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The effect of tube diameter on vertical two-phase flow regimes in small tubes

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Abstract

Flow boiling flow patterns in four circular tubes with internal diameters of 1.10, 2.01, 2.88 and 4.26 mm were investigated in the present project. The experiments were conducted in vertical upward two-phase flow using R134a as the working fluid. The observed flow patterns include dispersed bubble, bubbly, confined bubble, slug, churn, annular and mist flow. The flow characteristics in the 2.88 and 4.26 mm tubes are similar to those typically described in normal size tubes. The smaller diameter tubes, 1.10 and 2.01 mm, exhibit strong "small tube characteristics" as described in earlier studies. The sketched flow maps show that the transition boundaries of slug-churn and churn-annular depend strongly on diameter. On the contrary, the dispersed bubble to churn and bubbly to slug boundaries are less affected. The transition boundaries are compared with existing models for normal size tubes showing poor agreement.

Keywords: Flow patterns; Two-phase flow; Small diameter; Vertical

1. Introduction

The literature review carried out as part of this project revealed that there are a number of vague statements and discrepant results in the reported studies of two-phase flow regimes in small channels, which need further experimental work and theoretical investigation. To start with, the classification of normal, small and microchannels is not as yet well defined. Currently, the lack of general agreement on this issue makes the comparison between the experiments difficult, especially when using different fluids or at different experimental conditions. Engineers used to regard tube diameters in the order of centimetre and millimetre as normal and small-scale tubes, respectively. Now many researchers think the criterion ought to be based on the combination of channel size and fluid thermo-hydraulic properties rather than only on channel dimension. Kew and Cornwell [1] reported that two-phase flow exhibits different flow and heat transfer characteristics when the confinement number, $Co = (\sigma/\Delta\rho g D^2)^{1/2}$, is greater than 0.5. For instance, isolated bubbles prevail when $Co > 0.5$ and form a typical flow regime in small tubes, i.e. confined bubble flow. Brauner and Moalem-Maron [2] recommended Eötvös number, defined as $E\ddot{o} = (2\pi)^2\sigma/\Delta\rho g D^2$, as the criterion indicating confinement effects. They stated that surface tension dominates when $E\ddot{o} > 1$ and this marks the boundary for small passages. Triplett et al. [3] found that stratified flow became impossible when $E\ddot{o} > 100$ in their experiments indicating size effects. Akbar et al. [4] summarized the previous studies and concluded that the buoyancy effect can be negligible when the Bond number, $Bo = (\Delta\rho g D^2/\sigma)^{1/2}$, is less than 0.3 for which condition the flow regimes are insensitive to the channel orientation. In fact, all classification numbers, Co, $E\ddot{o}$ and Bo, consider the effect of fluid density, surface tension and channel size on two-phase flow. Table 1 illustrates the different results given by the above three criteria, i.e. the size of a tube that indicates deviation from normal size behaviour. The

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Nomenclature

Bo	Bond number $\left[\sqrt{D^2g(\rho_l-\rho_g)/\sigma}\right]$
Co	Confinement number $\left[\sqrt{\sigma/D^2g(\rho_l-\rho_g)}\right]$
D	tube diameter, m
$E\ddot{o}$	Eötvös number $[(2\pi)^2Co^2]$
g	gravitational acceleration, m/s^2
u	velocity, m/s
We	Weber number $[\rho Du^2/\sigma]$

Greek symbols

ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

g	saturated gas/vapour
gs	based on superficial gas velocity
l	saturated liquid
ls	based on superficial liquid velocity

Table 1
The different criteria for small tubes

Parameters	Air/water	R134a		
Pressure (MPa)	0.10	0.60	1.00	1.40
Temperature (°C)	25.0	21.6	39.4	52.5
Surface tension	7.20E−02	8.39E−03	6.15E−03	4.61E−03
Gas density	1.185	29.04	49.06	70.7
Liquid density	997.0	1218.2	1148.3	1090.2
Gravitational acceleration	9.81	9.81	9.81	9.81
	Critical diameter (mm)			
Criterion based on $E\ddot{o}=1$	17.1	5.3	4.7	4.3
Criterion based on $Co=0.5$	5.4	1.7	1.5	1.4
Criterion based on $E\ddot{o}=100$	1.71	0.53	0.47	0.43
Criterion based on $Bo=0.3$	0.81	0.25	0.23	0.20

discrepancy is quite large especially if $E\ddot{o}=1$ is included. For example, as seen in the table, for the air/water mixture the criteria give a range from 0.81 to 17.1 mm. Note that the diameter corresponding to $Co=0.5$ is 6.66 times that based on $Bo=0.3$. Similarly the diameter is proportional to $E\ddot{o}^{-1/2}$ so changing the criterion $E\ddot{o}=100$ to $E\ddot{o}=1$ increase the critical diameter by a factor of 10. Therefore, the need for further work to clarify and conclude on the classification of normal and small size tubes is obvious. The distinction between small diameter channels, minichannels and microchannels based on heat transfer results, is not clearly established in the literature, Kandlikar [5]. He reviewed the developments and application of flow boiling in channels and summed up that: 3 mm may be the lower limit for the hydraulic diameters of the conventional evaporator tubes; channels employing hydraulic diameter between 200 and 3 mm maybe referred to as minichannels; tubes with 10–200 μm hydraulic diameter could be considered as microchannels. This is of course a general classification and further verification and adoption maybe needed.

In addition to the above, there is also inconsistency on the identification of flow patterns. Some flow maps sketched by different researchers may be dissimilar even though they used similar tubes under similar conditions. Fig. 1 compares the vertical upward flow maps by Oya [6], Barnea et al. [7], Fukano and Kariyasaki [8], and Mishima and Hibiki [9]. The disagreements are obvious. For example, large differences exist at the transition boundaries of dispersed bubble (or bubble) flow to intermittent flow and the transition boundary of intermittent to annular flow predicted by Barnea et al. and the rest of the researchers. Furthermore, the flow pattern descriptions presented by different researchers show variations. Oya preferred a detail classification. He reported simple bubble, granular-lumpy bubble, simple slug, fish-scale type slug, piston, long piston, froth and annular in his experiments. From his description and sketch, simple bubble and granular-lumpy bubble are bubble flow and the other, except annular, are intermittent flow. In the flow map reported by Barnea et al. the flow patterns were classed as dispersed bubble, elongated bubble, slug, churn and annular. They grouped

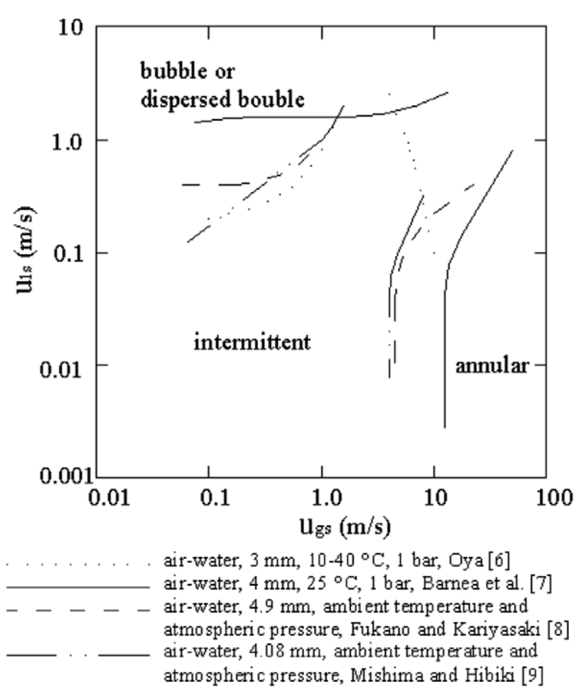

Fig. 1. Comparison of the air–water vertical upward flow maps at room condition.