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Review:

Liquid film dryout model for predicting critical heat flux in annular two-phase flow*

Bo JIAO†, Li-min QIU, Jun-liang LU, Zhi-hua GAN†‡

(*Institute of Refrigeration and Cryogenic Engineering, Zhejiang University, Hangzhou 310027, China*)

†E-mail: jiaobo_0_0@163.com; gan_zhihua@zju.edu.cn

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Abstract: Gas-liquid two-phase flow and heat transfer can be encountered in numerous fields, such as chemical engineering, refrigeration, nuclear power reactor, metallurgical industry, spaceflight. Its critical heat flux (CHF) is one of the most important factors for the system security of engineering applications. Since annular flow is the most common flow pattern in gas-liquid two-phase flow, predicting CHF of annular two-phase flow is more significant. Many studies have shown that the liquid film dryout model is successful for that prediction, and determining the following parameters will exert predominant effects on the accuracy of this model: onset of annular flow, inception criterion for droplets entrainment, entrainment fraction, droplets deposition and entrainment rates. The main theoretical results achieved on the above five parameters are reviewed; also, limitations in the existing studies and problems for further research are discussed.

Key words: Annular two-phase flow, Critical heat flux (CHF), Liquid film dryout, Deposition rate, Entrainment rate
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INTRODUCTION

Gas-liquid two-phase flow and heat transfer always exist in different types of heat exchangers in many industrial applications, such as boiling tubes, gas-liquid mixers, gas-liquid separators, distillation towers, and condensers. Studies on them gradually become a particular discipline, critical to the national economy. The establishment and development of this discipline are closely related to the progress of engineering technology. In the early period, many accidents happened because of lacking such relevant knowledge as boiler explosion in steam locomotives and boats. Nuclear accidents of the American Three Mile Island nuclear power plant and the Russian Chernobyl nuclear power plant are the most severe ones. It is the accidents that impel the researchers from all over the world to investigate the mechanism of critical heat flux (CHF) of gas-liquid two-phase flow and build its prediction models.

A number of detailed mechanisms triggering CHF have been proposed, roughly classified into two different types (Collier, 1972). One occurs at low vapor quality: a vapor film, formed between liquid phase and the heated wall, stops bubbles flowing out and liquid flowing in; as a result, the wall is superheated. The other occurs in annular flow at high vapor quality: liquid phase flows partly in liquid film adjacent to the wall and partly as droplets in gas core; mass transfer exists at the two-phase interface, such as liquid evaporation, droplets deposition and entrainment. Due to droplets entrainment and liquid evaporation, the mass flow rate of liquid film decreases gradually along the heated tube. When it is down to zero or close to zero at the exit of tube, CHF is reached. The two mechanisms are often called by departure from nucleate boiling (DNB) and annular film dryout (AFD) (Collier, 1972). In both cases, heat transfer from the heated wall suddenly deteriorates and wall temperature rapidly increases since the wall is almost covered by gas phase. The occurrence of either

‡ Corresponding author
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one can cause significant damage to the system and hence should be avoided in industrial applications.

It is well known that annular flow occurs in a wide range of vapor quality (roughly from around 0.1 up to unity) (Celata *et al.*, 2001), and consequently is the most common flow pattern in gas-liquid two-phase flow. Accurate prediction of CHF due to AFD becomes particularly important for engineering applications. Fig.1 shows the flow patterns in upward two-phase flow in vertical tubes, where are three main heat transfer regions: single phase flow, sub-cooled and saturated flow boiling. Generally, in the saturated flow boiling region, the flow pattern varies from bubbly, slug, churn and finally to annular flow (Celata *et al.*, 2001). L is the length, and subscripts sp, bub, ann represent single phase, bubble and annular flow, respectively. In annular flow, there is a complicated process of mass transfer at the two-phase interface. Droplets are entrained to gas core from liquid film; meanwhile, partial droplets in the gas core also deposit to liquid film and partial liquid is evaporated by heat input. Based on the mechanism, Whalley *et al.*(1974) proposed a mathematical model for AFD, considering the steady state with constant physical properties. They provided the following expression for the axial variation of mass flux of liquid film along the heated tube:

$$\frac{\mathrm{d}G_{\mathrm{lf}}}{\mathrm{d}z}=\frac{4}{D}(m_{\mathrm{d}}-m_{\mathrm{e}}-m_{\mathrm{ev}}), \tag{1}$$

where G is the mass flux, z is the axial coordinate, m is the mass transfer rate at the interface, and D is the diameter; subscripts lf, d, e, ev represent liquid film, deposition, entrainment, and evaporation, respectively. $m_{\mathrm{ev}}=q/h_{\mathrm{fg}}$ where q is the heat flux and h_{fg} is the latent heat of vaporization.

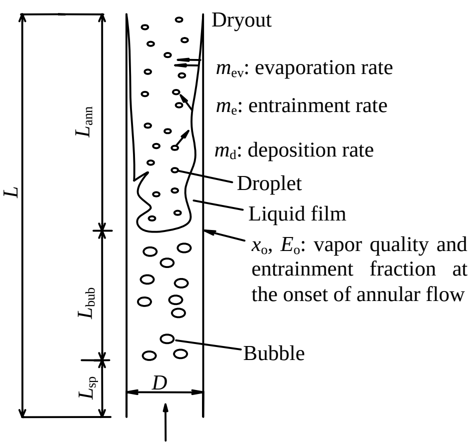

Fig.1 Schematic of the flow pattern in upward two-phase flow vertical tubes (Okawa *et al.* 2003)

Extensive studies have proved that the liquid film dryout model is very successful for predicting CHF of annular flow. According to Eq.(1), accurate correlations for the following parameters are important: the initial mass flux of liquid film at the onset of annular flow G_{lfo}, droplets entrainment and deposition rates. G_{lfo} can be determined by:

$$G_{\mathrm{lfo}}=G(1-x_{\mathrm{o}})(1-E_{\mathrm{o}}), \tag{2}$$

where subscript o represents the onset of annular flow; x is the vapor quality and E is the entrainment fraction —the ratio of the droplets mass entrained to gas core to the total mass of liquid phase, varying between 0 and a value close to 1, calculated by:

$$E=(J_{\mathrm{l}}-J_{\mathrm{lf}})/J_{\mathrm{l}}, \tag{3}$$

where J is the volumetric flux; subscript l represents liquid phase. Since droplets entrainment occurs under certain conditions, its inception criterion is also indispensable. In this paper, the main theoretical developments, achieved on all components in the liquid film dryout model, are reviewed, including onset of annular flow, inception criterion for droplets entrainment, entrainment fraction, droplets deposition and entrainment rates. We also discuss limitations in the existing studies and problems for further research. Moreover, it should be noticed that: (1) Annular flow also occurs in the downward two-phase flow in vertical tubes, the horizontal tubes, and the tubes with certain inclinations. The studies under discussion of this paper can be applied for annular flow in any flow conditions. However, most of them focus on the phenomena in upward two-phase flow in vertical tubes, and generally use air-water or stream-water as working fluid; (2) Owing to its base on annular flow pattern, the liquid film dryout model cannot be applied for predicting CHF, which is mainly caused by other mechanisms such as DNB.

ONSET OF ANNULAR FLOW

As being valid only for annular flow regions, Eq.(1) should be integrated from the onset of annular flow to the exit of tube, which is marked by L_{ann} in Fig.1. The first question is therefore how to determine the onset of annular flow. At present, many studies are based on empirical correlations; for example, Wallis proposed the correlations for gas superficial velocity (Wallis, 1961) and vapor quality (Wallis, 1969) at the onset of annular flow, respectively:

$$J_{go} = \sqrt{gD(\rho_l - \rho_g)} \Big/ \rho_g^{0.5}, \quad (4)$$

$$x_o = \frac{0.6 + 0.4\sqrt{gD(\rho_l - \rho_g)\rho_l} \Big/ G}{0.6 + \sqrt{\rho_l / \rho_g}}, \quad (5)$$

where g is the gravitational acceleration and ρ is the density; subscript g represents gas phase. The above equations have been widely applied in other studies; for example, Eq.(4) is used in the models of Hewitt and Govan (1990) and Govan (1988), and Eq.(5) is deployed in the models of Okawa *et al.*(2003; 2004b). Another correlation for gas superficial velocity was proposed by Mishima and Ishii (1984):

$$J_{go} = \left[\frac{\sigma g(\rho_l - \rho_g)}{\rho_g^2}\right]^{0.25} \left\{\frac{\rho_l \sigma}{\sqrt{\sigma / [g(\rho_l - \rho_g)]}}\right\}^{0.1}, \quad (6)$$

where σ is the surface tension. Eq.(6) is also widely used in related studies, including the models of Celata *et al.*(2001), Bai *et al.*(2003), and Fan *et al.*(2006). Compared with Eqs.(4) and (5), Eq.(6) includes the effect of surface tension, neglecting the effect of diameter, however. In addition, some studies provide a fixed value of vapor quality or void fraction for the onset of annular flow. For instance, Whalley and Jepson (1994) suggested that x_o be equal to 0.01 at low pressure, and about 0.15 at high pressure; Katto (1984) and Lee *et al.*(2000) both proposed that α_o was in the range of 0.60~0.85.

J_g and α are both functions of x. The former can be expressed as Gx/ρ_g and the correlation for the latter depends on the model of the relationship between α and x, such as the homogeneous model or drift flux model. Therefore, the criteria for the onset of annular flow are essentially based on x. At present, most of the studies just employ one of them in their models, without discussing the effect of different criteria on the model accuracy. To our knowledge, only Govan (1988) pointed that the prediction of CHF was not sensitive to x_o. Paucity of relevant information on this thus calls up further research to reach an agreement or find out new characteristics.

INCEPTION CRITERIA FOR DROPLETS ENTRAINMENT

In annular flow, the surface of liquid film is not smooth but covered with waves. The shape of waves depends on the velocities of liquid and gas phase. The experiments on the process of droplets creation (Woodmansee and Hanratty, 1969; Azzopardi and Whalley, 1980; Asali *et al.*, 1985; Schadel *et al.*, 1990) indicate that droplets cannot be generated until the mass flux of liquid film exceeds a certain value and the roll waves are formed. Droplets can be entrained to gas core in different ways, which depends upon the force acting on the wave crests and the shape of interface. Based on the experimental results, the entrainment mechanisms in concurrent two-phase flow were divided into four basic types by Ishii and Grolmes (1975) (Fig.2):

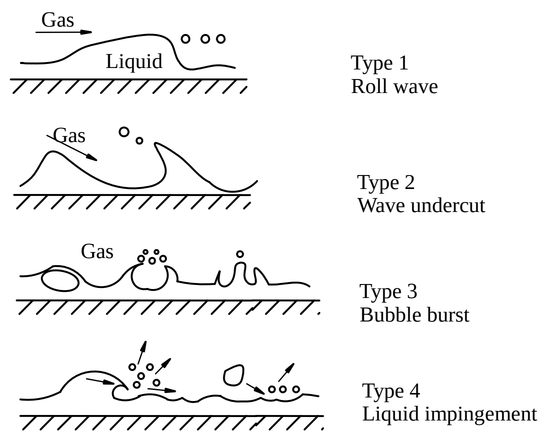

Fig.2 Schematic of the four types of entrainment mechanism (Ishii and Grolmes, 1975)

In the first type, the tops of large amplitude roll waves are sheared off from wave crests by the turbulent gas flow, which is commonly observed in the experiments (Rossum, 1951; Hewitt and Hall-Taylor, 1970). The second type of entrainment is caused by undercutting the liquid film by the gas flow. The third type is related to the moving and bursting of bubbles. When the bubble reaches the interface, a thin layer of liquid film is formed at the top of the bubble, eventually rupturing into droplets as the bubble enters into the gas core. The fourth type is caused by the impingement to the surface of liquid film; advancing roll-wave fronts may produce small size droplets by this mechanism. In general, these four types do not exist in isolation, but affecting the mass and momentum transfer between liquid and gas phase together (Ishii and Grolmes, 1975).

Ishii and Grolmes (1975) performed a careful investigation on the available experimental data of entrainment inception in concurrent two-phase flow. The data were plotted on the liquid Reynolds number Re_{lf} versus the critical gas velocity u_{g}, and according to the result, there were at least three different regimes for each fluid, as shown in Fig.3. They held that the wave should penetrate through the gas boundary layer, in order to have a full dynamic interaction between the turbulent gas core and the liquid film. Based on the above assumption, a correlation for the critical Reynolds number of liquid film Re_{lfc} was proposed.

$$Re_{\mathrm{lfc}} = (y^+/0.347)^{1.5}(\rho_{\mathrm{l}}/\rho_{\mathrm{g}})^{0.75}(\mu_{\mathrm{g}}/\mu_{\mathrm{l}})^{1.5}, \quad (7)$$

where μ is the dynamic viscosity and y^+ is the dimensionless distance from the wall; subscript c represents critical value. The amplitude-film thickness relation and the standard boundary layer theory indicate that y^+ is in the range of 30/4~30/2, where 30 stands for the thickness of the sub-layer and the buffer layer. By taking the mean value, 10 was set for y^+. The critical value determined by Eq.(7) sets the

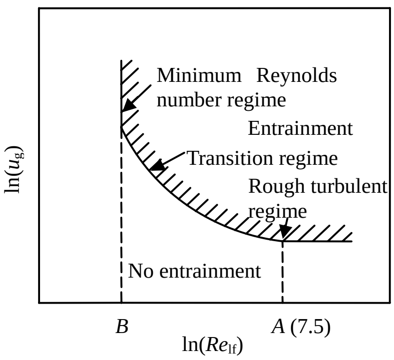

Fig.3 Schematic of the inception criteria for droplets entrainment (Ishii and Grolmes, 1975)

absolute limit for the onset of entrainment (Point *B* in Fig.3), below which entrainment cannot occur irrespective of the gas velocity.

Fig.3 also shows the absolute limit (Point *A*) of the critical gas velocity. For the first type of entrainment mechanism, Ishii and Grolmes (1975) developed the following correlation on the basis of the balance among the viscous force inside liquid film, the surface tension and the shear stress acting on the wave crests:

$$\frac{\mu_{\mathrm{l}} J_{\mathrm{gc}}}{\sigma}\sqrt{\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{l}}}} \geq \begin{cases} N_{\mu}^{0.8}, & N_{\mu} < 1/15 \ (Re_{\mathrm{lf}} > 1635); \\ 0.1146, & N_{\mu} > 1/15 \ (Re_{\mathrm{lf}} > 1635), \end{cases} \quad (8)$$

where the viscosity number N_μ is given as:

$$N_{\mu} = \frac{\mu_{\mathrm{l}}}{\left(\rho_{\mathrm{l}}\sigma\sqrt{\sigma/[g(\rho_{\mathrm{l}}-\rho_{\mathrm{g}})]}\right)^{1/2}}. \quad (9)$$

In the transition region between the two limits, the critical gas velocity becomes a function of liquid film Reynolds number, which indicates that the liquid film flow and gas flow both contribute to the momentum exchange. The visualization carried by Rossum (1951) showed that the entrainment mechanism at a lower Reynolds number of liquid film was similar to the second type in Fig.2. Hence, Ishii and Grolmes (1975) built a model for that and developed the following correlation for the transition region:

$$(\mu_{\mathrm{l}} J_{\mathrm{gc}}/\sigma)\sqrt{\rho_{\mathrm{g}}/\rho_{\mathrm{l}}} \geq 1.5 Re_{\mathrm{lf}}^{-1/3}. \quad (10)$$

For the first type of entrainment mechanism, Asali *et al.*(1985) analyzed the stability of roll waves on the interface, and provided a correlation between the critical Reynolds number of liquid film and the parameter group $(\mu_{\mathrm{l}}/\mu_{\mathrm{g}})(\rho_{\mathrm{g}}/\rho_{\mathrm{l}})^{0.5}$. Owen and Hewitt (1987) modified the correlation by considering the effect of liquid evaporation:

$$Re_{\mathrm{lfc}} = \exp[5.8504 + 0.4249(\mu_{\mathrm{g}}/\mu_{\mathrm{l}})\sqrt{\rho_{\mathrm{l}}/\rho_{\mathrm{g}}}]. \quad (11)$$

According to some following studies, the above equations (Eqs.(7)~(11))—though can be used as the criteria for the onset of droplets entrainment under many conditions—still had some deficiencies in explaining the effects of some parameters. For example, in the experiments for the first type of entrainment mechanism, Willetts (1987) found that surface tension had an effect on the critical Reynolds number of liquid film, which was not accounted for in Eqs.(7) and (11). Azzopardi (1997) reported that pipe diameter and liquid viscosity both had significant effects on the critical Reynolds number of liquid film. However, Eqs.(7) and (11) do not include the effect of pipe diameter. For liquid viscosity, Eq.(7) overestimates its effect, while Eq.(11) underestimates that. In addition, Azzopardi (1997) noted that the predictions of Eq.(7) were obviously smaller than the experimental data, able to be modified by using 30 for y^+. The experimental investigation by Jepson (1992) at a lower Reynolds number of liquid film indicated that the predictions of Eq.(10) were also much smaller than the experimental data.

As seen from the above summary, the available studies usually use the critical Reynolds number of liquid film or the critical gas superficial velocity as the inception criterion for droplets entrainment. The developed correlations, notwithstanding their validity under many conditions, should be further investigated because of their certain limitations in explaining the effects of some parameters.

ENTRAINMENT FRACTION

The distribution of liquid phase flow between the liquid film and the entrained drops is characterized by entrainment fraction E. Govan (1988) found that the prediction of CHF was sensitive to the entrainment fraction at the onset of annular flow E_o. The mass transfer between liquid and gas phases is complicated and entrainment fraction is a dynamic equilibrium between the competing effects of entrainment and deposition (Whalley and Jepson, 1994). Therefore, there is little experimental data about E_o, which is almost empirically assumed in the present models. For example, Whalley *et al.*(1974) and Saito *et al.*(1978) assumed that E_o was equal to 0.9, while Hewitt and Govan (1990) used 0.99; Govan *et al.*(1988) and Sugawara (1990) both chose different values according to different conditions. Based on the tentative calculations, Celata *et al.*(2001) found the value according best with the experimental data. Besides, some studies made E_o equal to the value at equilibrium state (Lee *et al.*, 2000; Okawa *et al.*, 2003; 2004b). The comparisons between the experimental data and the predictions with 0.01 or 0.99 for E_o were performed by Hewitt and Govan (1990), as shown in Fig.4, where T accounts for temperature, and subscript w represents wall. It can be seen that the assumed value of E_o has little effect at lower mass flux, but exerting a significant effect at higher mass flux. Only the conditions in Fig.4 were discussed in the study of Hewitt and Govan (1990) which also did not explain the criterion for high or low mass flux in general conditions. Therefore, the validity of this conclusion in a wider range was not shown clearly.

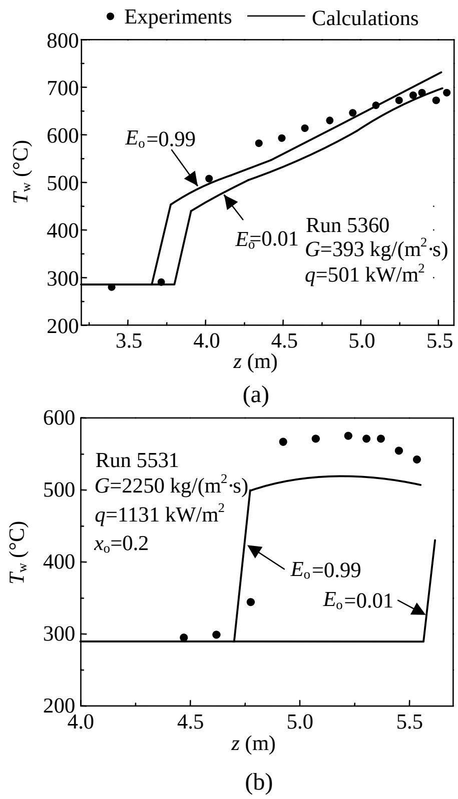

Fig.4 Comparisons with post-dryout data (a) at low mass flux and (b) at high mass flux (Hewitt and Govan, 1990)

Theoretical studies on entrainment fraction are mostly based on the equilibrium state, at which entrainment rate is equal to deposition rate. Wicks and Dukler (1960) correlated the droplets mass flow in terms of the Martinelli parameter. This correlation—though reported to reach a reasonable agreement—is dimensional, which limits the applicable ranges. In order to eliminate the problem, Paleev and Filippovich (1966) introduced a dimensionless gas flux, and proposed the following correlation by fitting to the data combination from Armand (1964), Hujghe and Mondin (1961), Collier and Hewitt (1961), Magiros and Dukler (1961), and their experiments (Paleev and Agafonova, 1962), as shown in Fig.5:

$$1-E_{\mathrm{eq}}=0.985-0.44\lg\left[\left(\frac{\rho_{\mathrm{gh}}}{\rho_{\mathrm{l}}}\right)\left(\frac{\mu_{\mathrm{l}}J_{\mathrm{g}}}{\sigma}\right)^2\times 10^4\right], \quad (12)$$

where subscript eq represents equilibrium state; ρ_{gh} is the homogeneous model of gas core density and given as:

$$\rho_{\mathrm{gh}}=\rho_{\mathrm{g}}+\rho_{\mathrm{l}}(J_{\mathrm{l}}-J_{\mathrm{lf}})/J_{\mathrm{g}}. \quad (13)$$

Fig.5 shows that the predictions of Eq.(12) can agree well with the experimental data in a certain range. However, it neglects the effects of tube diameter and liquid Reynolds number, and cannot explain the criterion for the onset of entrainment. The problems were modified by Ishii and Mishima (1989), who correlated entrainment fraction in terms of Weber number and liquid Reynolds number and used the hyperbolic tangent function as the inception criterion for entrainment. By fitting to the data from Steen and Wallis (1964) and Cousins *et al.*(1965) and Cousins and Hewitt (1968a) (0.1~0.27 MPa), as shown in Fig.6, they provided the following correlations:

$$E_{\mathrm{eq}}=\tanh(7.25\times 10^{-7}We^{1.25}Re_{\mathrm{l}}^{0.25}), \quad (14)$$

$$We=\frac{\rho_{\mathrm{g}}J_{\mathrm{g}}^2D((\rho_{\mathrm{l}}-\rho_{\mathrm{g}})/\rho_{\mathrm{g}})^{1/3}}{\sigma}, \quad (15)$$

$$Re_{\mathrm{l}}=\rho_{\mathrm{l}}J_{\mathrm{l}}D/\mu_{\mathrm{l}}. \quad (16)$$

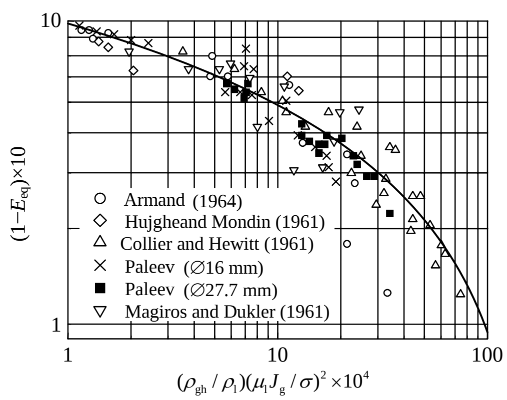

Fig.5 Correlation of entrainment fraction at the equilibrium state (Paleev and Filippovich, 1966)

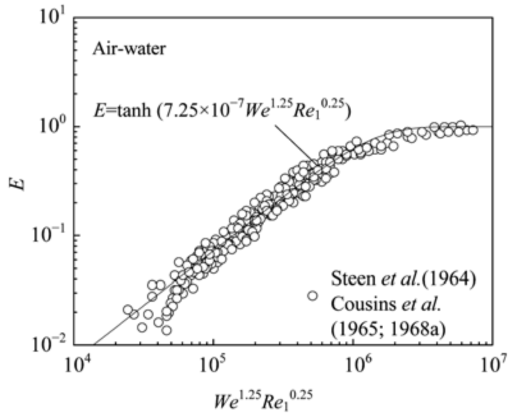

Fig.6 Correlation of entrainment fraction at the equilibrium state (Ishii and Mishima, 1989)

Utsuno and Kaminaga (1998) compared the predictions of Eq.(14) with the experimental data at high pressures (3~9 MPa) from Singh *et al.*(1969), Keeys *et al.*(1970) and Wurtz (1978b). As the results show in Fig.7a, they are not valid for high pressures, especially at lower values of $We^{1.25}Re_{\mathrm{l}}^{0.25}$. According to Eqs.(14)~(16), E_{eq} is related to $J_{\mathrm{g}}^{2.5}J_{\mathrm{l}}^{0.5}$. Utsuno and Kaminaga (1998) proposed that the scattering in Fig.7a was caused by the overestimated effect of gas flux, due to an increment in gas density at high pressures. Therefore, they changed the dimensionless parameter into $We^{0.5}Re_{\mathrm{l}}$, making E_{eq} related to $J_{\mathrm{g}}J_{\mathrm{l}}$. By fitting to the same data (Fig.7b), the following correlation was proposed:

$$E_{\mathrm{eq}}=\tanh[0.16(We^{0.5}Re_{\mathrm{l}})^{0.16}-1.20]. \quad (17)$$

All the correlations above are based on the equilibrium state. However, the entrance effect was studied experimentally by Cousins *et al.*(1965) and Gill *et al.*(1962). Results show that entrainment fraction varies obviously within a certain distance from the entrance of tube, which is also sensitive to liquid injection method. Entrainment fraction keeps constant when the axial distance z is greater than a certain value, indicating that the equilibrium state is reached. For the case with the relatively smooth injection of liquid as a film, Ishii and Mishima (1981) provided a dimensionless length scale ζ:

$$\zeta=(z/D)(Re_{\mathrm{l}}^{0.5}/We^{0.25}). \quad (18)$$

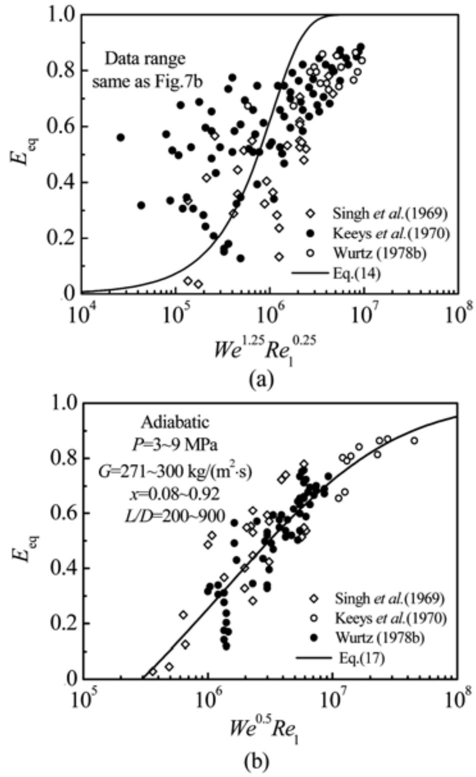

Fig.7 Adjustment of the (a) correlation of Ishii and Mishima (1989) and (b) proposed correlation for E_{eq} at high pressures (Utsuno and Kaminaga, 1998)

By fitting to the data obtained by Cousins *et al.*(1965) and Gill *et al.*(1962), the relationship between entrainment fraction and the dimensionless length was proposed:

$$E=(1-\exp(-1.87\times10^{-5}\zeta^2))E_{eq}, \quad (19)$$

where E_{eq} is determined by Eqs.(14)~(16). The above equation can be rewritten as:

$$\left(\frac{We^{0.25}D}{E_{eq}Re_l^{0.5}}\right)\frac{\partial E}{\partial z}=3.74\times10^{-5}\zeta\exp(-1.87\times10^{-5}\zeta^2). \quad (20)$$

Fig.8 shows the comparisons between the predictions of Eq.(20) and the experimental data. Although the experimental data is considerably scattered, the general trend can be predicted. It is furthermore indicated that the entrance region is in the range of 0<ζ<440 (Kataoka *et al.*, 2000). When ζ is more than 440, the equilibrium state is reached with constant entrainment fraction.

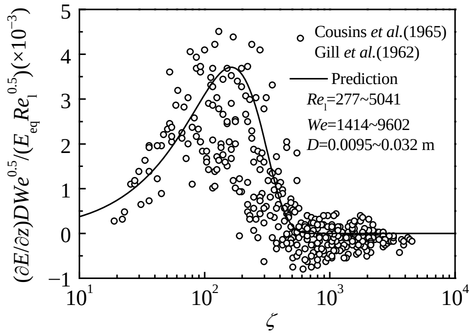

Fig.8 $\frac{\partial E}{\partial z}DWe^{0.5}/(E_{eq}Re_l^{0.5})$ vs ζ for the data of Cousins *et al.* and Gill *et al.* (Ishii and Mishima, 1981)

In addition to the correlations obtained by fitting to the experimental data, some studies focus on the analytical model based on the entrainment mechanism. Deposition rate is therein generally assumed proportional to the droplet concentration in gas core C:

$$m_d=k_dC=k_d(G_l-G_{lf})/(J_gS), \quad (21)$$

where k is the mass transfer coefficient and S is the slip ratio. With the condition that deposition rate is equal to entrainment rate at the equilibrium state: $m_d\approx m_e$, entrainment fraction can be given as:

$$E_{eq}=(G_l-G_{lf})/G_l=k_eJ_gS(k_dG_l). \quad (22)$$

Dallman *et al.*(1979) provided a linear relation for entrainment rate by assuming that k_d and k_e could be independent of liquid flow:

$$\frac{m_e}{J_g(\rho_g\rho_l)^{0.5}}=k_eJ_g^n(G_{lf}-G_{lfc})D/4, \quad (23)$$

where G_{lfc} is the critical mass flux of liquid film at the onset of entrainment. From Eqs.(21)~(23), the following correlation can be obtained:

$$\frac{E_{eq}/E_M}{1-(E_{eq}/E_M)}=\frac{k_eDJ_g^{n+2}S(\rho_g\rho_l)^{0.5}}{4k_d}, \quad (24)$$

where E_M=1−(G_{lfc}/G_l). As can be seen, the correlation of E_{eq} can be determined if k_d and k_e are known. Most recent studies discuss the creation of roll waves by the theory of Kelvin-Helmholtz instability, and assume that entrainment rate is related to the growth of roll waves. Deposition rate is considered able to be linearly correlated in terms of the root-mean-square of droplets velocity fluctuations. Related studies have been reviewed in details by Dykhno and Hanratty (1996). Meanwhile, they pointed that the correlations obtained by this method could be useful to interpret the effects of gas velocity, tube diameter, and fluid properties. However, their predictions do not accord well with the experimental data, which is partly caused by the linear assumptions for deposition and entrainment rates without considering the effects of slip ratio, friction velocity, and droplets turbulence. Besides, the assumption, that k_d and k_e are independent of liquid flow, is the basis of the method. However, many studies (Andreussi and Azzopardi, 1983; Govan *et al.*, 1988; Schadel *et al.*, 1990; Hay *et al.*, 1996) have shown that it is only valid for lower liquid mass flux. The linear assumption thus fails to explain the physical characteristic of droplets deposition and entrainment. Recently, detailed investigations on the effect of droplets turbulence have been performed by Hanratty *et al.*(2000) and Pan and Hanratty (2002). Since their models are still based on the linear assumption, the original problems remain unsolved completely.

Okawa *et al.*(2002) also deduced theoretically a correlation for E_{eq}. According to their assumption, for the first type of entrainment mechanism in Fig.2, the entrainment rate could be correlated in terms of the dimensionless number π_e, which was given as the ratio of interfacial shear force to the retaining force of surface tension acting on the phase interface:

$$\pi_e = f_i \rho_g J_g^2 \delta / \sigma, \tag{25}$$

$$m_e = k_e \rho_l \pi_e (\rho_l / \rho_g)^n, \tag{26}$$

where f is the friction factor and δ is the liquid film thickness; subscript i represents the interface between liquid and gas phase. Based on neglecting the effect of gravity by assuming sufficiently thin liquid film, δ is determined by the balance between the interfacial shear stress and the wall friction force.

$$f_i \rho_g u_g^2 = f_w \rho_l u_{lf}^2, \tag{27}$$

where subscript w represents wall. In Eq.(27), neglecting the effect of gravity also makes the following relation valid: $u_g \approx J_g$, $u_{lf} \approx 0.25 J_l D/\delta$. Substituting them into Eq.(27) yields the following correlation (Okawa *et al.*, 2002):

$$\delta = \frac{1}{4}\sqrt{\frac{f_i \rho_l}{f_w \rho_g}} \frac{(1-E_{eq})J_l}{J_g} D, \tag{28}$$

where the friction factors f_i and f_w can be evaluated by the empirical correlations (Wallis, 1969).

It is also supposed that m_d is proportional to C, as shown in Eq.(21). C can be approximated to $E_{eq}\rho_l J_l / J_g$ by assuming that the relative velocity between gas phase and droplets is negligible, and that superficial velocity of liquid is much smaller than that of gas. At the equilibrium state $m_d \approx m_e$, the correlation for E_{eq} can be expressed as:

$$\frac{E_{eq}}{1-E_{eq}} = \frac{1}{4}\frac{k_e}{k_d}\frac{\sqrt{f_i f_w}\sqrt{\rho_g \rho_l} J_g^2 D}{\sigma}\left(\frac{\rho_l}{\rho_g}\right)^n. \tag{29}$$

From Eq.(29), the determination of E_{eq} requires three known parameters: k_e, k_d and n. According to different conditions, Okawa *et al.*(2002) chose the different empirical correlations for k_d, provided by Govan *et al.*(1988) and Sugawara (1990), respectively. However, the parameters of k_e and n were obtained from the comparisons with experimental data. Okawa *et al.*(2002) compared the predictions of Eq.(29) with a great deal of experimental data (Cousins *et al.*, 1965; Bennett *et al.*, 1966; Cousins and Hewitt, 1968a; Hewitt and Pulling, 1969; Singh *et al.*, 1969; Keeys *et al.*, 1970; Yanai, 1971; Whalley *et al.*, 1973; Nigmatulin *et al.*, 1976; Wurtz, 1978b; Asali, 1984; Owen *et al.*, 1985). By fitting to these data, the best agreement, with the errors in a range of −50%~100%, was obtained when k_e and n were equal to 1.8×10^{-4} and 0.2, respectively.

From the above summary, it is clear that no theoretical studies have been performed for the initial entrainment fraction at the onset of annular flow, mainly because of the lack of experimental data, which are very difficult to measure in most experiments. Therefore, its value is empirically estimated in the present models. Most theoretical studies are based on the equilibrium state: Some have developed empirical correlations by fitting to experimental data, which makes them valid in specific ranges; others have focused on analytical models based on the physical characteristic. With the linear theory, several correlations have been deduced from droplets deposition and entrainment rates. However, the basic assumption in linear theory has been showed invalid in a wide range by many experimental investigations. A reasonable correlation in theory has been deduced, containing some uncertain empirical parameters, which need to be determined by the experimental data. To our knowledge, the obtained correlation provided for non-equilibrium states can accord with the trend of experimental data; the predicted values still have some disparities as compared with the real ones. Therefore, the existing theoretical studies on entrainment fraction are not sufficient to explain the physical characteristics.

DROPLETS DEPOSITION RATE

The process of droplets deposition is known to be very complex. At present, theoretical studies are mostly based on the linear assumption that deposition rate is proportional to the droplet concentration in gas core (Eq.(21)). They focus on the correlation for the mass transfer coefficient k_d, being classified by the related parameters (Okawa and Kataoka, 2005): Whalley (1977) and Ueda (1979a) used the surface tension σ to correlate k_d, but most available correlations deployed the gas superficial velocity J_g (Alexander and Coldren, 1951) or the droplet concentration in the gas core C (Govan *et al.*, 1988; Schadel *et al.*, 1990; Utsuno and Kaminaga, 1998; Okawa *et al.*, 2002), and some considered the influence of both of them (Paleev and Filippovich, 1966; Namie and Ueda, 1972; 1973; Andreussi, 1983; Sugawara, 1990; Okawa and Kataoka, 2005).

Among these studies, some (Alexander and Coldren, 1951; Paleev and Filippovich, 1966; Namie and Ueda, 1972; 1973; Andreussi, 1983; Schadel *et al.*, 1990) carried out their respective experiments to deduce the correlations for k_d. The correlation of Namie and Ueda (1972; 1973) is the most general one when droplets have no large initial velocity and are controlled by turbulent diffusion. It is based on the detailed physical analysis of flow structure, droplets diameter, and turbulent diffusivity of gas and droplets. However, some parameters like droplets diameter cannot be measured in many experiments. The correlation of Paleev and Filippovich (1966) has a similar functional form and agrees well with that of Namie and Ueda (1972; 1973) in the average droplets diameter. The former can be regarded as a simplified correlation of the latter (Kataoka *et al.*, 2000). The correlations of Alexander and Coldren (1951), Schadel *et al.*(1990), Paleev and Filippovich (1966), and Andreussi (1983) are listed in Table 1 with their applicable ranges. These correlations were based on limited experimental data, and their validities in wider ranges were not shown clearly. Therefore, in order to broaden the applicable range, some researchers (Govan *et al.*, 1988; Sugawara, 1990; Utsuno and Kaminaga, 1998; Okawa *et al.*, 2002; Okawa and Kataoka, 2005) developed the correlations for k_d by fitting to a combination of experimental data obtained at different conditions.

By examining a combination of data from Willetts (1987), Cousins and Hewitt (1968a, 1968b), Bennett *et al.*(1966), Lee (1965), Lee and Obertelli (1963) and their experiments, Govan *et al.*(1988)

Table 1 Correlations for the mass transfer coefficient in droplets deposition

Parameter related	Reference	Number of data	Correlation		Applicable range
J_g	Alexander and Coldren (1951)	5	$k_d=0.00335J_g^{1.17}$	(30)	$24<J_g<91$
C	Schadel *et al.*(1990)	58	$k_d=\begin{cases}0.034/(D^{0.6}C), & C\le 0.078/D^{0.6};\\ 0.021/D^{0.6}, & C>0.078/D^{0.6}\end{cases}$	(31)	$20<J_g<120$ $0.12<G_1<1.0$
J_g and C	Paleev and Filippovich (1966)	55	$k_d=\dfrac{0.022J_g}{Re_g^{0.25}}\left(\dfrac{C}{\rho_l}\right)^{-0.26}\left(\dfrac{\rho_g}{\rho_l}\right)^{0.26}$	(32)	$3000<Re_g<850$ $0.1<C<1.3$ $P\approx0.1$ (MPa)
	Andreussi (1983)	24	$k_d=0.115u_f/(1+2.3C/\rho_g)$	(33)	$J_g>40$

It should be noticed that u_f represents friction velocity. Since it is usually related to J_g in the calculations, the correlations with u_f are classified into those with J_g in this paper found that the droplet concentration in gas core C had an important effect on k_d, as well as surface tension, gas density, and tube diameter. They plotted the data on the dimensionless parameter $k_d(\rho_g D/\sigma)^{1/2}$ vs C/ρ_g (Fig.9), and developed the following correlation:

$$k_d\sqrt{\frac{\rho_g D}{\sigma}}=\begin{cases}0.18, & C/\rho_g<0.3;\\ 0.083(C/\rho_g)^{-0.65}, & C/\rho_g>0.3.\end{cases} \quad (34)$$

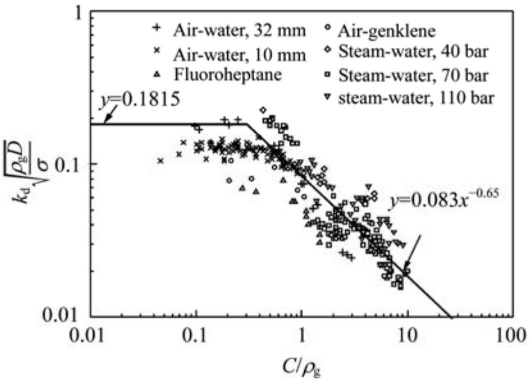

Fig.9 Dependence of $k_d(\rho_g D/\sigma)^{1/2}$ on C/ρ_g (Govan *et al.*, 1988)

Although Eq.(34) is discontinuous, Okawa *et al.*(2002) thought that considerable scattering still existed and the discontinuity of the experimental data seemed obscure. According to the same data, they proposed the following single correlation:

$$k_d\sqrt{\rho_g D/\sigma}=0.0632(C/\rho_g)^{-0.5}. \quad (35)$$

Okawa *et al.*(2002) pointed that Eq.(35) was as accurate as Eq.(34), able to predict approximately two-thirds of the experimental data within the errors of ±30%. However, Eqs.(34) and (35) do not include the effect of J_g although they are based on a combination of data.

Utsuno and Kaminaga (1998) compared the predictions of the correlation of Paleev and Filippovich (1966) with the experimental data at a high pressure (6.9 MPa) obtained by Bennett *et al.*(1966) and Hewitt *et al.*(1969). Results indicate that they cannot accord well with each other, as shown in Fig.10 by the dash lines. For this reason, by accounting for the effects of J_g and C, Utsuno and Kaminaga (1998) provided the following correlation by fitting to these data:

$$k_d=41.2(C/\rho_g)^{-0.36}\mu_g Re_g^{0.15}/(\rho_g D). \quad (36)$$

The predictions of Eq.(36) are shown by the solid lines in Fig.10. Although Eq.(36) was based on the data at the pressure of 6.9 MPa, Utsuno and Kaminaga (1998) proved that it was also valid in the pressure range of 3 to 9 MPa via the comparisons between the predicted and measured mass flux of liquid film (Bennett, 1969; Keeys, 1970; Wurtz, 1978b) (Fig.11).

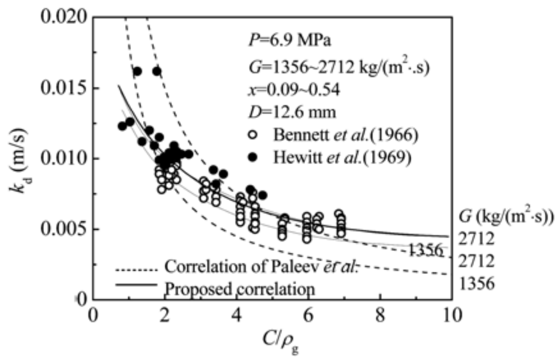

Fig.10 Adjustment of the correlation for k_d at high pressures (Utsuno and Kaminaga, 1998)

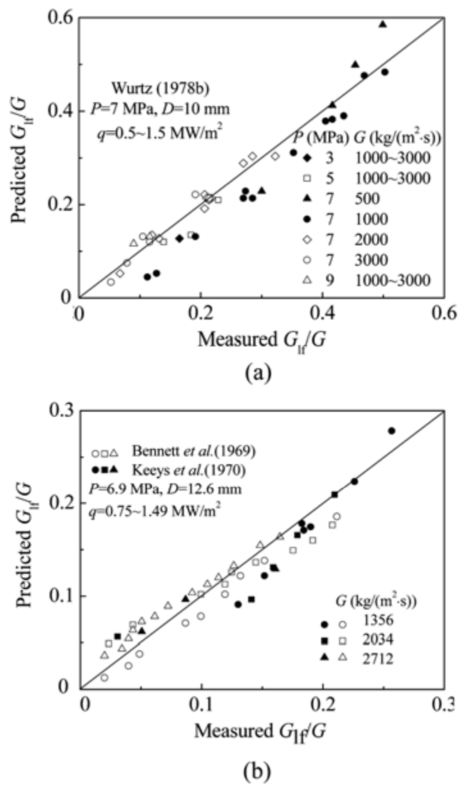

Fig.11 Comparisons with the data (a) from 3 to 9 MPa and (b) at 6.9 MPa between calculations and experimental data of G_{lf}/G (Utsuno and Kaminaga, 1998)

By considering the analogy between mass and heat transfer, Sugawara (1990) combined the data obtained at high pressure (Bennett *et al.*, 1966; Hewitt *et al.*, 1969) and atmospheric pressure (Paleev and Filippovich, 1966; Cousins and Hewitt, 1968a) to develop a correlation with Schmidt number *Sc* (Fig.12):

$$k_{\mathrm{d}} = 0.009 J_{\mathrm{g}} (C/\rho_{\mathrm{g}})^{-0.5} Re_{\mathrm{g}}^{-0.2} Sc^{-2/3}. \quad (37)$$

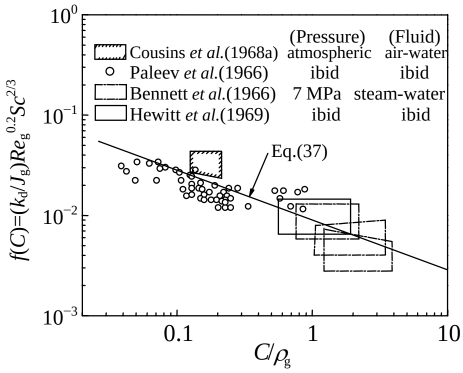

Fig.12 Comparisons between the calculations of deposition model and experimental data (Sugawara, 1990)

Compared with Eqs.(34) and (35), Eqs.(36) and (37) include the effect of J_{g}, while neglecting the effect of σ. The effects of these parameters (J_{g}, C, σ) are all included in the correlation of Okawa and Kataoka (2005). They examined the data from Cousins and Hewitt (1968a), Govan *et al.*(1988), Schadel *et al.*(1990) and their experiments (Okawa *et al.*, 2005), and found two different regions depending on the effects of J_{g} and C. When C becomes larger, k_{d} decreases monotonously with an increment in C, while the influence of J_{g} on k_{d} is rather obscure; when C gets smaller, k_{d} increases with J_{g}, while the dependence of k_{d} on C is not clear. The boundary of C between the two regions is in the range of 0.1~0.2. According to the results, Okawa and Kataoka (2005) proposed the following correlations for the two regions (Fig.13):

$$k_{\mathrm{d}} \sqrt{\frac{\rho_{\mathrm{g}} D}{\sigma}} = \min[0.19(C/\rho_{\mathrm{g}})^{-0.2}, 0.105(C/\rho_{\mathrm{g}})^{-0.8}],\ C>0.2, \quad (38)$$

$$k_{\mathrm{d}} = 0.17 u_{\mathrm{f}},\ C<0.1, \quad (39)$$

where the interval between 0.1 and 0.2 utilizes the smooth transition between the two correlations.

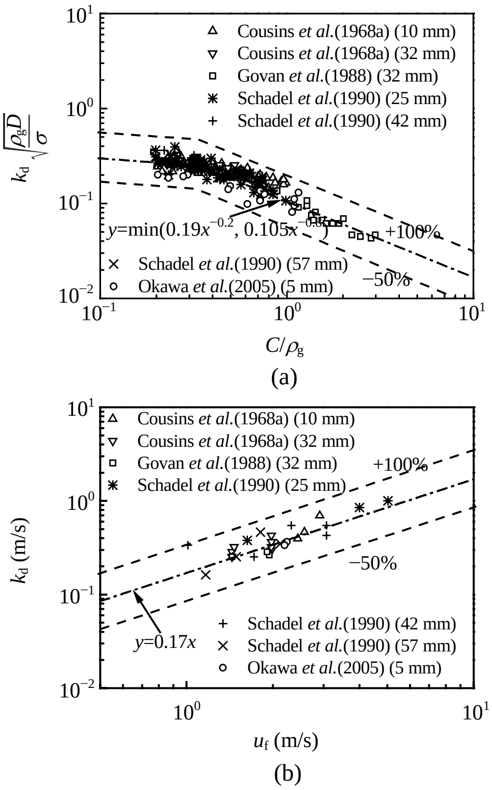

Fig.13 Proposed correlations for k_{d} at low and high droplet concentrations (Okawa and Kataoka, 2005). (a) C>0.2; (b) C<0.1

The above correlations are mostly proposed by fitting to the data from the adiabatic experiments, thus may not explain correctly the effect of liquid evaporation. Peng (2008) investigated theoretically the effect of heat flux on deposition rate in the dryout region. According to him, the interface turbulence had to overcome the interface evaporation velocity to allow the droplets to deposit. Therefore, the effect of heat flux depends on the relative scale of the velocities of interface turbulence fluctuation, evaporation and gas core turbulence fluctuation; accordingly an interfacial turbulence model was developed. It was found that k_{d} was proportional to the radial fluctuation velocity υ'_y, which can be expressed as

$$(\upsilon'_y / J_{\mathrm{g}}) Pr_{\mathrm{g}}^{2/3} (\rho_{\mathrm{l}}/\rho_{\mathrm{g}})^{-0.2} = Re_{\mathrm{g}}^{-0.2}, \quad (40)$$

where *Pr* is the Prandtl number. Peng (2008) pointed that Eq.(40) had a similar functional form with Eq.(37). Hence, by introducing the same droplet concentration factor, he provided the following correlation for k_{d}:

$$k_{\mathrm{d}} = 5.0\times10^{-3}\frac{J_{\mathrm{g}}}{Re_{\mathrm{g}}^{0.2}Pr_{\mathrm{g}}^{2/3}}\left(\frac{C}{\rho_{\mathrm{g}}}\right)^{-0.5}\left(\frac{\rho_{\mathrm{l}}}{\rho_{\mathrm{g}}}\right)^{0.2}. \quad (41)$$

Although Eq.(41) was theoretically deduced by considering the effect of heat flux, it was only validated via the comparisons between the measured values of CHF and the predictions of the liquid film dryout model. The comparisons between the measured deposition rate and the predictions of Eq.(41) were not performed. It may be related to the lack of experimental data about deposition rate under diabatic conditions. Besides, it was developed for the dryout region and its validity in the other heated region before dryout was not explained.

From the description, it can be inferred that theoretical studies on deposition rate are mostly based on the linear assumption that deposition rate is proportional to the droplet concentration in gas core. Many researchers have been developing the correlations for the mass transfer coefficient in the process of droplets deposition, and making the correlations more accurate and applicable in wider ranges. At first, some used the data from their respective experiments; their correlations are relatively accurate, but only applicable in a limited range. Then, others used a combination of data under different conditions; their correlations are hence applicable in a wider range, while their predictions show relatively larger deviation from the experimental values. Under some conditions, the errors can be around one order of magnitude (Okawa and Kataoka, 2005); in addition, the present correlations are mostly provided according to the data at adiabatic conditions. The effect of heat flux on deposition rate has been paid little attention and available theoretical studies on that have not been fully validated.

DROPLETS ENTRAINMENT RATE

Since droplets entrainment and deposition usually coexist at the gas-liquid interface, it is difficult to measure directly the entrainment rate in a number of experiments. Hence, most correlations are indirectly deduced. At present, most theoretical studies are performed for the steady state and the first type of entrainment mechanism in Fig.2. Under the steady state and without phase change, the mass balance at the interface can be written as:

$$m_{\mathrm{e}} = \frac{D\rho_{\mathrm{l}}J_{\mathrm{l}}}{4}\left(\frac{\partial E}{\partial z}\right)+m_{\mathrm{d}}. \quad (42)$$

Many studies neglect the variation of E with z, and the correlation of m_{e} can thus be determined by that of m_{d}. By considering that the process of droplets entrainment was similar to that of droplets deposition, the following correlation with the similar form as that of deposition rate, was provided by Hutchinson and Whalley (1973)

$$m_{\mathrm{e}} = kC_{\mathrm{eq}}, \quad (43)$$

where k is equal to that in the process of droplets deposition. It was argued that the dominant effect relevant to entrainment was the existence of sufficient shear stress at the interface to overcome the containment effect of surface tension. They correlated C_{eq} as a term of Weber number ($We=\tau_{\mathrm{i}}\delta/\sigma$), but the dependence of C_{eq} on We cannot accord well with the experimental data. Furthermore, the liquid film thickness δ cannot be measured directly in many experiments. Therefore, although Eq.(43) is conceptually right, there are some difficulties associated with its application (Kataoka *et al.*, 2000).

With a similar manner, Ueda (1979b) presented the following correlation for m_{e} by fitting to his experimental data:

$$m_{\mathrm{e}} = 3.54\times10^{-3}[(\tau_{\mathrm{i}}/\sigma)(J_{\mathrm{l}}/\sigma)^{0.6}]^{0.57}, \quad \text{when} \quad (\tau_{\mathrm{i}}/\sigma)(J_{\mathrm{l}}/\sigma)^{0.6} > 120, \quad (44)$$

where τ is the shear stress. Although Eq.(44) can agree well with his experimental data, it is dimensional and the parameter J_{l}/σ is not based on the entrainment mechanism. Therefore, the correlation may not be applied in general cases (Kataoka *et al.*, 2000).

Sugawara (1990) also used a similar manner to develop a correlation for m_{e}. Therein a dimensionless parameter S_{R} was proposed to include the effects of the hydrodynamic equivalent wave height and the density ratio between gas and liquid phase:

$$S_R = (\tau_i \Delta h_{eq} / \sigma)(J_g \mu_l / \sigma)(\rho_l / \rho_g)^n, \quad (45)$$

where n is an empirical parameter and is determined by the experimental data. Δh_{eq} is the wave height at equilibrium state and is calculated by the following hydrodynamic equivalent wave roughness k_s (Wurtz, 1978b):

$$k_s = 0.57\delta_a + 21.73\times10^3\delta_a^2 - 38.8\times10^6\delta_a^3 + 55.68\times10^9\delta_a^4, \quad (46)$$

where subscript a represents average value. Comparing the predictions of Eq.(46) with the data at atmospheric and high pressure (0.3~0.6 MPa) (Hewitt and Pulling, 1969; Keeys *et al.*, 1970), Sugawara (1990) found that it could accord well with the data at high pressure but overestimate those at atmospheric pressure. Hence, Sugawara modified Eq.(46) to examine the dependence of m_e on S_R, and obtained the following correlations (Fig.14):

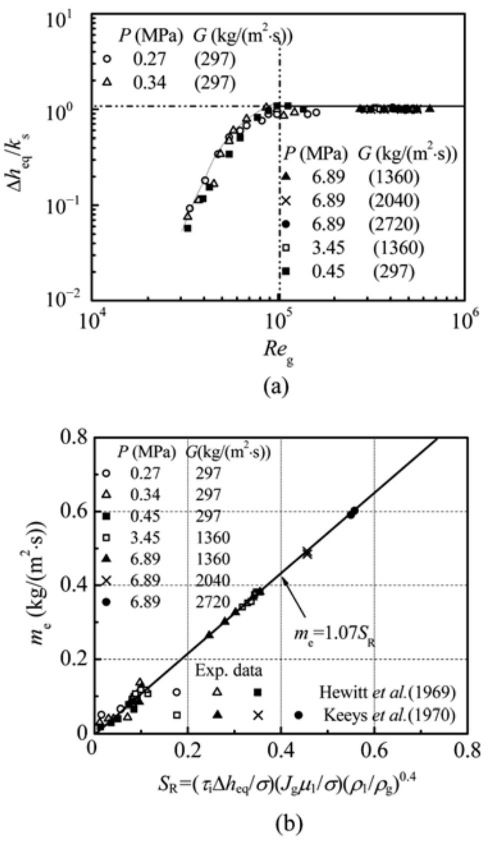

Fig.14 Modified correlation of Δh_{eq} (a) and the dependence of m_e on S_R (b) (Sugawara, 1990)

$$\frac{\Delta h_{eq}}{k_s} = \begin{cases} 1, & Re_g > 1.0\times10^5; \\ 2.136\lg(Re_g) - 9.68, & Re_g \le 1.0\times10^5, \end{cases} \quad (47)$$

$$m_e = 1.07 S_R = 1.07\left(\frac{\tau_i \Delta h_{eq}}{\sigma}\right)\left(\frac{J_g \mu_l}{\sigma}\right)\left(\frac{\rho_l}{\rho_g}\right)^{0.4}. \quad (48)$$

The similar method was also used by Okawa *et al.*(2004b). They assumed that m_e could be correlated in terms of the ratio of interfacial shear stress to surface tension π_e:

$$m_e = k_e \rho_l \pi_e^n, \quad (49)$$

where k_e is the mass transfer coefficient in the process of droplets entrainment. The correlation of π_e is given by Eq.(25). By utilizing the droplet concentration in gas core ($C\approx E_{eq}\rho_l J_l/J_g$) and the equilibrium condition ($m_d \approx m_e$), Eq.(49) can be rewritten as:

$$E_{eq} k_d J_l / J_g \approx k_e \pi_e^n. \quad (50)$$

Eq.(50) shows that the determinations of k_e and n require the correlation for k_d. According to different conditions, Okawa *et al.*(2004b) utilized the correlations of Govan *et al.*(1988) and Sugawara (1990), respectively. Then, they examined the relationship between π_e and the parameter $E_{eq}k_d J_l/J_g$, by a combination of data from their experiments (Okawa *et al.*, 2004a) and many other researchers (Cousins *et al.*, 1965; Bennett *et al.*, 1966; Cousins and Hewitt, 1968a; Hewitt and Pulling, 1969; Singh *et al.*, 1969; Keeys *et al.*, 1970; Yanai, 1971; Whalley *et al.*, 1973; Nigmatulin *et al.*, 1976; Wurtz, 1978b; Asali, 1984; Owen *et al.*, 1985). By fitting to these data (Fig.15), the parameters k_e and n were given as:

$$k_e = 6.8\times10^{-4};\ n = 0.5\ (\pi_e > 0.295), \quad (51a)$$

$$k_e = 1.6\times10^{-3};\ n = 1.2\ (0.0675 < \pi_e < 0.295), \quad (51b)$$

$$k_e = 3.1\times10^{-2};\ n = 2.3\ (\pi_e < 0.0675). \quad (51c)$$

In the above studies, the inception criterion for droplets entrainment is neglected. Based on their respective experimental data, Dallman *et al.*(1979) and Schadel *et al.*(1990) defined the same dimensionless parameter m_e^*, with the critical mass flux of

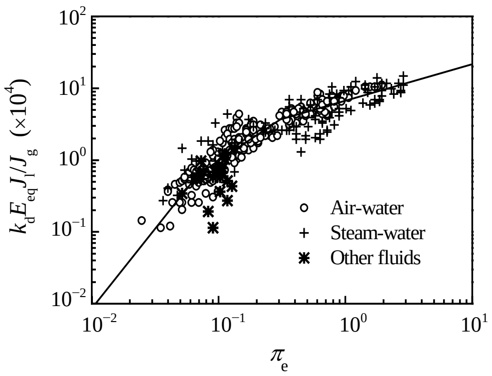

Fig.15 Relation between π_e and the parameter $E_{eq}k_dJ_l/J_g$ for equilibrium annular flow without phase change (Okawa *et al.*, 2004b)

liquid film for the onset of entrainment, and developed the following correlations:

$$m_e^* = m_e / [J_g(\rho_g \rho_l)^{0.5}], \tag{52}$$

$$m_e^* = C_1 J_g D(G_{lf} - G_{lfc}), \tag{53}$$

$$m_e^* = C_2 D(G_{lf} - G_{lfc}), \tag{54}$$

where C_1 and C_2 are the empirical coefficients and G_{lfc} is determined by Eq.(11). From Eqs.(53) and (54), they both found the dimensionless entrainment rate m_e^* proportional to the residual mass flux of liquid film with respect to the critical value for the onset of entrainment. Dallman *et al.*(1979) proposed 6.7×10^{-6} s^2/kg for C_1, and Schadel *et al.*(1990) provided 4.70×10^{-4} m·s/kg for C_2. Since the correlations are proposed from limited experimental data and the obtained empirical parameters have no physical meanings, it is expected that Eqs.(53) and (54) may not be applied in general cases.

Govan *et al.*(1988) also used the critical mass flux of liquid film for the onset of entrainment. A correlation for m_e was provided by directly fitting to a combination of data from many investigators (Gill *et al.*, 1964; Cousins *et al.*, 1965; Mingh, 1965; Cousins and Hewitt, 1968a; 1968b; Gill *et al.*, 1969; Hewitt and Pulling, 1969; Singh *et al.*, 1969; Keeys *et al.*, 1970; Whalley *et al.*, 1974; Brown *et al.*, 1975; Nigmatulin *et al.*, 1976; Brown, 1978; Wurtz, 1978a; Azzopardi *et al.*, 1983; Leman, 1983; Asali, 1984; Owen and Hewitt, 1986; Willetts, 1987), as shown in Fig.16. According to Govan *et al.*(1988), two-thirds of these data could be predicted by the following correlation within errors between −45% and +80%:

$$m_e = 5.75\times10^{-5} G_g \left[(G_{lf} - G_{lfc})^2 \frac{D\rho_l}{\sigma\rho_g^2} \right]^{0.316}. \tag{55}$$

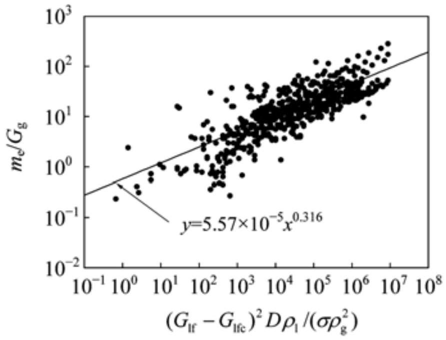

Fig.16 Correlation of entrainment rate (Govan *et al.*, 1988)

Okawa and Kataoka (2005) modified the dimensionless parameter π_e by using the critical gas superficial velocity for the onset of entrainment:

$$\pi_{e1} = f_i \rho_g (J_g^2 - J_{gc}^2)\sigma / \delta, \tag{56}$$

where J_{gc} is calculated by Eq.(8) or Eq.(10). They also pointed that the correlation of m_e deduced from the correlation of m_d could include the errors in predicting m_d from an empirical correlation, such as Eqs.(43), (50) and (58) to be explained later. Therefore, the volumetric entrainment rate $U_e=m_e/\rho_l$ was defined and then correlated in terms of π_{e1}. They deduced the following correlation from the experimental data of deposition rate (Fig.17):

$$U_e = \min(k_{e1}\pi_{e1}, k_{e2}\pi_{e1}^{0.5}), \tag{57}$$

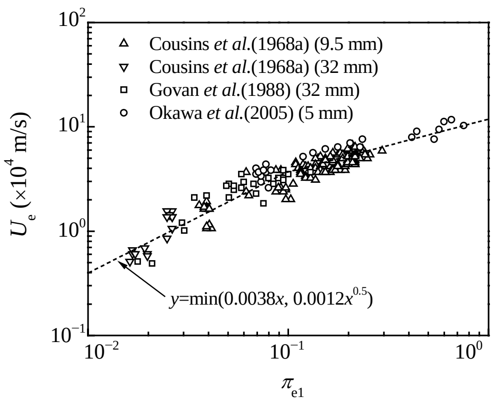

Fig.17 Dependence of volumetric entrainment rate on π_{e1} (Okawa and Kataoka, 2005)

where the mass transfer coefficient k_{e1}=3.8×10^{-3} m/s, k_{e2}=1.2×10^{-3} m/s.

The first term at the right of Eq.(42) is neglected in all the studies above. Kataoka *et al.*(2000) used the correlation of the relationship between entrainment fraction and axial distance (Ishii and Mishima, 1981) (Eq.(19)), to include the entrance effect. In their analysis, the correlation proposed by Paleev and Filippovich (1966) for m_d was employed. Substituting Eqs.(19) and (32) into Eq.(42) yields the following correlation:

$$m_e = 0.935\times10^{-5}\zeta\exp(-1.87\times10^{-5}\zeta^2) \times\rho_l J_l Re_l^{0.5} We^{-0.25} E_{eq} + 0.022\rho_l J_l Re_l^{-0.26} \times(\mu_g/\mu_l)^{0.26} E_{eq}^{0.74}(1-\exp(-1.87\times10^{-5}\zeta^2))^{0.74}. \quad (58)$$

Eq.(58) was simplified by Kataoka *et al.*(2000) with some reasonable assumptions, and validated by the experimental data from Cousins *et al.*(1965) and Gill *et al.*(1962). The simplified correlations for the developing and fully developed entrainment regions were given as:

$$\frac{m_e D}{\mu_l} = 0.72\times10^{-9} Re_l^{1.75} We(1-E_{eq})^{0.25} \times(1-E/E_{eq})^2 + 6.6\times10^{-7}(Re_l We)^{0.925} \times(\mu_g/\mu_l)^{0.26}(1-E)^{0.185}, \quad E/E_{eq}<1, \quad (59a)$$

$$\frac{m_e D}{\mu_l} = 6.6\times10^{-7}(Re_l We)^{0.925}(\mu_g/\mu_l)^{0.26} \times(1-E)^{0.185}, \quad E/E_{eq}>1. \quad (59b)$$

Lopez de Bertodano *et al.*(1997) compared the predictions of Eq.(59b) with the data from Cousins and Hewitt (1968a) and their experiments, as shown in Fig.18a, but found that they could not accord well with each other. They considered that the form of the interfacial wave had an important effect on droplets entrainment, which was not included in the models of Kataoka *et al.*(2000) and the other studies mentioned above. For this reason, they modified Eq.(59b) with the theory of Kelvin-Helmholtz instability, and provided the following correlation:

$$\frac{m_e D}{\mu_l} = 4.47\times10^{-7}(\mu_g/\mu_l)^{0.26} \times[We_g(\rho_l/\rho_g-1)^{1/2}(Re_{lf}-Re_{lfc})]^{0.925}, \quad (60)$$

where the coefficient was determined by the least squares fitting. Fig.18b shows the comparisons between the predictions of Eq.(60) and the experimental data; it indicates the correlation collapses the data well for m_eD/μ_l<1, but for higher values the data still deviate from the linear trend (Lopez de Bertodano *et al.*, 1997).

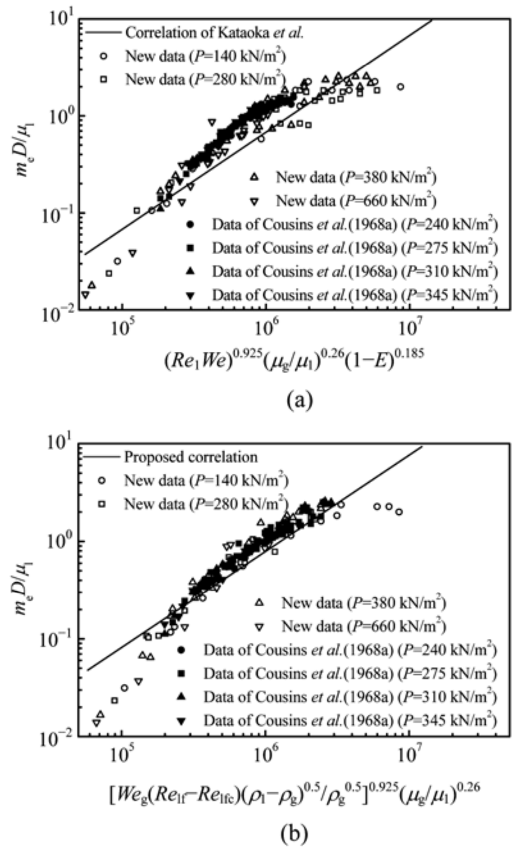

Fig.18 Comparisons between the experimental data and the predictions of the correlation of Kataoka *et al*.(2000) (a) and the new one (b) (Lopez de Bertodano *et al.*, 1997)

All the correlations above are provided for the first type of entrainment mechanism in Fig.2, which is caused by shearing-off roll wave crest by the turbulent gas flow. In a heated tube, the bubbles in the liquid film are formed because of nucleate boiling. Droplets can be entrained by the moving and bursting of the bubbles from the liquid film to the gas core (Fig.2). Ueda *et al.*(1981) developed an empirical correlation for that:

$$m_{eb} = C_3(q/h_{fg})^{2.5}[\delta/(\sigma\rho_g)]^{0.75}, \quad (61)$$

where subscript b represents boiling effect; C_3 is an empirical coefficient, depending on the type of working fluid, and it is 477, 663 and 133 for water, R-113 and R-11, respectively. Ueda *et al.*(1981) considered that the reason could be related to the nucleation site density described by the different liquid-surface combination. Based on the study of Ueda *et al.*(1981), some models for the diabatic systems (Celata *et al.*, 2001; Bai *et al.*, 2003; Okawa *et al.*, 2004b; Fan *et al.*, 2006) define the total entrainment rate m_{et} as the sum of the two terms due to the first and third types of entrainment mechanism, respectively:

$$m_{\mathrm{et}} = m_{\mathrm{e}} + m_{\mathrm{eb}}. \quad (62)$$

Peng (2008) considered that the shape of roll waves could be affected in the diabatic systems and proposed that the interfacial evaporation velocity could be calculated by

$$u_{\mathrm{ev}} = q/(\rho_{\mathrm{g}} h_{\mathrm{fg}}). \quad (63)$$

From the University of Ottawa CHF database, Peng (2008) found that the relative injection rate $X=u_{ev}/J_g$ varied in a certain range when CHF was reached. According to his assumption, the process of the liquid evaporation through the interfacial gas boundary layer could resemble that of gas injection through a permeable wall, which was experimentally investigated by Olson and Eckert (1966). Based on their conclusions, Peng suggested that the interfacial shear stress (wall friction) could be estimated by about 20% lower than that without interfacial evaporation when X (gas injection velocity) was close to the lower boundary in the certain range, while the effect of interfacial evaporation on the interfacial shear stress (the effect of gas injection velocity on wall friction) could be neglected when X (gas injection velocity) was close to the upper boundary. Therefore, Eq.(62) was modified by Peng (2008) into the following one:

$$m_{\mathrm{et}} = \left[\frac{0.8(X''_{\mathrm{lim}} - X) + (X - X'_{\mathrm{lim}})}{X''_{\mathrm{lim}} - X'_{\mathrm{lim}}} \right] m_{\mathrm{e}} + m_{\mathrm{eb}}, \quad (64)$$

where superscripts ′ and ″ represent the lower and upper boundaries, respectively. However, Eq.(64) had the same problems as those found in Eq.(41), which was provided by Peng (2008) for deposition rate with the effect of heat flux.

The preceding summary indicates that the theoretical studies on entrainment rate are mostly based on the equilibrium state under adiabatic condition. A large number of researchers have proposed dimensionless parameters to correlate entrainment rate, and utilized the critical mass flux of liquid film or the critical gas superficial velocity as the inception criterion of entrainment. Different correlations obtained by fitting to experimental data from different conditions have the similar problems as those in the correlations of deposition rate. In addition, most of them are indirectly deduced from the correlations of entrainment fraction and deposition rate, whose errors can be included in them. A few correlations are directly derived from the experimental data of deposition rate, while their validities in a wider range should be approved further. The effect of interfacial phase change starts to attract the attention of researchers; notably up to now, the available correlation is just based on an analogy approach, having not been fully validated.

It should be noticed that the development in theoretical studies is closely related to the progress on the experiments. At present, the correlations of entrainment fraction, deposition and entrainment rates are mostly obtained by fitting to experimental data. To provide the foundation for theoretical studies, many experimental studies on the interfacial mass transfer in gas-liquid two-phase annular flow have been performed carefully (Lee and Obertelli, 1963; Gill *et al.*, 1964; Cousins *et al.*, 1965; Lee, 1965; Mingh, 1965; Bennett *et al.*, 1966; Cousins and Hewitt, 1968a; 1968b; Gill *et al.*, 1969; Hewitt *et al.*, 1969; Singh *et al.*, 1969; Hewitt and Pulling, 1969; Keeys *et al.*, 1970; Yanai, 1971; Whalley *et al.*, 1973; 1974; Brown *et al.*, 1975; Nigmatulin *et al.*, 1976; Brown, 1978; Wurtz, 1978a; 1978b; Azzopardi *et al.*, 1983; Leman, 1983; Asali, 1984; Owen *et al.*, 1985; Owen and Hewitt, 1986; Willetts, 1987).

CONCLUSION

Annular flow is an important flow pattern in gas-liquid two-phase flow, whose CHF has a predominant effect on the safe operation of numerous industrial applications. Many studies have proved that the liquid film model can be used for predicting CHF in annular flow. This five-part model includes onset of annular flow, inception criterion for droplets entrainment, entrainment fraction, droplets deposition and entrainment rates, which can significantly affect the model's accuracy. Most theoretical studies carried on the five parts are reviewed in this paper, showing that though many useful conclusions have been obtained, some limitations can be still found in the existing studies and need further investigations. In a word, most theoretical studies focus on the equilibrium state under adiabatic conditions. The main correlations are obtained by fitting to experimental data, enabling their validity only in a certain range. The analytical models for the process of mass transfer at the interface are primarily based on the linear assumption. However, it is questionable that the complex phenomena like the droplets deposition and entrainment could be explained by a linear function. In addition, most industrial applications are at non-equilibrium conditions, especially in diabatic systems, which have been somehow neglected at present. As a result, the correlations developed for equilibrium state are directly used for non-equilibrium conditions, empowering significant effects upon the predictions of CHF under diabatic conditions. In our opinions, the visual experiments should be further performed, especially for diabatic systems. Based on the observed mechanism, the nonlinear model for the physical characteristic of droplets deposition and entrainment, with the effect of heat flux, would be a better tool for predicting CHF, worthy of our further efforts.

Moreover, with the rapid development in the industrial technology, many new subjects have been introduced for the studies on mass transfer at the two-phase surface. Large scale industrial equipment keeps on springing up, such as 1000 MW supercritical and super-supercritical power plants, 1000 MW advanced pressurized water reactor (PWR) nuclear power plants, large scale oil refinery units, petro-chemical equipment and offshore oilfields. It is a question whether the process of mass transfer at the two-phase surface in the new applications abides by the obtained theoretical principles. Cryogenic two-phase flow and heat transfer can be encountered commonly in space technology and cold neutron source systems. However, the available results are mostly proposed for moderate temperature working fluids, whereas little attention has been paid to the cryogenic working fluids. Microstructure heat transfer has become an international research frontier, because of the rapid developments of modern micro-electronics and micro electronic mechanical systems, and the increasingly severe problems on the heat emission of VLSI electronic devices. The present theoretical studies are, however, not provided for the microstructure systems, and it is thus unclear if there are new characteristics on the process of mass transfer at two-phase flow interface in microstructure systems. Relevant studies on them will have important realistic implications, and the above questions will be gradually solved with further advances of the studies on two-phase flow and heat transfer.

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