CONF-9308330--12

WSRC-MS-92-390

TWO-PHASE INTERFACIAL AREA AND FLOW REGIME MODELING IN FLOWTRAN-TF CODE (U)

by S. Y. Lee

Westinghouse Savannah River Company
Savannah River Site
Aiken, South Carolina 29808

Other Authors:

F. G. Smith, III
(WSRC)
G. P. Flach
(WSRC)
L. L. Hamm
(WSRC)

A paper proposed for Publication
at/in the 1993 National Heat Transfer Conference
Atlanta, GA
08/08-11/93

DISCLAIMER

Two-phase Interfacial Area and Flow Regime Modeling in FLOWTRAN-TF Code

F. G. Smith, III, S. Y. Lee, G. P. Flach, and L. L. Hamm
Westinghouse Savannah River Company
Aiken, SC 29801

ABSTRACT

FLOWTRAN-TF is a new two-component, two-phase thermal-hydraulics code to capture the detailed assembly behavior associated with loss-of-coolant accident analyses in multichannel assemblies of the SRS reactors. The local interfacial area of the two-phase mixture is computed by summing the interfacial areas contributed by each of three flow regimes. For smooth flow regime transitions, the code uses an interpolation technique in terms of component void fraction for each basic flow regime.

INTRODUCTION

FLOWTRAN-TF is a new two-component, two-phase thermal-hydraulics code to perform the transient assembly behavior associated with large break accident analyses under cocurrent air-water downward flow in the assemblies of the production reactors at the Savannah River Site (SRS) [2]. Each assembly consists of three main annular channels (inner, middle and outer channels) with ribs. Under this unique channel geometry, the code considers gas and liquid phases separately through two sets of conservation equations to describe the balance of mass, momentum, and energy for each phase. Mass, momentum, and energy are exchanged from one phase to the other at the interface of two phases. The complicated interfacial transfer mechanisms are affected by the interfacial area concentration and the driving force. This area concentration is defined as interfacial area per unit volume of the two-phase mixture and is related to the structure of the two-phase flow field. The driving forces for the interphase transport characterize the transport mechanisms associated with local flow regimes, and they must be modeled separately in terms of local thermal-hydraulic variables. Basic macroscopic parameters related to the structure of two-phase flow are void fraction, bubble size and number density, and interfacial area concentration. From geometrical considerations, it can be shown that bubble number density and bubble size are the important parameters in determining the interfacial area concentration. For a separated flow such as annular flow or liquid film flow, channel geometry has a significant effect on the interfacial area concentration. For instance, hydraulic diameter is a key parameter in formulating the interfacial area concentration under annular flow regime. For transition flow regimes such as bubbly-slug or slug-annular flow, bubble size and channel wall effect may be important.

This paper presents the basic formulation of the interfacial area concentration in each flow regime and the flow regime modeling based on the literature, which were used for the development of the FLOWTRAN-TF code.

MODELING AND FORMULATIONS

A rational approach is to establish basic formulations of the interfacial area concentration for each main flow regime as well as for the transition regimes since a universal model, which is applicable to all flow regimes, is not available yet. Then, the two-phase flow regime map has a strong influence on the constitutive relationships associated with interfacial transport mechanisms in the two-fluid model formulation. The modeling of flow regime map for the FLOWTRAN-TF code implementation is discussed later.

• Interfacial area concentration

The interfacial area concentration is defined as

$$a_i \equiv \left(\frac{\text{total interfacial area within a computational cell}}{\text{computational cell volume}} \right) \tag{1}$$

The code considers the flow regime of two-phase flow to be a superposition of the contributions from the three flow regimes, bubbly, slug, and annular flow. The local interfacial area of the two-phase mixture is computed by summing the interfacial areas contributed by each of the three flow regimes.

$$a_i = \sum_m a_{i,m} = a_{i,b} + a_{i,s} + a_{i,a} \tag{2}$$

For smooth interfacial area transitions among the three basic regimes, the FLOWTRAN-TF code uses an interpolation technique in terms of component void fraction for each flow regime. The detailed formulation for the computation of each component void fraction in total local void fraction is described in the section on the flow regime map. The total void fraction (α_g) is divided into three components as follows:

$$\alpha_g = \alpha_{g,b} + \alpha_{g,s} + \alpha_{g,a} \tag{3}$$

where $\alpha_{g,b}$, $\alpha_{g,s}$, and $\alpha_{g,a}$ are defined as bubbly, slug, and annular regime component void fractions, respectively.

The following establishes the basic formulations of the interfacial area concentration in pure bubbly, annular, and slug flows, as well as in the bubbly-slug and slug-annular transition regimes.

Interfacial area concentration in bubbly flow regime:

At void fractions below $\alpha_g = 0.25$, purely bubbly flow is assumed to exist from the FLOWTRAN-TF flow regime map. For interfacial area concentration calculations, bubbles are assumed to be spherical since bubble size in this flow regime is relatively small. The maximum allowable bubble diameter is chosen as the minimum of three different criteria, that is,

$$(d_b)_{max} = \min\left\{ d_b|_{E_o=6},\ D_h,\ \left(\frac{6}{\pi} V_b\right)^{1/3} \right\} \qquad (4)$$

An Eotvos number (Eo) comes directly from equating surface tension force to buoyancy force in static equilibrium. In this situation, all the bubbles within a stagnant liquid are assumed to be spherical. The hydraulic diameter of a thin annular channel with ribs is approximately equal to (D_o - D_i). The second criterion is based on the appropriate condition that maximum size of equivalent spherical bubbles within a ribbed annular channel can not exceed the channel hydraulic diameter (D_h). The bubble diameter is constrained by the entire volume of gas phase (V_b) in the computational mesh cell forming a single bubble. Given the assumed upper bound on pure bubbly flow of α_g= 0.25, the maximum bubble diameter associated with this criterion for SRS assembly geometry is about 2 cm. For bubble properties at room temperature, Eo = 6 corresponds to a bubble diameter of about 0.7 cm. This is less than any other parameter ($(D_h)_{min} \approx 0.76$ cm). Thus, the Eo criterion (Eo = 6) mainly limits the maximum bubble size for bubbly flow regime.

Following RELAP5, the average bubble diameter (d_o) is taken, a priori, as one half the maximum diameter ($d_{b,\,max}$). RELAP5 uses a Weber number criterion (We = 10) to determine the maximum bubble size [12]. The Weber number is related to the Eotvos number when the drag force for a single bubble is balanced by its buoyancy force. That is,

$$\frac{1}{2}\left(\frac{\pi d_b^{\,2}}{4}\right) C_d\, \rho_f\, u_r^{\,2} = \Delta\rho\, g \left(\frac{\pi d_b^{\,3}}{6}\right) \qquad (5)$$

Then, equation (5) becomes

$$We = \frac{4\,Eo}{3\,C_d} \qquad (6)$$

In equation (6) drag coefficient (C_d) for the flow over a spherical bubble is dependent on liquid Reynolds number [8]. When C_d is assumed to be unity over a wide range of Reynolds numbers, FLOWTRAN-TF's Eotvos criterion corresponds to a Weber number of 8.

The interfacial area concentration is formulated by using the concept of the Sauter mean diameter [15] defined as

$$d_{sm} = \frac{\int_0^\infty d_b^3 \, P(d_b) \, dd_b}{\int_0^\infty d_b^2 \, P(d_b) \, dd_b} \tag{7}$$

where $P(d_b)$ is the probability density function of a bubble having a diameter between d_b and $d_b+\delta d_b$ within the control volume. Physically, the Sauter mean diameter represents a bubble whose surface area to volume ratio is the same as that of the whole mixture. Wallis [15] recommends the Nukiyama-Tarasawa probability function for the distribution of drop diameters. In dimensionless form with the coefficients recommended by Wallis [15], which corresponds to quantization on a basis of bubble volume and a specified value of bubble mean diameter,

$$P(d_b^*) = 4 \left(d_b^*\right)^2 e^{-2 d_b^*} \tag{8}$$

where $d_b^* = d_b/d_b'$ and d_b' is the most probable bubble diameter in the bubble size distribution function.

Evaluation of the integral in equation (7) yields the following relationship between Sauter mean diameter and the most probable diameter using the distribution function and the Euler's integral [1]:

$$d_{sm}^* \equiv \frac{d_{sm}}{d_b'} = \frac{5}{2} \tag{9}$$

Likewise, the dimensionless average droplet diameter is defined as

$$d_o^* \equiv \frac{d_o}{d_b'} = \int_0^\infty d_o^* \, P(d_o^*) \, dd_o^* \tag{10}$$

d_o^* is equal to 1.5 using the distribution function, equation (8). The interfacial area per unit two-phase mixed volume can be expressed by using the definition of the Sauter mean diameter as

$$a_{i,b} = \frac{6 \, \alpha_{g,b}}{d_{sm}} \tag{11}$$

Using the results of equations (9) and (10), equation (11) can be expressed in terms of the mean bubble diameter (d_o) as

$$a_{i,b} = \frac{3.6 \, \alpha_{g,b}}{d_o} \tag{12}$$

In a two-phase flow system, the size distribution of bubbles is commonly determined by the dynamics of bubble breakup and coalescence due to a number of processes such as strong velocity gradient, turbulent flow field, and flow oscillation. In the FLOWTRAN-TF code, the maximum bubble size in the bubbly flow regime is determined by the critical Eotvos number (Eo_{crit}). The value of Eo_{crit} is chosen as 6 based on the static force balance between the surface tension force and the buoyancy force of a single bubble in stagnant liquid. With the spherical shape and size distribution of the bubbles within a continuous liquid phase given by the above model, the interfacial area per unit volume can be determined by equation (12) for a given void fraction in the bubbly flow regime.

Interfacial area concentration in annular flow regime:

Above a void fraction of 0.75, annular flow is assumed to occur from the flow regime map of the FLOWTRAN-TF code. The interfacial area in this case can be calculated from separated flow considerations. For the ribbed annular geometry shown in Figure 1, a constant value of liquid film thickness δ on the surfaces is assumed. The interfacial area per unit channel height is just the perimeter between the two phases, while the volume per unit channel height is the cross-sectional area of the flow channel. Then, the interfacial area per unit volume becomes

$$a_{i,a} = \frac{P_i}{A_c} \tag{13}$$

In the FLOWTRAN-TF code, the interfacial perimeter is computed from the geometrical input information and the computed cell averaged void fraction. That is,

$$P_i = P_w - 8\,\delta \tag{14}$$

where

$$P_w = \frac{4\,A_c}{D_h} \tag{15}$$

and

$$\delta = \frac{(1 - \alpha_{g,a})\,A_c}{P_w} \tag{16}$$

The resulting equation for the interfacial area concentration is obtained from equation (13) by using equations (14) to (16).

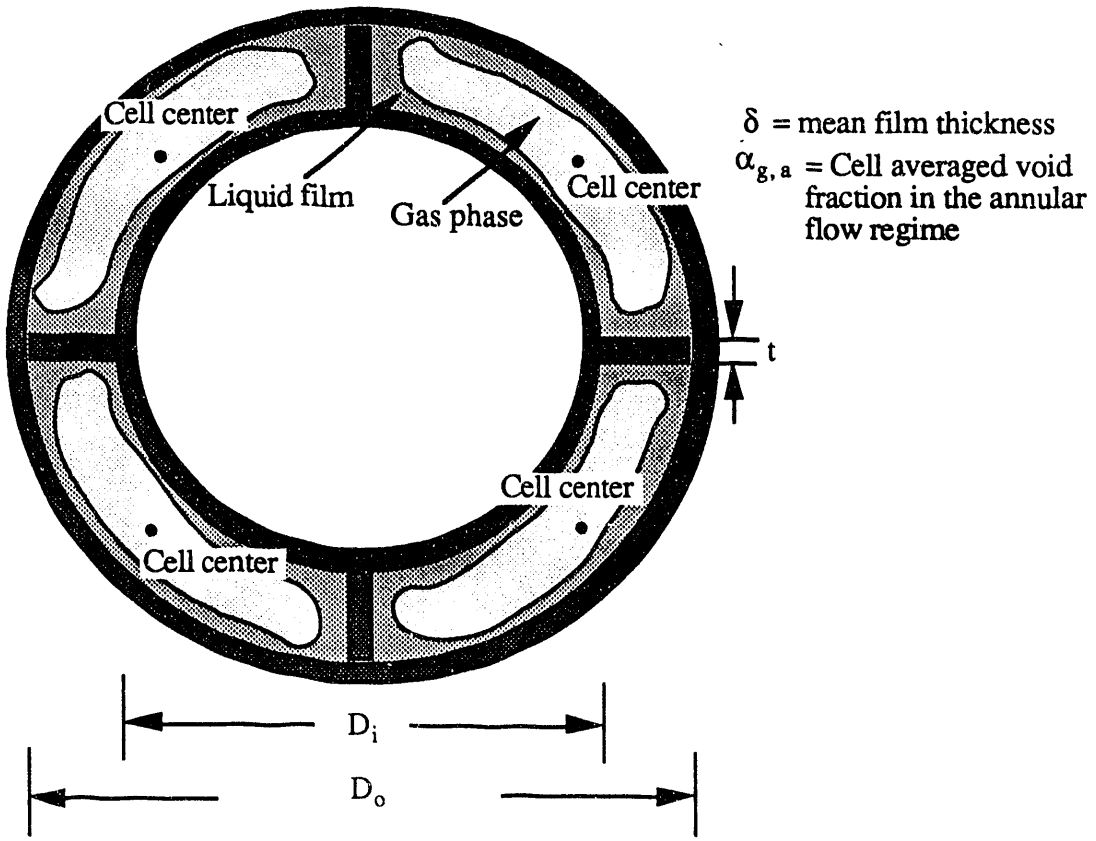

Figure 1. The computational model for the interfacial area concentration in the annular flow regime.

$$a_{i,a} = \frac{4}{D_h} - \frac{2\,D_h}{A_c}(1 - \alpha_{g,a}) \qquad (17)$$

Equation (17) is derived from the condition that mean film thickness is uniform.

Interfacial area concentration in slug flow regime:

Pure slug flow is assumed to exist only at a single value of void fraction, $\alpha_g = 0.52$ in the FLOWTRAN-TF code. In practice, the derivation for slug flow is of interest mainly in computing the slug contribution to interfacial area for the bubbly-slug and slug-annular flow regimes.

For the formulation of interfacial area for a pure slug within a computational cell as illustrated in Figure 1, one quadrant of an annulus is approximated as a rectangular channel of wide span a and

width b. The long slug bubble is then approximated as a right rectangular parallelpiped with wide span of slug bubble (d_b) >> narrow span (b_b) and bubble length (ℓ_b). The distance between noses of successive bubbles is denoted as L. When V_c is the control volume for the computation of interfacial area concentration in slug flow, the resulting equation becomes

$$a_{i,s} = \frac{A_{i,s}}{V_c} \approx \frac{2\left(d_b\,\ell_b + b_b\,\ell_b + d_b\,b_b\right)}{a\,b\,L} \tag{18}$$

$$= \frac{2\,d_b\,\ell_b\left(1 + \frac{b_b}{d_b} + \frac{b_b}{\ell_b}\right)}{a\,b\,L} = \frac{2\,d_b\,\ell_b\,C_1}{a\,b\,L}$$

where C_1 is the correction factor associated with the geometrical shape of the slug bubble and is always greater than unity. In a thin rectangular channel, the hydraulic diameter is given by

$$D_h = \frac{4\,A_c}{P_w} \approx 2\,b \tag{19}$$

Since a slug bubble is physically constrained by the flow geometry, the ratio of the parameters in equation (18) may be approximated as

$$\frac{d_b}{a} \approx 0.88 \tag{20}$$

Ishii and Mishma [10] used the ratio of the bubble diameter to channel diameter as 0.88 for a slug bubble in a tube. Thus, void fraction for the slug flow ($\alpha_{g,s}$) within a control volume can be estimated as

$$\alpha_{g,s} = \frac{V_{b,s}}{V_c} = \frac{C_2\,d_b\,b_b\,\ell_b}{a\,b\,L} = \frac{(0.88)^2\,C_2\,\ell_b}{L} \tag{21}$$

where C_2 is the geometrical correction factor generated from the computation of slug bubble volume. C_2 is expected to be closely equal to unity from the model assumption.

The interfacial area per unit two-phase mixed volume in equation (18) can be obtained in terms of $\alpha_{g,s}$ and hydraulic channel diameter by using equations (19) to (21).

$$a_{i,s} = \frac{2\,d_b\,\ell_b\,C_1}{a\,b\,L} = 4.545\left(\frac{C_1}{C_2}\right)\frac{\alpha_{g,s}}{D_h} \tag{22}$$

where (C_1/C_2) is greater than unity.

When (C_1/C_2) in equation (22) is equal to C (roughness coefficient), equation (22) becomes identical to the result of Ishii and Mishma [10] for a slug flow in tube. In the FLOWTRAN-TF code, C is set to be 1.5.

Interfacial area concentration in bubbly-slug flow regime:

The bubbly-slug mixed region in the two-phase flow regime map of the FLOWTRAN-TF code is considered to occur at void fractions between 0.25 and 0.52. As discussed previously, the interfacial area concentration for the mixed flow regime is the sum of the interfacial area concentration for each of the two flow regimes, bubbly and slug flows, considered independently. Based on the computed void fraction for each flow regime ($\alpha_{g,b}$ and $\alpha_{g,s}$), the total interfacial area concentration for the bubbly-slug regime is evaluated as

$$a_i = a_{i,b} + a_{i,s} = \frac{3.6\,\alpha_{g,b}}{d_o} + \frac{4.5\,C\,\alpha_{g,s}}{D_h} \qquad (23)$$

Interfacial area concentration in slug-annular flow regime:

For a void fraction of 0.52 to 0.75, two-phase flow regime is assumed to be in a transition between the slug and annular regimes. The partitioning of the void fraction between these two regimes is computed in a manner analogous to that described above for the bubbly-slug regime. The expression for the total interfacial area concentration for slug-annular flow is given by using equations (17) and (22). That is,

$$a_i = a_{i,s} + a_{i,a}\left(\frac{\alpha_{g,a}}{\alpha_g}\right) = \left(\frac{\alpha_{g,a}}{\alpha_g}\right)\left[\frac{4}{D_h} - \frac{2\,D_h}{A_c}(1 - \alpha_{g,a})\right] + \frac{4.5\,C\,\alpha_{g,s}}{D_h} \qquad (24)$$

In equation (24), interfacial area concentration due to the annular flow contribution is interpolated in terms of the ratio of annular flow void to total void fraction to satisfy a physical constraint. That is, annular void fraction ($\alpha_{g,a}$) should approach zero as the slug flow contribution to total void fraction becomes dominant.

- Flow regime map

The topology of a two-phase flow typically has a strong influence on the various constitutive terms appearing in the two-phase conservation equations, such as interfacial drag, wall heat transfer and interfacial heat and mass transfer among others. Universal models for the constitutive terms, applicable to all flow regimes, are generally not available. Rather the flow regime is first deduced from global flow information such as void fraction and superficial velocities. Then a flow regime specific model is selected to model each constitutive term. This approach is taken in FLOWTRAN-TF. Clearly, accurate inference of flow regime is an important prerequisite for modeling each constitutive term. The FLOWTRAN-TF map relies directly on Taitel et al. [13] and on the works of Barnea and Barnea et al. [3, 4, 6] which address downward flow. The regime transition logic is based on RELAP [12]. The flow regime transition models were chosen due to their relatively strong mechanistic basis. These four references [3, 4, 6, 13] represent an evolution of flow regime logic applicable to the whole range of pipe inclinations with the later references building upon earlier ones. The discussion below begins with a summary of the flow regime transition logic developed by Barnea et al. for the special case of vertically downward two-phase flow encountered in FLOWTRAN-TF applications. Computational implementation is presented next with the bulk of the discussion covering interpolation between flow regimes. Finally, the FLOWTRAN-TF flow regime map exactly as coded is illustrated.

With respect to constitutive models, no distinction is made in FLOWTRAN-TF between the bubbly and dispersed bubble regimes and the slug and churn regimes. Therefore, the bubbly and dispersed bubble regimes and the slug and churn regimes may be combined leaving three fundamental flow regimes which will be termed 'bubbly', 'intermittent or slug', and 'annular'. Barnea et al. used 'intermittent' to describe the slug and churn regimes. However, the combined slug and churn regimes are termed 'slug' in discussing the FLOWTRAN-TF implementation following RELAP. The discussion about flow regimes is confined to downward two-phase flows. According to Barnea et al., the dispersed bubble regime occurs for void fractions between 0 and 0.52 when the turbulence level is sufficiently high. The criterion for sufficient turbulence is when the liquid superficial velocity exceeds a threshold. The bubbly regime occurs for liquid flowrates below this threshold when the void fraction is less than 0.25 and if the Taylor bubble rise velocity is greater than the velocity of small bubbles. This is the case except for very small pipes. For void fractions less than 0.25 and the Taylor bubble rise velocity less than the bubble rise velocity, the flow is intermittent. The flow regime is intermittent regardless of pipe size for void fractions between 0.25 and 0.52 if the liquid superficial velocity is less than the threshold mentioned above. The regime is also intermittent, without qualification, if the void fraction is between 0.52 and 0.76. The flow regime is annular if the void fraction is greater than 0.76. Barnea et al. illustrated the flow regime map in superficial velocity coordinates for the case of downflow.

For all FLOWTRAN-TF applications identified to-date, the channel sizes are sufficiently large that the bubble regime exists. Recognizing this situation, the bubbly-slug transition defined by the void fraction criterion of Taitel et al. [13] is always assumed to apply in FLOWTRAN-TF implementation; that is, an explicit check for bubble existence using a channel size criterion is not performed by the FLOWTRAN-TF. In addition, all FLOWTRAN-TF applications identified to-date involve relatively low velocities such that dispersed bubble flows with void fractions between 25% and 52% are rarely encountered. In FLOWTRAN-TF, the annular transition is defined to occur at 75% void instead of 76% void following RELAP. With these modifications the FLOWTRAN-TF flow regime map becomes simply

Bubbly (bubbly or dispersed bubble)	$0 \le \alpha_g \le 0.25$
Slug (slug and churn)	$0.25 < \alpha_g < 0.75$
Annular	$0.75 \le \alpha_g \le 1$

The 'slug' regime in FLOWTRAN-TF includes both the slug and churn flow regimes described by Barnea et al. Similarly, the 'bubbly' regime includes the bubbly and dispersed bubble regimes. Further note that void fraction alone defines the flow regime in FLOWTRAN-TF. In order to transition continuously between the three fundamental flow regimes of bubbly, slug and annular, FLOWTRAN-TF uses an interpolation scheme following RELAP. For void fractions up to and including 0.25, the regime is considered purely bubbly. Likewise, for void fractions down to and including 0.75, the regime is considered purely annular. At $\alpha_g = 0.52$ the regime is considered to be purely slug. For the interval $0.25 < \alpha_g < 0.52$ the regime is considered to be a mixture of bubbly and slug. Similarly the interval $0.52 < \alpha_g < 0.75$ comprises the slug-annular regime. With this approach, five two-phase flow regimes (bubbly, bubbly-slug, slug, slug-annular, annular) are created from three fundamental regimes (bubbly, slug, annular). The total void fraction is split into three components defined by

$\alpha_{g,b} \equiv$ bubbly regime void fraction, V_b/V_c

$\alpha_{g,s} \equiv$ slug regime void fraction, V_s/V_c

$\alpha_{g,a} \equiv$ annular regime void fraction, V_a/V_c

so that equation (3) is satisfied. No more than two flow regime void fractions are non-zero for a given total void. The parameters $\alpha_{g,b}$ and $\alpha_{g,s}$ are not convenient interpolation parameters in the bubbly-slug region. Rather, the bubbly-slug interpolation scheme is formulated in terms of a local bubble void fraction $\alpha^*_{g,b}$ defined to be the volume of small bubbles divided by the liquid volume; that is, $\alpha^*_{g,b}$ is the local void fraction in the predominantly liquid slugs separating Taylor bubbles. This local bubble void fraction may be written as

$$\alpha^{*}_{g,b} = \frac{\alpha_g - \alpha_{g,s}}{1 - \alpha_{g,s}}$$

and rearrangement gives

$$\alpha_{g,s} = \frac{\alpha_g - \alpha^{*}_{g,b}}{1 - \alpha^{*}_{g,b}} \tag{25}$$

Because $\alpha^{*}_{g,b}$ varies from 0.25 to 0 between the endpoints $\alpha_g = 0.25$ and 0.52, respectively, the desired interpolation is easily accomplished by choosing the power law function

$$\alpha^{*}_{g,b} = \alpha^{**}_{g,b}\left(\frac{\alpha^{**}_{g,s} - \alpha_g}{\alpha^{**}_{g,s} - \alpha^{**}_{g,b}}\right)^{n_{bs}} \tag{26}$$

where

$\alpha^{**}_{g,b} \equiv 0.25$

$\alpha^{**}_{g,s} \equiv 0.52$

$n_{bs} \equiv 4$

The selection $n_{bs} = 4$ maintains a relatively sharp transition consistent with the physical models presented above without making it so sharp that numerical difficulties might be experienced. The chosen interpolation scheme is not unique; other schemes could be devised which serve the same purpose. Following calculation of the local void fraction using equation (26) and the slug void fraction using equation (25), the bubbly void fraction is computed from

$$\alpha_{g,b} = \alpha_g - \alpha_{g,s} \tag{27}$$

using equation (3) with negligible contribution of annular flow ($\alpha_{g,a} = 0$). In an analogous manner, the slug-annular transition is defined by the equations

$$\alpha_{g,s} = \frac{\alpha_g - \alpha^{*}_{g,a}}{1 - \alpha^{*}_{g,a}} \tag{28}$$

$$\alpha^{*}_{g,a} = \alpha^{**}_{g,a}\left(\frac{\alpha_g - \alpha^{**}_{g,s}}{\alpha^{**}_{g,a} - \alpha^{**}_{g,s}}\right)^{n_{sa}} \tag{29}$$

$$\alpha_{g,a} = \alpha_g - \alpha_{g,s} \tag{30}$$

where

$\alpha^{**}_{g,s} \equiv 0.52$

$\alpha^{**}_{g,a} \equiv 0.75$

$n_{sa} \equiv 4$

The two interpolation schemes yield continuous, but relatively sharp, regime transitions. Figure 2 illustrates the final flow regime map implemented in FLOWTRAN-TF. For some constitutive term models, the only flow regime distinction required is that of 'dispersed' versus 'separated' two-phase flow. Examples are the wall heat transfer and drag models. For these cases, the bubbly and slug regimes are classified as dispersed while annular is synonymous with separated flow. The flow regime map shown in Figure 2 generally applies to the constitutive terms at all mesh cells.

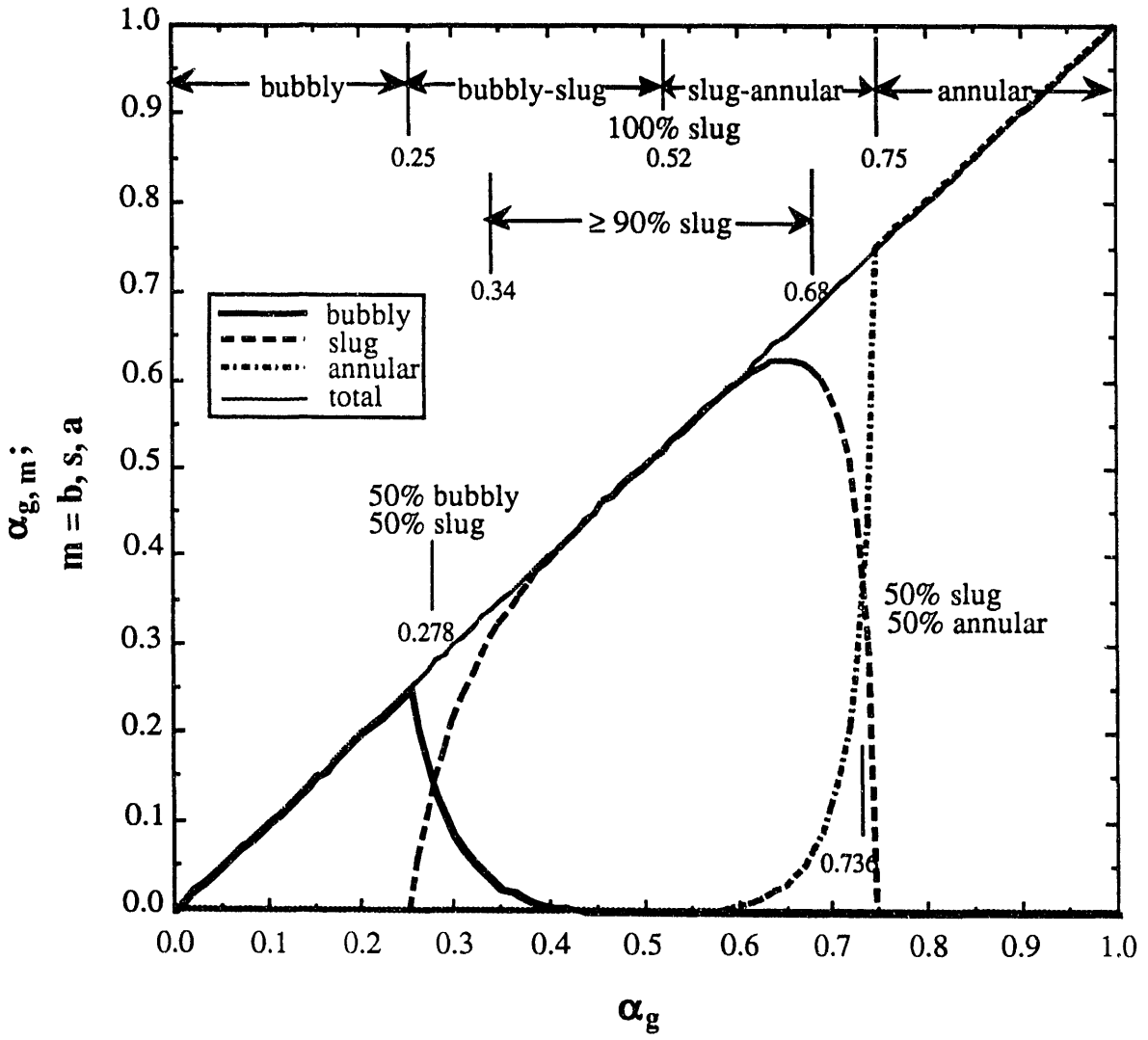

Figure 2. Two-phase flow regime map in the FLOWTRAN-TF code.

CONCLUSIONS

In this paper the mechanistic models of interfacial area concentration in each basic flow regime and flow regime map have been developed for the closure of constitutive relations in the two-fluid model of the FLOWTRAN-TF code. When total cell-averaged void fraction is computed as a local parameter at each time step within the code, the interfacial area concentrations are formulated in terms of local component void fraction contributed to each flow regime to evaluate the interfacial exchange terms. Then, component void fraction for each flow regime is determined by the flow regime modeling, which is based on the concept that two-phase flow structure is a superposition of the contributions from the three basic flow regimes, bubbly, slug, and annular flows.

NOMENCLATURE

a = Wide span of rectangular geometry
a_i = Interfacial area
A_c = Flow area of computational cell
b = Narrow span of rectangular geometry
b_b = Narrow span of slug bubble
C = Roughness coefficient
C_d = Drag coefficient
d_b = Bubble diameter or wide span of slug bubble
do = Average bubble diameter
D = Channel diameter
g = Gravity
L = Distance between noses of successive slug bubbles
P = Perimeter
u = Velocity
V = Volume

Greek Symbol

α_g = Void fraction
δ = Mean liquid film thickness
σ = Surface tension
ρ = Density
$\Delta\rho$ = $\rho_f - \rho_g$

ℓ_b = Length of slug bubble

Subscripts

a = Annular flow
b = Bubble or bubbly flow
bs = Bubbly slug flow
c = Computational cell or control
f = Liquid phase
g = Gas phase
h = Hydraulic
i = Inner or interfacial
o = Outer
r = Relative
s = Slug flow
sa = Slug annular flow
w = Wet

Dimensionless Parameters

Eo = Eotvos number ($\Delta\rho\ g\ d_b^2 / \sigma$)
Re = Reynolds number ($\rho\ u\ D_h / \mu$)
We = Weber number ($\rho_f\ d_b\ u_r^2 / \sigma$)

REFERENCES

1. Abramowitz, M. and Stegun, I. A., 1972, Handbook of Mathematical Functions, Dover Publications, Inc., New York.

2. Aleman, S. E., Flach, G. P., Hamm, L. L., Lee, S. Y., and Smith, F. G., III, 1991, "FLOWTRAN-TF: A New Thermal-Hydraulics Code to Model SRS Reactor Assemblies", ANS, Transactions, v64, pp. 689-690.

3. Barnea, D., 1986, "Transition from Annular Flow and from Dispersed Flow-Unified Models for the Whole Range of Pipe Inclinations", Int. J. Multiphase Flow, v12 n5, pp. 733-744.

4. Barnea, D., 1987, "A Unified Model for Predicting Flow-Pattern Transitions for the Whole Range of Pipe Inclinations", Int. J. Multiphase Flow, v13 n1, pp. 1-12.

5. Barnea, D., O. Shoham, and Y. Taitel, 1982a, "Flow Pattern Transition for Downward Inclined Two-Phase Flow; Horizontal to Vertical", Chem. Engr. Science, v37 n5, pp. 735-740.

6. Barnea, D., O. Shoham, and Y. Taitel, 1982b, "Flow Pattern Transition for Vertical Downward Two Phase Flow", Chem. Engr. Science, v37 n5, pp. 741-744.

7. Barnea, D., and Taitel, Y., 1986, "Flow Pattern Transition in Two-Phase Gas-Liquid Flows", Chapter 16 in Encyclopedia of Fluid Mechanics, Volume 3 edited by N. P. Cheremisinoff, Gulf Publishing Company, Houston.

8. Bird, R. B., Stewart, W. E., and Lightfoot, E. N., 1960, Transport Phenomena, John Wiley & Sons, New York.

9. Clift, R., Grace, J. R., and Weber, M. E., 1978, Bubbles, Drops, and Particles, Academic Press, New York.

10. Ishii, M. and Mishima, K., 1980, "Study of Two-Fluid Model and Interfacial Area," NUREG/CR-1873.

11. Mishima, K., and M. Ishii, 1984, "Flow Regime Transition Criteria for Upward Two-Phase Flow in Vertical Tubes", Int. J. Multiphase Flow, v27 n 5, pp. 723-737.

12. Ransom, V. H., Wagner, R. J., Trapp, J. A., Feinauer, L. R., Johnson, G. W., Kiser, D. M., and Riemke, R. A., 1985, "RELAP5/MOD2 Code Manual Volume 1: Code Structure, System Models, and Solution Methods," NUREG/CR-4312, EGG-2396.

13. Taitel, Y., D. Barnea, and A. E. Dukler, 1980, "Modelling Flow Pattern Transitions for Steady Upward Gas-Liquid Flow in Vertical Tubes", AIChE J., v26 n3, pp. 345-354.

14. Taitel, Y., and A. E. Dukler, 1976, "A Model for Predicting Flow Regime Transitions in Horizontal Gas-Liquid Flow", AIChE J., v22 n1, pp. 47-55.

15. Wallis, G., 1969, One-Dimensional Two Phase Flow, McGraw-Hill, New York.

END

DATE FILMED

7/9/93