Improvement of Offtake Models for 1-D System Analysis Codes

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1. Introduction

The Onset of Liquid Entrainment (OLE) models have been widely used for the prediction of gas-liquid two phase flow behaviors through upper branch of the pipe. Many experiments for the liquid entrainment have been performed utilizing different sizes of test facilities to mainly investigate flow behaviors during Small Break Loss of Coolant Accidents (SBLOCAs). A stratified flow can occur in the horizontal pipe during SBLOCA, which strongly influences the gas and liquid flow rate through the break. The liquid entrainment is thus considered highly important, in case where horizontally stratified flow is found inside the pipes. The OLE models implemented in many 1-D system analysis codes have been developed in 1980s by Smoglie [1] and Schrock [2], and proven to be suitable for simulating liquid entrainment in upward branches for nuclear reactors. However, a series of recent computational benchmarks to OLE studies using KfK and UCB models has uncovered evidence of systemic biases in the predictions of distance from the branch entrance to the gas-liquid interface at beginning of liquid entrainment, h_b, showing consistent under predictions in the model coefficient for large h_b/d and over predictions of it for small h_b/d on the order of 20% or more across multiple studies, where d is a branch diameter. In this paper the bias in prediction of OLE is characterized over wide ranges of branch diameters from 0.003 to 0.02, and a modified OLE model developed considering interfacial drag term for different sizes of pipes and branches to enhance model predictions was proposed.

2. Description of the actual work

2.1. OLE benchmark studies

A theoretical consideration for the beginning of liquid entrainment in upward braches is presented in this section by introducing OLE models based on the potential flow theory [1]. Figure 1 presents a sink at the spherical coordinates with h_b, the height of gas above the horizontal interface, and R, the distance from the sink. The velocity field generated by sink is then

$$v=-\frac{\partial \phi}{\partial R}=-\frac{2q}{4\pi R^2}=-\frac{W_{3g}}{2\pi\rho_g R^2} \qquad (1)$$

where the q, and W_{3g} represents volume and mass flow rates, respectively, ρ_g the gas density, and ϕ the velocity potential defined as,

$$\phi=-\frac{2q}{4\pi R} \qquad (2)$$

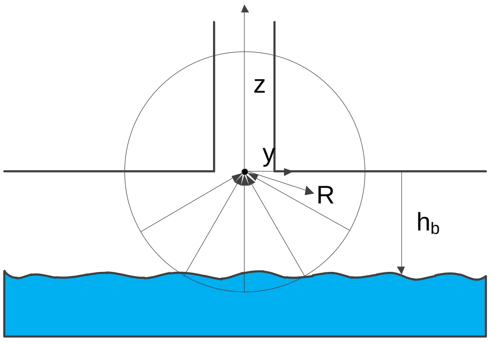


Figure 1. Description of coordinates used to investigate the beginning of liquid entrainment in upward branches.

Note that the inlet, outlet, and branch variables are characterized by the indices 1, 2, and 3. For the streamline along the z axis the Bernoulli equation takes the following form.

$$p+\frac{1}{2}\rho_g v^2+\rho_g gR=const \qquad (3)$$

where p and g are pressure and gravitational acceleration, respectively. The upward force per unit volume due to the Bernoulli effect can be derived by differentiating pressure with respect to the R as follows.

$$\frac{dp}{dR}=-\rho_g v\frac{dv}{dR}+\rho_g g=\frac{W_{3g}^2}{2\pi^2\rho_g R^5}+\rho_g g \qquad (4)$$

OLE correlations currently implemented in many system analysis codes were derived based on the theoretical background of balance equation such that the beginning of liquid entrainment is supposed to occur when the upward forces, e.g. the pressure drop, are equal to the gravitational force acting on the liquid. The final form of the KfK model determined by the balance equation is

$$h_b=K\frac{W_{3g}^{0.4}}{\left[g\rho_g\left(\rho_l-\rho_g\right)\right]^{0.2}} \qquad (5)$$

or

$$Fr_g\left[\rho_g/\left(\rho_l-\rho_g\right)\right]^{0.5}=K'\left(h_b/d\right)^{2.5} \qquad (6)$$

where ρ_l is the liquid density and Fr_g is the gas Froude number defined as $Fr_g \equiv V_{3g}/\sqrt{gd}$ with the gas velocity at upward branch, V_{3g}. KfK test data of OLE when expressed in terms of Equation (5) and (6) give the value of the constant K and K' as 1.67 and 0.35, respectively (see Figure 2).

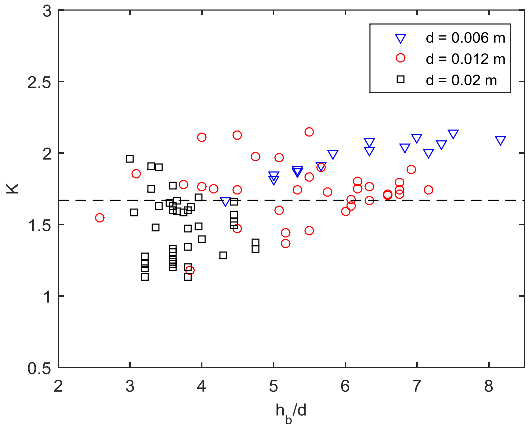


Figure 2. Beginning of liquid entrainment in upward branches

Employing OLE data measured from KfK test facilities, verification and validation were performed by conventional KfK model. Nodalization for the test section of KfK experimental facility is presented in Figure 3 with a brief description of each component. Air and water flows enter the horizontal pipe of 0.206 m inner diameter and a total length of 6 m, reach a short transparent section, located about 4.5 m downstream of the inlet, and finally they are directed towards branches perpendicular to the horizontal pipe.

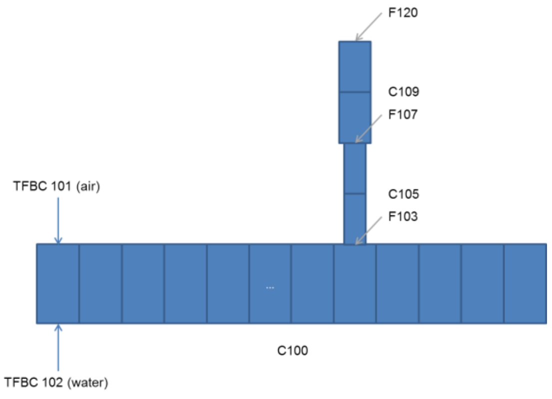
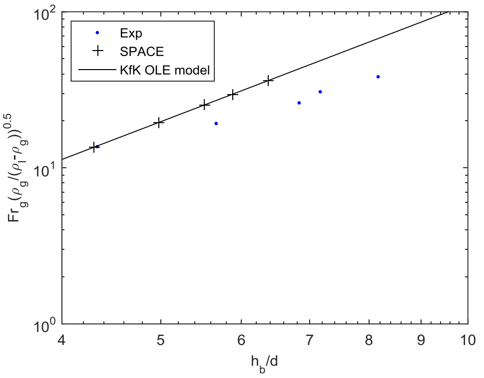
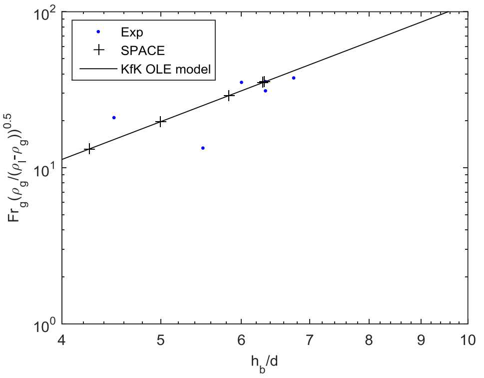


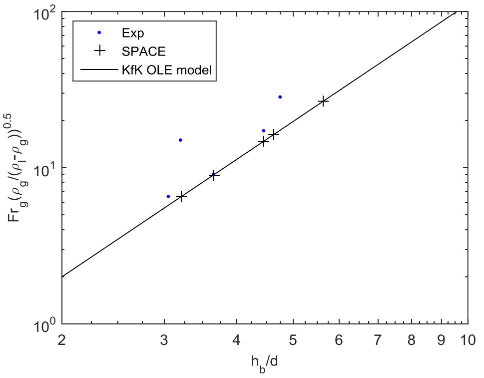
Figure 3. Nodalization of the test section used for OLE and quality measurements.



(a) branch diameter 0.006 m



(b) branch diameter 0.012 m



(c) branch diameter 0.02m

Figure 4. Beginning of liquid entrainment for different branch diameters

Figure 4 presents calculation results obtained by SPACE [3] along with KfK OLE model and experimental data for the branch diameters, 0.006, 0.012, and 0.020 m, respectively. Overall a good agreement between the proposed model and the data throughout the h_b/d range investigated is apparent since the model was developed utilizing the KfK test data. It was also confirmed that the SPACE calculation results, i.e., the numerical results, are overlapped with the model, i.e., the theoretical results, implying that the model is properly implemented in SPACE. However, a relatively large deviation between SPACE calculations and KfK test data (on the order of 20% or more) is observed especially for large h_b/d , i.e. small branch diameter. The detailed comparison of the KfK experimental data with model prediction is presented in Figure 5 illustrating predicted relative errors against KfK OLE data. The relative deviation shown in the figure was calculated by the following form of equation.

$$\frac{\dfrac{h_b\left[g\rho_g\left(\rho_l-\rho_g\right)\right]^{0.2}}{W_{3g}^{0.4}}-1.67}{1.67} \qquad (7)$$

The code validation study of OLE has revealed evidence of a systemic bias in predicted OLE when using KfK model, where the value of K is consistently over predicted for small h_b/d and it is under predicted for large h_b/d .

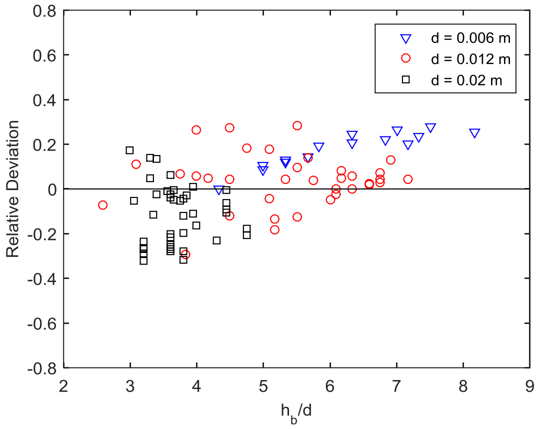


Figure 5. Predicted relative errors against KfK OLE data

2.2. Improvement of OLE model

Because of the fact that the interfacial drag, which was not considered in developing original KfK OLE model, produces non-trivial upward force, an accurate accounting for the interfacial drag is essential. The beginning of liquid entrainment occurs when the upward force produced by the pressure drop and interfacial drag overcomes the gravitational force acting on the liquid. Thus the condition for the beginning of liquid entrainment for upward branches is:

$$F_p+F_i+F_g=\frac{W_{3g}^2}{2\pi^2\rho_g h_b^5}+\rho_g g+C_i v_g v_g \rho_g a_i-\rho_l g=0 \qquad (8)$$

where F_p, F_i, and F_g are pressure drop, interfacial drag, and gravitational forces, respectively, C_i the interfacial drag coefficient, v_g the gas velocity, a_i the interfacial area concentration, and $W_{3g}\equiv V_{3g}\rho_g\pi\left(\frac{d}{2}\right)^2$. After rearranging the Equation (8), a general form of the correlation for the onset of liquid entrainment is derived as

$$\frac{h_b\left[g\rho_g\left(\rho_l-\rho_g\right)\right]^{0.2}}{W_{3g}^{0.4}}=\left[K_1\left(\frac{h_b}{d}\right)^5+K_2\right]^{0.2} \qquad (9)$$

or

$$\frac{1}{\tilde{K}_2}\left(\frac{h_b}{d}\right)^5=\frac{Fr_g^{\,2}\left[\rho_g/\left(\rho_l-\rho_g\right)\right]}{1-\tilde{K}_1 Fr_g^{\,2}\left[\rho_g/\left(\rho_l-\rho_g\right)\right]} \qquad (10)$$

where $\tilde{K}_1=K_1\frac{\pi^2}{16}$ and $\tilde{K}_2=K_2\frac{\pi^2}{16}$. K_1 and K_2 are constants to be determined by fitting experimental data. The coefficient of K_1 and K_2 are determined as K_1 = 1.0698E-3 and K_2 = 8.32 by fitting the KfK experimental data presented in Figure 2. The interfacial drag is approximated by the following form of equation assuming that the frictional force is inversely proportional to branch diameter.

$$C_i v_g v_g \rho_g a_i \cong \frac{\tilde{K}}{d}V_{3g}V_{3g}\rho_g \qquad (11)$$

For branches perpendicular to the horizontal pipe, it is reasonable to assume that frictional forces vertically applied to liquid layer become larger when branch diameter is smaller since the angle of a locally raised cone-shaped liquid mass produced by the gas accelerated toward the sink becomes larger as the branch diameter decreases. This leads to larger interfacial drag vertically applied to liquid layer.

KfK test data and proposed model, i.e., Equation (9), were plotted against h_b/d in Figure 6. The proposed model can completely approximate the increasing trend of experimental data over entire ranges of the variable h_b/d from 2.5 to 8.2 such that the relative errors and biases against KfK OLE data were reduced as shown in Figure 7.

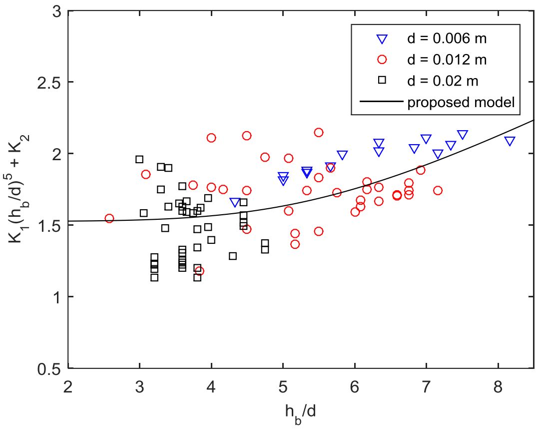


Figure 6. Beginning of liquid entrainment in upward branches estimated by proposed model.

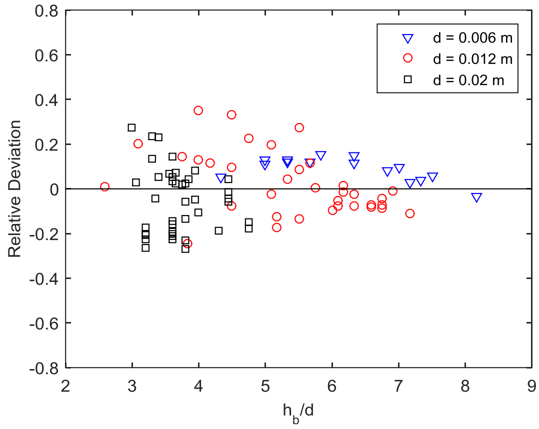


Figure 7. Predicted relative errors against KfK OLE data obtained using modified KfK model.

The OLE model was now employed for the validation of the UCB OLE test to evaluate reliability of the proposed OLE model. UCB test data, utilized to calculate left hand side of Equation (9), along with conventional and proposed models are presented in Figure 8. Significant biases observed when calculated by conventional KfK model were mitigated by calculating OLE using the proposed model.

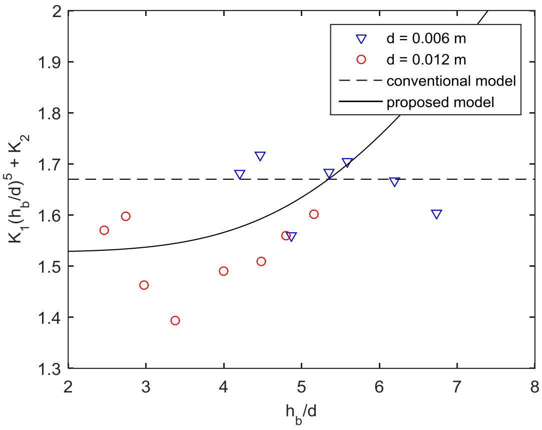


Figure 8. Beginning of liquid entrainment of UCB tests estimated by proposed model

3. Summary and conclusions

The bias in prediction of OLE is characterized over wide ranges of branch diameters from 0.003 to 0.02, and subsequently a modified OLE model developed considering interfacial drag term for different sizes of pipes and branches to enhance model predictions was proposed. The modified OLE model was derived based on the condition for the beginning of liquid entrainment; the beginning of liquid entrainment occurs when upward force produced by the pressure drop and interfacial drag overcomes the gravitational force acting on the liquid. The proposed model can completely approximate the increasing trend of experimental data over entire ranges of the variable h_b/d from 2.5 to 8.2 such that the relative errors and biases against KfK OLE test data was reduced. The OLE model was employed for the validation of the UCB OLE test as well to evaluate reliability of the proposed OLE model. Significant biases observed when calculated by conventional KfK model were removed by calculating OLE using the proposed model.

ACKNOWLEDGMENT

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