

PREDICTION OF ADIABATIC BUBBLY FLOWS IN TRACE USING THE INTERFACIAL AREA TRANSPORT EQUATION

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Abstract

The conventional thermal-hydraulic reactor system analysis codes utilize a two-field, two-fluid formulation to model two-phase flows. To close this model, static flow regime transition criteria and algebraic relations are utilized to estimate the interfacial area concentration (a_i). To better reflect the continuous evolution of two-phase flow, an experimental version of TRACE is being developed which implements the interfacial area transport equation (IATE) to replace the flow regime based approach. Dynamic estimation of a_i is provided through the use of mechanistic models for bubble coalescence and disintegration. To account for the differences in bubble interactions and drag forces, two-group bubble transport is sought. As such, Group 1 accounts for the transport of spherical and distorted bubbles, while Group 2 accounts for the cap, slug, and churn-turbulent bubbles. Based on this categorization, a two-group IATE applicable to the range of dispersed two-phase flows has been previously developed. Recently, a one-group, one-dimensional, adiabatic IATE has been implemented into the TRACE code with mechanistic models accounting for: (1) bubble breakup due to turbulent impact of an eddy on a bubble, (2) bubble coalescence due to random collision driven by turbulent eddies, and (3) bubble coalescence due to the acceleration of a bubble in the wake region of a preceding bubble. To demonstrate the enhancement of the code's capability using the IATE, experimental data for a_i , void fraction, and bubble velocity measured by a multi-sensor conductivity probe are compared to both the IATE and flow regime based predictions. In total, 50 air-water vertical co-current upward and downward bubbly flow conditions in pipes with diameters ranging from 2.54 to 20.32 cm are evaluated. It is found that TRACE, using the conventional flow regime relation, always underestimates a_i . Moreover, the axial trend of the a_i prediction is always quasi-linear because a_i in the conventional code is predominantly determined by the pressure. It is found that TRACE with the IATE significantly improves prediction results, yielding a $\pm 10.3\%$ difference with the data. In addition, the IATE always predicts the correct axial trend of a_i and can also predict non-linear axial development that reflects the bubble interactions along the flow. Additional studies are being performed to implement a two-group IATE to further expand the capability of the code.

Keywords: interfacial area transport equation, TRACE, two-phase flow, code development.

1. Introduction

The two-fluid model provides the most detailed treatment in modelling two-phase flow through separate balance equations of mass, momentum, and energy for each phase. However, the advantages of the more complex two-fluid model over a simpler mixture or drift-flux approach can only be realized with accurate interfacial transfer terms. These terms provide the coupling of the two phases across the interface for the transfer of mass, momentum, and energy. Exchanges across the interface are a function of both a driving force of the transfer process and the interfacial structure. Hence, the interfacial area concentration (a_i), or surface area per unit mixture volume, has a critical role in closing the two-fluid model

Conventionally, estimates of a_i in nuclear system analysis codes such as TRACE and RELAP, which employ the two-fluid model, are obtained from flow regime specific relations after the flow regime has been determined using static transition criteria. This process does not capture the dynamic evolution of the interfacial structures as it is based on criteria developed in a limited range of fully-developed, steady-state flow conditions. Furthermore, it is influenced by the subjectivity of flow regime identification. Consequently, this approach can lead to significant discrepancies, artificial discontinuities, and numerical instabilities [1, 2].

Therefore, a mathematical model that can account for the dynamic change of the interfacial structure is consistent with the two-fluid model and reduces the shortcomings identified with the flow regime based approach. To provide a dynamic prediction of a_i using mechanistically modelled source and sink terms, the interfacial area transport equation (IATE) has been under development for the past 15 years. Due to its dynamic approach, this model eliminates artificial bifurcations related to the flow regime transitions in the conventional models. Furthermore, it prevents artificial discontinuities since it dynamically models the two-phase flow evolution across flow regime boundaries. Therefore, use of the IATE in analyzing the interfacial transfer and regime transitions is not only rational, but it can also make a significant improvement in thermal-hydraulic system analysis.

The foundation of the IATE was first established by Kocamustafaogullari and Ishii in 1995 [3]. Wu et al. [4] then established the a_i source and sink terms in the IATE by mechanistically modeling the major bubble interaction phenomena in the bubbly flow regime. Later, with improved source and sink terms, Kim [5] established the IATE applicable to a vertical confined bubbly flow. In the model evaluation studies by Ishii et al. [6], and Kim et al. [7], the model showed good agreement with an extensive database acquired in various sizes of vertical round pipe and a confined rectangular test duct. The IATE was also developed for vertical co-current downward bubbly flow [8], and showed promising results. Sun [9] and Fu [10] developed the IATE for a wide range of two-phase flow regimes spanning from vertical bubbly to churn-turbulent two-phase flow for rectangular and round flow channels, respectively. In all of the evaluation studies, the model predictions compare well with the experimental data with a relative difference of less than $\pm 20\%$ in general [11]. The comprehensive mathematical formulations of both the one-group and two-group IATEs can be found in the work by Ishii and Kim [12].

Considering one-group transport, applicable to spherical and distorted bubbly flows, the mechanisms that constitute the a_i source and sink terms include: (1) Break-up due to the impact of turbulent eddies (TI), (2) coalescence through random collision driven by turbulent eddies (RC), and (3) coalescence due to the acceleration of an upstream bubble in the wake of preceding

downstream bubble (WE). The one-group interfacial area transport equation can be given by [4, 5]:

$$\frac{\partial a_i}{\partial t} + \nabla \cdot (a_i \mathbf{v}_i) = \frac{2}{3} \left(\frac{a_i}{\alpha} \right) \left(\frac{\partial \alpha}{\partial t} + \nabla \cdot \alpha \mathbf{v}_s \right) + \frac{1}{3\psi} \left(\frac{\alpha}{a_i} \right)^2 [R_{TI} - R_{RC} - R_{WE}] \quad (1)$$

where R_{TI} , R_{RC} , and R_{WE} are the source/sinks associated with turbulence impact breakup, random collision coalescence, and wake entrainment, respectively.

To be applicable in a wider range of dispersed two-phase flow conditions, however, a multi-group approach is necessary to treat the bubbles according to their different characteristic shapes, drag forces, and interactions. A two-group approach is considered to adequately capture the physics in the flow, while not imposing an excessive computational burden. Group one is defined to include the spherical and distorted bubbles, while group two consists of the larger cap, slug, and churn-turbulent bubbles. To define the group boundary, the maximum distorted bubble limit, as given by Ishii and Zuber [13] is employed. Above this limit, the bubbles become cap-shaped, and the interfacial drag begins to deviate from that of small bubbles.

For two-group transport, the IATE is formulated by integrating the general transport equation over the particle size of each group. As a result, the two-group IATE is established [12]:

$$\begin{aligned} \frac{\partial a_{i1}}{\partial t} + \nabla \cdot (a_{i1} \bar{\mathbf{v}}_{i1}) = & -C \left(\frac{D_{sc}}{D_{sm1}} \right)^2 \frac{a_{i1}}{\alpha_1} \left[\frac{\partial \alpha_1}{\partial t} + \nabla \cdot \alpha_1 \bar{\mathbf{v}}_{g1} \right] \\ & + \frac{2}{3} \frac{a_{i1}}{\alpha_1} \left[\frac{\partial \alpha_1}{\partial t} + \nabla \cdot \alpha_1 \bar{\mathbf{v}}_{g1} \right] + \sum_j \phi_{j1} \end{aligned} \quad \text{Group One} \quad (2)$$

$$\begin{aligned} \frac{\partial a_{i2}}{\partial t} + \nabla \cdot (a_{i2} \bar{\mathbf{v}}_{i2}) = & C \left(\frac{D_{sc}}{D_{sm1}} \right)^2 \frac{a_{i1}}{\alpha_1} \left[\frac{\partial \alpha_1}{\partial t} + \nabla \cdot \alpha_1 \bar{\mathbf{v}}_{g1} \right] \\ & + \frac{2}{3} \frac{a_{i2}}{\alpha_2} \left[\frac{\partial \alpha_2}{\partial t} + \nabla \cdot \alpha_2 \bar{\mathbf{v}}_{g2} \right] + \sum_j \phi_{j2} \end{aligned} \quad \text{Group Two} \quad (3)$$

where the subscripts i , 1 , and 2 , denote the interface, group one and group two, respectively. The parameter C denotes the intergroup transfer coefficient due to pressure effects. In two-group transport, additional mechanisms and interactions, ϕ , are considered for the j interaction terms. The model of Fu [10] is chosen to be implemented for the current study as it applies to small diameter pipes, less than 10 cm, which has a greater database for assessing the model. A summary of the source/sink terms in the two-group IATE is given by Fu [10].

2. IMPLEMENTATION

For implementation of the one-group and two-group IATEs, a three-field version of TRACE is utilized, namely TRACE 4.291b developed by Schilling [14]. The inclusion of additional fields is necessary when there is mechanical and/or thermal non-equilibrium between different

components of the same fluid. This can be highlighted in the case of annular flow with droplets where the continuous film and the dispersed droplets may move with different velocities. Thus in order to capture this effect, two velocity fields is required. In addition to the conventional TRACE fields, k dispersed gas fields can be tracked in TRACE v4.291b allowing the dispersed phase to be partitioned into k groups based on bubbles having similar size, drag, and interaction mechanisms. In the current study, the number of groups is set to be one or two for one-group and two-group IATE predictions, respectively. In both cases, the conventional TRACE gas field void fraction is set to zero.

With the inclusion of the additional field for dispersed bubbles, the number of field equations in TRACE increases to eight for the one-group condition and ten for the two-group condition. The additional equations account for the mass balance and equation of motion for each group of bubbles. The energy equations are not required since the current study focuses only on the adiabatic condition. Hence, for the adiabatic condition, the modified TRACE version contains mass balance equations for the mixture and the dispersed gas fields, given by:

$$\frac{\partial \left[\alpha_f \rho_f + \sum_k \alpha_k \rho_g \right]}{\partial t} + \nabla \cdot \left[\alpha_f \rho_f \vec{v}_f + \sum_k \alpha_k \rho_g \vec{v}_{gk} \right] = 0 \quad (4)$$

$$\frac{\partial (\alpha_1 \rho_g)}{\partial t} + \nabla \cdot (\alpha_1 \rho_g \vec{v}_{g1}) + \Delta m_{12} = 0 \quad (5)$$

$$\frac{\partial (\alpha_2 \rho_g)}{\partial t} + \nabla \cdot (\alpha_2 \rho_g \vec{v}_{g2}) - \Delta m_{12} = 0 \quad (6)$$

where the subscript k denotes the additional bubble groups with $k=1$ representing the group-one bubbles and $k=2$ representing the group-two bubbles. While phase change is ignored in this work, the intergroup mass transfer between the two dispersed gas groups due to interactions and pressure change is accounted for by Δm_{12} .

For the equations of motion, an additional equation is supplied for each group k . This is because a major reason for separating the bubbles into two groups is their different drag characteristics and motion, where each group can have a different characteristic velocity. Hence, the equations of motion for the liquid and dispersed gas field groups are given by:

$$\begin{aligned} & \frac{\partial \vec{v}_f}{\partial t} + \vec{v}_f \nabla \cdot \vec{v}_f + \sum_k \frac{c_{igk}}{(1 - \alpha_{tot}) \rho_f} |\vec{v}_f - \vec{v}_{gk}| (\vec{v}_f - \vec{v}_{gk}) \\ & + \frac{1}{\rho_f} \frac{\partial P}{\partial x} + \frac{c_{wf}}{(1 - \alpha_{tot}) \rho_f} |\vec{v}_f| \vec{v}_f + g \cos \theta = 0 \end{aligned} \quad (7)$$

$$\frac{\partial \vec{v}_{gk}}{\partial t} + \vec{v}_{gk} \nabla \cdot \vec{v}_{gk} + \frac{c_{igk}}{\alpha_k \rho_g} |\vec{v}_{gk} - \vec{v}_f| (\vec{v}_{gk} - \vec{v}_f) + \frac{1}{\rho_g} \frac{\partial P}{\partial x} + g \cos \theta = 0 \quad (8)$$

where c_{igk} , c_{wf} , P and g denote the interfacial drag between continuous liquid and the k^{th} bubble group, the wall drag on the liquid phase, pressure, and gravity, respectively. The inclusion of the equations of motion for the dispersed gas field groups requires additional closure relations for the interfacial drag, wall drag, and phase change for each group. For simplicity, the wall drag to each bubble group is ignored, as is the phase change. The interfacial drag relation for each bubble group is given by:

$$c_{igk} = \frac{C_{Dk} \alpha_k \rho_f}{D_{smk}} \quad (9)$$

where the drag coefficients are obtained from Ishii and Chawla [15]. Since the current study focuses on the adiabatic condition, the energy equations are not considered.

Within the conventional TRACE two-fluid model, the interfacial transfer terms are written in terms of the interfacial mass transfer term, Γ , which is obtained through the heat conduction limited model [16] that depends on a_i . To estimate a_i TRACE relies on flow regime based correlations. A summary of the employed regions and correlations are given in Table 1 [16]. Here, the subscripts DB, SB, and LB denote dispersed bubbly, small bubbles and large bubbles, respectively. However, for the adiabatic conditions considered in the current study, a_i is not required by the conventional TRACE (henceforth referred to as non-transport TRACE, or TRACE-NT) to close the two-fluid model because there is no mass generation. In the revised transport TRACE version (TRACE-T), however, the introduction of Equation (9) for the interfacial drag requires a_i to close the two-fluid model.

Table 1 Flow regime boundary definitions and a_i closure relations of TRACE-NT.

Regime	α Boundary	a_i Relation
Bubbly	$\alpha_{DB} = \begin{cases} \frac{G \leq 2000 \text{ [kg/m}^2\text{s]}}{0.3} \\ \frac{2000 < G < 2700 \text{ [kg/m}^2\text{s]}}{0.3 + 0.2 \left(\frac{G - 2000}{2700 - 2000} \right)} \\ \frac{G \geq 2700 \text{ [kg/m}^2\text{s]}}{0.5} \end{cases}$	$a_{i,DB} = \frac{3\alpha}{\sqrt{\sigma / g \Delta \rho}}$
Bubbly/Slug	$\alpha_{DB} < \alpha < 0.50$	$a_i = a_{i,SB} + a_{i,LB} = \frac{6\alpha}{d_{DB}} \left(\frac{1-\alpha}{1-\alpha_{DB}} \right) + \frac{C^*}{D^*} \left(\frac{\alpha - \alpha_{DB}}{1 - \alpha_{DB}} \right)$
Interpolation Region	$0.50 < \alpha < 0.75$	Interpolated between Boundary Values of Bubbly/Slug and Annular Mist Regimes
Annular Mist	$\alpha > 0.75$	$a_i = a_{i,film} + a_{i,droplet} = \frac{4}{D_h} \sqrt{\alpha} + \frac{6\alpha \alpha_d}{(1 - \alpha_d) d_d}$

3. ONE-GROUP IATE ASSESSMENT

The current study seeks to systematically evaluate the IATE, starting with the one-group transport equation. Thus, the adiabatic form of the one-group IATE of Equation (1) is implemented into TRACE and is solved explicitly in each computational volume. Two similar code versions, namely: TRACE-T, which includes the one-group IATE and TRACE-NT that utilizes the flow regime dependent correlations of the conventional TRACE, are generated for comparison to experimental data. To specify the coefficients for the mechanistic models found in Equation (1), the one-group model coefficients suggested by Ishii et al. [17], developed for vertical air-water bubbly two-phase flow in round pipes, are employed.

To assess the one-group IATE, several databases for air-water flows in round pipes with diameters ranging from 2.54 to 20.32 cm in both co-current upward and downward flows are investigated [8, 10, 18, 19, 20, 21]. These databases consist of comprehensive local two-phase flow parameters in various flow conditions measured by a multi-sensor conductivity probe [22] at three axial positions. The local data obtained from the multi-sensor conductivity probe includes: interfacial area concentration (a_i), void fraction (α), bubble velocity (v_g), and Sauter mean diameter (D_{sm}). Local pressure measurements are obtained at the three measurement ports as well. At each axial location, the conductivity probe is traversed along the radial direction, and thousands of bubbles are sampled at each radial point to reduce the measurement error to within $\pm 7\%$ [23]. In selecting the database for assessment, considerations are made to select: (1) reliable data and (2) the data that reflects one-group transport. In view of selecting reliable data, a simple data evaluation is performed by comparing the $\langle \alpha v_g \rangle$ measured by the probe with the $\langle j_{g,local} \rangle$ measured by the gas rotameter and local pressure gauge. Only the conditions that benchmark within $\pm 10\%$ are employed for evaluation. In total, 50 flow conditions are evaluated using the one-group IATE in TRACE-T.

The TRACE nodalizations of these experiments are generated based on the measurement port locations. The specified values of void fraction in the FILL component, and pressure in the BREAK component, are iterated upon to match the experimental conditions at the first measurement port to within 0.1%. It is found that additional iteration yields little to no effect on the solution. For TRACE-T, the initial condition of a_i is also specified to start the transport equation calculation, and the same iteration criteria are applied. Although bubble velocity is measured in the experiments, no iteration is performed since TRACE estimates this value directly from an equation of motion.

3.1 Pressure and void fraction predictions

To assess the one-group IATE in TRACE-T, all experimentally measured values are compared to the code predictions. These include: pressure, void fraction, bubble velocity, and interfacial area concentration. Since, the code revisions should not significantly affect the pressure and void fraction predictions, these are discussed first. For pressure estimation, both TRACE-T and TRACE-NT implement the same pressure drop correlation. In general, the predicted pressure drops are found to be nearly identical, with only small differences which can be attributed to the use of different interfacial drag relations in the two codes, as will be discussed shortly. A characteristic prediction of the pressure is shown in Figure 1(a). The void fraction predictions,

shown in Figure 1(b), of the two codes are also found to be nearly identical, as expected. This is because in the adiabatic case with a constant inlet condition, the change in void fraction is dependent primarily on the volume expansion due to the pressure drop.

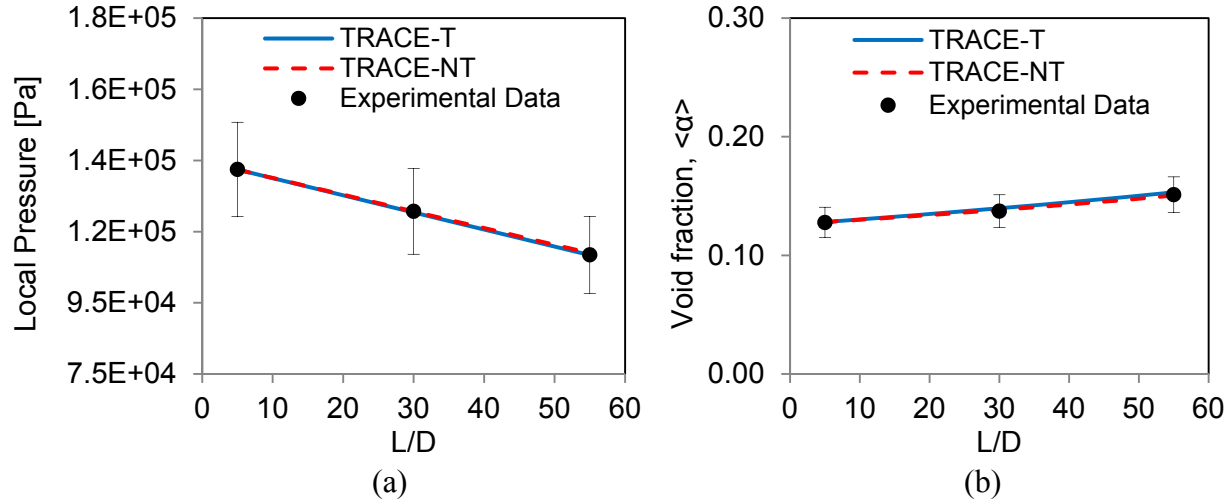


Figure 1 Characteristic code predictions of (a) pressure and (b) void fraction for Run 2-8 ($j_g = 0.506$ m/s and $j_f = 2.336$ m/s) with $\pm 10\%$ error bars shown.

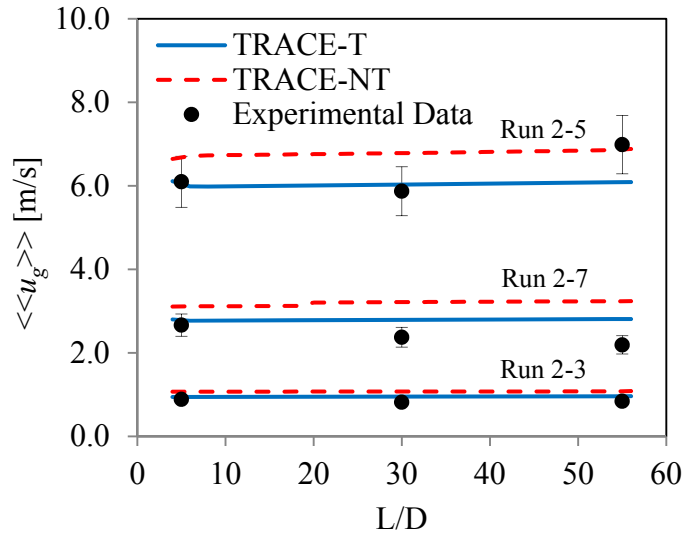


Figure 2 Characteristic code predictions for void-weighted bubble velocity with $\pm 10\%$ error bars shown. Run 2-3 ($j_g=0.039$ m/s and $j_f=0.682$ m/s), Run 2-5 ($j_g=0.538$ m/s and $j_f=5.100$ m/s), and Run 2-7 ($j_g=0.138$ m/s and $j_f=2.486$ m/s)

3.2 Bubble velocity predictions

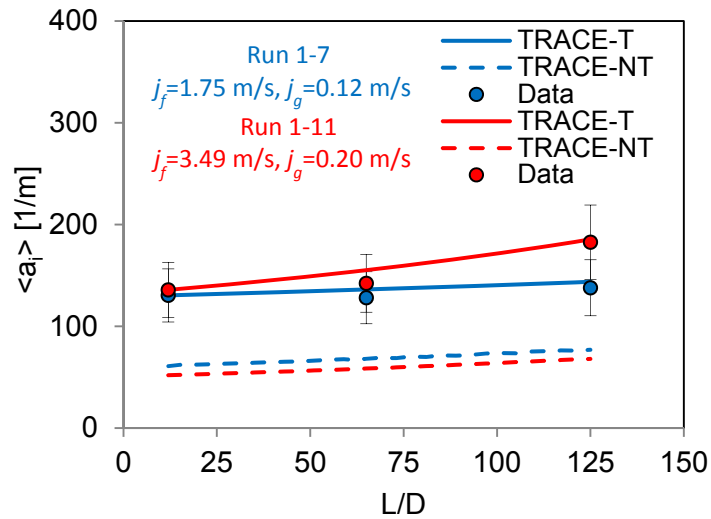
As discussed in Section 2, the implementation of the IATE into the experimental three-field version of TRACE affects both the prediction of bubble velocity and the interfacial area concentration. In TRACE, the gas velocity is determined through an equation of motion, however, TRACE-T and TRACE-NT utilize different closure relations for the interfacial drag coefficient. While TRACE-T employs Equation (9) to specify the interfacial drag, TRACE-NT

relies on an approach utilizing drift-flux relations [16]. Hence, the predictions are evaluated to observe the differences of the models. In assessing the two relations for specifying interfacial drag, the void-weighted bubble velocity available from the 48.3 mm co-current upward flow experiment is employed. As shown in Figure 2, differences in the bubble velocity predictions and experimental data are found. It is observed that the velocity predictions made by the drift-flux approach tend to over-estimate the experimental data compared to those made by the one-group interfacial drag coefficient which yields better results. Moreover, the difference between the predictions is found to increase as the velocity increases. Even though Equation (9) reduces the disagreement with experiment data, the deviations can still be as large. While outside the scope of the current work, additional studies are needed to assess and improve the drag relations for the prediction of velocities.

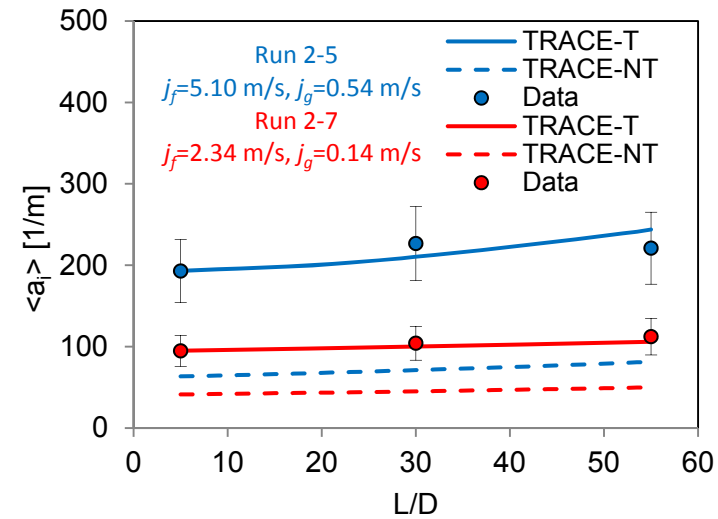
3.3 Interfacial area concentration predictions

In general, a_i predictions made by the newly developed TRACE-T, employing the one-group IATE, agree very well with the experimental data, within an average difference of $\pm 10\%$, while those made by TRACE-NT can show significant disagreement. From the present study, several characteristics are found in the a_i predictions of the conventional TRACE-NT code. These are summarized as follows:

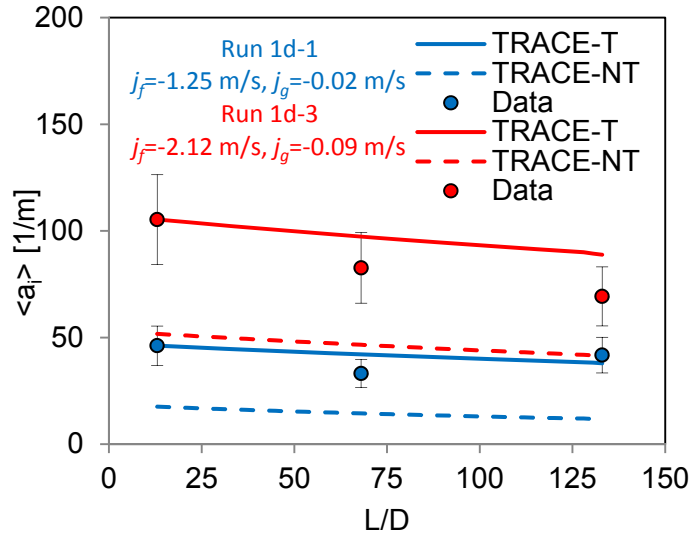
- (1) TRACE-NT always underestimates the data and displays a quasi-linear increasing/decreasing trend of a_i in the axial direction depending on the flow direction. The predictions are quasi-linear as the bubbly flow relation in Table 1 depends primarily on pressure. Hence, the predictions are increasing for upward flow, where pressure decreases in the axial direction, and are decreasing for downward flow, where pressure increases. Several characteristic conditions are shown in Figure 3. In the Figure, experiments that demonstrate linear development, generally pressure dominated, and conditions with small non-linear developments, where bubble interaction begin to have an effect, are shown. It can be observed that TRACE-T predicts both increasing and decreasing development trends well in all cases.
- (2) As shown in Figure 3, TRACE-NT always underestimates the experimental data, implying that the predicted bubble sizes are larger than experimentally measured. Another major difference observed from Figure 3, is that TRACE-T and TRACE-NT do not have the same initial value. For TRACE-T the initial experimental value is specified, whereas for TRACE-NT the initial values are calculated based on the bubbly flow relation in Table 1. For example, in Run 2-7 of Figure 3(b), the initial bubble size for TRACE-NT is estimated to be 5.4 mm, while the experimentally measured size for this condition is only 2.4 mm. It should be noted that bubbly flow relation of TRACE-NT is the arithmetic mean size of the spherical/distorted bubble region and hence over estimates the more finely dispersed bubbly flow represented by the current experimental data. One could argue in a pressure dominated condition that if an improved bubble size relation is employed in TRACE-NT, a prediction similar to TRACE-T can be obtained. However, this is not sufficient for conditions where bubble interactions dominate the pressure effect as will be shown.



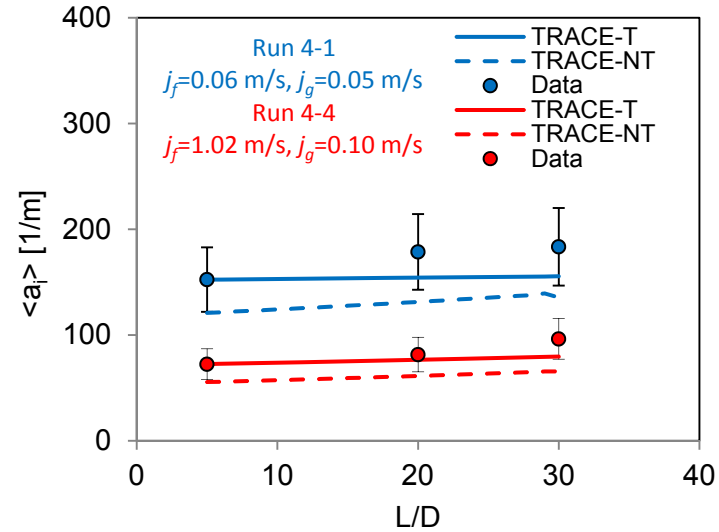
(a) 2.54 cm co-current vertical upward



(b) 4.83 cm co-current vertical upward



(c) 2.54 cm co-current vertical downward



(d) 10.16 cm co-current vertical upward

Figure 3 Characteristic TRACE-T and TRACE-NT predictions for a_i development with $\pm 20\%$ error bars shown.

- (3) For many of the test conditions, the axial development of a_i does not match the quasi-linear trends of TRACE-NT. Moreover, in certain conditions, TRACE-NT predicts the opposite trend of a_i compared to the experimental data as shown in Figure 4. In Figure 4(a), a downward flow condition, the high turbulence of the liquid causes the bubbles to break up and increase the a_i . However, TRACE-NT predicts a decreasing trend due to the increasing pressure. In Figure 4(b), an upward flow condition, TRACE-NT predicts an increasing trend due to pressure, while the data has a decreasing trend in the a_i due to increased coalescence. In both conditions, TRACE-T predicts the experimental data very well. These conditions highlight the increased prediction capability that can be obtained by inclusion of the IATE in the closure models. Moreover, adjustment of the predicted bubble size relation mentioned previously would not capture the effect of bubble break-up and coalescence as does the IATE.

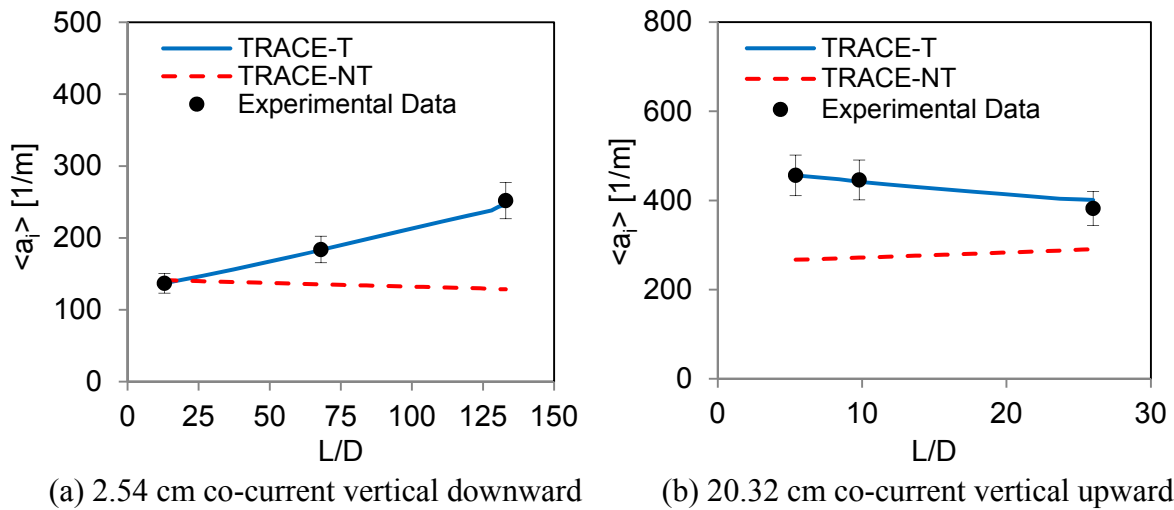


Figure 4 TRACE-T and TRACE-NT predictions a_i development with opposite axial trends (a) Run 1d-5 ($j_g = -0.404$ m/s and $j_f = -3.110$ m/s) (b) Run 8-2 ($j_g = 0.300$ m/s and $j_f = 0.420$ m/s) with $\pm 10\%$ error bars shown.

For all of the evaluated conditions, it is found that the one-group IATE yields a significantly higher accuracy in predicting the development of the a_i , reducing the average percent difference to $\pm 10\%$. To expand the applicability of TRACE-T, TRACE-T2 is currently being developed to include the two-group IATE, applicable to comprehensive dispersed two-phase flow conditions.

4. CONCLUSION

The current study seeks to implement a transport equation in TRACE, which enables dynamic prediction of the evolution of the a_i along the flow field. This is achieved through mechanistic models of various bubble interactions and does not rely on flow regime specific relations. As a first step, the one-group interfacial area transport equation applicable to adiabatic air-water bubbly flow through vertical round pipes is implemented. In total, 50 flow conditions from experiments with a variety of diameters are evaluated.

The two-phase pressure drop and void fraction for all of the flow conditions are predicted well and are identical regardless of the TRACE version. In estimating the bubble velocity, TRACE-T employs an interfacial drag coefficient that accounts for the multi-group bubble transport. In TRACE-NT, however, the interfacial drag is estimated through a drift-flux formulation. It is found that the drift-flux based approach over estimates the bubble velocity as compared to the modified interfacial drag relation in TRACE-T. Moreover, the modified relation increases the agreement with the experimental data.

In the prediction of a_i , it is found that the one-group IATE provides a significant improvement over the TRACE-NT estimations, yielding an average of $\pm 10\%$ difference with the experimental data. This assessment clearly demonstrates the shortcoming of TRACE-NT due to the lack of modeling dynamic bubble interactions. TRACE-T, on the other hand, provides good prediction results for all test conditions, including those where various bubble interactions are actively present. However, it is noted that a two-group IATE is necessary to increase the prediction capability of TRACE-T and this implementation is ongoing work.

5. References

- [1] Mortensen, G. A., "Long-term plan for NRC thermal-hydraulic code development." Report to U.S. NRC under contract DE-AC07-94ID13223, 1995.
- [2] Kelly, J. M., 1997. "Thermal-hydraulic modeling needs for passive reactors," Proc. OECD/CSNI Specialist Meeting on Advanced Instrumentation and Measurement Techniques, Santa Barbara, CA, 1997.
- [3] Kocamustafaogullari, G., and Ishii, M., "Foundations of the interfacial area transport equation and its closure relations," *Int. J. of Heat and Mass Trans.*, 38, 3, 1995, 481-493.
- [4] Wu, Q., Kim, S., Ishii, M., and Beus, S. G., "One-group interfacial area transport in vertical bubbly flow," *Int. J. of Heat and Mass Trans.*, 41, 8-9, 1998, 1103-1112.
- [5] Kim, S., "Interfacial area transport equation and measurement of local interfacial characteristics," Ph.D. Thesis, Purdue University, 1999.
- [6] Ishii, M., Kim, S., and Uhle, J., "Interfacial area transport equation: Model development and benchmark experiments," *Int. J. Heat and Mass Trans.*, 45, 2002, 3111-3123.
- [7] Kim, S., Ishii, M., Sun, X., and Beus, S. G., "Interfacial area transport and evaluation of source terms for confined air-water bubbly flow," *Nuc. Eng. and Des.*, 219, 2002, 61-65.
- [8] Ishii, M., Paranjape, S. S., Kim, S., and Sun, X., "Interfacial structures and interfacial area transport in downward two-phase bubbly flow," *Int. J. of Multiphase Flow*, 30, 2004, 779-801.
- [9] Sun, X., "Two-group interfacial area transport equation for a confined test section," Ph. D. Thesis, Purdue University, 2001.
- [10] Fu, X. Y., "Interfacial area measurement and transport modeling in air-water two-phase flow," Ph.D. Thesis, Purdue University, 2001.
- [11] Ishii, M., Kim, S., Sun, X., and Hibiki, T., "Interfacial area transport equation and implementation into two-fluid model," *J. of Thermal Sci. and Eng. Appls*, 1, 2009, 1-7.

- [12] Ishii, M. and Kim, S., "Development of one-group and two-group interfacial area transport equation," *Nuc. Sci. and Eng.*, 146, 2004, 257-273.
- [13] Ishii, M., and Zuber, N., "Drag coefficient and relative velocity in bubbly, droplet, or particulate flows," *AIChE Journal*, 25, 1979, 843-855.
- [14] Schilling, J., "An implementation and evaluation of a dynamic flow regime model for dispersed bubble phases within the computer code TRACE," MS Thesis, The Pennsylvania State University, 2007.
- [15] Ishii, M., and Chawla, T. C., "Local drag laws in dispersed two-phase flow," Argonne National Laboratory Report, ANL-79-105 (NUREG/CR-1230), 1979.
- [16] TRACE V5.0 Theory Manual, "Field equations, solution methods and physical models," Division of Risk Assessment and Special Projects, 2007.
- [17] Ishii, M., Kim, S., and Kelly, J. M., "Development of interfacial area transport equation," *Nuc. Eng. and Tech.*, 37, 2005, 401-412.
- [18] Hibiki, T., and Ishii, M., "One-group interfacial area transport of bubbly flows in vertical round tubes," *Int. J. of Heat and Mass Trans.*, 43, 2000, 2711-2726.
- [19] Smith, T., R., "Two-group interfacial area transport equation in large diameter pipes," Ph.D. Thesis, Purdue University, 2002.
- [20] Ishii, M., Hibiki, T., and Schlegel, J. P., "Data report for Task 1: Void fraction in large diameter pipes, Subtask 3: Interfacial area concentration data for 0.203 m test section, PU/NE-10-09, April 2010.
- [21] Ishii, M., Hibiki, T., and Schlegel, J. P., "Data report for Task 1: Void fraction in large diameter pipes, Subtask 3: Interfacial area concentration data for 0.152 m test section, PU/NE-10-10, June 2010.
- [22] Kim, S., Fu, X. Y., Wang, X., and Ishii, M., "Development of the miniaturized four-sensor conductivity probe and the signal processing scheme," *Int. J. Heat and Mass Trans.*, 43, 2000, 4101-4118.
- [23] Wu, Q. and Ishii, M., "Sensitivity study on double-sensor conductivity probe for the measurement of interfacial area concentration in bubbly flow," *Int. J. Multiphase Flow*, 25, 1, 1999, 155-173.