

DROPLET ENTRAINMENT RATE IN GAS-LIQUID ANNULAR FLOW

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Abstract

Droplet entrainment and deposition are the two most important physical phenomena in the gas-liquid annular two-phase flow. Modeling of these phenomena is essential for the estimation of dryout margins in the Light Water Reactors (LWRs) and the boilers. In this study, gas-liquid annular two-phase flow experiments are performed in a vertical round tube test section under adiabatic conditions. Air-water and organic fluid Freon-113 are used as the test fluids. The experiments covered a wide range of pressure and flow conditions. Liquid film extraction technique was used for the measurement of droplet entrainment and deposition rates. Additionally, the thickness of liquid film was measured in the air-water experiments using the ring type conductance probes. In this paper, the experimental data on entrainment rate is used to analyze the currently available correlations in the literature. The analysis showed that the existing correlations failed to predict the data at high gas velocity conditions. At high gas velocity, the experimental entrainment rate approaches a maximum limiting value; however, the correlations predicted continuously increasing entrainment rate as the gas velocity increases.

Introduction

Study of gas-liquid annular two-phase flow is important for the design and operation of several industrial systems including the Light Water Reactors (LWRs), boilers, refrigeration systems, and many gas-liquid contacting equipments in the chemical industry. The annular two-phase flow in a round tube is characterized by the presence of a liquid film on the wall and a gas-phase flowing through the center of the tube. The liquid film interface is typically covered by the large amplitude kinematic waves (disturbance waves) and relatively small amplitude dynamic waves (ripple waves). A shearing-off of the crest of these disturbance waves results in transfer of some amount of liquid from the liquid film to the central gas core flow in the form of entrained droplets [1]. Furthermore, droplets entrained in the gas core also continuously deposit on the liquid film surface by various deposition mechanisms [2]. The prediction of these droplet entrainment and deposition rates is essential for the modelling of annular flow. In the current study, the droplet entrainment and deposition rates are measured in the air-water and organic fluid (Freon-113) experiments. This paper presents the analysis of the entrainment rate data. The analysis of the deposition rate data is available in Reference [2].

Several empirical correlations are available in literature for the estimation of a fraction of liquid flowing in the form of entrained droplets (i.e., entrainment fraction) through the central gas core of the annular flow [3-5]. The entrainment fraction represents an integral effect of the droplet entrainment and the deposition phenomena. It is a relatively stable parameter and easier to measure

and correlate compared to the entrainment and deposition rates [6]. However, droplet entrainment and deposition rates are more mechanistic parameters. The use of these rate correlations is more appropriate for the transient analysis. Consequently, the correlations for entrainment and deposition rates are indispensable. Table 1 summarizes the important entrainment rate correlations considered in the current study.

Researcher	Correlation
Kataoka and Ishii, 2000 [6]	$\frac{\dot{\epsilon}D}{\mu_f} = 6.6 \times 10^{-7} \text{Re}_f^{0.74} \text{Re}_{ff}^{0.185} \text{We}^{0.925} \left(\frac{\mu_g}{\mu_f} \right)^{0.26} = 6.6 \times 10^{-7} \times \gamma$
Lopez de Bertodano et al., 1998 [7]	$\frac{\dot{\epsilon}D}{\mu_f} = 4.47 \times 10^{-7} \left[(\text{Re}_{ff} - \text{Re}_{ffOE}) \text{We} \frac{\Delta\rho}{\rho_g} \right]^{0.925} \left(\frac{\mu_g}{\mu_f} \right)^{0.26}$
Pan and Hanratty, 2002 [8]	$\dot{\epsilon} = 0.22 [1 - \exp(X/500,000)] X = (\rho_f \rho_g)^{0.5} \frac{(v_g - v_{gc})}{\sigma} \left(\frac{\dot{m}_{ff} - \dot{m}_{ffOE}}{\pi D} \right)$
Okawa and Kataoka, 2005 [9]	$\frac{\dot{\epsilon}}{\rho_f} = \min \left(3.8 \times 10^{-3} \frac{f_i \rho_g (j_g^2 - j_{gc}^2)}{\sigma/\delta}, 1.2 \times 10^{-3} \sqrt{\frac{f_i \rho_g (j_g^2 - j_{gc}^2)}{\sigma/\delta}} \right)$

Table 1: Entrainment rate correlations

Kataoka and Ishii [6] entrainment rate correlation was developed based on the Ishii and Mishima [3] entrainment fraction correlation. As noted earlier, the droplet entrainment mechanism considered for the development of this correlation is the shearing-off of the disturbance wave crests. The Kataoka and Ishii correlation is applicable to the entrance region (developing region) as well as to the equilibrium region where the droplet entrainment rate is expected to be similar to the deposition rate. The Kataoka and Ishii correlation applicable for the equilibrium annular flow region is shown in Table 1. The entrainment rate measurements in the current study are also performed in the equilibrium annular flow.

Lopez de Bertodano et al. [7] carried out air-water and organic fluid (Freon-113) experiments in 0.01 m diameter test section. They measured droplet entrainment rate and entrainment fraction using the liquid film extraction technique. The entrainment rate correlation developed by Lopez de Bertodano et al. combined features of the Kataoka and Ishii and the Dallman et al. [10] correlations. Pan and Hanratty showed that this correlation predicted the surface tension and density ratio effect better than the other correlations [8]. Pan and Hanratty also proposed the entrainment rate correlation based on the previous work performed by Tatterson [11], Schadel and Hanratty [12], and Dallman et al. [12]. For the development of their correlation, the entrainment of droplets was assumed due to the Kelvin-Helmholtz instability. The Pan and Hanratty correlation related the entrainment rate to the liquid film flow rate and the gas velocity using the dimensional mass deposition coefficient. Okawa and Kataoka [9] used air-water annular flow experiment data for the development of their correlation relating the entrainment rate to the ratio of interfacial shear and the surface tension forces acting on the surface of liquid film.

The objectives of this paper are to analyze the above correlations using the air-water and Freon-113 entrainment rate data obtained in the current study and to identify the potential limitations of these correlations, to perform the parametric analysis of the entrainment rate data, and to propose the requirements for the future entrainment rate correlations. In addition, a detailed discussion on the

potential limitations of the film extraction technique for the measurement of entrainment and deposition rates is presented.

1. Experiment

The air-water and Freon-113 experiments were performed in 0.094 and 0.01 m diameter test sections, respectively. Both the experiments were performed under adiabatic condition. The gas- and liquid-phases for the Freon-113 experiments were saturated at the test section pressure. In both the experiments, droplet entrainment fraction, entrainment rate, and deposition rate were measured by the liquid film extraction technique [4]. Additionally, double ring type conductance probes were used for the measurement of liquid film thickness and disturbance wave properties in the air-water experiments [13]. All the measurements were performed in an equilibrium annular flow region. A developing length selected for the air-water experiment was 210 times the diameter of the test section. For the Freon-113 experiments, the developing length was 400 times the diameter of the test section. These lengths were selected based on the Ishii and Mishima [3] entrainment fraction correlation. Detailed information about the design and operation of the test facilities, liquid film extraction method, film thickness measurement probe, and parametric range covered in the experiments is available in References [4, 5, 13].

Table 2 shows the range of parameters covered by the air-water and Freon-113 experiments. As seen from the table, the experiments were performed at three different pressure conditions. The pressure conditions in the Freon-113 experiments were selected to simulate the high pressure steam-water flow conditions.

The entrainment fraction data has been analyzed in References [4, 5] and a new correlation was proposed for the prediction of entrainment fraction. The analysis of the liquid film thickness and disturbance wave measurement data is presented in Reference [13].

Air-water			Freon-113		
P (bar)	j_g (m/s)	j_f (m/s)	Pr (bar)	j_g (m/s)	j_f (m/s)
1.2	15.0 to 100.0	0.05 to 0.5	2.8	12.0 to 24.0	0.08 to 0.4
4.0	15.0 to 100.0	0.05 to 0.75	5.0	11.0 to 17.0	0.13 to 0.4
6.0	15.0 to 65.0	0.05 to 0.5	8.5	16.0 to 11.0	0.13 to 0.4

Table 2: Range of experimental parameters

2. Measurement of Entrainment Rate

The estimation of droplet entrainment and deposition rates in annular flow using the film extraction technique involves extraction and measurement of the liquid film flow rates at two successive locations or ports on the test section. A complete extraction of the liquid film at the upstream film-extraction port leaves only the entrained droplets flowing in the central gas core. These droplets deposits on the test section wall between the two extraction ports, forming a new liquid film which is extracted at the 2nd (downstream) extraction port. The liquid film flow rate measured at the second extraction port provides estimation of the deposition rate. Since the measurements in the current study were performed in an equilibrium annular flow region, the measured deposition rate is same as the entrainment rate. The deposition length (z_d) between two-extraction ports for the current

experiment was 0.45 m, respectively. This length provides measurable liquid film flow rate at the second extraction port.

This technique has been used very extensively in the past for the measurement of entrainment fraction and droplet entrainment-deposition rates in annular flow. However, the measurements may be affected due to the limitations of the film extraction technique including an incomplete extraction of liquid film at the 1st extraction port, re-entrainment of the newly deposited liquid film, and preferential deposition of the droplets over the deposition length. Consequently, the assessment of the experimental data must be performed to ascertain that it is not affected by these limitations of the measurement technique.

2.1 Incomplete Extraction of Liquid Film

Inadequate or incomplete extraction of liquid film at the 1st extraction port results in overestimation of entrainment fraction and the entrainment-deposition rates. This measurement limitation of the film extraction technique becomes important under high liquid flow conditions, because there is a possibility of flow regime transition from annular mist to annular wispy flow at high liquid flow rates [14]. Sekoguchi and Takeishi [15] reported the existence of large-amplitude huge waves (larger than regular disturbance waves) at higher liquid flow conditions in annular flow. These waves are much larger and faster than the regular disturbance waves and may escape the extraction at the 1st extraction port. Therefore, the application of the liquid film extraction technique is limited to the annular mist flow regime in which the liquid film is relatively thin.

Error introduced in the measurement of entrainment fraction and entrainment-deposition rates due to the above limitation is clearly visible in Figure 1, which is plotted for the air-water data obtained by Lopez de Bertodano et al. [16]. As seen from Figure 1, the measured entrainment fraction and entrainment rate for the liquid-phase Reynolds number greater than 7000 show significantly different trends compared to the trends observed for the lower Reynolds number data. The entrainment fraction and entrainment rate are relatively high for these liquid-phase Reynolds number conditions. It appears that as the gas velocity increases, the liquid film thickness decreases, and under high gas velocity the trends become similar to the lower liquid flow rate data.

In order to determine the applicability range of the film extraction technique, a reliable criterion is essential for the prediction of flow regime transition from the annular flow regime with regular disturbance waves to the annular flow with huge waves. It is noted that an empirical criterion is proposed by Hewitt and Roberts [17] for the prediction of transition to annular wispy flow. However, this transition is expected to occur at much higher liquid flow compared to the liquid flow at which the huge waves start to appear on the liquid film surface [5, 15]. For the air-water flow in 0.01m diameter tube at atmospheric pressure, Hewitt and Roberts criterion predicts the transition to annular wispy flow at liquid-phase Reynolds number 12000. On the contrary, the film thickness measurement presented in Reference [18] shows that the huge waves start to appear on the liquid film surface at liquid-phase Reynolds number 7000. It should be noted that this Reynolds number is same as the Reynolds number at which the Lopez de Bertodano et al. data starts showing the unusual trends (see Figure 1). Consequently, for the air-water experiments in 0.01m diameter tube, the film extraction technique is not reliable for the liquid-phase Reynolds number greater than 7000. Since the current air-water experiments are conducted for the liquid-phase Reynolds number less than 5000, it is expected that the measured data is not affected by this measurement technique

limitation. Similarly, it is expected that the transition from regular disturbance waves to huge waves in Freon-113 may take place at much lower liquid-phase flow rate than the prediction of the Hewitt and Roberts criterion. For Freon-113 at 8.5 bar, the Hewitt and Roberts criterion predicted transition to annular wispy flow at liquid-phase Reynolds number 54000. However, the current Freon-113 data indicated the effect of incomplete extraction at much lower liquid-phase Reynolds number (around 13600).

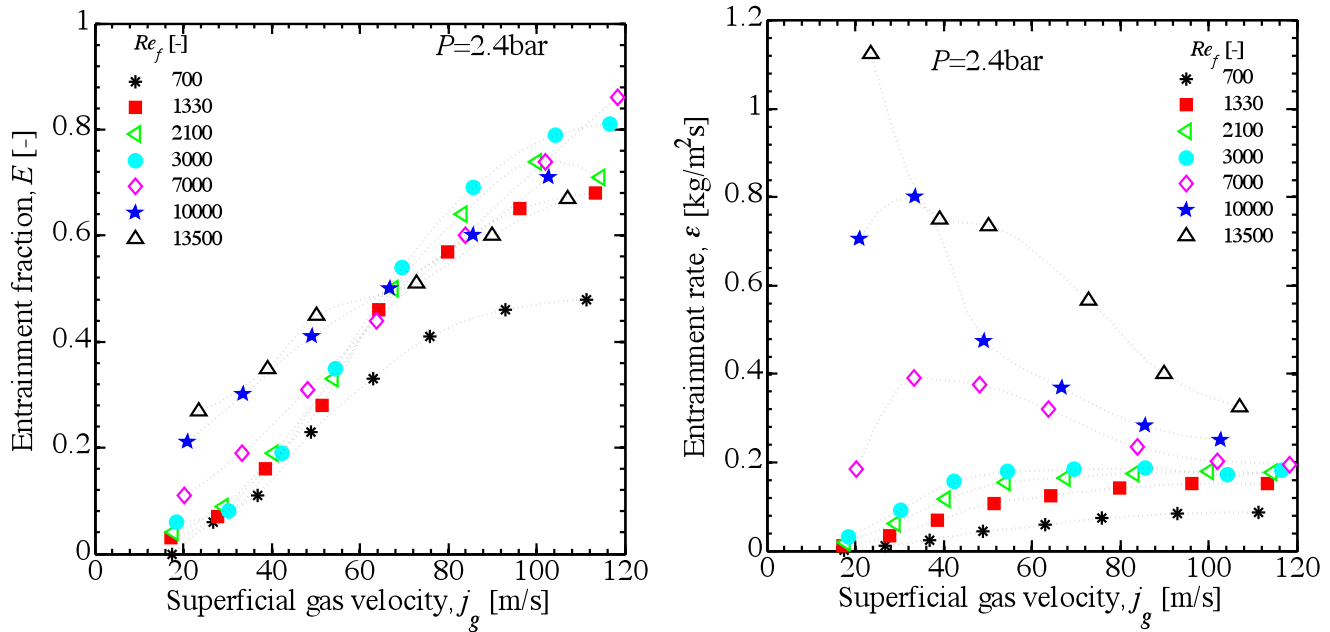


Figure 1: Error due to the incomplete extraction of liquid film at 1st extraction unit (Lopez de Bertodano et al. [16] data)

Similar trends of decreasing entrainment rate with the increasing gas velocity have been observed in several other experimental data in the literature [19, 20]. Unfortunately, many researchers have used these data for the correlation development without noticing this potential error which can occur due to the limitation of the film extraction technique.

2.2 Re-entrainment of the Deposited Liquid

If the deposition length between the two extraction ports is long enough, re-entrainment of the newly deposited liquid film prior to its extraction at the 2nd port can cause error in measurement of the deposition rate. This limitation of the film extraction technique can lead to the under-estimation of deposition and entrainment rates. Consequently, this measurement limitation can potentially bound the validity of the film extraction technique to the low liquid and gas flow conditions at which the deposition rate is relatively small. Particularly, at high gas velocity conditions, the deposition rate is high and the critical liquid film flow rate required for the onset of entrainment is low (see onset of entrainment correlation by Ishii and Grolmes [1]).

In order to determine that the measured data is not affected by this limitation, it is necessary to compare the liquid film flow rate measured at the 2nd extraction port with the equilibrium liquid film flow rate. The equilibrium liquid film flow rate at the 2nd extraction port can be estimated using the entrainment fraction correlation such as Sawant et al. [5] correlation. The Sawant et al. [5]

correlation shows that for the current air-water and Freon-113 data the liquid film Reynolds number measured at the 2nd extraction port is substantially lower than the calculated equilibrium liquid film Reynolds number. Therefore, it can be concluded that the current experimental data is not affected by this measurement limitation of the film extraction technique.

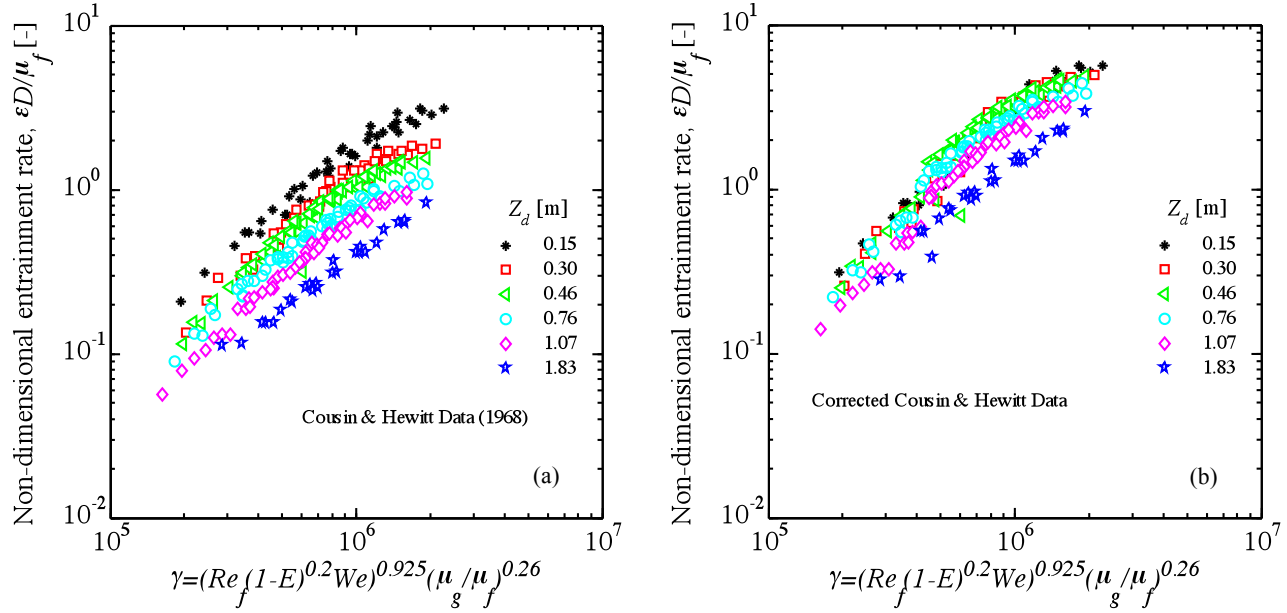


Figure 2: Cousins and Hewitt [21] data; a) effect of deposition length on measured entrainment rate, b) data corrected by Okawa and Kataoka [9] correction factor

2.3 Preferential Droplet Deposition

The mechanisms of droplets deposition depend on the droplet size and initial velocity [2]. The large droplets possess higher inertia and deposit by direct impact type of mechanism. The smaller droplets interact with the gas-phase turbulence and get transported up to viscous wall layer and eventually deposit on the wall surface by crossing the viscous wall layer with the velocity imparted to them by the gas core turbulence. These different mechanisms can lead to the non-uniform deposition over the deposition length between the two extraction ports. As a result of this, the measured deposition rate depends on the deposition length selected for the experiment. The shorter deposition length leads to the over-estimation of the deposition rate due to the preferential deposition of the larger droplets. As discussed earlier in Section 2.2, the longer deposition length can lead to the under-estimation of deposition rate due to the re-entrainment of the liquid film. Figure 2a clearly shows this effect on the entrainment rate measurements obtained by Cousins and Hewitt [21]. In Figure 2, non-dimensional entrainment rate is plotted against a non-dimensional parameter γ in the Kataoka and Ishii correlation (see Table 1). It can be observed that the entrainment rate decreases as the deposition length increases. Recently, Okawa and Kataoka [9] derived following correction factors using the Cousins and Hewitt data and several other air-water data available in literature to account for this effect:

$$\dot{d}_{corr} = \dot{d}_{exp} f(z^*) \quad (1)$$

where,

$$f(z^*) = 1 / (0.4 + 0.6e^{-0.05z^*}) \text{ for } C/\rho_g < 0.15$$

$$f(z^*) = 1 / (0.28 + 0.72e^{-0.06z^*}) \text{ for } C/\rho_g > 0.15$$

where, z^* is non-dimensional deposition length given by $z^* = z_d/D$ and $\dot{d}$ and C are droplet deposition rate [$\text{kg/m}^2 \text{ s}$] and droplet mass concentration in gas core [kg/m^3], respectively. As shown in Figure 2b, the data corresponding to different deposition lengths are now collapsed well by this correction factor, except for the data obtained at very long deposition length (6 ft). Probably, at this deposition length, the error due to the re-entrainment of the deposited liquid film is expected to affect the measurement.

3. Results and Discussion

3.1 Assessment of the Existing Correlations

The entrainment rate data measured in the air-water experiments at 4.0 bar and liquid-phase Reynolds number from 450 to 5000 are plotted against the superficial gas velocity in Figure 3a. The figure also shows the predictions of the Kataoka and Ishii correlation. The measured entrainment rate increases with the increasing gas-phase velocity and liquid-phase Reynolds number. However, at higher gas-phase velocities, the entrainment rate asymptotically approaches a maximum limiting value. The Kataoka and Ishii correlation successfully predicted the experimental data at low gas velocity conditions. However, at high gas velocities, the correlation predicted continuously increasing entrainment rate. Similar trends were observed for the remaining air-water data (at 1.2 bar and 6.0 bar) and the Freon-113 data. It should be noted that, for the above comparisons, the liquid film Reynolds number (Re_{ff}) in the Kataoka and Ishii correlation was calculated using the liquid film flow rate measured at the 1st extraction port.

In order to describe the above results, it is essential to consider the trends in the measurement of entrainment fraction. Analysis of the entrainment fraction data is presented in References [4, 5]. The entrainment fraction also showed limiting behavior under high gas velocity conditions. Similar to the maximum entrainment rate, the maximum or limiting entrainment fraction was found to increase with the increasing liquid-phase Reynolds number. The entrainment fraction correlation proposed by Ishii and Mishima over-predicted the maximum entrainment fraction (or under-predicted the minimum liquid film flow rate). As noted earlier, the Ishii and Mishima correlation was used as the basis for the development of the Kataoka and Ishii entrainment rate correlation. Since the measured liquid film flow rate in the limiting region (i.e., at high gas velocity) is higher than the liquid film flow rate predicted by the Ishii and Mishima correlation, the Kataoka and Ishii correlation using the measured liquid film flow rate significantly over-predicted the entrainment rate data in the limiting region.

Entrainment rate in the Kataoka and Ishii correlation is proportional to the liquid film Reynolds number (Re_{ff}) and the Weber number (We) (see Table 1). As we have noted earlier, in the limiting entrainment fraction and entrainment rate region (i.e., at high gas velocity), the liquid film flow approaches minimum limiting flow rate. Therefore, contrary to the trends in the experimental data, the Kataoka and Ishii correlation indicates that in the limiting liquid film flow region the entrainment rate should continuously increase with the increasing gas velocity. Although the over-prediction of the entrainment rate is a conservative behavior from the standpoint of estimation of dryout margin, it is essential to address the fundamental inconsistency in the correlation.

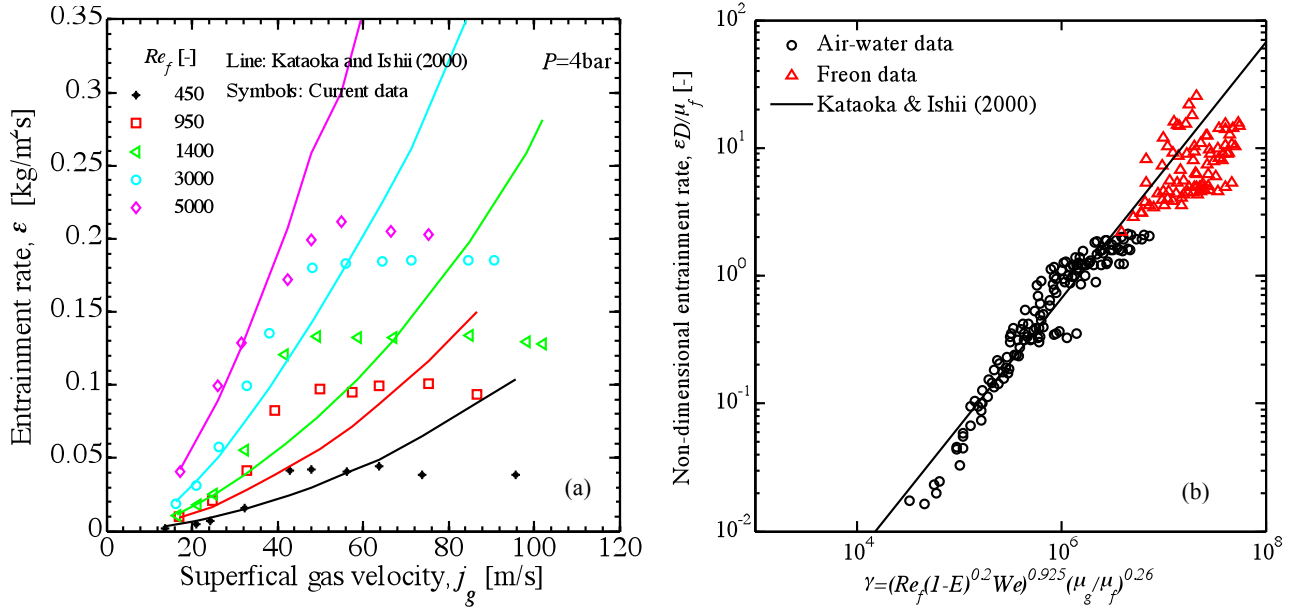


Figure 3: Comparison with Kataoka and Ishii [6] correlation.

Figure 3b shows the comparison of all the air-water and Freon-113 data collected in the current study against the Kataoka and Ishii correlation. The non-dimensional entrainment rate is plotted against the non-dimensional parameter γ in the correlation. Even though the correlation failed to predict the local trends (particularly at high gas velocity), it successfully collapsed the air-water and the Freon-113 data. This shows that the non-dimensional numbers used in this correlation are appropriate.

Figure 4a and 4b shows the comparison of the Lopez de Bertodano et al. and Pan and Hanratty correlations against the air-water entrainment rate data measured at 4.0 bar and liquid-phase Reynolds number 450 to 5000. As observed from the figures, these correlations also failed to predict the limiting entrainment rate under high gas velocity conditions. Lopez de Bertodano et al. proposed a constant value of 80 for the onset of entrainment liquid-film Reynolds number ($Re_{f,OE}$). As noted earlier, at higher gas velocity the liquid film flow rate approaches a minimum liquid flow rate. Consequently, contrary to trends in the experimental data, the Lopez de Bertodano et al. correlation also indicates that in the limiting liquid film flow region (at high gas velocity), the entrainment rate should increase with the increasing gas velocity. Similar conclusion can be made for the Pan and Hanratty correlation.

The correlation proposed by Okawa and Kataoka is compared against the current data in Figures 5a and 5b. As noted earlier, this correlation was developed based on the data that was corrected for the effect of preferential deposition of the droplets over the deposition length. Therefore, for the current comparison, the measured entrainment rate is corrected using the Okawa and Kataoka correction factors in correlation Eq. (1). As seen from Figure 5a, the Okawa and Kataoka correlation predicted the data satisfactorily at low flow of gas- and liquid-phases. At high gas velocity, the correlation predicted continuously increasing entrainment rate. Furthermore, the data at high liquid flow rate is significantly over-predicted. In Figure 5b, all the current air-water data is plotted against the non-dimensional parameter (π_{el}) in the Okawa and Kataoka correlation. Most of the data is over-predicted by the correlation. Furthermore, the correction factor proposed by Okawa and Kataoka

(see Eq. 1) are purely empirical. Consequently, the corrected entrainment rate shows unrealistic trends at high gas velocity (for e.g., see Figure 5a and $Re_f = 950$).

In summary, the correlations in Table 2 failed to predict the entrainment rate at high gas velocity.

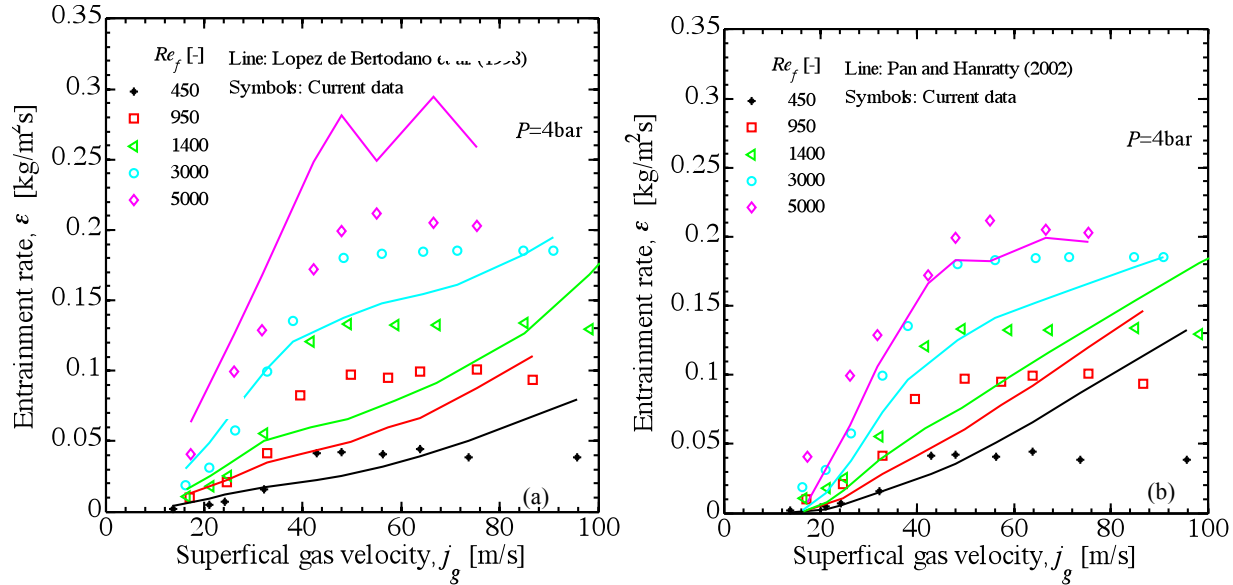


Figure 4: Comparison with Lopez de Bertodano et al. [7] and Pan and Hanratty [8] correlations

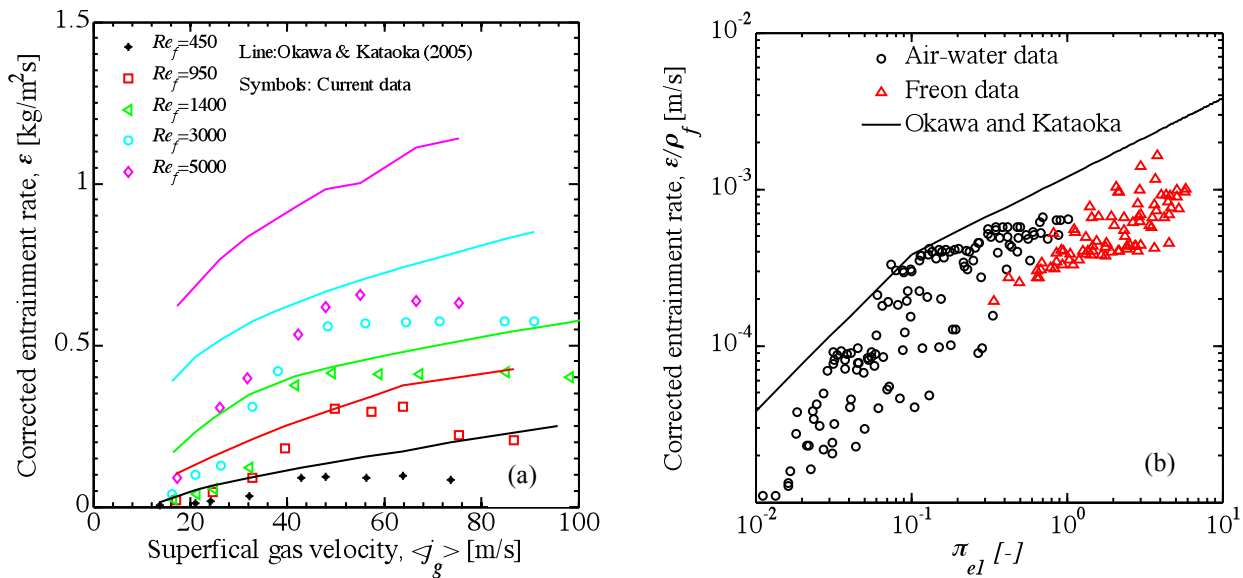


Figure 5: Comparison with Okawa and Kataoka [9] correlation.

3.2 Entrainment Rate Mechanisms

In this section, the air-water entrainment rate data is further analyzed to study the dependence on two non-dimensional numbers; liquid-phase Reynolds number (Re_f) and modified Weber number (We):

$$Re_f = \frac{j_f \rho_f D}{\mu_f} \quad (2)$$

$$We = \frac{\rho_g j_g^2 D}{\sigma} \left(\frac{\Delta \rho}{\rho_g} \right)^{1/4} \quad (3)$$

This Weber number was used by Sawant et al. [4, 5, 13] to correlate the entrainment fraction and disturbance wave properties measured in the current experiments. In Figure 6a, the entrainment rate measured at three different pressure conditions in the air-water experiments is plotted against the Weber number (We). The selected data corresponds to the liquid-phase Reynolds number 950. From Figure 6a, it can be concluded that the Weber number successfully collapsed the data corresponding to different pressure conditions. As discussed earlier, for a given liquid-phase Reynolds number, entrainment rate approaches a maximum entrainment rate at high gas velocity.

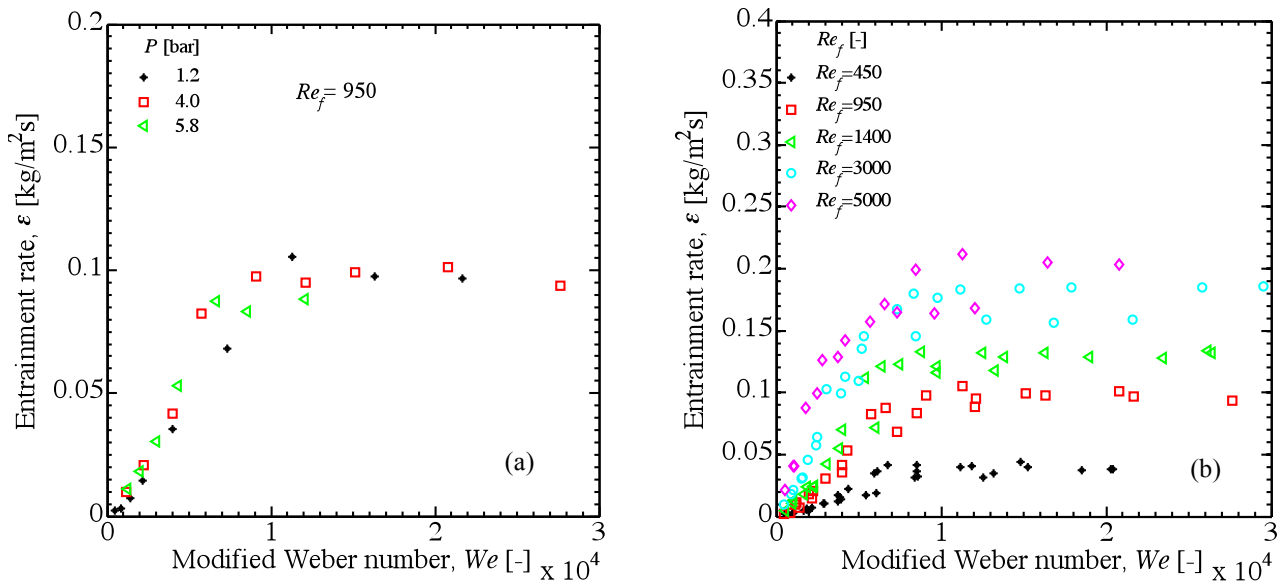


Figure 6: Effect of Pressure and Reynolds Number on Entrainment Rate

In order to study the effect of liquid-phase Reynolds number, the air-water entrainment rate data is plotted against the Weber number in Figure 6b with the liquid-phase Reynolds number used as parameter. As observed from the figure, the two non-dimensional numbers, Weber number and liquid-phase Reynolds successfully collapsed the data at all pressure conditions and liquid-phase Reynolds number conditions. It appears that similar to the maximum entrainment fraction [4, 5] the maximum entrainment rate is also function of liquid-phase Reynolds number. It can be observed from Fig. 6b that initially entrainment rate increases linearly with the Weber number. However, the rate of increase gradually decreases at high Weber number conditions, and eventually it approaches a constant limiting value at very high Weber number. The increase in liquid-phase Reynolds number results in increase of entrainment rate.

4. Conclusions

Limitations of the liquid film extraction technique for the measurement of droplet entrainment fraction and entrainment-deposition rates in annular flow have been identified and analyzed. It was found that the current air-water and Freon-113 experiment data are not affected by the limitations of the film extraction technique that are caused by the incomplete extraction of liquid film and re-entrainment of the deposited liquid film. However, the data requires correction for the effect of preferential droplet deposition. The empirical correction factor proposed by Okawa and Kataoka to account for this limitation was found to alter the data trends under high gas velocity condition.

The analysis revealed that the existing correlations predicted continuously increasing entrainment rate under high gas velocity, which is in contradiction with the maximum limiting entrainment rate observed in the experimental data. The analysis also showed that similar to the entrainment fraction, the entrainment rate data can be correlated using two non-dimensional numbers: liquid-phase Reynolds number and Weber number. A new improved correlation is necessary for the prediction of entrainment rate which can also account for the existence of maximum entrainment rate.

5. Nomenclature

C	droplet mass concentration in the gas core [kg/m^3]
D	test section diameter [m]
$\dot{d}$	droplet deposition rate [$\text{kg/m}^2\text{s}$]
E	entrainment fraction [-]
g	gravitational acceleration [m s^{-2}]
j	area averaged superficial velocity [m/s]
k_A	droplet atomization coefficient [s^2/kg]
Pr	pressure [bar]
P	Wetted perimeter [m]
Re	Reynolds number [-]
W	mass flow rate [kg/s]
We	Weber number [-]
z_d	deposition length [m]

Greek Symbols

δ	liquid film thickness [m]
$\dot{\epsilon}$	droplet entrainment rate [$\text{kg/m}^2\text{s}$]
μ	dynamic viscosity [kg/ms]
ρ	mass density [kg/m^3]
σ	surface tension [N/m]
γ	non-dimensional parameter Kataoka and Ishii correlation (see Table 1)

Subscripts

$corr$	corrected
exp	experimental
f	liquid phase
ff	liquid film
g	gas phase

gc critical at onset of entrainment
 OE onset of entrainment

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