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Implementation of Drift-Flux Correlations in ARTIST and its Assessment in Comparison with THETIS Void Distribution

B. J. Yun, H. C. Kim, S. K. Moon and W. J. Lee

Korea Atomic Energy Research Institute
P.O. Box 105 Yusong, Taejon, 305-600, Korea

Abstract

Non-homogeneous, non-equilibrium drift-flux model was developed in ARTIST code to enhance capability of predicting two-phase flow void distribution at low pressure and low flow conditions. The governing equations of ARTIST code consist of three continuity equations (mixture, liquid, and noncondensibles), two energy equations (gas and mixture) and one mixture momentum equation constituted with the drift-flux model. In order to provide the *Co* and the V_{gj} of drift-flux model, four drift-flux correlations, which are Chexal-Lellouche, Ohkawa-Lahey, GE Ramp and Dix models, are implemented. In order to evaluate the accuracy of the drift flux correlations, the steady state void distributions of the THETIS boil-off tests are simulated. The results show that the drift-flux model is quite satisfactory in terms of accuracy and computational efficiency. Among the four drift-flux correlations, the Chexal-Lellouche model showed wide applicability in the prediction of void fraction from low to high pressure condition. Especially, the axial void distribution at low pressure and low flow is far better than those of both the two-fluid model of RELAP5/MOD3 code and the homogeneous model. Thus, the drift-flux model of the ARTIST code can be used as an efficient tool in predicting the void distribution of two-phase flow at low pressure and low flow conditions.

1. Introduction

A system transient analysis code, ARTIST (Advanced Real Time Integrated Simulation Tool) (Kim, 1998) can treat the low pressure and low flow transient condition as well as Non-LOCA transient when noncondensible gas presents in the system. The governing equations of the ARTIST code consist of three continuity equations (mixture, liquid, and noncondensibles), two energy equations (gas and mixture) and one mixture momentum equation constituted with the drift-flux model. The flow quality expressed in terms of the relative velocity is used in the formulation of the drift-flux model. As the numerical solution scheme for the node-flowpath thermal-hydraulic network, the implicit one-step method defined by backward differentiation of the linearized conservation equations is employed.

In the drift-flux model, the difficulties associated with a two-fluid model, such as mathematical complications and uncertainties in specifying interfacial momentum transfer terms, can be significantly reduced by representing the motion of the whole mixture by a mixture momentum equation and the relative motion between the phases. It can be said that the drift-flux model is an approximate formulation in comparison with more rigorous two-fluid formulations. However, the advantages of the drift-flux formulation, in addition to its simplicity, are that it provides a means for accounting for non-uniform flow and void distributions through empirically determined correlation parameters. Therefore, if the drift flux correlation is properly chosen, then it is possible to enhance capability of predicting two-phase void distribution at low pressure and low flow conditions without numerical instabilities frequently appeared in two-fluid model codes.

In this paper, area averaged one-dimensional conservation equations of the ARTIST code are described. In order to provide the concentration parameter and the drift velocity, four drift-flux correlations, which are Chexal-Lellouche (1992), Ohkawa-Lahey (1980), GE Ramp (1977) and Dix (1971), are implemented in ARTIST. The steady state void distributions along the axial location of the THETIS (Thermal Hydraulic Emergency Cooling Test Installation) boil-off tests (Croxford, 1989) are simulated using the above four correlations and the results are compared each other. Additionally the results are compared with those of the two-fluid six-equation model (RELAP5/MOD3) and the homogeneous model of ARTIST

2. Thermal Hydraulic Model

A non-homogeneous, non-equilibrium drift-flux model of two-phase flow can be established from the two-fluid model. The governing equations of the ARTIST code consist of three continuity equations (mixture, liquid, and noncondensibles), two energy equations (gas and mixture) and one mixture momentum equation.

One-dimensional drift-flux equations for the ARTIST non-equilibrium thermal hydraulics model set are as follows(Kim et al.1998).

Mixture Mass Equation

$$A\frac{\partial r_m}{\partial t} + \frac{\partial W_m}{\partial x} = 0 \tag{1}$$

Liquid Mass Equation

$$A\frac{\partial[(1-a)r_l]}{\partial t} + \frac{\partial[(1-x_f)W_m]}{\partial x} = -\Gamma_g \tag{2}$$

Noncondensible Gas Mass Equation

$$A\frac{\partial(a r_N)}{\partial t} + \frac{\partial}{\partial x}\left(\frac{r_N}{r_g}x_f W_m\right) = 0 \tag{3}$$

Mixture Momentum Equation

$$A\frac{\partial}{\partial t}\left(\frac{W_m}{A}\right) + \frac{\partial}{\partial x}\left(\frac{x_f^2}{a r_g} + \frac{(1-x_f)^2}{(1-a)r_l}\right)\frac{W_m^2}{A} = -A\frac{\partial P}{\partial x} - K\Phi^2\frac{W_m\,|W_m|}{r_l A} + rgA \tag{4}$$

Mixture Thermal Energy Equation

$$A\frac{\partial}{\partial t}\left(r_m e_m\right) + \frac{\partial}{\partial x}\left(x_f h_g + (1-x_f)h_l\right)W_m = q_w' \tag{5}$$

Vapor Enthalpy Equation

$$A\frac{\partial}{\partial t}\left(a r_g h_g\right) + \frac{\partial}{\partial x}\left(x_f h_g W_m\right) = \Gamma_g h_{sg} + q_{wg}' + q_{ig}' \tag{6}$$

where,

$$r_m = a r_g + (1-a) r_l$$

$$h_m = \frac{1}{r_m}\left[a r_g h_g + (1-a) r_l h_l\right]$$

$$e_m = \frac{1}{r_m}\left[a r_g e_g + (1-a) r_l e_l\right]$$

$$x_f = \frac{a r_g}{r_m} + \frac{a r_g (1-a) r_l}{r_m W_m} v_r A$$

The relative velocity, v_r, can be expressed in terms of drift-flux parameters as follows

$$v_r = \frac{V_{gj}\left\{1 - a\left(1 - r_g / r_l\right)\right\} - G_o (1 - C_o) / r_l}{\left\{1 - a\, C_o\left(1 - r_g / r_l\right)\right\}(1 - a)} \tag{7}$$

In order to provide the *Co* and the V_{gj} of eq. (7), four drift-flux correlations, which are Chexal-Lellouche (1992), Ohkawa-Lahey (1980), GE Ramp (1977) and Dix (1971), are implemented in the ARTIST code. Chexal-Lellouche is flow regime independent model that covers the full range of channel size, pressure, flow direction and void fraction. Ohkawa-Lahey model has also a full range capability including CCFL as well as vertical up flow. GE Ramp and Dix models are developed for vertical flow situation under boiling water reactor .

The flow system can be represented by the so-called node-flowpath network. By applying the conservation Eqs. (1) ~ (6) to the node-flowpath thermal hydraulic network and using the implicit one-step method, we can set up a system of linearized discretized conservation equations for each node and flowpath. After all the required terms including the drift flux parameters, are defined from the constitutive relations using the values of the previous time step, the discretized mass and energy equations are substituted into the discretized momentum equations. This yields a linear system of equations for the changes in mass flow (DW_m), whose coefficient matrix is a block type matrix. This system of equations is solved using the block inversion technique. The solution is completed by solving for the mass and energy changes from the corresponding equations (Porsching, 1971).

3. Assessment of THETIS Void Distribution Experiments

To evaluate the accuracy of four drift flux correlations of the ARTIST code, the steady state void distributions along the axial location of the boil-off tests in the THETIS facility at UKAEA Winfrith, are simulated and the measured void fraction data are compared with the calculation results by four correlations implemented in ARTIST. Additional calculations are performed using the two-fluid six-equation model (RELAP5/MOD3) and the homogeneous model(*Co*=1&V_{gj} =0) of ARTIST for comparison. Table 1 summarizes the experimental conditions for the particular tests to be simulated..

Table 1 THETIS Test Conditions

Test	Pressure (bar)	Flow(kg/s)	Inlet Temp. (K)	Power (kW)
561-2	2.00	0.120	352.	100.
551-2	5.25	0.0974	342.	100.
553-4	10.21	0.0474	310.	100.
555-6	20.15	0.053	356.	100.
557-8	40.26	0.036	310.	100.

<u>Simulation of the THETIS Experiments</u>

Fig. 1 shows the schematic diagram of the THETIS test facility. The test facility was represented by 15 nodes in ARTIST simulation. The test section (the pin bundle and enclosing shroud tube) was modeled with 14 nodes. The heated part of the test section was represented by the nodes numbered 2¡ 13, each height of 0.3 m. Nodes numbered 1 and 14 represented the unheated part of the bundle. To maintain the pressure boundary condition, very large volume (node 15) is used to represent the steam drum. In order to simulate the heat input from the heating rods, external heat input, which is connected to node number 3¡ 13, is used It was deduced that a layer of sub-cooled water, 0.3 m deep, had formed in the annular space between the shroud tube and pressure vessel during the tests, causing high heat losses at the base of the cluster (Croxford, 1989). To simulate these heat losses, heat input into the lowest one volume of the heated length was neglected. The steady make-up flow of the experiment was simulated by boundary conditions of flow and specific enthalpy.

In RELAP5/MOD3(1995) simulation, the test facility was represented using 26 hydrodynamic volumes. The test section was modeled using a "PIPE" component. The heated part of the test section was represented by the nodes numbered 2¡ 25, each height of 0.15 m. Nodes numbered 1 and 26 represented the unheated part of the bundle. Heat structures, representing the heating rods, were connected to nodes 4¡ 25. To simulate heat losses, heat input into the lowest two volumes of the heated part (volumes 2 and 3 in the present simulation) was neglected. In order to model radial thermal conduction, the pins were represented as cylindrical heat structures with nine radial mesh points. The steady make-up flow was simulated using a "TIME DEPENDENT VOLUME" and "JUNCTION" connected to the bottom of the cluster. The top of the test section was connected to a "TIME DEPENDENT VOLUME" to maintain the fixed boundary pressure.

Axial void fraction distribution at steady state was obtained in two stages. The make-up flow rate and temperature, and system pressure were set to the values listed in Table 1 as initial conditions. And then the power was slowly ramped up to the value of the experiment and the null transient calculation was continued until obtaining a steady equilibrium condition.

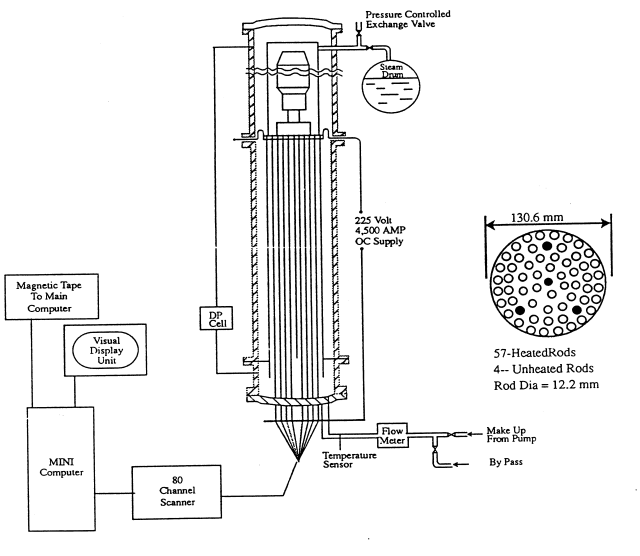

Fig. 1 Schematic Diagram of THETIS Facility

Results and Discussions

The measured and calculated void fractions versus elevation in the bundle for Test Number 561-1 (2.00 bar) are shown in Fig. 2(a). The drift-flux corrleations except Chexal-Lellouche model were failed to converge. It shows the wide applicability of the Chexal-Lellouche correlation. It is noted that the model satisfies all kinds of criteria providing various limits or features that a void model should have so as to be useful as a general purpose void model and then it is formulated by a functional form of continuous and smooth shape for the wide range of void fraction, flow rate and pressure.

The figure shows that Chexal-Lellouche correlation over-predicts slightly the measured data, however, the characteristic shape are in good agreement with that of measured data. Especially, void profile in the upper half region of the drift-flux model is more close to the test data than those of RELAP5/MOD3 and the homogeneous model. In this calculation, RELAP5/MOD3 shows large unreasonable oscillations of void fraction (about 35 %) and thus, computation time was markedly increased. In calculations, even though the maximum time step size of 0.01 sec was failed to remove the oscillations. The drift-flux model calculation, which is 0.01 sec of time step, also shows the oscillations of about 5 % amplitude in void fraction.

Fig. 2(b) shows the results for Test Number 551-2 (5.25 bar). The characteristic shape of void distribution and the measured void fraction are well predicted by all drift-flux correlations of ARTIST. The difference in predicted void fraction between four drift-flux correlations is negligible at low void fraction and it is increases up to 15% as the void fraction is increased. However, all of the drift-flux correlations show more close prediction to the test data than that of the RELAP5/MOD3 and homogeneous model even though all of the models overpredict the void fraction compared to the measured data. The RELAP5/MOD3 calculation also shows oscillations of void fraction with approximately 10 % amplitude. In ARTIST calculation, oscillation of void fraction was not observed and the calculation was performed with the time step of 0.01 sec.

The above two comparisons show that the drift-flux model is more appropriate in the prediction of void fraction under low flow and low pressure conditions.

Results for Test Numbers 553-4 (10.21 bar), 555-6 (20.15 bar), and 557-8 (40.26 bar) are shown, respectively, in Fig. 2(c), (d), (e). In the Test Number 553-4 (10.21 bar), the measured void fraction data are not available in the region of the top half of the bundle. The four drift-flux correlations show a gradual increase along the bundle elevation as in the measured data and show similar value of void fraction for all data sets. The maximum difference in predicted void fraction between four drift-flux correlations is 10 % for 10 bar and it is decreased to 5% for 40 bar. It shows that the effect of relative velocity, which is caused by the difference of density between steam and liquid phases, is decreased as the pressure goes up. However, all of the drift-flux correlations of ARTIST and RELAP5/MOD3 underpredict the void fraction compared to the measured data in this medium pressure and the error is increased at lower elevations. In ARTIST, subcooled boiling model is not modeled and heat flux is provided as input.

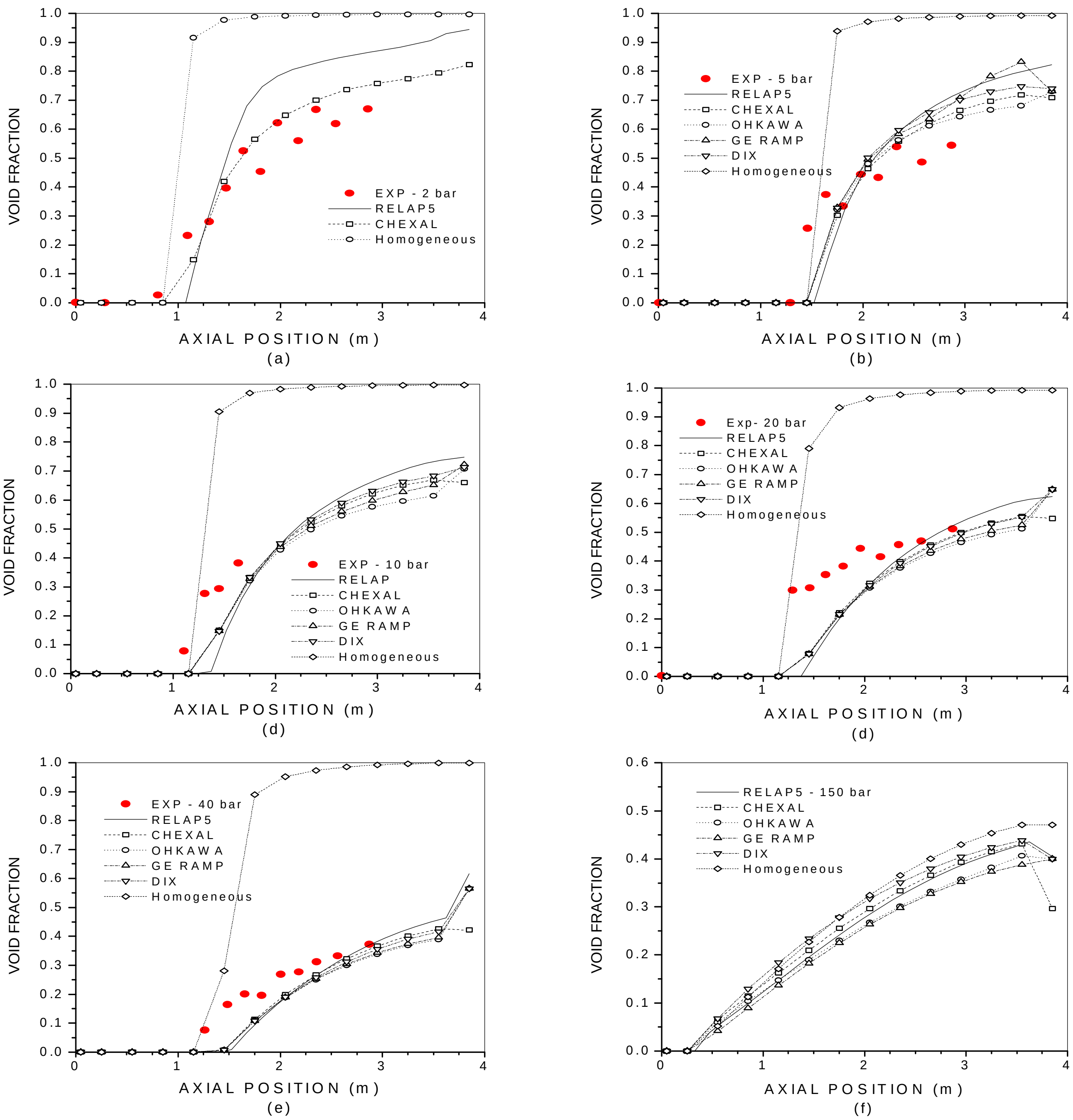

Fig. 2 Void Fraction vs. Elevation

Therefore, it is expected that there is a discrepancy in the void fraction at the lower elevation where subcooled boiling is dominant. RELAP5/MOD3 uses a subcooled boiling model, however, the results of RELAP5/MOD3 does not show the subcooled boiling phenomenon well. In RELAP5/MOD3, maximum time step was set to 0.1 sec and the calculations were continued maintaining the maximum time step.

In all test conditions, results of homogeneous model showed unrealistic over-prediction in void fraction. It shows that homogeneous flow model is not appropriate for low and intermediate pressure two-phase conditions. Even though the test at high pressure was not carried out in the THETIS experiment, the calculation of high pressure and high flow case was performed in order to compare the results of the drift-flux model, the homogeneous model, and the two-fluid model. Pressure of 150 bar, flow rate of 1200 kg/m^2sec (flow velocity of 2 m/sec.), heat flux of 1.271 X 10^5 W/m^2sec and make-up flow enthalpy of 1611 kJ/kg (corresponding to 150 bar and 615.2 K) are arbitrarily selected. As can be seen in Fig. 2(f), the results show similar trend in high pressure condition. From these results, it can be deduced that the non-homogeneous is important as goes to low pressure condition.

4. Conclusions

Four drift-flux correlations were implemented in the ARTIST code. Then, the correlations were assessed in comparison with the steady state void distributions of THETIS boil-off tests. The results show that the Chexal-Lellouche void fraction model is quite satisfactory in terms of accuracy and computational efficiency. Especially, the axial void distribution at low pressure and low flow is far better than those of other correlations including the two-fluid model of RELAP5/MOD3 code and the homogeneous model. Thus, the Chexal-Lellouche void fraction model of the ARTIST code can be used as an efficient tool in predicting the void distribution of two-phase flow at low pressure and low flow conditions.

Acknowledgement

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Nomenclatures

A	Flow area
e	Specific internal energy
C	Concentration parameter
G_o	Mass flux
g	Gravitational acceleration
h	Specific enthalpy
j	Volumetric flux
K	Friction factor
P	Pressure
q'_{ig}	Interfacial heat transfer rate to vapor per unit length
q'_{w}	Total wall heat transfer rate per unit length
q'_{wg}	Wall heat transfer rate to vapor per unit length
V_{gj}	Drift velocity
x_f	Flow quality
Gg	Vapor generation rate per unit length
a	Void fraction
r	Density
f^2	Two-phase friction multiplier

<u>*Subscripts*</u>

g	Vapor
l	Liquid
m	Mixture
N	Non-condensible
s	Saturation

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