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Numerical Investigation on Wake of Single Air Bubble Rising in Narrow Rectangular Channel

L.Q. Zhang, Y.P. Huang, Y.F. Zan, J.F. Wang
CNNC Key Laboratory on Nuclear Reactor Thermal Hydraulics Technology
Nuclear Power Institute of China, Chengdu, China
Liqinzhang001@163.com, hyanping007@163.com, yfzan@163.com, walojef@163.com;

Abstract

A wake is closely related to bubble interaction, which might influence the flow regime's evolution and transition in two phase flow. In the present paper, length and flow patterns of the wake of a single air bubble rising in a vertical narrow rectangular channel was numerically studied, and correlations with dimensionless numbers, obtained from dimensional analysis for wake length calculations, were fitted. The cross section of the rectangular channel was 60×2 mm^2, and bubbles with diameter of 2.0-22.0 mm rising in a stagnant fluid were calculated with the VOF model. Investigations on the wake of single air bubbles are of fundamental significance to disclosure differences between air-water and vapor-water two phase flow regimes from the microscopic view in a narrow rectangular channel.

Keywords: Flow pattern, wake, single air bubble, rectangular channel, two-phase flow, thermal hydraulics

1. Introduction

The phenomena of gas-liquid two phase flow can be found in numerous fields in engineering, e.g., nuclear reactor, power plant equipment, chemical, electrical, aviation industry. Flow patterns are the basis for choosing the right formula to do calculations of two phase flow, especially in safety analysis of nuclear reactor. A narrow rectangular channel is widely used in smaller volume and high efficient heat exchange systems in fields of advanced nuclear reactor systems, microelectronics, fusion reactor systems and so on. Flow patterns and transition criteria were investigated by many researchers in narrow rectangular channels [1-3]. Their experiments showed that the flow patterns and transition criterions were different for air-water systems and vapor-water systems. Flow pattern images and transition criterion used now are mainly obtained from air-water systems under adiabatic conditions. But practical applications are vapor-water systems under heating or cooling conditions. So finding out the mechanism for differences between air-water flow patterns and vapor-water flow patterns is of significant importance for exact calculation of two phase flows in narrow rectangular channels in two phase flow systems.

Bubbly flow is the most common two phase flow state where the gas phase is distributed in the form of dispersed bubbles in continuous liquid phase. Of the bubble motion characteristics, the wake of bubbles describes the velocity field, temperature field, and pressure field affected by the bubble motion, which affects interaction and coalescence between two consecutive bubbles and influences flow patterns and it's final transition .

The flow in the wake region has been studied by several authors. Moissis and Griffith (1962)[4] concluded that there was a minimum distance between two consecutive rising Taylor bubbles $l_{\min}$, above which there was no interaction. Pinto and Peiheiro et al (1998)[5] reported that the minimum distance $l_{\min}$ between two Taylor bubbles can be divided into two parts: one occupied by the wake of the leading bubble l_w and the other corresponds to the region where the liquid coming from the wake of the leading bubble recovers its initial condition i.e., the length needed to have again motionless liquid. A few investigations investigated length and flow pattern of the wake. Campos and Carvalho (1988)[6] did a photographic study of the flow in the wake of individual Taylor bubbles rising in stagnant liquids. The authors identified three different flow patterns in the wake (laminar, transitional and turbulent). They stated that for sufficiently long bubbles (longer than $Z^* = (ga^2 2\nu + U_b)/2g$, where a is the thickness of the stabilized annular liquid film flowing around the bubble, U_b stands for the bubble velocity, g is the acceleration due to gravity and ν is the kinematic viscosity of the fluid) the type of flow pattern in the wake and wake length depend only on the inverse viscosity number $N_f = (gD^3)^{1/2}/\nu$, where D is the pipe inner diameter. They also obtained the correlations for wake length and volume: $l_w / D = 0.30 + 1.22\times10^{-3} N_f, V_w / D = 7.50\times10^{-4} N_f$ for $200 < N_f < 800$. Pinto and Pinheiro et al. (1998) [5] defined the transitional parameter for flow pattern of wake of Taylor bubble rising in stagnant water: when $N_f < 500$, it is laminar flow with closed and axisymmetric wake with internal recirculatory flow, and when $500 < N_f < 1500$, it is transitory flow with closed asymmetric wake with transitionalrecirculatory flow, and when $N_f > 1500$, it is turbulent flow with open and perfectly mixed wake. The authors proposed a dimensionless parameter $\mathrm{Re}_{U_{rel}}$ ($\mathrm{Re} = \dfrac{\rho_l U_{rel} D}{\mu_l}$, where U_{rel} are relative velocity of bubble to liquid, ρ_l and μ_l are density and viscosity of liquid) to identify flow pattern of a wake for Taylor bubble rising in co-current flowing liquid. When $\mathrm{Re}_{U_{rel}} < 175$, the wake is laminar, and when $175 < \mathrm{Re}_{U_{rel}} < 525$, wake is transitory, and when $\mathrm{Re}_{U_{rel}} > 525$, wake is turbulent. Nogueira et al. (2006)[7] confirmed critical dimensionless numbers defined by Pinto and Pinheiro et al(1998)[5] for Taylor bubble rising in stagnant and co-current flowing fluid. For flowing liquid, Nogueira et al. (2006) [7] obtained the correlation for wake length and volume: $l_w / D = 0.083 + 3.6\times10^{-3}\,\mathrm{Re},\ V_w / D = 1.4\times10^{-3}\,\mathrm{Re} - 0.022$. Liu et al (2013)[8], studied wake structure of N_2Taylor bubble rising in liquid N_2 with PIV, and analysed effects of pipe diameter and tilt angle. Results showed that the wake was highly symmetric in inclined pipes. Size of vortex in the wake increased as tilt angle decreased. Critical dimensionless numbers for wake flow pattern transitions varied according to conclusions by Pinto and Pinheiro et al. (1998)[5]

which might indicate that the criterion obtained from gas bubble rising in water cannot be applied for vapor bubbles.

However, all research above are all about the Taylor bubble rising in annular pipe, which might not applicable for small bubbles rising in narrow rectangular channels. In the present paper, wake length and wake flow patterns are calculated and identified for 2.0-22.0 mm gas bubbles rising in stagnant water through a narrow rectangular channel of $60\times 2\times 400$ mm^3 using the VOF model, and all cases were performed at atmospheric pressure and 15^{o}C, which might be of fundamental significance for identifying the flow regimes differences between air-water two phase flow and vapor-water two phase flow in narrow rectangular channels.

2. Numerical method

In this study, the volume of fluid (VOF) model in the commercial CFD code Fluent is used to simulate air bubbles rising in stagnant water through a narrow rectangular channel. The gas and liquid phase are considered as incompressible fluids and the flow is assumed to be laminar.

In the VOF model, the governing equations are solved using the volume fraction α in each cell. $\alpha = 1.0$ means that the cell is full of air, and $\alpha = 1.0$ means that the cell is full of water. For $0.0 < \alpha < 1.0$, the cell contains an interface of two phases. In each control volume, the volume fractions of all phases sum to unity,

$$\sum_{k=1}^{2} \alpha_k = 1 \qquad (0.1)$$

The tracking of the interface between the phases is accomplished by the solution of a continuity equation for the volume fraction of any of the phases. For the kth phase, the volume fraction equation has the following form:

$$[\frac{\partial(\alpha_{\mathrm{k}})}{\partial t} + \nabla\cdot(\alpha_k \overline{u_k})] = \frac{s_{m,k}}{\rho_k} \qquad (0.2)$$

Where $s_{m,k}$ is the mass source term. In this study, this mass source term is zero due to no mass and heat transfer between air and water under adiabatic condition.

The fields for all variables and properties are shared by the phases. Based on the local volume fraction α_k ($k = g$ for air and $k = l$ for $water$), the appropriate properties and variables will be assigned to each control volume within the domain. The density of each cell is determined as follows:

$$\rho = \alpha_g \rho_g + \alpha_l \rho_l \quad (0.3)$$

All other properties (such as viscosity) are computed in this manner.

In the VOF model, a single momentum equation for an incompressible flow is solved throughout the domain, and the obtained velocity field is shared among the phases:

$$\frac{\partial}{\partial t}(\rho\vec{u})+\nabla\cdot(\rho\vec{u}\vec{u})=-\nabla p+\nabla\cdot\left[\mu\left(\nabla\vec{u}+\nabla\vec{u}^{\mathrm{T}}\right)\right]+\vec{F}+\rho\vec{g} \qquad (0.4)$$

Where $\vec{u}$ is treated as a mass-averaged velocity:

$$\vec{u}=\frac{\alpha_2\rho_2\overrightarrow{u_2}+\alpha_1\rho_1\overrightarrow{u_1}}{\rho} \qquad (0.5)$$

In the momentum equation, the accumulation and convective momentum terms in every cell balance the pressure forces, shear forces, gravitational body forces and additional forces $\vec{F}$, which might be added depending upon the problem. In this bubble simulation, $\vec{F}$ is the surface tension force per unit volume.

Without a phase change, the calculation for air bubbles rising in water doesn’t solve the energy equation. The calculated model is shown in Fig.1. It is a narrow rectangular channel with 60 mm, 2 mm and 400 mm in x, y, and z direction separately. The inlet bottom surface was the velocity inlet boundary, and the outlet top surface was the set pressure outlet boundary with other remaining surfacesconsisting of insulated wall boundaries with non-slip conditions. Constant continuum surface stress and contact angle of 60 degree were adopted. Hexahedral structural mesh was used. The initial shape of the bubble was a cylinder with 2mm in height. Adopting single precision, with the pressure-based solver, PRESTO method for discrete pressure, second order upwind format to solve the momentum equation, PISO method to couple pressure and velocity, we solved all cases, with 0.001s as transient time steps, in parallel. According to the analysis of the grid sensitivity, a hexahedron with a volume of 0.5 mm^3 was employed as each grid.

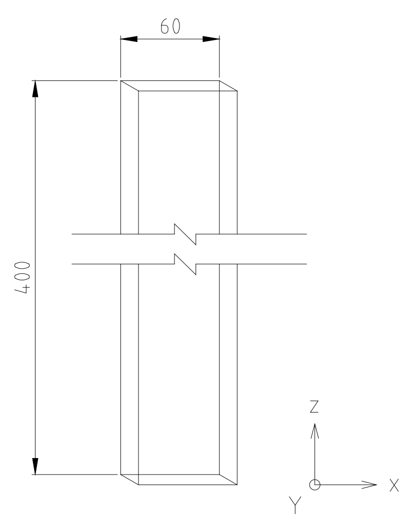


Fig .1 Calculating model

3. Theory

In this study, we applied dimensional analysis to determine dimensionless groups that influence wake length of a single air bubble rising in narrow rectangular channel with stagnant water. A sketch of the top view of a channel is shown in Fig. 2.

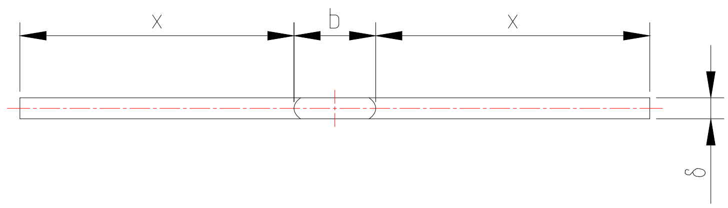


Fig. 2 Sketch of top view of a bubble rising in a narrow rectangular channel

We assume that the bubble locates in the center of the channel, and the bubble contacts the channel wall due to the narrow gap. Minimum bubble volume was that of a spherical ball with diameter of δ. Character size of the bubble was *b*. The wake length depends on seven parameters

$$l_w = f(\delta, x, \Delta\rho, \rho_l, \mu_l, \mu_g, u_{rel}) \qquad (0.6)$$

Where δ is the channel gap, x is the space between bubble edge and channel wall in the wide side, ρ_l and ρ_g are densities of liquid and bubble separately, $\Delta\rho = \rho_l - \rho_g$, μ_l and μ_g are viscosities of liquid and bubble separately, u_{rel} is the relative velocity between bubble and falling liquid film on both sides of bubble. The equation(0.6)'s dimensional analysis can be obtained through traditional $\pi - theorem$ techniques where the chosen independent variables were δ, ρ_l and u_{rel}. Thus, the four dimensionless groups are

$$\pi_1 = \frac{l_w}{\delta} \qquad (0.7)$$

$$\pi_2 = \frac{x}{\delta} \qquad (0.8)$$

$$\pi_3 = \frac{\Delta\rho}{\rho_l} \qquad (0.9)$$

$$\pi_4 = \frac{\mu_l}{\rho_l u_{rel}\delta} = \frac{1}{\mathrm{Re}_{rel,l}} \qquad (0.10)$$

$$\pi_5 = \frac{\mu_g}{\rho_l u_{rel}\delta} = \frac{1}{\mathrm{Re}_{rel,g}} \qquad (0.11)$$

Because $\Delta\rho \sim \rho_l$,so π_3~1 and can be considered negligible. In the same manner, μ_g ~0, so π_3~0 and can be considered negligible as well. Then wake length can be written as

$$\frac{l_w}{\delta} = f(1,1,1,\frac{x}{\delta},\frac{1}{\mathrm{Re}_{rel,l}}) \quad (0.12)$$

Finally, we obtained

$$l_w = f(\mathrm{Re}_{rel,l})x \quad (0.13)$$

$$l_w = C\,\mathrm{Re}_{rel,l}^n\, x \quad (0.14)$$

Where C is a dimensionless coefficient. According to mass conservation, in stagnant water, the water pushed upward by the rising bubble equals to the falling water through both sides of the bubble. Then we can get

$$u_b b\delta = -u_l(W-b)\delta \quad (0.15)$$

Where u_b and u_l are velocities of bubble and liquid separately. $W = 2x + b$, and W is the width of channel. On the basis of equation(0.14), the relative velocity between bubble and liquid can be written as

$$u_{rel} = \frac{W}{W-b}u_b \quad (0.16)$$

On the basis of equation(0.15), we can get $\mathrm{Re}_{rel,l}$ with measured u_b and character size of the bubble.

4. Results and Discussion

4.1 Rising velocity

To validate numerical result, we make a comparison between numerical and experimental data[9] (Fig. 1). The trend of rising velocity changing along with bubble diameter is similar. The difference is that numerical data are about 14%, in average, higher than numerical data for the same diameter. The difference between numerical and experimental data might be due to calculation error. This can be attributed to the difference of channel length. Experimental data were obtained for a test section with a length of 790 mm, and numerical data were obtained for a test section with length of 400 mm which is long enough for bubbles to achieve stable conditions and for watching bubble wake lengths. Both cross section of the channels were 60 $\times$ 2 mm^2. On the basis of velocity comparison, we can find that the numerical data were valid to analyze wake length and flow pattern in the wake.

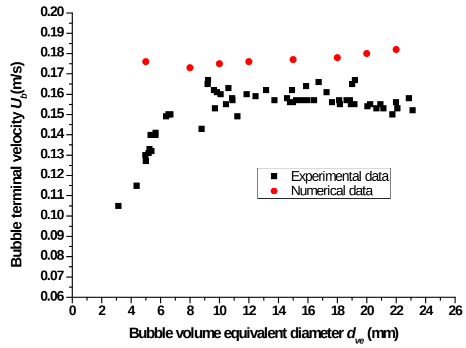


Fig. 3 Rising velocity of a single bubble in a narrow rectangular channel with stagnant water

4.2 Wake length

When the liquid velocity in the cross section below bubble is less than 8e-5 m/s, it can be considered as stagnant. Distance between that cross section and bubble bottom surface is defined as wake length. From numerical analysis, we measured the parameter in equation(0.13). Changing equation(0.17), we get:

$$\ln(l_w / x) = n\ln(\mathrm{Re}_{rel,l}) + \ln C \qquad (0.18)$$

Having obtained data of l_w, x and $\mathrm{Re}_{rel,l}$, through linear fitting we can obtain $n = 0.93$ and $C = 0.0076$. Fitting values and numerical data are shown in Fig. 4. The standard error of n and C are 0.03 and 0.24 separately. In narrow rectangular channels with a cross section of 60 × 2 mm^2 and length of 400 mm, for bubble diameters less than 15 mm ($\mathrm{Re}_{rel,l} < 9550$), the wake length can be calculated by

$$l_w = 0.0076\,\mathrm{Re}_{rel,l}^{0.93}\,x \qquad (0.19)$$

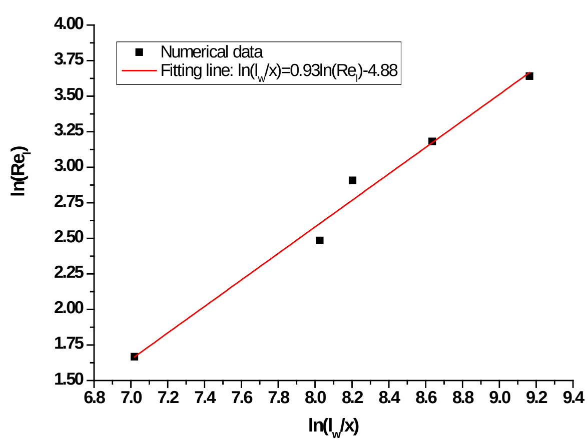
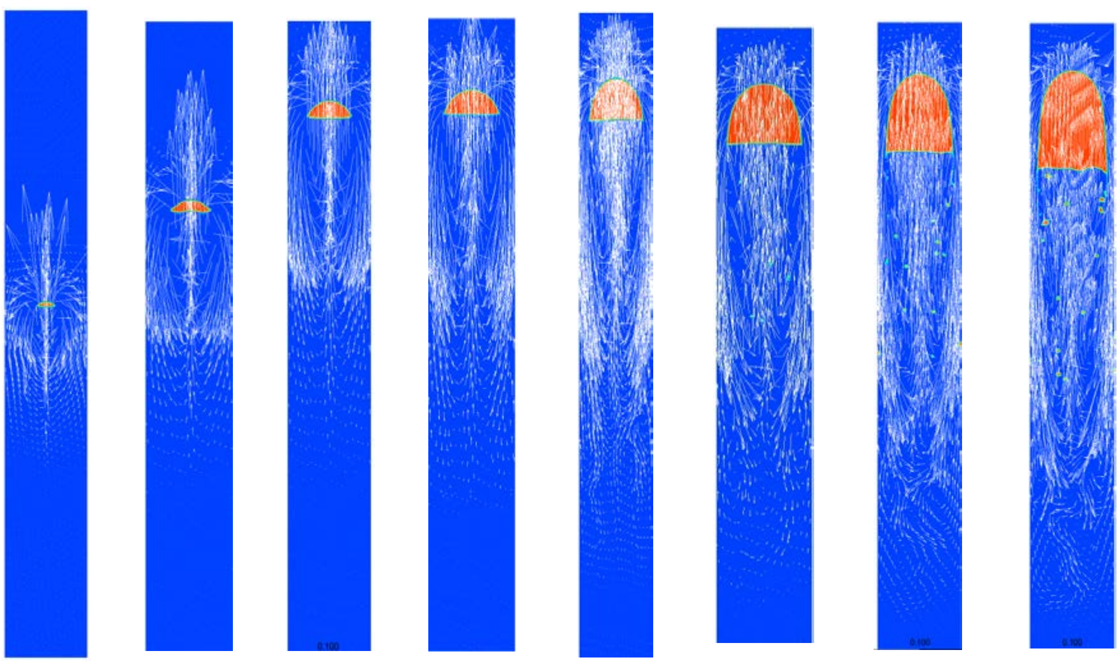


Fig. 4 Fitting line and numerical data of wake length

4.3 Flow pattern

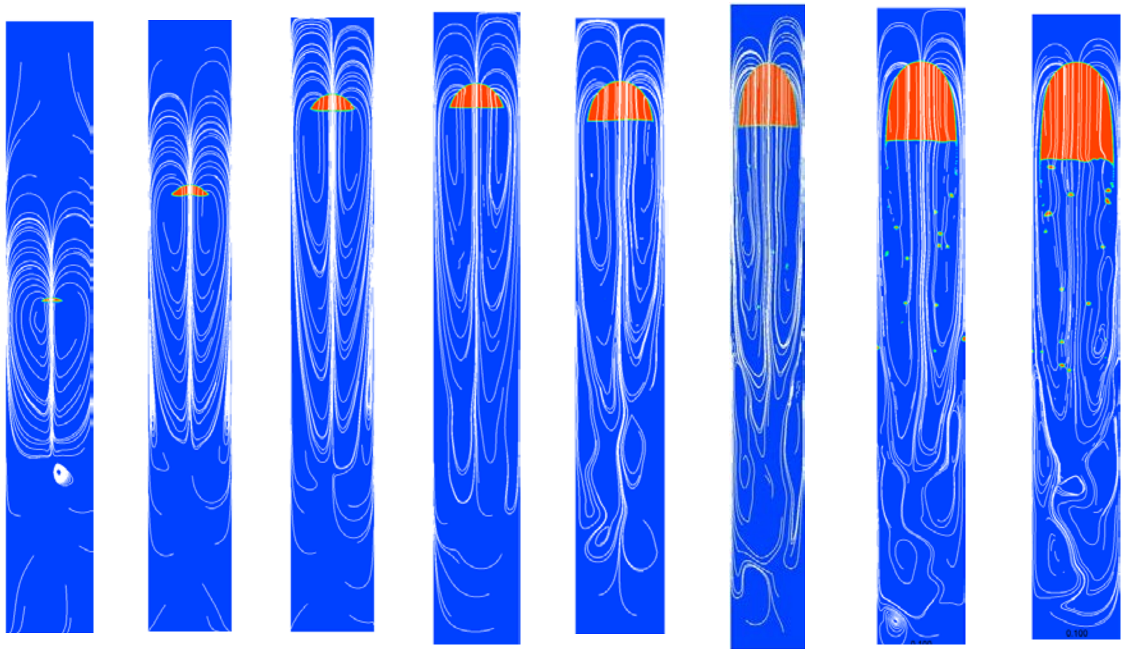
There are three types of flow pattern [7]: laminar wake, transient wake and turbulent wake. Laminar wake was defined as closed axisymmetric wake with symmetric internal toroidal vortex lying in a plane perpendicular to the column axis. Transient wake was defined as closed asymmetric wake with flat rear surface of the bubble and the vortex ring showing a periodic undulation movement whose frequency increases with character dimensionless number (For a bubble rising in a pipe the dimensionless number is N_f, for a bubble rising in narrow rectangular channel the dimensionless number is $\mathrm{Re}_{rel,l}$, defined in the theory section in the paper). Turbulent wake was defined as opened wake with recirculatory flow, and the wake does not have a well-defined boundary with some randomly located recirculating regions for lower values of $\mathrm{Re}_{rel,l}$ or with turbulent eddies several diameters below the rear of the bubble for higher values of $\mathrm{Re}_{rel,l}$.

Fig. 5 shows wake structures (vector fields and streamline) of bubbles with different diameters. According to the wake flow pattern definitions, when the bubble is smaller or equivalent to 10 mm ($\mathrm{Re}_{rel,l} < 3654$), the wake is laminar. When the bubble diameter is greater than 15 mm ($\mathrm{Re}_{rel,l} > 9550$), one has a turbulent wake. The transition value for laminar and transient wake is between 10 mm and 12 mm ($3654 < \mathrm{Re}_{rel,c1} \leq 5630$), and the transition value for transient and turbulent wake is between 12 mm and 15 mm ($5630 < \mathrm{Re}_{rel,c2} \leq 9550$).



d_{ve}=5 mm	d_{ve}=8 mm	d_{ve}=10 mm	d_{ve}=12 mm	d_{ve}=15 mm	d_{ve}=18 mm	d_{ve}=20 mm	d_{ve}=22 mm
$\mathrm{Re}_{rel,l}$=1118	$\mathrm{Re}_{rel,l}$=3059	$\mathrm{Re}_{rel,l}$=3654	$\mathrm{Re}_{rel,l}$=5630	$\mathrm{Re}_{rel,l}$=9550	$\mathrm{Re}_{rel,l}$=14349	$\mathrm{Re}_{rel,l}$=21497	$\mathrm{Re}_{rel,l}$=35864

Fig. 5(a) Vector field of liquid velocity in the wake



d_{ve}=5 mm $Re_{rel,l}$=1118 | d_{ve}=8 mm $Re_{rel,l}$=3059 | d_{ve}=10 mm $Re_{rel,l}$=3654 | d_{ve}=12 mm $Re_{rel,l}$=5630 | d_{ve}=15 mm $Re_{rel,l}$=9550 | d_{ve}=18 mm $Re_{rel,l}$=14349 | d_{ve}=20 mm $Re_{rel,l}$=21497 | d_{ve}=22 mm $Re_{rel,l}$=35864

Fig. 5(b) Streamline of liquid velocity in the wake

5. Conclusions

In the present paper, length and flow pattern of the wake of a single air bubble rising in a vertical narrow rectangular channel were numerically studied, and fit the correlations with dimensionless numbers obtained from dimensional analyses for wake length calculations. Test section was 60 × 2 × 950 mm^3, and bubbles with diameter of 2.0-22.0 mm were investigated. Conclusions can be drawn as follows.

(1) The numerical bubble rising velocity is about 14% on average higher than that of the experimental data, and this might be caused by the different channel length, which can be investigated further in detail.

(2) The length of a wake for bubble diameters less than 15 mm can be calculated by equation(0.20).

(3) There are laminar wakes for bubble diameters less than 10 mm ($Re_{rel,l} < 3654$), and turbulent wakes for bubble diameters greater than 15 mm ($Re_{rel,l} > 9550$).

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References

[1] J. F. Wang, Y.P. Huang, Y.L. Wang, "Visualized experimental observation on flow patterns in a single-side heated narrow rectangular Channel," Nuclear Power Engineering, Vol. 31, No.6, 2010, pp. 80-92 (In Chinese).

[2] Y.L. Wang, B.D. Chen, Y.P. Huang, et al., "Experimental Research on evolvement of Density Wave Oscillation in Parallel Narrow Rectangular Channels," Nuclear Power Engineering, Vol.32, No.5, 2011, pp. 75-79 (In Chinese).

[3] J. Huang ,Y.P. Huang, J. Ma, Wang, Y.L. Wang, et al., "Visual study on bubbles by longitudinal vortex in narrow channel," Chemical Engineering (China), Vol.40, No7, 2012, pp. 46-51 (In Chinese).

[4] R. Miussis, P. Griffith, "Entrance effects in a two phase slug flow,"J. Heat Transfer,Vol. 84, 1962, pp. 29-39.

[5] A. M. F. R. Pinto, M.N. P. Coelho, J.B.L.M. Campos, "Coalescence of two gas slugs rising in a co-current flowing liquid in vertical tubes." Chemical Engineering Science, vol53, 1998, pp: 2973-2983.

[6] J. B. L. M.Campos, J.R.F.G. Carvalho, "An experimental study of the wake of gas slugs rising in liquids." Journal of Fluid Mechanics, Vol. 196, 1988, pp: 27-37.

[7] S. Nogueiraa, M. L.Riethmuller, J. B. L. M. Camposa, A. M. F. R. Pinto, "Flow patterns in the wake of a Taylor bubble rising through vertical columns of stagnant and flowing Newtonian liquids: An experimental study. " Chemical Engineering Science,Vol. 61, 2006, pp: 7199-7212.

[8] Y.P. Liu, P.Y. Wang, J. Wang, Z.H. Du, "Investigation of Taylor bubble wake structure in liquid nitrogen by PIV technique." Cryogenics, Vol.55-56, 2013, pp: 20-29.

[9] Y.P. Liu, P.Y. Wang, J. Wang, Z.H. Du, "Experimental Observations on Wake Characteristics of a Rising Bubble in a Vertical Narrow Rectangular Channel." Nuclear Engineering and Radiation Science, Vol.1, 2014.

[10] R.G. Sousa, A.M.F.R. Pinto, J.B.L.M. Campos, “Effect of gas expansion on the velocity of a Taylor bubble: PIV measurements.” International Journal of Multiphase Flow, Vol.32, 2006, pp: 1182–1190.

[11] L.M.T. Santosa, M.T.M. S.Estevesb, M.N.C. Pinheiro, "Effect of gas expansion on the velocity of individual Taylor bubbles rising in vertical columns with water: Experimental studies at atmospheric pressure and under vacuum." Chemical Engineering Science, Vol.63, 2008, pp: 4464-4474.

[12] L.M.T. Santosa, M.N. C. Pinheiro, "Flow around individual Taylor bubbles rising in a vertical column with water: Effect of gas expansion." International Journal of Multiphase Flow, Vol.63, 2014, pp: 39-51.