A prediction method for entrained liquid fraction in adiabatic gas-liquid flow at high reduced pressure

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Abstract. A goal of the study is development of an approximate but well-grounded model of entrainment/deposition processes in annular two-phase flow at high reduced pressures ($p/p_{cr} > 0.45$). Nakazotomi and Sekoguchi (1996) have presented the unique experimental data on liquid distribution between the core and the film in air/water two-phase flow at high pressures, up to 20 MPa; at pressures higher 10 MPa the data feature with abnormally high fraction of entrained liquid and manifest very strong deviation from any known empirical correlations, including the recent one by Cioncolini and Thome (2012). In deducing the approximate model of droplets entrainment, we used the experimental observations, according to which a liquid film becomes thin and smooth at high reduced pressures. A plenty of tiny droplets detach from the liquid film surface at the points, which spacing is determined as a length scale in Weber number for gas flow. This spacing and the liquid film thickness are assumed being the parameters controlling a droplet departure diameter. These assumptions allow developing an equation for calculating entrainment intensity at high reduced pressures. A balance between the flows of droplets entrainment and deposition due to turbulent diffusion corresponds to the dynamic equilibrium. The equation based on this balance contains one unknown numerical factor and allows one to calculate liquid distribution in a channel cross section. Comparing the calculation results with the experimental data for the water–air flows at high reduced pressures (more than 0.45) has shown their good agreement at the universal value of the numerical constant.

1. Introduction
Earlier [1] the authors have developed the method of calculation of liquid fraction in a flow core at high reduced pressures. The pressure range corresponds to the needs of thermal hydraulics of nuclear power plants (NPP). Besides, among rather scarce studies of steam-water flows at pressures typical for the NPP equipment, only in the works by B.I. Nigmatulin et al. presented in the monograph [2], measuring the droplets entrainment was complicated by the oncoming process of their deposition from the core. Therefore, the authors referred mainly to these data and tested the droplet entrainment model [3] (used in [1]) on the unique results [4] for steam-water flows at pressures of $1 \div 12$ MPa.

In [3], the droplet entrainment from the surface of a turbulent film with large-scale waves on its surface is considered. Analysis of the characteristic scales of the process (a probable wavelength of large disturbance, a period of energy-carrying vortices in the gas core, a size of droplets entrained) and the assumption on the possibility of expressing friction factor at the interface through the relative film thickness lead to an equation for the mass flux density of droplets entrained:
\[ E = A_0 \left( \frac{\xi}{8} \rho' \right)^{1/2} \frac{\Gamma_f w_0^*}{d}, \]

where \( d \) is a channel diameter, \( \rho' \) is liquid density, \( \sigma \) is surface tension, \( w_0^* \) is superficial gas velocity, \( m_r \) is liquid flow rate in the film, \( \Gamma_f = \frac{m_r}{\pi d} \) is liquid flow rate per unit length of the tube perimeter, \( \xi \) is friction factor, \( A_0 = 4.5 \cdot 10^{-4} \) is numerical factor.

It is essential that the approximate model [3] gives a "natural" linear dependence of entrainment rate on the flow rates both of liquid and of gas (vapor). Eq. (1) was confirmed by the experimental data [4], where influence of the superficial vapor velocity at a constant liquid film flow rate and liquid flow rate at a fixed vapor velocity on the entrainment rate were separately studied.

In [1] it is shown that Eq. (1) approximately keeps its validity in the presence of a counterflow of deposited drops. Firstly, due to huge difference of specific volumes of liquid and vapor, the presence of droplets in the channel core slightly changes gas velocity. Secondly, the results of [5] support this hypothesis. Its final equation for entrained liquid fraction contains only one nondimensional parameter, flow core Weber number, which obviously determines only the intensity of entrainment, but not deposition. As the first approximation gas Weber number is used, then there is a need in the iterative procedure, which allows to estimate an influence of droplets in the core on the intensity of entrainment. Since the replacement of the gas density in the Weber number by the average core density increases the fraction of the experimental points falling within the range ± 50% from the calculated value by only 4% (from 75 to 78.9%), presence of droplets in the core of the real annular flow, indeed, slightly changes the perturbing effect of the gas on the film surface.

Equality of the entrainment rate \( E \) and deposition \( D \) determines the state of dynamic equilibrium, which is established in the annular flow at a distance of about 200 calibers from the cross section of the flow formation. Most of the experimental data on liquid distribution between the flow core and the film on the channel wall was obtained at this flow state. In work [6], a numerical simulation of the annular flow with a homogeneous vapor-drop core was performed at relatively high reduced pressures, the equation (1) published later in [3] being used to calculate the rate of droplets entrainment. The results of this simulation tested on experimental data [2], led to the conclusion that turbulent diffusion of liquid drops is the most probable mechanism of their deposition onto the film surface. The balance of the droplet deposition flux, built up on the basis of the Reynolds analogy between momentum and droplet mass transfer in the flow core, and the entrainment flux (1) gives an equation for the liquid distribution between the core and the liquid film, containing only one empirical numerical factor:

\[ \frac{m_E}{m_L} = \frac{1}{2} \left[ 1 - \frac{m_G}{m_L} A_1 + \left( 1 - \frac{m_G}{m_L} A_1 \right)^2 + \frac{4 m_G}{m_L} \right]^{1/2}, \]

where \( A_1 = 4.5 \cdot 10^{-4} \left( \frac{\xi}{8} \rho' \right)^{1/2} \), \( A_2 = \frac{4}{\pi d^2} \left( \frac{\xi^* / 8}{1 - 12.7 \sqrt{\xi^*/8}} \right) \), \( \rho' \) is gas density, \( \nu \) is the liquid kinematic viscosity, \( m_G \) is gas mass flow, \( m_E \) is liquid mass flow in the channel core, \( m_L = m_E + m_r \) is total liquid mass flow, \( \xi^* = (1.82 \lg \text{Re}_G - 1.64)^2 \) is friction factor, \( \text{Re}_G = \frac{4 m_G}{\pi d \mu^*} \) is the gas core Reynolds number.

The correspondence of calculations according to (2) with the experimental data for two-phase single-component flows (water, R-113) in the range of reduced pressures 0.04 ÷ 0.53 was surprisingly good. It is significant that the relatively new experimental data on R-113, as well as the data on steam-water flows by Nigmatulin and his co-workers occur to be consistent with the prediction in the best
measure. At the same time, it was established [1] that the majority of the experimental data on low-pressure gas-water flows do not agree with the calculations.

We have many times emphasized [1, 3, 9] that the equation by Cioncolini-Thome [5] for the entrained liquid fraction in annular flow is the best empirical correlation today. At the same time, it was pointed out that it does not reflect influence of liquid flow rate in the film on the intensity of droplet entrainment, although it was revealed in a number of the experiments. In the recent publication [7], it is shown that the experimental values of the entrained liquid fraction obtained in [8] at high pressures greatly exceed the calculated ones according to [5]. It is clear that any empirical correlation cannot be universal. The two empirical correlations of [7] seem rather pointless, because they have no physical content, incorrect on dimension and do not add anything to the tabular data of [8].

2. Analysis

It was noted in [9] that in the case of a thin laminar film, droplet breakage is associated with the action of large energy-carrying vortices on the film surface. Such vortices in the reference system moving with the average velocity of the main stream near the film boundary are directed opposite to the main stream. The velocity slowing near the film should lead to its local thickening. As a result, waves break out from the crests of the waves and the droplets are carried away by the vortices.

The model [9] was designed for low-pressure (close to atmospheric) gas flows. The paper [8] contains qualitative remarks that at very high pressures (above 10 MPa) at the large fraction of the entrained liquid, the film becomes smooth. At the highest of the pressures, 20 MPa studied in this work, the droplet flow rate measured by the isokinetic probe was in some cases higher than the total liquid flow at the inlet (!). This forces to be cautious in relation to the part of the experimental data [8], where the measured fraction of the droplet was noticeably more than 50%. However, qualitative changes in the structure of the two-phase flow at a pressure above ~ 0.5 \( p_{cr} \) were noted in the studies [10, 11]. For this article, the most noticeable is change of the profile of a liquid mass velocity from a \( M \)-shape at \( p \leq 10 \) MPa to a convex one at higher pressures (up to 13.7 MPa). As it should be clear, we are talking about the distribution of liquid droplets in the core of the flow.

The above observations are used in a new model of drop entrainment from the surface of a smooth film at very high pressures. According to [3], the intensity of droplet entrainment from the surface of a liquid film can be estimated as

\[
E \sim \rho' N \omega d_p^3, \tag{3}
\]

where \( N \) is a number of crests of waves per unit surface area; \( \omega \) is frequency of droplet breakdown; \( d_p \) is a drop diameter.

For high pressures, typical values of a hydrodynamic head are \( \rho^* w_0^* = 10^3 + 10^4 \) m/s. For Weber number \( We_{cr} = \frac{\rho^* w_0^* z_0}{\sigma} = 10 \), corresponding to beginning the drop entrainment from the surface of the film [12] the characteristic linear scale to within a factor \( C_l \) is equal to

\[
l_0 = C_l \frac{\sigma}{\rho^* w_0^* z_0}. \tag{4}
\]

The smallness of this scale and the very high values of the hydrodynamic head allow assuming that at high pressures the short waves form on the surface of the film, from the crests of which a lot of small drops break off at high frequencies. Their total number per unit surface of the film
\[ N - \frac{1}{l_0^2} = C_2 \left( \frac{\rho^* w_0^*}{\sigma} \right)^2, \]

where \( C_2 \) is a numerical factor of the order of 0.01.

As in [3], the frequency \( \omega \) of droplet detachment is assumed to be determined by impact of the energy-carrying turbulent vortices of the flow core on the film surface:

\[ \omega \sim \frac{w_0^*}{d}. \]

In the review article [13] it is reported that in many studies of two-phase flows the frequency of perturbation waves, from crests of which the drops detach, contains an additional multiplier in the form of vapor/liquid densities ratio:

\[ \omega \sim \frac{w_0^*}{d} \left( \frac{\rho^*}{\rho} \right)^n. \]  

(6a)

At pressures close to atmospheric, \( n = 0.5 - 0.64 \). At high pressures, the value of \( n \) may be different.

The droplet diameter under the conditions should depend on the thickness of the film and the characteristic distance between the crests of the waves. When choosing the form of this dependence, we were guided by dimensions consideration and by the desire to retain the form of the dependence on gas and liquid flow rates obtained in equation (1) in the final relation for \( E \). As a result, it was accepted:

\[ d_p = \left( l_0 \delta^2 \right)^{1/3}. \]

(7)

The expression for the thickness of a laminar film \( \delta \) was obtained by the authors in [9]

\[ \delta = C_2 \left( \frac{\nu \Gamma_c}{\rho^*} \right)^{1/2} \frac{1}{w_0^*}. \]

(8)

Substituting expressions (4) - (8) into (3), we obtain an equation for calculating the rate of entrainment of droplets from the surface of the film to within a numerical constant

\[ E = C \frac{d^2 w_0^*}{\sigma d}, \]

where \( \mu \) is a liquid dynamic viscosity.

In an annular two-phase flow, there is always a counterflow of deposition, the main mechanism of which is turbulent diffusion [1, 6]. Intensity of droplet deposition in homogeneous vapor-drop flow is:

\[ D = \frac{4}{\pi d^2} \left( \frac{\varepsilon^*}{2/8} \right) m_E \frac{1}{\left( 1 - 12.7 \sqrt{\frac{\varepsilon^*}{2/8}} \right)} \]

(10)

Under the conditions of the dynamic equilibrium between droplet entrainment and deposition, typical for most experimental studies in this region \( E = D \). Thus, equating the expressions (9) and (10) one obtains:
C \frac{\mu \Gamma \varpi^* w_0^*}{\sigma d} = \frac{4}{\pi d^2} \left( \frac{\xi^*}{8} \right) m_F.

Taking into account that \( \Gamma_f = \frac{m_F}{\pi d}, w_0^* = \frac{4m_G}{\rho^* \pi d^2}, m_E = m_L - m_F \), one can obtain an expression for the liquid flow rate in the film to within a constant \( C \)

\[ m_F = m_L \left[ C \frac{8 \mu m_G \left( 1 - 12.7 \sqrt{\xi^* / 8} \right)}{\pi d^2 \sigma \rho^* \xi^*} + 1 \right]^{-1} \]  

(11)

Equation (11) contains one numerical factor, which was selected as a result of comparison with the available experimental data on gas-water flows at high reduced pressures [8].

3. Comparison with the experimental data

The above method of calculating the liquid film flow rate in an annular two-phase flow was tested on the available experimental data relating to the high reduced pressures, i.e. on the water-air mixture flow data presented in [8] \( (p/p_o > 0.45) \). Practical interest in liquid distribution between the core and the film is primarily due to the calculation of the boiling crisis, for which it is necessary to know the liquid flow rate in the film. At the entrained liquid fraction \( m_E > 0.7 \), the 10% error in computing \( m_E \) gives, as a minimum, an error of 50% in calculating \( m_F \). In practice, in this range of entrainment values, the calculated values differ from the experimental data up to 200%. This is probably due to the inaccuracy of the experiments at these parameters; above, we mentioned that in the experimental data table [8] there are values of \( m_E/m_L \) larger unit, for example, 1.05. It is easy to understand that near the unit even a 5% error in determining the fraction of entrainment gives multiple differences for the value of \( m_F \). Therefore, it was decided to limit the experimental data taken for comparison, by a condition \( m_E/m_L < 0.7 \).

As a result, a constant in Eq. (9) has been chosen as \( C = 0.42 \). In this case, Eq. (9) reflects well the trends observed in the experiments: 57% of the points fall within the deviation range \( \pm 30\% \). Using the expression (6a) for the droplet detachment frequency transforms (9) to the form:

\[ E = C_1 \left( \frac{\rho^*}{\rho'} \right)^n \frac{\mu \Gamma \varpi^* w_0^*}{\sigma d} \]  

(12)

The unknown values \( C_1 \) and \( n \) were also chosen as a result of comparison with the experimental data [8] at the entrained liquid fractions not exceeding 70%: \( C_1 = 8.2, n = 8/5 \). Finally, the equation for calculating the liquid flow rate in the film (11) is written as

\[ m_F = m_L \left[ 8.2 \left( \frac{\rho^*}{\rho'} \right)^n \frac{8 \mu m_G \left( 1 - 12.7 \sqrt{\xi^* / 8} \right)}{\pi d^2 \sigma \rho^* \xi^*} + 1 \right]^{-1} \]  

(13)

Figure 1 presents a comparison of the calculation results with the experimental data. This correction allowed to significantly improve the results: 67% of the points hit the range of deviations \( \pm 30\% \).
Figure 1. Calculated and experimental values of the liquid flow rate in the film for the data of [8].

Figures 2-4 show the calculated and experimentally measured dependences of liquid flow rate in the film on the air flow rate with a fixed total liquid flow rate for various pressures. Comparison of the experimental [8] and the calculated data shows the advantage of the proposed method over the existing correlations. As can be seen, the Cioncolini and Thome correlation [5], which used only one governing nondimensional criterion (Weber number), describes the experimental data very poorly (38% of the points fall within the accepted permissible range of deviations). The calculation by means of the purely empirical method of [7] gives a somewhat better agreement - 59% of the points are within the permissible range of deviations, but the absence of physical content in it does not allow to consider this model acceptable for practical calculations. It should be noted that all the considered calculation methods reproduce qualitatively the trends observed in the experiments.

Figure 2. Dependence of liquid flow rate in the film on the air flow rate at pressure $p = 10$ MPa and different liquid flow rates. The points are the experimental data [8], 1 is calculation by Eq. (13), 2 is calculation according to [5], 3 is calculation by the method of [7].
Figure 3. Dependence of liquid flow rate in the film on the air flow at pressure $p = 15$ MPa and different liquid flow rates. The points are the experimental data [8], 1 is calculation by Eq. (13), 2 is calculation according to [5], 3 is calculation by the method of [7].

Figure 4. Dependence of liquid flow rate in the film on the air flow at pressure $p = 20$ MPa and different liquid flow rates. The points are the experimental data [8], 1 is calculation by Eq. (13), 2 is calculation according to [5], 3 is calculation by the method of [7].

4. Conclusion
An approximate model of droplet disruption from the surface of a liquid film and a predicting equation for the entrainment intensity at high reduced pressures are proposed. The equation obtained allows to calculate the liquid flow rate in the film. It was tested on the available experimental data. Comparison of the calculation results with the experimental data for the water-air flow at high (> 0.45) reduced pressures showed good agreement between the calculated and experimentally measured values.

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