DEVELOPMENT OF INTERFACIAL AREA TRANSPORT EQUATION

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The interfacial area transport equation dynamically models the changes in interfacial structures along the flow field by mechanistically modeling the creation and destruction of dispersed phase. Hence, when employed in the numerical thermal-hydraulic system analysis codes, it eliminates artificial bifurcations stemming from the use of the static flow regime transition criteria. Accounting for the substantial differences in the transport mechanism for various sizes of bubbles, the transport equation is formulated for two characteristic groups of bubbles. The group 1 equation describes the transport of small-dispersed bubbles, whereas the group 2 equation describes the transport of large cap, slug or churn-turbulent bubbles. To evaluate the feasibility and reliability of interfacial area transport equation available at present, it is benchmarked by an extensive database established in various two-phase flow configurations spanning from bubbly to churn-turbulent flow regimes. The geometrical effect in interfacial area transport is examined by the data acquired in vertical air-water two-phase flow through round pipes of various sizes and a confined flow duct, and by those acquired in vertical co-current downward air-water two-phase flow through round pipes of two different sizes.

KEYWORDS : Interfacial Area Transport, Interfacial Area Concentration, Interfacial Structure, One-Group Transport, Two-Group Transport, Two-Fluid Model, Two-Phase Flow

1. INTRODUCTION

In general, physical problems of two-phase flow are described by macroscopic field equations and constitutive relations using continuous formulation. While advanced mixture models such as the drift-flux model [1] have been extensively used, more detailed analysis of two-phase flow is possible through the two-fluid formulation. Ishii [2] has formulated the two-fluid model by treating each phase of the two-phase mixture separately through two sets of governing equations, within which the transport of mass, momentum and energy between the two phases across the interface is described by the interfacial transfer terms in the field equations. In general, these interfacial transfer rates can be given by the product of the driving interfacial flux and interfacial area concentration (a_i) defined by the available interfacial area per unit mixture volume. Thus, it is essential to provid an accurate constitutive relation for ai to solve the two-fluid model.

In the current nuclear reactor system analysis codes and in many practical two-phase flow analysis, a_i is calculated by the flow regime dependent correlations that do not dynamically represent the changes in interfacial structure. The flow regime transition criteria are developed for a fully developed steady-state two-phase flow and is not capable of describing the evolution of interfacial structure. Furthermore, the two-fluid model with static flow regime transition criteria and regime dependent constitutive relations represents a conceptual inconsistency in modeling the dynamic phase interactions. Hence, the lack of proper mechanistic models for a_i presents a significant concern in the thermal-hydraulic safey analysis of a nuclear reactor. Some of the major shortcomings related to the use of static flow regime based criteria include [3,4]: (1) They reflect neither the true dynamic nature of changes in the interfacial structure, nor the gradual regime transition; (2) The compound errors stemming from the two-step flow regime based method can be significant; (3) They are valid in limited parameter ranges for certain operational conditions. Often the scale effects of geometry and fluid properties are not taken into account correctly. Hence, these models may cause signifi-cant discrepancies, artificial discontinuities and numerical instability; (4) When applied to the numerical code calcula-tion, they may induce numerical oscillation and may present bifurcation.

In view of this, Kocamustafaogullari and Ishii [5] proposed a dynamic approach to furnish a_i via transport equation. Wu et al.[6] established the source and sink terms of the a_i accounting for the three major bubble interaction mechanisms. It was followed by Kim [7] where the a_i transport equation applicable to the bubbly flow in a confined bubbly flow was established. The model was further evaluated by Ishii et al. [8] and Kim et al. [9], where an extensive database acquired in various sizes of round pipes was employed. The capability of a_i transport equation was also clearly demonstrated in the preliminary study incorporating the one-dimensional a_i transport equation into the US NRC consolidated code [10]. In view of characteristic transport mechanisms in a wide range of two-phase flow regimes, Sun [11] and Fu [12] developed the two-group interfacial area transport equation applicable to confined and round flow channels, respectively. Furthermore, the a_i transport equation for a co-current downward two-phase flow was developed by Paranjape et al.[13]. Similar efforts to provide dynamic models for a_i were also made by Millies et al.[16], Morel et al.[17] and Hibiki and Ishii [18]. More recently, the comprehensive mathematical formulation of a_i transport equation analogous to the Boltzmann transport equation was published by Ishii and Kim [19].

2. INTERFACIAL AREA TRANSPORT EQUATION

The interfacial area transport equation originates from the Boltzmann transport equation, where the particle transport is described by an integro-differential equation of the particle distribution function. Noting that the interfacial area of the fluid particle is closely related to the particle number, the interfacial area transport equation is formulated in a similar approach. By defining $f(V,x,v,t)$ the particle number density distribution function per unit mixture and bubble volume, assumed to be continuous and specifies the probable number density of fluid particles moving with particle velocity v, at a given time t, in a spatial range δx with its center-of-volume located at x with particle volumes between V and $V+\delta V$, we can obtain

$$\frac{\partial f}{\partial t}+\nabla\cdot\left(f\boldsymbol{v}\right)+\frac{\partial}{\partial V}\left(f\frac{dV}{dt}\right)=\sum_j S_j+S_{ph} \tag{1}$$

where d/dt denotes the substantial derivative. Eq. (1) is analogous to the Boltzmann transport equation of particles with the distribution function $f(V,x,t)$. Then, the particle number, void fraction and the interfacial area concentration can be specified by

$$n(\boldsymbol{x},t)=\int_{V_{min}}^{V_{max}} f(V,\boldsymbol{x},t)dV\ , \tag{2}$$

$$\alpha(\boldsymbol{x},t)=\int_{V_{min}}^{V_{max}} f(V,\boldsymbol{x},t)VdV\text{ , and} \tag{3}$$

$$a_i(\boldsymbol{x},t)=\int_{V_{min}}^{V_{max}} f(V,\boldsymbol{x},t)A_i(V)dV \tag{4}$$

where V and A_i represents the volume and surface area of a fluid particle, respectively.

The transport equation given by Eq. (1) is much too detail to be employed in practice. Hence, a more practical form of transport equation can be obtained by averaging Eq. (1) over all particle sizes. Then, the transport equations for the particle number, void fraction and interfacial area concentration can be obtained, respectively as [5-7] :

$$\frac{\partial n}{\partial t}+\nabla\cdot\left(n\boldsymbol{v}_{pm}\right)=\sum_j R_j+R_{ph}\ , \tag{5}$$

$$\alpha(\boldsymbol{x},t)=\int_{V_{min}}^{V_{max}} f(V,\boldsymbol{x},t)VdV\text{ , and} \tag{6}$$

$$\frac{\partial a_i}{\partial t}+\nabla\cdot\left(a_i\boldsymbol{v}_i\right)=\frac{2}{3}\left(\frac{a_i}{\alpha}\right)\left(\frac{\partial\alpha}{\partial t}+\nabla\cdot\alpha\boldsymbol{v}_g-\eta_{ph}\right)+\frac{1}{3\psi}\left(\frac{\alpha}{a_i}\right)^2\sum_j R_j+\pi D_{bc}^2R_{ph} \tag{7}$$

where v_{pm}, v_g and v_i are defined, respectively as

$$\boldsymbol{v}_{pm}(\boldsymbol{x},t)\equiv\frac{\int_{V_{min}}^{V_{max}} f(V,\boldsymbol{x},t)\boldsymbol{v}(V,\boldsymbol{x},t)dV}{\int_{V_{min}}^{V_{max}} f(V,\boldsymbol{x},t)dV}\ , \tag{8}$$

$$\boldsymbol{v}_g(\boldsymbol{x},t)\equiv\frac{\int_{V_{min}}^{V_{max}} f(V,\boldsymbol{x},t)V\boldsymbol{v}(V,\boldsymbol{x},t)dV}{\int_{V_{min}}^{V_{max}} f(V,\boldsymbol{x},t)VdV}\text{, and} \tag{9}$$

$$\boldsymbol{v}_i(\boldsymbol{x},t)\equiv\frac{\int_{V_{min}}^{V_{max}} f(V,\boldsymbol{x},t)A_i(V)\boldsymbol{v}(V,\boldsymbol{x},t)dV}{\int_{V_{min}}^{V_{max}} f(V,\boldsymbol{x},t)A_i(V)dV} \tag{10}$$

In Eqs. (5) through (7), S_j and S_{ph} represent the particle source/sink rates per unit mixture volume due to j^{th} particle interactions (such as disintegration or coalescence) and that due to phase change, respectively. Hence, the number source/sink rate is defined by

$$R(\boldsymbol{x},t)=\int_{V_{min}}^{V_{max}} S(V,\boldsymbol{x},t)dV \tag{11}$$

and similarly, the nucleation source rate per unit mixture volume is defined by

$$\eta_{ph}\equiv\int_{V_{\min}}^{V_{\max}} S_{ph}VdV \tag{12}$$

Furthermore, ψ in Eq. (7) accounts for the shapes of the fluid particles of interest, origniating from

$$n = \psi \frac{a_i^3}{\alpha^2} \tag{13}$$

and is defined by

$$\psi = \frac{1}{36\pi}\left(\frac{D_{sm}}{D_e}\right)^3 \tag{14}$$

2.1 One-Group a_i Transport Equation

In the one-group formulation, the dispersed bubbles are assumed to be spherical in shape and their interactions are binary. Hence, all the fluid particles of interest are considered to be in the same group in view of their transport mechanisms. Considering that the one-group equation accounts for the bubble transport in the bubbly flow, three interaction mechanisms are identified as the major mechanisms that goven the change in the a_i, such that: (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 the following bubble in the wake of the preceding bubble (*WE*). Then, the one-group interfacial area transport equation for the vertical air-water bubbly two-phase flow is given by [6,7,9]:

$$\frac{\partial a_i}{\partial t} + \nabla\cdot(a_i v_i) = \frac{2}{3}\left(\frac{a_i}{\alpha}\right)\left(\frac{\partial \alpha}{\partial t} + \nabla\cdot\alpha v_g\right) + \frac{1}{3\psi}\left(\frac{\alpha}{a_i}\right)^2\left[R_{TI} - R_{RC} - R_{WE}\right] \tag{15}$$

with

$$R_{TI} = C_{TI}\left(\frac{nu_t}{D_b}\right)\exp\left(-\frac{We_{cr}}{We}\right)\sqrt{1-\frac{We_{cr}}{We}}, \text{ where } We > We_{cr} \tag{16}$$

$$R_{RC} = C_{RC}\left[\frac{n^2 u_t D_b^2}{\alpha_{\max}^{1/3}(\alpha_{\max}^{1/3} - \alpha^{1/3})}\right]\left[1-\exp\left(-C\frac{\alpha_{\max}^{1/3}\alpha^{1/3}}{\alpha_{\max}^{1/3} - \alpha^{1/3}}\right)\right], \text{ and} \tag{17}$$

$$R_{WE} = C_{WE} C_D^{1/3} n^2 D_b^2 u_r \tag{18}$$

Here, the source term due to phase change (R_{ph}) has been omitted accounting for the adiabatic condition.

The one-group a_i transport equation was evaluated by extensive data obtained in both the upward and downward adiabatic two-phase flows in various sizes of pipes and in two flow channel geometries. The coefficients determined based on the benchmark study are summarized in Table 1, and they are coefficients applicable for (1) vertical air-water two-phase flow in 12.7, 25.4, 50.8, 101.6 and 152.4 mm ID pipes, (2) vertical co-current downward air-water two-phase flow in 25.4 and 50.8 mm ID pipes, and (3) vertical air-water two-phase flow in a confined test section of 200 mm by 10 mm cross-sectional area. Some of the notable findings in this study can be summarized as: (1) The coefficients for the round pipe geometries remained the same regardless the pipe sizes; (2) While the mechanisms governing the bubble coalescence remain similar regardless the flow direction, it was clear that they were affected by the channel geometry [15]; (3) The contribution from the *TI* disintegration mechanism in downward flow was found to be weaker than that in the upward flow due to the characteristic core-peaking phenomenon observed in the co-current downward flow [13-15]; (4) The swirling motion of bubbles in downward flow induced large scale eddies, so as to sweep the bubble clusters as a whole, instead of affecting individual bubbles to disintegrate [14]; and (5) Neither the pipe sizes nor the flow direction affected the *RC* and *WE* mechanisms.

The characteristic results from the model evaluation studies are shown in Figs. 1 and 2. In Figs. 1(a), (b) and (c), some characteristic results from the upward flow in round pipes of 25.4 mm, 50.8 mm IDs and those for the confined test section are shown, respectively. The results from the co-current downward flow in 24.5 mm and 50.8 mm ID pipes are shown in Fig. 2. The model predictions agree well with the experimental data in all the flow conditions within 20% difference, mostly falling within 10% difference.

In Figs. 3 (a) and (b), results from the preliminary code implementation study employing the one-group a_i transport equation are present. The results clearly show that in both TRAC and TRAC-M code predictions, predictions made employing the one-group a_i transport equation is significa-

Table 1. Summary of Coefficients in the One-Group Interfacial Area Transport Equation [7,8,14]

Mechanisms	Round Pipes *vertical upward*	Round Pipes *vertical co-current downward*	Confined Test Section *vertical upward*
TI (*Source*)	0.085 (We_c=6.0)	0.034 (We_c=6.0)	0.026 (We_c=8.0)
RC (*Sink*)	0.004 (C=3; a_{max}=0.75)	0.004 (C=3; a_{max}=0.75)	0.003 (C=3; a_{max}=0.75)
WE (*Sink*)	0.002	0.002	0.042

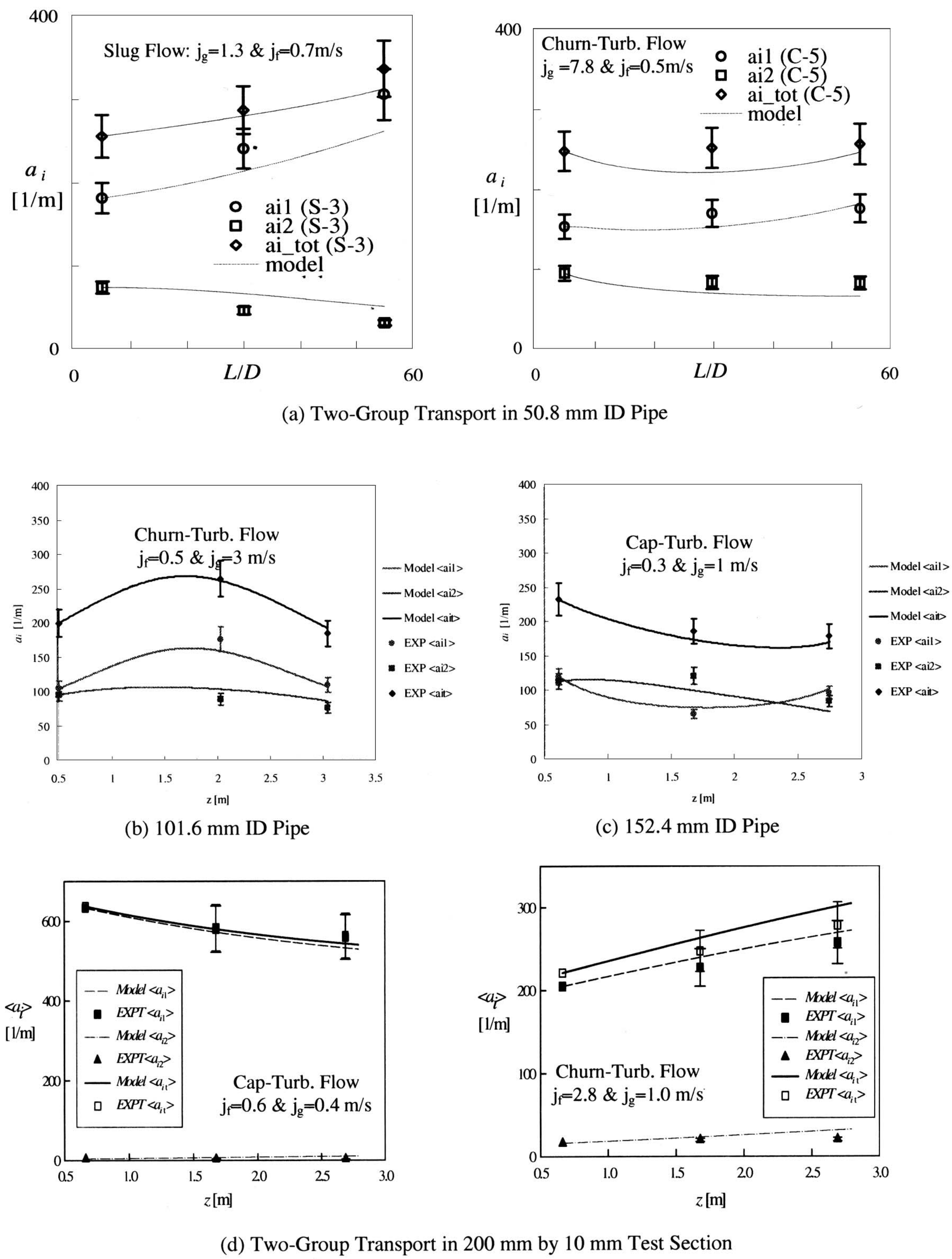

Fig. 1. Characteristic Results from the One-Group Model Evaluation Studies for Vertical Air-Water Two-Phase Flows (a) Upward Flow in Eound Pipe Geometries: 25.4 mm ID Pipe [8] (b) Upward Flow in 50.8 mm ID Pipe [8] and (c) Upward Flow in Test Section with Cross Sectional Flow Area of 200 mm by 10 mm [7,9]

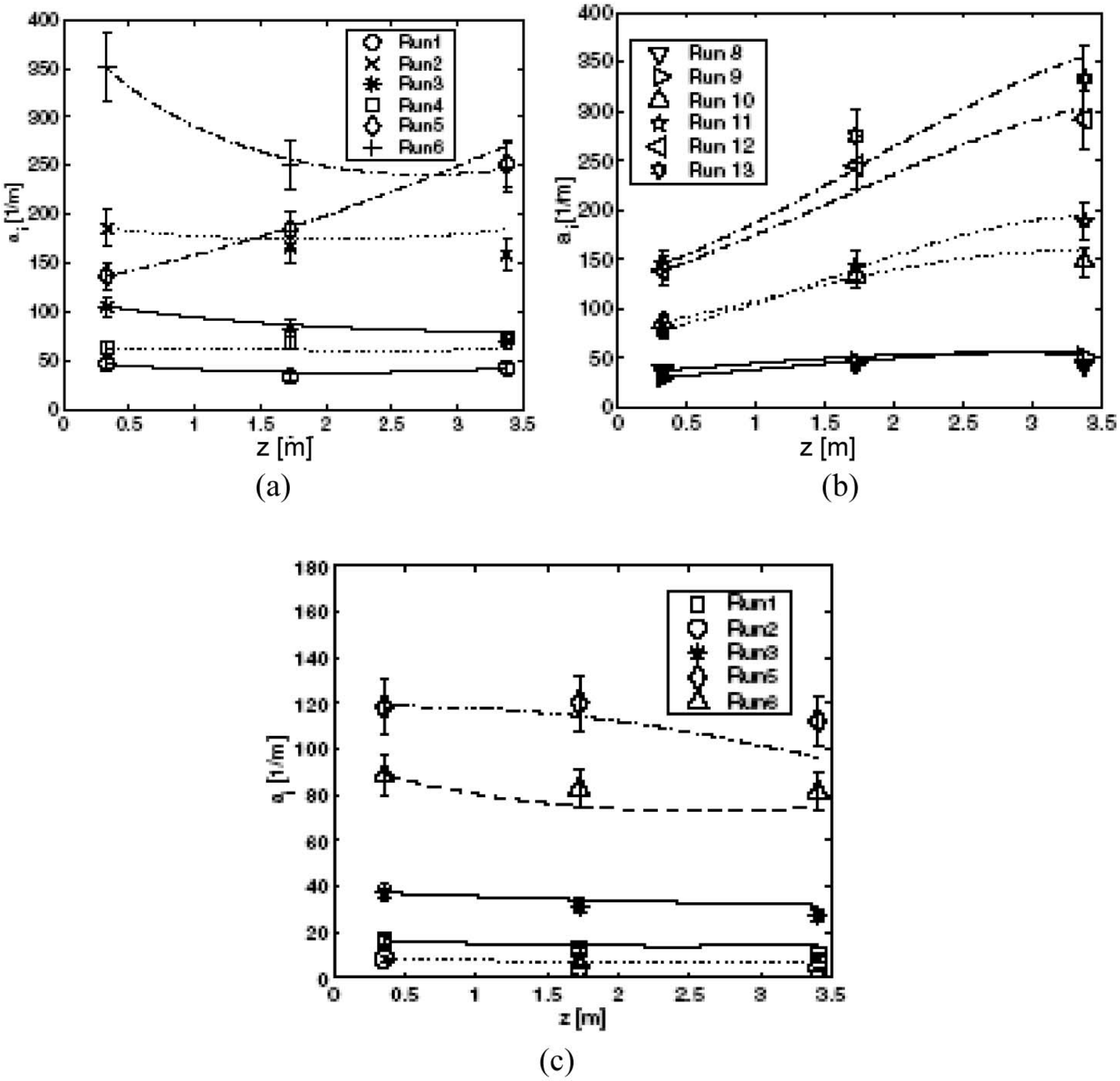

Fig. 2. Characteristic Results from the One-Group Model Evaluation Studies for Vertical Air-Water Co-Current Downward Two-Phase Flow [13-15] (a) & (b) 25.4 mm ID Pipe and (b) 50.8 mm ID Pipe

ntly more accurate than those predicted based on conventional approaches.

2.2 Two-Group a_i Transport Equation

To describe the interfacial area transport in various two-phase flow regimes, the two-group transport equation should be employed. This is because the differences in bubble sizes or shapes cause substantial differences in their transport mechanisms and interaction phenomena. Therefore, two transport equations for two characteristic groups of bubbles are sought, such that the group 1 equation describes the transport of small dispersed and distorted bubbles, and the group 2 equation describes the transport phenomena of cap/slug/churn-turbulent bubbles. As a result, the following two-group interfacial area transport equations were established [19]:

$$\frac{\partial a_{i1}}{\partial t}+\nabla\cdot\left(a_{i1}\boldsymbol{v}_{i1}\right)= \quad \textit{: for group 1}$$
$$\left(\frac{2}{3}-CD_{c1}^{*\,2}\right)\frac{a_{i1}}{\alpha_1}\left[\frac{\partial\alpha_1}{\partial t}+\nabla\cdot\left(\alpha_1\boldsymbol{v}_{g_1}\right)-\eta_{\mathrm{ph1}}\right]+\sum_j\phi_{j,1}+\phi_{\mathrm{ph}} \tag{19}$$

$$\frac{\partial a_{i2}}{\partial t}+\nabla\cdot\left(a_{i2}\boldsymbol{v}_{i2}\right)=\frac{2}{3}\frac{a_{i2}}{\alpha_2}\left[\frac{\partial\alpha_2}{\partial t}+\nabla\cdot\left(\alpha_2\boldsymbol{v}_{g_2}\right)-\eta_{\mathrm{ph2}}\right] \quad \textit{: for group 2}$$
$$+CD_{c1}^{*\,2}\frac{a_{i1}}{\alpha_1}\left[\frac{\partial\alpha_1}{\partial t}+\nabla\cdot\left(\alpha_1\boldsymbol{v}_{g_1}\right)-\eta_{\mathrm{ph1}}\right]+\sum_j\phi_{j,2}+\phi_{\mathrm{ph2}} \tag{20}$$

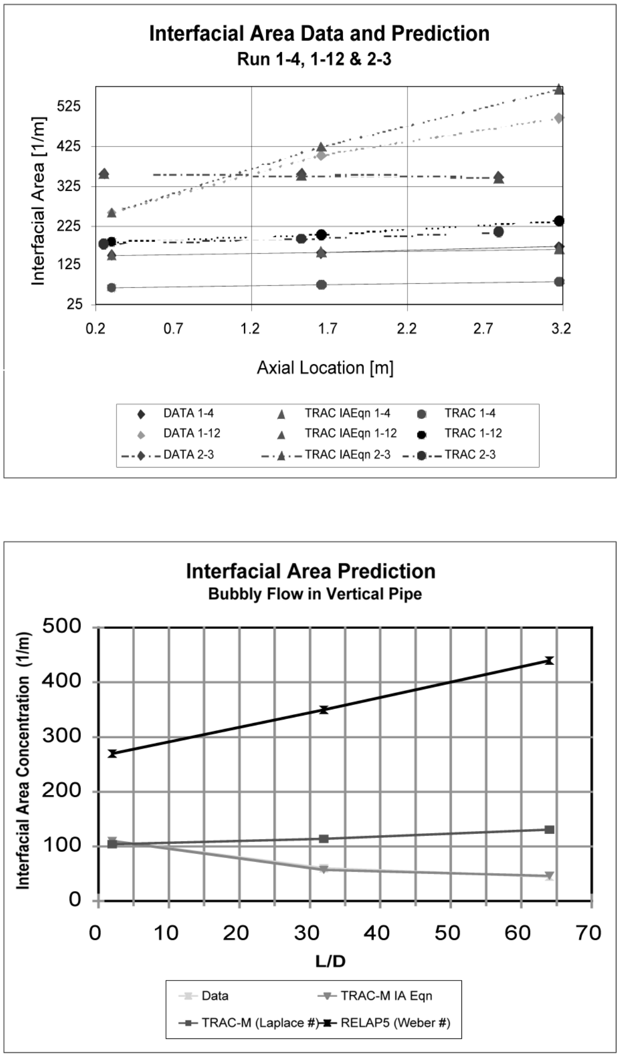

Fig. 3. Results from the Preliminary Code Implementation Study of the One-Group Interfacial Area Transport Equation Via TRAC and TRAC-M Thermal-Hydraulic Safety Analysis Codes10

Here, the subscripts 1 and 2 denote Group 1 and Group 2, respectively, and the non-dimensional parameter D^*_{c1} is defined as the ratio between the critical bubble size and the average size of Group 1 bubbles:

$$D^*_{c1} = D_c / D_{sm1}, \tag{21}$$

where D_c and D_{sm1} are the volume-equivalent diameter of a bubble with critical volume V_c and the Sauter mean diameter of Group 1 bubbles, respectively. The coefficient C in the equation accounts for the inter-group transfer at the group boundary due to expansion, compression, and phase change. It should be noted that the phase change terms for Group 2 bubbles, η_{ph2} and ϕ_{ph2}, may be neglected in Eq. (20) in general two-phase flow conditions with no rapid condensation.

In the development of two-group interfacial area transport equation, major difficulties arise from the existence of various types of bubbles and their complicated interactions. First, additional bubble interaction mechanisms related to the large bubble transport need to be modeled. Two major mechanisms can be identified as; shearing off of small bubbles at the base rim of large cap bubbles (*SO*) and break-up of large cap bubbles due to the surface instability at the interface (*SI*). In addition to these, mechanisms applicable to both group 1 and group 2 bubbles should be carefully considered. Therefore, some of the existing models applicable to one-group transport need to be extended to account for the group 2 bubbles. Furthermore, interactions between the bubbles in the same group (intra-group interaction) and those between the bubbles of two different groups (inter-group interactions) need to be modeled, along with inter-group transfer at the group boundary due to expansion and compression. It is also noted that in two-group transport formulation, the particle distribution function needs to be properly averaged due to the existence of various types of bubbles in the two-group transport. In the present model, the distribution functions for group 1 and group 2 bubbles were assumed to be uniform for simplicity [11,12]. For detailed mathematical derivations of the two-group source and sink terms and the model coefficients in the two-group transport equation, authors recommend the readers to refer to the references given above.

The two-group interfacial area transport equation was evaluated by an extensive database established in the adiabatic vertical upward air-water two-phase flows in two flow channel geometries: i.e. the round pipes of various sizes and a confined test section. For the round pipe geometry, a comprehensive database in four different pipes was established in bubbly, slug and churn-turbulent flow regimes. The pipe sizes employed for experiment were 50.8, 101.6 and 152.4 mm in inner diameters. For the confined geometry, a test section with 10 mm x 200 mm cross-sectional area was employed, and the local two-phase flow parameters were acquired in bubbly, cap-turbulent and churn-turbulent flow regimes. In total, 204 data points were evaluated for the two-phase flow in round pipes, and 71 data points were evaluated for the confined geometry. Accounting for the difference in flow channel geometries and their influences in bubble transport, two sets of coefficients were determined based on the experimental data as shown in Table 2. In general, the model showed good agreement with the data as summarized in Fig. 4. In Fig. 5, some characteristic results are shown. In the present model, the phase change was neglected to reflect the adiabatic experimental conditions.

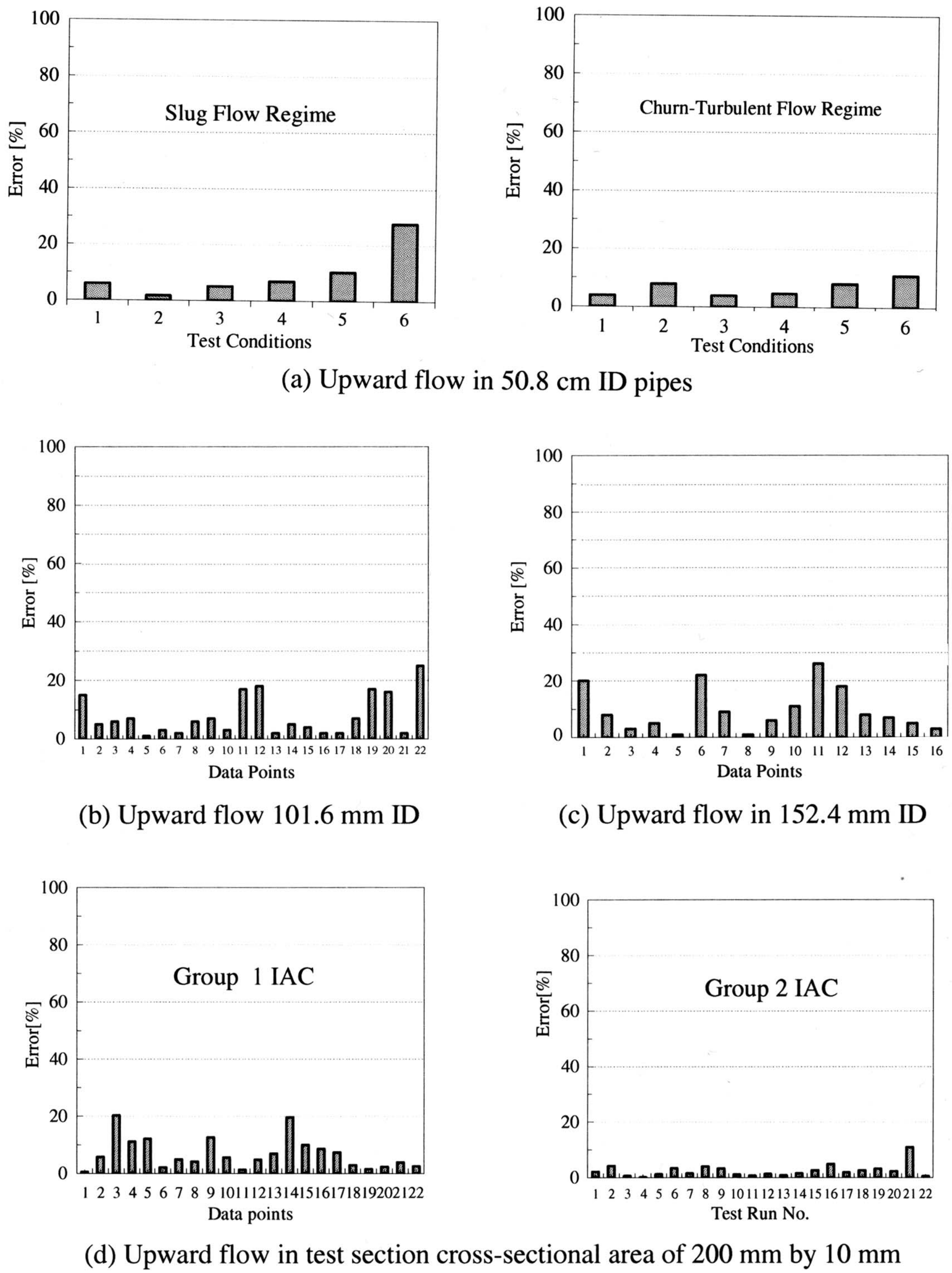

Fig. 4. Relative Errors in the Two-Group Model Evaluation Studies [11,12].

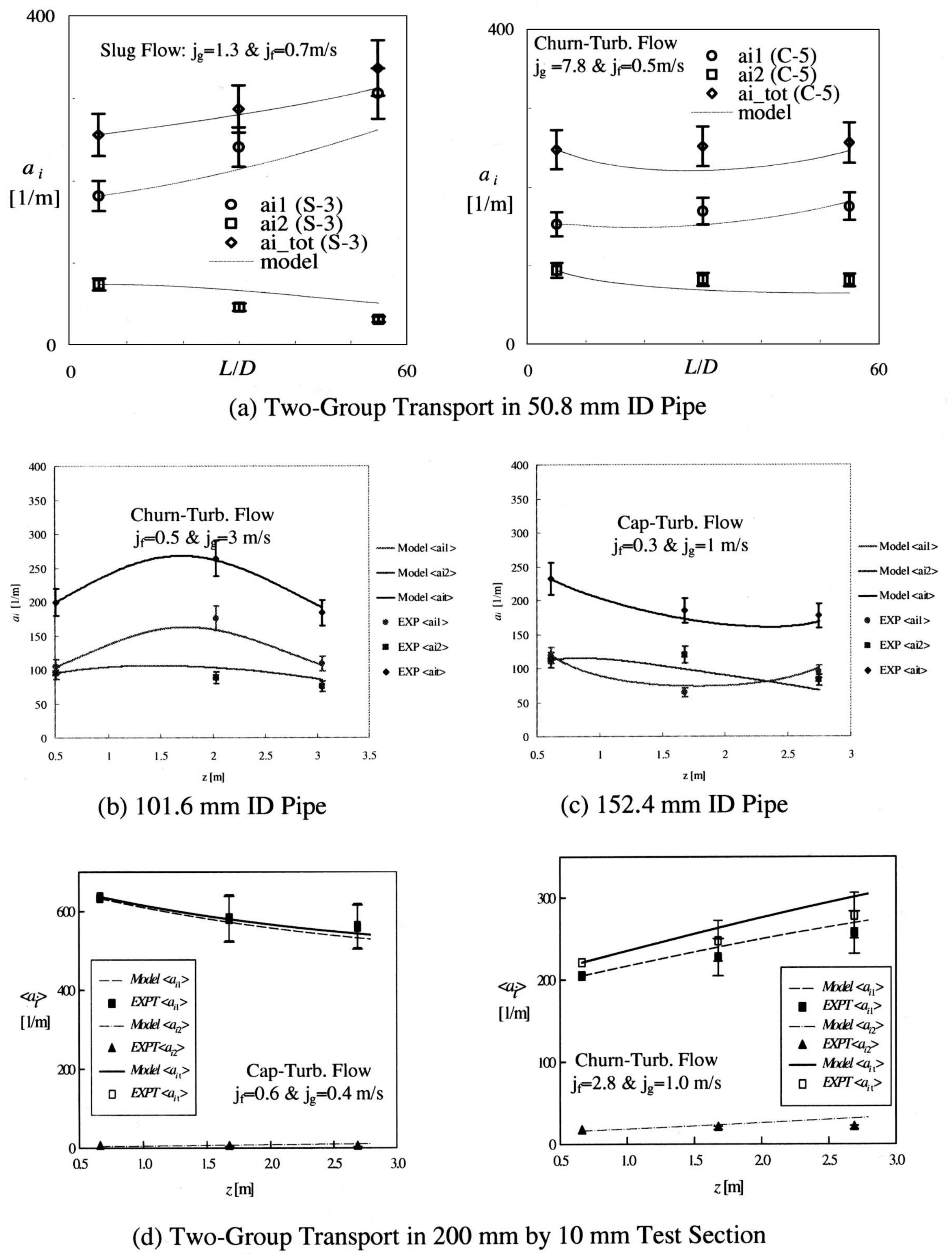

Fig. 5. Characteristic Results from the Two-Group Model Evaluation Studies for Vertical Upward Air-Water Two-Phase Flows (a) 50.8 mm ID Pipe[12], (b)101.6 mm ID Pipe[43], (c) 152.4 mm ID Pipe[43], and (d) 200 mm by 10 mm Duct [11].

Table 2. Summary of Model Coefficients in the Two-Group Interfacial Area Transport Equation for Round Pipes and Confined Test Section [11,12]

Mechanisms *numbers in the parenthesis denote the group number*		Round Pipe *vertical upward (Fu, 2001)*	Confined Test Section *vertical upward (Sun, 2001)*
TI	$(1) \longmapsto (1) + (1)$	0.085	0.03 $We_{C,TI1}=6.5$
	$(2) \longmapsto (2) + (2)$	N/A	0.03 $We_{C,TI2}=7.0$
RC	$(1) + (1) \longmapsto (1)$	0.004	0.005 $C_{RC1}=3.0$
	$(1) + (2) \longmapsto (2)$	0.004	0.005
	$(2) + (2) \longmapsto (2)$	0.004	0.005 $C_{RC2}=3.0$
WE	$(1) + {}^{*}n(1) \longmapsto (1)$	0.002	0.002
	$(2) + n(1) \longmapsto (2)$	0.015	0.002
	$(2) + n(2) \longmapsto (2)$	10.0	0.005
SO	$(2) \longmapsto (2) + n(1)$	0.031 $\gamma_{so}=0.032$ $\beta_{so}=1.6$	$C_{SO}=3.8\text{x}10^{-5}$ $C_d=4.8$ $We_{c,SO}=4500$
C	inter-group coeff.	≈ 0	$4.44 \times 10^{-3} \left(\frac{\langle D_{sm1} \rangle}{D_c} \right)^{0.36} \langle \alpha_1 \rangle^{-1.35}$

* *n denotes multiple bubble interaction*

3. GUIDELINES FOR FUTURE STUDY

As demonstrated in many studies, the present two-group a_i transport equation can be successfully applied to predict the interfacial area transport in various adiabatic two-phase flow conditions with relatively high confidence. Moreover, the preliminary code implementation study demonstrated significant improvements in the code calculation results. Nevertheless, the present model has been evaluated in limited two-phase flow conditions, and additional studies are necessary to establish a more robust model. In view of this, some guidelines for the future study on interfacial area transport equation are presented in this section.

<u>Subcooled Boiling Two-phase Flow</u> : The study on subcooled boiling is of great importance, because it provides the boundary condition for the onset of the vapor generation. In subcooled boiling, the existence of the thermodynamic non-equilibrium between the phases makes it a difficult problem [20-22]. Due to the importance of the subject, there have been a number of studies over the past four decades. However, reliable mechanistic models are not available yet. Kocamustafaogullari and Ishii [23] and Riznic and Ishii [24] performed some pioneering studies. At present, however, the models applicable to a broad range of wall superheat, nucleation surface, and working fluids are yet to be established. Recently, there have been some studies to develop generalized models for the active site density, bubble departure size and frequency in forced-convection subcooled boiling process [25-28].

<u>Co-current and Counter-current Downward Two-phase Flow</u> : The co-current downward two-phase flow conditions can be encountered in transient conditions in the reactor system such as LOHS by feedwater loss or secondary pipe break, LOCA and when relief valve opens. In Boiling Water

Reactor, the co-current downward two-phase flow can be encountered in the later stage of ECCS injection, signified by the counter current flow limitation phenomena. The recent results from the downward two-phase flow experiments demonstrated that the interfacial structures in the downward two-phase flow are significantly different from those in the upward two-phase flow [13-15]. Furthermore, the channel size effect in flow regime transition in the co-current downward flow was far more significant than that in the upward flow [13,14,27]. Hence, continuing efforts on the development of interfacial area transport equation for the co-current downward and countercurrent two-phase flow are indispensable in view of safety analysis.

Two-phase Flow in Horizontal and Combinatorial Flow Channels : In horizontal flow, the interfacial structure, regime transition and fluid particle interaction mechanisms differ significantly from those in the vertical flow. In particular, the pressure difference between the two phases and the phase separation phenomenon in the stratified and intermittent flow need to be accurately modeled. In the current one-dimensional two-fluid model, there is no mechanism to govern the phase distribution along the vertical direction of the flow. This presents a serious shortcoming, because the flow can never develop into a stratified flow. Hence, efforts on developing mechanistic models on the phase separation phenomenon and the gravity effects in horizontal two-phase flow are indispensable in dynamic modeling of flow regime transition. Some of the recent experimental studies on local two-phase flow parameters in horizontal flow can be found in Sharma et al. [30], Iskandrani and Kojasoy [31], and Lewis et al. [32]. In their studies, internal structures and local two-phase flow parameters in various horizontal two-phase flow regimes are studied in detail. Furthermore, mechanisms resulting in bubble break-up and coalescence are identified.

Two-phase Flow Under Microgravity Condition : The recent development in the space technology requires higher efficiency heat removal system that can be achieved through two-phase flow heat removal system. In the larger spacecraft such as the International Space Station, the application of thermal bus or two-phase thermal control system has been studied [33]. In fact, there have been many studies to investigate the dynamics of two-phase flows under microgravity condition [34-40]. However, the prediction of two-phase flow behaviors in microgravity environment is yet to be resolved due to the fundamental difficulties of a two-phase flow stemming from the complicated interfacial transfer phenomena and the limitation of accurate constitutive relations. Under the microgravity condition, the two-phase flow structure may not reach an equilibrium condition and the two fluids may be loosely coupled. Hence, the inertia terms of each fluid should be considered separately by employing the two-fluid model. Much of the previous studies on microgravity two-phase flow relied on flow regime transition or transition criteria [35-38], which is consistent with the traditional approach under normal gravity condition. However, it is expected that the two-phase flow does not reach a steady-state condition and the interfacial structure does not reach an equilibrium stable configuration under the microgravity condition. Therefore, the use of flow regime dependant closure relations developed for the fully-developed steady-state two-phase flow is not realistic and may cause significant errors. In view of this, some preliminary studies on the interfacial area transport under microgravity condition have been done by Takamasa et al. [40], Ishii et al. [41], and Vasavada et. al. [42].

Interfacial Area Transport in Fuel Rod Bundle Geometry : Two-phase flow in rod bundles geometry can be encountered in reactor cores and steam generators. Conventionally, as a first order approximation, the experimental results from a pipe flow are employed to study the subchannel in the rod bundles. However in flow regimes such as slug or churn-turbulent flow, the lateral distributions of flow parameters in rod bundles are no longer uniform and are expected to be different from the ones in the pipe flow, due to the open boundary between the subchannels. Therefore, both experimental and analytical studies accounting for such geometrical effects are needed for the interfacial area transport equation applicable to the two-phase flow in rod bundle geometry.

4. SUMMARY

The interfacial area transport equation can make a significant improvement in the current capability of the two-fluid model, and hence the performance of current system analysis code. Unlike the conventional flow regime dependent correlations, the interfacial area transport equation dynamically predicts the changes in the interfacial structure through mechanistic modeling of fluid particle interactions. Thus, it eliminates a number of problems stemming from inherent shortcomings of the conventional static approach.

The one-group and two-group interfacial area transport equations currently available for the adiabatic two-phase flow are reviewed including the evaluation results obtained through extensive experimental studies. The database employed in the evaluation study includes the data acquired in vertical air-water two-phase flow in (1) upward flow of pipes with 25.4 mm, 50.8 mm, 101.6 mm and 152.4 mm IDs for bubbly, slug, cap-turbulent and churn-turbulent flow conditions; (2) co-current downward flow in pipes of 25.4 mm and 50.8 mm IDs for bubbly flow conditions; and (3) upward flow in 200 mm by 10 mm confined test duct for bubbly, cap-turbulent and churn-turbulent flow conditions. Throughout the evaluation studies, predictions made by both the one-group and two-group interfacial area transport equations agree well with the experimental data with a relative error of less than $\pm$20%, mostly falling within $\pm$10 %. Furthermore, the preliminary test incorporating the one-group transport equation into the USNRC consolidated code showed a significant improvement in the code prediction.

Nevertheless, the current model has been validated in a limited two-phase flow conditions, and continuing studies are needed to establish a more comprehensive model. In view of this, authors present some guidelines for the future studies on interfacial area transport. They include: Interfacial area transport in (1) sub-cooled boiling condition, (2) co-current and counter-current downward two-phase flow, (3) horizontal and combinatorial flow channels, (4) microgravity condition and (5) rod bundle geometry

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