainty of ±0.2% of reading. Heat inputs to the test section and the preheater are measured using a watt transducer with an uncertainty of ±0.01% of full scale. The pressures of the fluid at the inlet and outlet of the test section are monitored using a pressure transducer with an uncertainty of ±2.1 kPa. The inlet and outlet temperatures of the test section are measured by thermocouple probes with an uncertainty of ±0.1 °C. The uncertainty of vapor quality at the test section inlet is approximately ±4%.

3. Two-phase flow patterns in the horizontal rectangular channel

3.1. Flow patterns

The flow patterns in a narrow channel having a larger ratio of channel width to gap space will significantly vary along with channel width and length. Generally, larger coalesced bubbles occupy most areas in the directions of channel width and length. However, the variations of flow patterns along with channel depth are insignificant (Xu, 1999). Therefore, this study observes the flow patterns in the directions of channel width and length. It should be noted that the photographs and schematics for flow patterns are taken in the vertically downward direction.

Fig. 2 shows photographs and schematics of the flow patterns observed in this study. The dominant flow regimes observed for the flow boiling of CO_2 in the narrow channel are bubbly flow, intermittent flow (slug or churn flow), and annular flow.

Bubbly flow. Generally, bubbles form and grow at the sides and bottom of the channel. Small discrete bubbles exist at the sides of the channel, while relatively large discrete bubbles exist at the channel center because the released small bubbles from the channel wall are merged together and then congregated at the channel center.

Intermittent flow. This flow is characterized by a packing of small and large sized bubbles. Larger bubbles at the channel center occasionally merge together, which form longish and bigger bubbles. The bubbles are flattened due to the confinement of the walls. In addition, the mixture of liquid and small bubbles exists at the channel sides. A boundary between the vapor and the mixture of liquid and bubbles shows very complex shape.

Annular flow. This flow consists of a vapor core and a liquid film surrounding the core. As the vaporization proceeds at moderate vapor qualities, the vapor region at the channel center becomes wider and the liquid film slowly appears at the channel sides. Finally, large bubbles at the channel sides are absorbed into the vapor core and the nucleate boiling is gradually suppressed. Entrainment of small liquid droplets into the vapor core occurs due to continuous breaking of the liquid wave and bubble bursting on the surface of the liquid film.

As shown in Fig. 3, the experimental data of CO_2 in the narrow rectangular channel are then represented in the flow regime map as a function of mass flux G and vapor quality x. When the mass flux is smaller than 500 kg/m^2 s, the flow transition from bubbly to slug occurs at a quality of approximately 0.03 due to an easy coalescence of adjacent bubbles. As the mass flux increases, the identities of bubbles and slugs can be maintained up to the transition boundary to annular flow. Therefore, for mass flux greater than 868 kg/m^2 s, the flow regime directly transits from bubbly to annular flow without having intermittent flow. Generally, the vapor quality for annular flow tran-

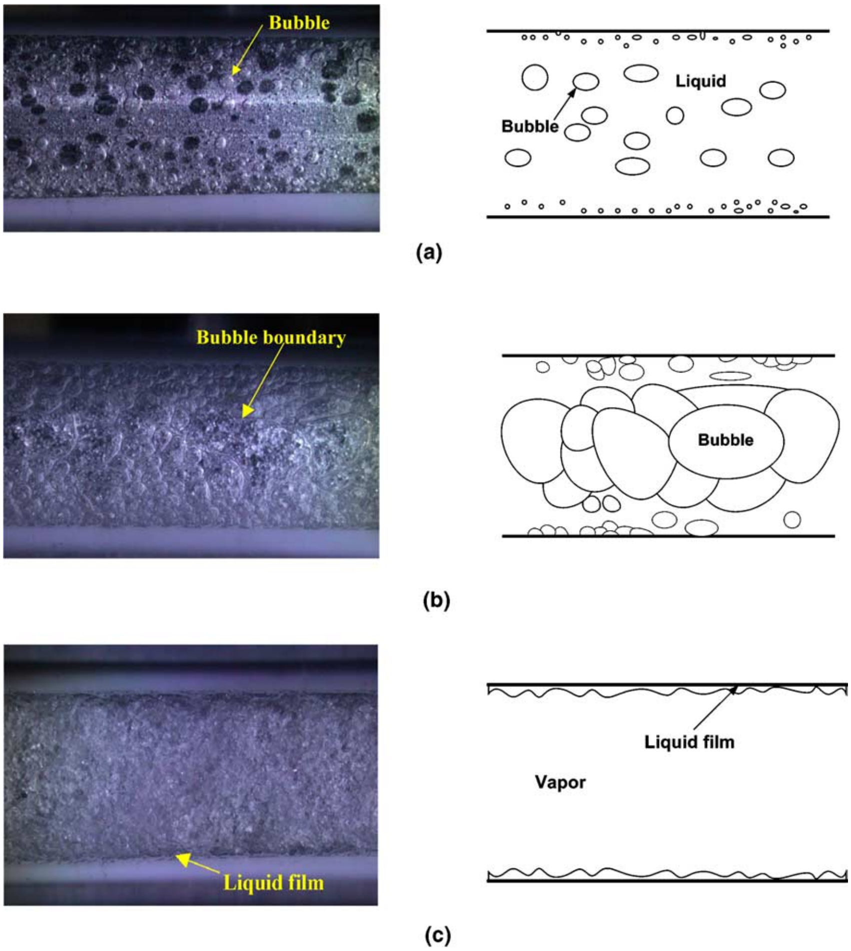

Fig. 2. Flow regimes in horizontal narrow channel flow: (a) bubbly flow, (b) intermittent flow, and (c) annular flow.

sition becomes lower with a rise of mass flux. In addition, when the mass flux is greater than 868 kg/m^{2}s, the vapor quality for annular flow transition becomes nearly constant.

The effects of mass flux on the flow regimes of CO_2 are also investigated by varying mass flux from 217 to 868 kg/m^{2}s at a heat flux of 100 kW/m^2 and a vapor quality of 0.18. The vapor region at the channel center increases with a rise of mass flux, while the liquid film thickness at the channel sides is reduced. Liquid droplet entrainment into the vapor core increases with a rise of mass flux due to a higher vapor velocity with wavy interface. As the mass flux increases, the flow transitions of bubbly–slug and slug–annular flow occur at a lower vapor quality. These early transitions are closely related with the large liquid droplet entrainment.

Fig. 4 shows the schematics of the flow patterns during the transition process from bubbly to annular flow. With an increase of vapor quality, all regions of the channel are packed with spherically uniform bubbles. Then, bubble boundaries become more uncertain at the channel center and annular flow pattern starts to appear. This flow transition occurs when small bubbles having

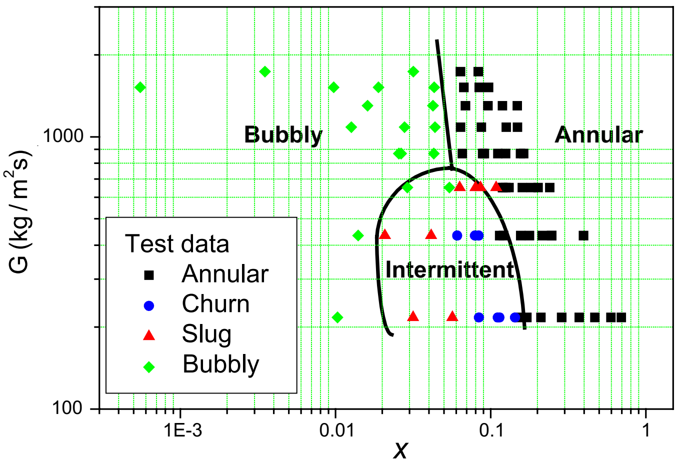

Fig. 3. Flow regime map with respect to mass flux and vapor quality.

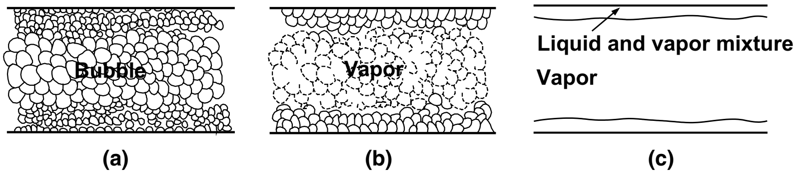

Fig. 4. Schematics of bubbly to annular flow transition: (a) bubbly, (b) bubbly–annular, and (c) annular.

their identities induced by liquid turbulent fluctuations are merged by bubble fluctuations and packing. Therefore, the superficial liquid velocity whose magnitude determines the bubble identities is a dominant parameter for this flow transition.

3.2. Comparison with existing flow pattern data and maps

The present data are compared with the flow patterns obtained from the literature as shown in Table 2. The visualization tests in these studies were conducted in small gap sized channels and a small diameter tube with different working fluids: CO_2, steam–water, air–water, and N_2–water solution of ethanol. Pettersen (2002) and Hosler (1968) observed flow patterns at heating conditions, while Wambsganss et al. (1991), Wilmarth and Ishii (1994), and Fujita et al. (1995) measured flow patterns at adiabatic conditions.

Fig. 5(a) compares the present data with Pettersen's (2002) data as a function of superficial liquid velocity j_f and superficial vapor velocity j_g. Although there is big difference in test section geometries, the annular flow regime observed in this study is consistent well with that visualized by Pettersen (2002). Elongated bubbles or slug flow patterns observed by Pettersen (2002) correspond to the intermittent flow regime in this study.

Table 2
Data source used in this study

	Fluids	Pressure (MPa)	Flow rate (kg/m^{2}s)	Heat flux (kW/m^2)	Geometry and orientation (mm)
Present	CO_2	4.0	217–868	0–250.0	Horizontal, rectangular channel 2.0×16.0
Pettersen (2002)	CO_2	3.5, 5.7	93–584	0, 13	0.98 mm horizontal, transparent tube
Hosler (1968)	Steam–water	1–13.8	136–5424	5678.0 (max.)	Vertical, rectangular channel 3.4×25.4
Wambsganss et al. (1991)	Air–water	Atmosphere	50–2000	Adiabatic	Horizontal, rectangular channel 3.18×19.05
Wilmarth and Ishii (1994)	Air–water	Atmosphere		Adiabatic	Vertical, horizontal, rectangular channels, 1×20, 2×15
Fujita et al. (1995)	N_2–water solution of ethanol	Atmosphere		Adiabatic	Horizontal, rectangular channels 0.2×10, 1.2×10, 2×10

Fujita et al. (1995), Wambsganss et al. (1991), Wilmarth and Ishii (1994) developed flow regime maps in vertical/horizontal narrow channels and a capillary tube at adiabatic conditions. Based on their flow maps, the transition boundaries for bubbly–slug, slug–annular, and plug–slug flow are drawn as a function of superficial liquid and vapor velocities in Fig. 5(b), and those are compared with the present data. Although their test sections have a similar hydraulic diameter with this study, the transition boundaries show large deviations from the present data except the bubbly flow region suggested by Wilmarth and Ishii (1994). These significant deviations may be due to the differences in heating conditions and the boiling characteristics of CO_2. The flow transition at heating conditions can occur at a lower superficial vapor velocity as compared with that at adiabatic conditions. This trend is closely related with chaotic bubble formation and unstable movement of detached bubbles under heating conditions, which increases the probability of contacts between bubbles. CO_2 shows more active bubble formation and larger liquid droplet entrainment than air–water mixture due to a lower surface tension, which also causes an easy flow transition at a lower superficial vapor velocity.

Fig. 5(c) shows the comparison of the Hosler map (1968) at 2.1 MPa and 13.8 MPa with the present data. Generally, the transitions of the Hosler map exist at a higher superficial vapor velocity as compared with the present data. As the saturation pressure increased, a direct transition from bubbly to annular flow was observed in Hosler's data (1968). When Hosler's data (1968) were compared with those for air–water mixture tested under adiabatic conditions, the flow regime transitions occurred at a lower superficial vapor velocity, which were relatively close to those of CO_2. These trends can be caused by the differences in fluid properties. As shown in Table 3, the density ratio of liquid to vapor, surface tension, and liquid viscosity of CO_2, which are important fluid properties determining flow regimes in a small sized tube (Fujita et al., 1995), show the similar order of magnitude as those of steam–water. However, there are large differences in these fluid properties between CO_2 and air–water. In addition, the heating conditions significantly affects the flow regimes.

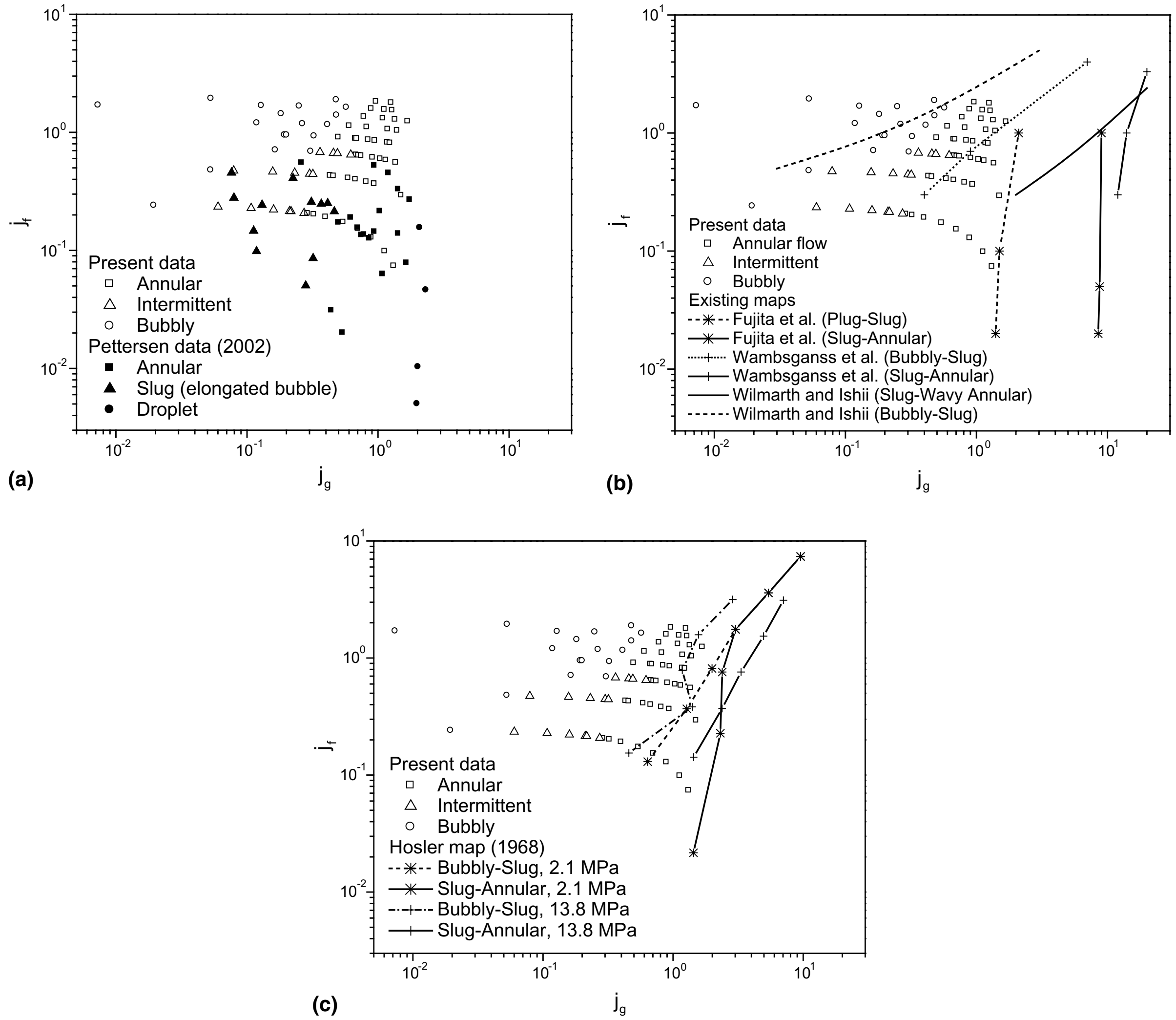

Fig. 5. Comparison of the present data with existing flow regime maps. (a) Comparison with Pettersen's data (2002). (b) Comparison with the maps of Fujita et al. (1995), Wilmarth and Ishii (1994), and Wambsganss et al. (1991). (c) Comparison with the Hosler map (1968).

Table 3
Properties of CO_2, steam–water, and air–water

Fluids	$\rho_l - \rho_v$ (kg/m^3)	ρ_l/ρ_v	σ (N/m)	μ_l (Pa s)
CO_2 at 5 °C	783	7.85	0.0036	9.6×10^{-5}
Steam–water at 13.8 MPa	540	7.32	0.0065	7.23×10^{-5}
Air–water at 20 °C and 1 atm	997	864	0.072	1.0×10^{-3}

4. Transition criteria of flow regimes

The flow transitions of bubbly–slug, slug–annular, and bubbly–annular for CO_2 are distinctly observed in the test data of this study and Pettersen (2002). Possible flow transition criteria of CO_2 in a narrow rectangular channel are proposed by comparing the existing transition criteria with the present data and considering physical phenomena during the transition process.

The transition from bubbly to slug flow in vertical upward flow has been generally estimated by using the drift-flux model as given by

$$j_g/\varepsilon = C_0 j + f(v_\infty, \varepsilon) \tag{1}$$

where j and j_g are mean volumetric flux and superficial vapor velocity, respectively. C_0 is distribution parameter and $f(v_\infty, \varepsilon)$ indicates relative bubble velocity as a function of bubble rising velocity v_∞ and void fraction ε. However, the bubble rising velocity v_∞ in horizontal narrow channel flow is negligible due to the constraint of gap space.

Hibiki and Mishima (2001) suggested a void fraction of 0.2 for the flow transition from bubbly to slug flow in a narrow channel, while Spindler and Hahne (1999) proposed a void fraction of 0.25 in horizontal large diameter tubes. Wilmarth and Ishii (1994) also reported that the bubbles were evenly distributed and the transition void fraction became lower with a decrease in the gap size. Based on the present data for CO_2 and C_0 reported by Zuber et al. (1967), this study proposes a distribution parameter C_0 of 1.11 and a void fraction ε of 0.2 for estimation of the transition boundary between bubbly and slug flow in a narrow rectangular channel.

As shown in Fig. 6, both the present and Pettersen's data (2002) are compared with Hibiki and Mishima's (2001) flow regime transition criteria for upward gas–liquid flow in vertical narrow rectangular channels. For the bubbly to slug flow transition in vertical narrow channels, the relative velocity was set to zero. Therefore, their flow transition criterion for bubbly to slug flow is well consistent with the present flow patterns measured in the horizontal narrow channel.

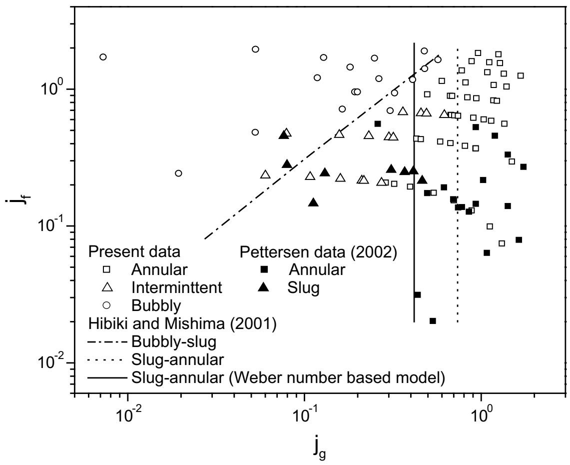

Fig. 6. Comparison of flow pattern data with existing flow regime transition criteria.

The flow transition from slug to annular in a narrow horizontal channel is resulted from a breaking of interface between frothy slugs due to fluctuation of the slugs. As noted, the interface is maintained by surface tension, and the fluctuation is related with inertial force of vapor. As the channel size decreases, the effects of surface tension on flow patterns increase and the horizontal orientation with a small gap makes the forces related with the gravitation, such as buoyancy force, negligible. Zhao and Rezkallah (1993) reported that the influence of surface tension and inertial force were very significant at micro-gravity conditions. They predicted slug–annular flow transition at micro-gravity conditions using the Weber number based model. Generally, the slug–annular flow transition of CO_2 in a narrow horizontal channel is very similar to that at micro-gravity conditions (Akbar et al., 2003). Based on this analogy, the Weber number based model (Eq. (2)) is adopted for prediction of the slug to annular flow transition in a narrow horizontal channel.

$$We_{gs} = \rho_g j_g^2 d_h / \sigma \approx 20 \tag{2}$$

In Eq. (2), ρ_g is vapor density, d_h is hydraulic diameter of test channel, and σ is surface tension. As We_{gs} is close to 20, the density of liquid droplets in frothy slugs decreases, and the frothy slugs become thinner until the flow is fully developed (Zhao and Rezkallah, 1993; Bousman et al., 1996).

As shown in Fig. 6, Hibiki and Mishima (2001) also proposed slug–annular flow transition criteria using a constant value of superficial vapor velocity. However, their transition superficial vapor velocity for slug–annular flow is much higher than the measured data because the physical phenomena for gas–liquid flow in vertical narrow channels are much different from those observed in the horizontal narrow channel. Therefore, the proposed Weber number based model as given in Eq. (2) yields better agreement with the present and Pettersen's data (2002) as compared with the Hibiki and Mishima transition criteria.

As mentioned earlier, the superficial liquid velocity is dominant parameter in maintaining bubble identities. When the superficial liquid velocity is higher than some limit value, a direct transition from bubbly to annular flow can occur. Since an appropriate criterion for this direct transition is not provided in open literature, the flow transition criterion for bubbly–annular is proposed based on the present data along with Weber number, including the superficial liquid velocity. Eq. (3) shows the lower limit of superficial liquid velocity j_f to maintain small bubbles when the superficial vapor velocity j_g for agglomeration satisfies the limit given in Eq. (2)

$$We_{fs} = \rho j_f^2 d_h / \sigma > 100 \tag{3}$$

In this study, Eq. (1) is used in prediction of the bubbly–annular transition with a void fraction ε of 0.35 and a distribution parameter C_0 of 1.05, which are determined based on the present data and Zuber et al.'s data (1967), respectively. The proposed transition criteria of bubbly–annular flow show good agreement with the test data.

5. Conclusions

Two-phase flow regimes of CO_2 in the horizontal narrow rectangular channel are visualized at heating conditions, and then analyzed by comparing the present data with the existing flow regime maps and transition criteria. CO_2 shows mainly bubbly, slug, and annular flow patterns during the flow boiling process in the narrow rectangular channel. Based on the present data, a flow regime map is developed for the horizontal narrow rectangular channel. Among the existing flow regime maps for vertical or horizontal narrow channels and a capillary tube, the maps developed for CO_2 and high-pressure steam–water show similar results with the present data. However, other maps developed for air–water mixture show large deviations from the present data due to the differences in heating conditions and the boiling characteristics of CO_2. The proposed transition criterion of bubbly–slug flow, which is adopted from the Hibiki and Mishima transition criterion (2001), shows good agreement with the data. The Weber number based model yields relatively good predictions for the slug–annular transition of CO_2 in the narrow rectangular channel. Vapor inertial force and surface tension play an important role in the transition of slug–annular flow. When the superficial liquid velocity is higher than some limit value, the direct transition of bubbly–annular flow occurs.

Acknowledgments

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References

Akbar, M.K., Plummer, D.A., Ghiaasiaan, S.M., 2003. On gas–liquid two-phase flow regimes in microchannels. Int. J. Multiphase Flow 29, 855–865.

Bousman, W.S., Mcquillen, J.B., Witte, L.C., 1996. Gas–liquid flow patterns in microgravity: effects of tube diameter, liquid viscosity and surface tension. Int. J. Multiphase Flow 22, 1035–1053.

Fujita, H., Ohara, T., Hirota, M., Furuta, H., 1995. Gas–liquid flows in flat channels with small channel clearance. In: Proc. 2nd International Conference on Multiphase Flow '95-Kyoto, IA3-37-IA3-44.

Hibiki, T., Mishima, K., 2001. Flow regime transition criteria for upward two-phase flow in vertical narrow rectangular channels. Nucl. Eng. Des. 203, 117–131.

Hosler, E.R., 1968. Flow patterns in high pressure two-phase (steam–water) flow with heat addition. Chem. Eng. Prog. Symp. Ser. 64, 54–66.

Mishima, K., Hibiki, T., Nishihara, H., 1993. Some characteristics of gas–liquid flow in narrow rectangular ducts. Int. J. Multiphase Flow 19, 115–124.

Mishima, K., Ishii, M., 1984. Flow regime transition criteria for upward two-phase flow in vertical tubes. Int. J. Heat Mass Transfer 27, 723–737.

Pettersen, J., 2002. Flow vaporization of CO_2 in microchannel tubes. PhD thesis, Norwegian University of Science and Technology.

Spindler, K., Hahne, E., 1999. An experimental study of the void fraction distribution in adiabatic water–air two-phase flows in an inclined tube. Int. J. Therm. Sci. 38, 305–314.

Wambsganss, M.W., Jendrzejczyk, J.A., France, D.M., 1991. Two-phase flow patterns and transitions in a small, horizontal, rectangular channel. Int. J. Multiphase Flow 17, 327–342.

Wilmarth, T., Ishii, M., 1994. Two-phase flow regimes in narrow rectangular vertical and horizontal channels. Int. J. Heat Mass Transfer 37, 1749–1758.

Xu, J., 1999. Experimental study on gas–liquid two-phase flow regimes in rectangular channels with mini gaps. Int. J. Heat Fluid Flow 20, 422–428.

Xu, J.L., Cheng, P., Zhao, T.S., 1999. Gas–liquid two-phase flow regimes in rectangular channels with mini/micro gaps. Int. J. Multiphase Flow 25, 411–432.

Yun, R., Kim, Y., Kim, M.S., Choi, Y., 2003. Boiling heat transfer and dryout phenomenon of CO_2 in a horizontal smooth tube. Int. J. Heat Mass Transfer 46, 2353–2361.

Zhao, L., Rezkallah, K.S., 1993. Gas–liquid flow patterns at microgravity conditions. Int. J. Multiphase Flow 19, 751–763.

Zuber, N., Staub, F.W., Bijwaard, G., Kroeger, P.G., 1967. Steady state and transient void fraction in two-phase flow systems: Final report for the program of two-phase flow investigation, GEAP-5417. Research and Development Center Schenectady, New York, pp. 82–92.