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ANNULAR TWO-PHASE FLOW

Martin A. Lopez de Bertodano
Cheng-Shiun Jan
Stephen G. Beus

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BETTIS ATOMIC POWER LABORATORY WEST MIFFLIN, PENNSYLVANIA 15122-0079

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Droplet Entrainment Correlation for High Pressure Annular Two-Phase Flow

Martin A. Lopez de Betodano and Cheng-Shiun Jan

School of Nuclear Engineering

Purdue University

West Lafayette, IN 47907-1290

and

Stephen G. Beus

Bettis Atomic Power Laboratory

Westinghouse Electric Corporation

West Mifflin, PA 15122-0079

Abstract

The amount of entrainment in annular flow is essential to predict the point of dryout. Most of the entrainment correlations available in the literature are obtained from air-water low pressure data. However many important industrial applications involve high pressure annular flows. There are very few correlations applicable in this range and they are solely based on empirical data fits.

Comparing the low pressure entrainment data of Cousins and Hewitt (1968) and the high pressure data of Keeys et. al. (1970) and Wurtz (1978) with existing correlations, the agreement at high pressure is generally poor, except for the empirical correlation of Nigmatulin and Krushenok (1989) which depends on a Weber number that includes the droplet concentration.

We propose a new semi-mechanistic entrainment correlation for fully developed annular flow conditions: $E = \frac{0.9642}{1 + 3836 / We_c}$. It is developed based on the droplet

continuity equation and the entrainment rate model of Dallman et. al. (1979). This model is then modified to introduce a Weber number that includes the droplet concentration, We_c . This Weber number is shown to scale the available high and low pressure air-water and steam-water data better than the other definitions.

Because the new correlation is based on a model of entrainment rate it may be used as a starting point in the development of a correlation for this process applicable to high pressure water-steam annular flows. A correlation is suggested pending validation with high pressure entrainment rate data.

Nomenclature: (units in mks system)

C	droplet concentration in gas core (kg/m^3)
C_f	friction factor defined by eq. (30)
D	duct diameter (m)
$\dot{d}$	deposition rate ($\text{kg/m}^2 \text{ s}$)
E	entrainment fraction
E_M	theoretical maximum entrainment fraction
E_∞	equilibrium entrainment fraction
$\dot{\epsilon}$	entrainment rate ($\text{kg/m}^2 \text{ s}$)
j_f	volmetric flux of total liquid (m/s)
j_g	volmetric flux of gas (m/s)
k_A	entrainment coefficient (s^2/kg)
k_A^*	dimensionless entrainment coefficient defined by eq. (22)
k_D	deposition coefficient (m/s)
l	major geometric parameter defined by eq. (12) (m)
μ_f	viscosity of liquid (kg/m s)
P	duct parameter (m)
P_h	heated parameter (m)
P_w	wetted parameter (m)
p	pressure (kg/m s^2)
π	dimensionless complex defined by eq. (9)

Re_f	Reynolds number on the film
ρ_f	liquid density (kg/m^3)
ρ_g	gas density (kg/m^3)
ρ_{gc}	density of mixture in the gas core (kg/m^3)
σ	surface tension (kg/s^2)
τ	shear stress (kg/m s^2)
u_g	gas velocity (m/s)
u^*	gas friction velocity defined by eq. (26) (m/s)
We_C	Weber number defined by eq. (11)
We_D	Weber number defined by eq. (18)
We_l	Weber number defined by eq. (2)
W_G	mass flow rate of the gas (kg/s)
W_L	mass flow rate of the total liquid (kg/s)
W_{LE}	mass flow rate of the entrainment liquid (kg/s)
W_{LF}	mass flow rate of the liquid film (kg/s)
W_{LFC}	critical film flow rate (kg/s)
x	steam quality
Z	axial distance from inlet (m)

1. Introduction

The heat and mass transfer processes in annular two-phase flow are significantly affected by the droplet entrainment. The amount of entrained droplets is a function of the liquid film flow rate, and plays an important role in the prediction of burnout heat flux. Burnout heat flux, which causes the liquid film to dry out and hence the breakdown of heat transfer at the heated surface, is the most important design limit in nuclear reactor safety calculations. In order to predict burnout heat flux and other related phenomena

mechanistically, a reliable correlation for the entrainment fraction, i.e., the fraction of entrained liquid, in annular two-phase flow is necessary. In addition, such a correlation can be applied to refine the general thermohydraulic calculations in annular two-phase flow. In particular, a correlation applicable for the high pressure flows would be helpful in the analysis of the Emergency Core Cooling System (ECCS) transients in light water reactors. At present, several correlations are available for the entrainment fraction, such as Paleev and Filipovich (1966), Dallman, Laurinat and Hanratty (1979), Ishii and Mishima (1989), Nigmatulin and Krushenok (1989). However, it has been shown that these correlations have narrow ranges of applicability and/or insufficient accuracy. The purpose of the present study is to develop a more accurate correlation for the entrainment fraction which could be used in both high-pressure and low-pressure applications.

2. Previous Work

2.1 Available Data

A number of experiments for the measurements of entrainment fraction have been carried out over the past thirty years. A summary of some of these measurements is given by Wurtz (1978). The present work employs Cousins and Hewitt's low-pressure air-water data (1968), Keeys, Ralph and Roberts' high-pressure steam-water data (1970) and Wurtz' high-pressure steam-water data (1978) to evaluate the above mentioned correlations for the entrainment fraction.

The Experimental Data of Cousins and Hewitt

To evaluate the effect of various parameters on the rate of deposition, Cousins and Hewitt (1968) measured the droplet mass transfer coefficient using two closely positioned porous wall sections. These experiments were carried out in adiabatic, upwards, air-water flows in round tubes at near ambient temperature and low pressure, i.e. 0.14 to 0.24 MPa. A 2.2 m long and 9.5 mm ($3/8$ in.) I.D. bore acrylic resin tube was employed.

The distance necessary to reach an equilibrium condition is given by Kataoka and Ishii (1982) as follows:

$$Z \approx 440 D We_i^{0.25} / Re_f^{0.5} \quad (1)$$

where

$$We_i \equiv \frac{\rho_s j_s^2 D}{\sigma} \left(\frac{\Delta \rho}{\rho_s} \right)^{1/3} \quad (2)$$

$$Re_f \equiv \frac{\rho_f j_f D}{\mu_f} \quad (3)$$

In the case of Cousins and Hewitt's (1968) experiment, the value of $440 We_i^{0.25} / Re_f^{0.5}$ lies between 50 and 150. Hence, the entrainment fraction measured at the tube exit can be regarded as the equilibrium value, since Z/D is approximately 230 at this point.

As shown in Figure 1, the injected liquid film was removed by suction through porous wall section (S1) and the liquid film formed by redepositing droplets was removed by suction through porous wall section (S2). The flow rate of entrained liquid, $(W_{LE})_2$, at the end of porous wall section (S2) had been measured by using a cyclone separator. The flow rate of entrained liquid, $(W_{LE})_1$, was determined by a mass balance equation:

$$W_L = (W_{LF})_1 + (W_{LE})_1 \quad (4)$$

Here, W_L is inlet liquid flow rate, $(W_{LF})_1$ is the liquid film removal rate through porous wall section (S1).

This experiment is very important because the deposition rate is also measured with the second suction probe. Various deposition lengths were measured. Different deposition length gives different deposition rate. Only the data points with 0.3048 m deposition length are used in this paper.

The Experimental Data of Keeys, et al.

In contrast to Cousins and Hewitt's (1968) experiment, Keeys et al. (1970), measured the liquid entrainment in adiabatic annular steam-water flows at much higher pressures, viz., 3.447 and 6.894 MPa. The 12.6 mm I.D. test section was 3.66 m long. This ensured approximate equilibrium conditions at the liquid film extraction point. As shown in Figure 2, the liquid film flow rate is measured by extracting the film through a film removal device at the end of the test section. The steam which is inevitably removed with the liquid film is passed into a trace-heated cylinder and pumped back through another orifice 'O2'. When the pressure difference across orifice 'O2' is increased, the liquid film removal rate increases until a plateau is reached. The true liquid film flow rate was taken as this value.

The Experimental Data of Wurtz

Wurtz performed measurements of the film flow rate, pressure gradient, film thickness and burnout heat flux in high-pressure annular steam-water flow. The experiments were carried out at 3.0, 5.0, 7.0 and 9.0 MPa under both adiabatic and diabatic conditions. The 10 mm. I.D. tubular test section was 9.0 m long. The liquid film was taken off through a suction probe at the end of the test section where numerous 1.2 mm holes were drilled in the tube wall covering a length of 50 mm. Though these holes the liquid film on the wall was sucked off. This invariably removed some steam and droplets. To determine the real film flow rate, suction curves were plotted. An example suction curve is shown in figure 3, where W_L is the liquid flow rate in the suction mixture, W_g is the steam flow rate in the suction mixture, W is the total mass flow rate and x_{out} is the steam quality at the outlet of the test section. The line with the slope s_c was assumed to represent the situation where film and droplets were sucked off. The liquid film flow rate was then determined by the point of intersection of this line with the line $W_g = 0$.

It was found that some of these data fall below the entrainment inception criterion limit of van Rossum (1959). To ensure that the inception of droplet entrainment has been reached, only those data points whose gas velocity is larger than twice of the critical

velocity, which is the minimum gas velocity required for the onset of entrainment, are adopted in this paper.

2.2 Available Correlations

Several correlations have been developed for the entrainment fraction. Reviews of some of these correlations have been given by Ishii and Mishima (1989). In the present work, four existing correlations were compared with the experimental data of Cousins and Hewitt (1965), Keeys et al. (1970) and Wurtz (1978). They are the entrainment fraction correlations proposed by Paleev and Filipovich (1966), Ishii and Mishima (1989), Nigmatulin and Krushenok (1989) and the entrainment rate correlation proposed by Dallman, Jones and Hanratty (1979).

Paleev and Filipovich's Correlation

Using low-pressure air-water data, Paleev and Filipovich (1966) related the dimensionless gas flux, $\frac{\rho_{gc}}{\rho_f} \left(\frac{\mu_f j_g}{\sigma} \right)^2$, to the fraction of liquid flowing in the film and obtained:

$$\frac{W_{LF}}{W_L} = 0.985 - 0.44 \log \left[\frac{\rho_{gc}}{\rho_f} \left(\frac{\mu_f j_g}{\sigma} \right)^2 \times 10^4 \right] \quad (5)$$

Hence, the entrainment fraction can be expressed as:

$$E = \frac{W_{LE}}{W_L} = 0.015 + 0.44 \log \left[\frac{\rho_{gc}}{\rho_f} \left(\frac{\mu_f j_g}{\sigma} \right)^2 \times 10^4 \right] \quad (6)$$

Where ρ_{gc} is defined as:

$$\rho_{gc} \equiv \rho_g \left(\frac{W_G + W_{LE}}{W_G} \right) \quad (7)$$

However, as mentioned by Ishii and Mishima (1989), the diameter effect has not been included in it.

In figure 4, we compare Paleev and Filipovich's correlation with the data of Cousins and Hewitt (1965), Wurtz (1978), and Keays et al. (1970), the standard deviation being 0.325. Two remarks can be made about this comparison. First, the predictions of the Paleev and Filipovich's correlation seem to be poor when compared against a wide range of experimental data. In addition, the use of dimensionless gas flux, $\frac{\rho_{gc}}{\rho_f} \left(\frac{\mu_f j_g}{\sigma} \right)^2$, to correlate entrainment fraction can be seen to segregate high and low pressure data in two distinctive groups.

Ishii and Mishima's Correlation

Ishii and Mishima (1989) proposed a detailed correlation on the basis of entrainment inception criteria and a force balance at the wavy interface as follows:

$$E_{\infty} = \tanh(7.25 \times 10^{-7} We_l^{1.25} Re_f^{0.25}) \quad (8)$$

where We_l is defined in equation (2).

This correlation indicates that the equilibrium entrainment fraction E_{∞} depends on the total liquid Reynolds number and Weber number. Since it was developed using a limited set of experimental data in atmospheric air-water flows, it is expected that the correlation may not apply directly to high pressure situations.

Figure 5 compares Ishii and Mishima's correlation with the experimental data, the standard deviation being 0.132. It shows that there is excellent agreement between Cousins and Hewitt's low pressure data and equation (8), but the high-pressure data of Keays et al. and Wurtz tend to diverge from equation (8) considerably. Figure 5 also seems to show that the equilibrium entrainment reaches a limit below 1.0, suggesting that whenever there is entrainment, there is also deposition; or whenever there is any liquid, some of it will be on the walls.

Nigmatulin and Krushenok's Correlation

Nigmatulin and Krushenok (1989) developed an entrainment correlation using an extensive collection of Soviet high pressure water-steam data in tubes and annular channels. They proposed a dimensionless parameter π to describe the relation between the inertial forces of the gas-droplet core and the liquid surface tension. The entrainment was correlated as,

$$1 - E = 3.2 \pi^{-0.2}, \quad \pi \leq 7 \times 10^3 \quad (9a)$$

$$1 - E = 10^3 \pi^{-0.85}, \quad \pi > 7 \times 10^3 \quad (9b)$$

$$\pi = \left(\frac{\mu_f}{\mu_s} \right)^{0.3} We_c \quad (10)$$

where

$$We_c = \frac{\rho_{sc} j_s^2 l}{\sigma} \quad (11)$$

$$l = D \left(1 + \frac{P_h}{P_w} \right) \quad (12)$$

$$\rho_{sc} = \frac{(W_G + W_{LG})}{\left(\frac{W_G}{\rho_s} + \frac{W_{LG}}{\rho_f} \right)} \approx \frac{(W_G + W_{LG})}{W_G} \rho_s \quad (13)$$

P_h is the heated perimeter (m) and P_w is the wetted perimeter (m).

Figure 6 compares their correlation with the same set of experimental data used earlier, the standard deviation being 0.124. Although the high pressure data are reasonably correlated by this correlation, the low pressure data are not.

Dallman, Jones and Hanratty's Correlation

Dallman et al. (1979) correlated the entrainment rate from a liquid film as:

$$\dot{\varepsilon} = k_A \left(\frac{W_{LF} - W_{LFC}}{P} \right) u_s^2 \rho_s^{\frac{1}{2}} \rho_f^{\frac{1}{2}} \quad (14)$$

where k_A is an entrainment coefficient, P is the perimeter of the wetted surface and W_{LFC} is the critical liquid mass flow rate required for the onset of entrainment. For air-water upflow $k_A = 3.5 \times 10^{-6} \text{ s}^2/\text{kg}$ and $W_{LFC}/P = 0.046 \text{ kg/m s}$. A comparison with the deposition rate data of Cousins and Hewitt shown in figure 7 indicates good agreement.

The deposition rate is represented in terms of the concentration of droplets in the gas core, C , and the deposition coefficient k_D (m/s) as:

$$\dot{d} = k_D C \cong k_D \frac{\rho_s W_{LF}}{W_G} \quad (15)$$

At steady state, the rate of deposition from the gas core is equal to the entrainment rate from the liquid film, i.e.,

$$\dot{d} = \dot{\varepsilon} \quad (16)$$

Inserting equations (14) and (15) into equation (16), Dallman obtained:

$$\frac{E}{E_M} = \frac{\frac{k_A}{4k_D} D u_s^3 \rho_s^{\frac{1}{2}} \rho_f^{\frac{1}{2}}}{1 + \frac{k_A}{4k_D} D u_s^3 \rho_s^{\frac{1}{2}} \rho_f^{\frac{1}{2}}} \cong \frac{\frac{k_A \sigma j_s}{4k_D} We_D}{1 + \frac{k_A \sigma j_s}{4k_D} We_D} \quad (17)$$

Where we have defined

$$We_D \equiv \frac{\rho_s j_s^2 D}{\sigma} \sqrt{\frac{\rho_f}{\rho_s}} \quad (18)$$

$$E_M \equiv 1 - \frac{W_{LFC}}{W_L} \quad (19)$$

Using $\frac{k_A}{4k_D} = 5.4 \times 10^{-6} \text{ s}^3/\text{kg m}$ and $W_{LFC}/P = 0.046 \text{ kg/m s}$, a comparison for equation (17) with different experimental data is shown in figure 8. The standard

deviation is 0.434. Although equation (17) has a good agreement with low-pressure data, the figure shows that $Du_g^3 \rho_g^{0.5} \rho_f^{0.5}$ can not correlate the high pressure entrainment fraction data properly.

3. Proposed correlation

The foregoing comparisons show that We_c used by Nigmatulin and Krushenok is more appropriate than We_f or We_D to correlate high pressure data. On the other hand the derivation by Dallman et. al. based on mechanistic principles is more attractive than an empirical correlation of the data. Thus equation (14) may be modified as:

$$\dot{\varepsilon} \cong k_A \left(\frac{W_{LF} - W_{LFC}}{P} \right) u_s^2 \rho_{sg} \quad (20)$$

or

$$\frac{\dot{\varepsilon} D}{\mu_f} \cong k_A^* Re_f We_c (E_M - E) \quad (21)$$

where

$$k_A^* \equiv \frac{k_A}{4\sigma} \quad (22)$$

Figure 9 shows that the dimensionless group $Re_f We_c (E_M - E)$ scales the data. In a previous work by Kataoka and Ishii (1982), a similar dimensionless group, viz., the combination of Re_f and We_f , were used to correlate the entrainment rate. Let us assume that the entrainment rate can be presented as a function of $Re_f We_c (E_M - E)$, i.e.,

$$\frac{\dot{\varepsilon} D}{\mu_f} = \frac{a \theta}{1 + b \theta} \quad (23)$$

where

$$\theta \equiv Re_f We_c (E_M - E) \quad (24)$$

Curve fitting the data, the constants $a=1.791 \times 10^{-6}$ and $b=4.471 \times 10^{-7}$ are determined. The NFITTM computer program was used. It is based on the non-linear least squares algorithm of Berington (1969). Figure 9 shows a comparison of the data of Cousins and Hewitt (1968) and equation (21).

Equation (15) for the deposition rate can be rewritten as:

$$\frac{\dot{d}D}{\mu_f} = \frac{k_D}{j_s} \text{Re}_f E = \frac{k_D}{u^*} \left(\frac{u^*}{j_s} \text{Re}_f E \right) \quad (25)$$

where

$$u^* = \sqrt{\frac{\tau}{\rho}} \quad (26)$$

$$\tau = \frac{D}{4} \left(\frac{dp}{dx} \right) \quad (27)$$

and $\frac{k_D}{u^*}$ is given by Andreussi's correlation (1983), i.e.,

$$\frac{k_D}{u^*} = \frac{0.115}{1 + 2.3 \frac{C}{\rho_g}} \quad (28)$$

In figure 10 the deposition rate data of Cousins and Hewitt (1968) is plotted vs. $\frac{u^*}{j_s} \text{Re}_f E$. It shows that the dimensionless group $\frac{u^*}{j_s} \text{Re}_f E$ scales the data.

At steady state, equalizing equations (21) to (25) we have:

$$E = \frac{E_M}{1 + \frac{k_D}{u^*} \frac{u^*}{j_s} \frac{1}{k_A^* We_c}} = \frac{E_M}{1 + f\left(\frac{C}{\rho_g}\right) \sqrt{\frac{c_f}{2}} \frac{1}{k_A^* We_c}} \quad (29)$$

where c_f is defined by

$$\tau = c_f \frac{\rho_g j_s^2}{2} \quad (30)$$

Then, we make the approximation:

$$E \cong \frac{E_M}{1 + k/We_c} \quad (31)$$

Figure 11 is the plot of entrainment fraction versus We_c . $E_M = 0.9642$ and $k = 3836.17$ are determined by curve fitting with the computer program NFIT™. The standard deviation is 0.0389. Satisfactory agreement between prediction and experimental data can be seen to exist.

The experiments used to obtain correlations (23) and (31) were done with 10 mm pipe diameters approximately. A comprehensive study performed by Schadel et. al. (1990) shows that the entrainment rate dependence on u_g -- equation (14) -- changes with pipe diameter. Therefore the present correlations are not recommended for other pipe sizes. On the other hand equation (31) correlates data for very different density ratios and surface tensions so it may be applied to other fluids with some confidence even though it was derived specifically for steam-water.

4. Summary and conclusions

A review of available annular flow entrainment correlations using low pressure data by Cousins and Hewitt and high pressure data by Keeys et. al. and Wurtz show poor agreement. The best agreement for high pressure is obtained with Nigmatulin's correlation who based it on We_c in terms of the core density of the gas and the droplets. Therefore a new correlation is proposed that is based on We_c and the mechanistic analysis of Dallman et. al. which fits all the data significantly better.

Further improvements in the analysis of annular flow may be obtained in terms of the entrainment rate and deposition rate. The present analysis indicates that We_c is the better choice to correlate the entrainment rate and a comparison with the low pressure data of Cousins and Hewitt shows good agreement. However this hypothesis must wait until high pressure data for entrainment rate becomes available.

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Figure 1. Test section for Cousins and Hewitt's (1965) experiment

Figure 2. Test section for the experiment of Keeys, et al. (1970)

Figure 3 Example of the Suction Curve for Wurtz' (1978) experiments.

Figure 4 Comparison of Paleev's and Filipovich's (1966) correlation with the experimental data.

Figure 5 Comparison of Ishii's and Mishima's (1989) correlation with the experimental data.

Figure 6 Comparison of Nigmatulin's and Krushenok's (1989) correlation with the experimental data.

Figure 7 Comparison of entrainment measurements by Cousins and Hewitt (1968) with Dallman's correlation [equation (14)].

Figure 8 Comparison of entrainment fraction correlation of Dallman et. al. (1979) with the experimental data.

Figure 9 Comparison of $Re_f We_C (E_M - E)$ with entrainment rate data of Cousins and Hewitt (1968).

Figure 10 Comparison of $(u^* / j_g) Re_f E$ with deposition rate data of Cousins and Hewitt (1968).

Figure 11 Comparison of proposed correlation [eq. (31)] with experimental data.