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Effects of Turbulent Mixing and Void Drift Models on the Predictions of COBRA-IV-I

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Abstract

The predictions of the COBRA-IV-I code with the modified turbulent mixing and void drift models have been compared with the diabatic two-phase flow data on equilibrium quality. The turbulent mixing model based on an equal mass exchange of the existing COBRA-IV-I code has been modified to that based on an equal volume exchange between adjacent subchannels, and a void drift model has been newly incorporated in the code. To evaluate the performance of the equal volume exchange turbulent mixing model and the effects of the void drift model, the diabatic steam-water two-phase flow data obtained for the 9-rod bundle test under the typical operating conditions of the boiling water reactor (BWR) conducted by the General Electric (GE) were analyzed by the modified COBRA-IV-I code. The analysis indicates that the equal volume exchange turbulent mixing model with void drift predicts the observed two-phase flow data trends better than the equal mass exchange model, and to predict the correct data trends a more physically based void drift model need to be developed.

1. Introduction

In the subchannel approach which is widely used for the thermal-hydraulic analysis of the nuclear reactor core, the complex geometry of fuel assemblies is divided into arbitrary smaller sections called "subchannels". Using a lumped parameter approach, the one-dimensional conservation equations of mass, energy and momentum are written for each subchannel and solved numerically while taking into account the possible lateral interactions between adjacent subchannels such as diversion crossflow, turbulent mixing and void drift. The accuracy of a subchannel code is highly dependent on the modelings of these lateral interaction mechanisms. The diversion crossflow is the directed flow caused by the pressure gradients normal to the axial flow direction, and taken into account by a simplified lateral momentum equation. The turbulent mixing is caused by the high frequency fluctuations at the interface between adjacent subchannels. In single-phase flow there are momentum and energy exchanges between subchannels but little or no net mass transfer. In two-phase flow, however, a substantial net mass transfer has been experimentally observed in addition to momentum and energy transfer.[1] One of the plausible models explaining these phenomena is the equal volume exchange turbulent mixing model suggested by Lahey et al.[2]. Some advanced subchannel analysis codes such as ASSERT-4 have adopted this model. Recently Tapucu et al.[3] have evaluated the effects of turbulent mixing models on the predictions of subchannel codes. They compared the predictions of the subchannel codes COBRA-IV and ASSERT-4 with the air-water experimental data on void fraction, mass flow rate and pressure drop obtained for two interconnected subchannels, and concluded that the equal volume exchange approach of ASSERT-4 is better than the equal mass exchange approach of COBRA-IV. The conservation equations of these two codes are, however, basically different from each other, so that the diversion crossflow may have a significant effect on the code predictions. The void drift mechanism accounts for the tendency of the vapor phase to shift to higher velocity subchannels. Sadatomi et al.[4] have performed air-water two-phase test to observe the void drift phenomena between two subchannels. They analyzed the data using a simple one-dimensional subchannel code by incorporating both the void drift model of Lahey et al.[2]

based on the Levy[5]'s hypothesis, and the equal mass exchange turbulent mixing model in the momentum equation. In this paper, to investigate the thermal effects of these lateral exchange mechanisms, we have incorporated the equal volume exchange turbulent mixing and void drift models of Lahey et al.[2] directly into the mass, energy and momentum equations of the COBRA-IV-I code, and compared its predictions with the diabatic steam-water two-phase flow data obtained for the GE 9-rod bundle test under the typical operating conditions of BWR.

2. Background

The equal volume exchange turbulent mixing model implies that the lateral fluctuating fluid velocity from subchannel i to j and that from subchannel j to i are equal as follows:

$$v'_{ij} = v'_{ji}. \tag{1}$$

The fluctuating lateral mass flow rate per unit length across the gap from subchannel i to j can expressed as:

$$w'_{ij} = \rho_i v'_{ij} s_{ij}. \tag{2}$$

Rewriting Eq. (2) in terms of the mixing length theory, we can obtain:

$$w'_{ij} = \rho_i \left(\varepsilon / z^T_{ij}\right) s_{ij}, \tag{3}$$

where ε is the eddy diffusivity and z^T_{ij} is the effective turbulent mixing length. The net fluctuating lateral mass flow rate per unit length across the gap between subchannels i and j for two-phase flow can be represented as:

$$w'_{i\leftrightarrow j} = w'_{ij} - w'_{ji} = \left(\varepsilon / z^T_{ij}\right)_{TP} s_{ij}\left(\rho_i - \rho_j\right) = \left(\varepsilon / z^T_{ij}\right)_{TP} s_{ij}\left(\rho_f - \rho_g\right)\left(\alpha_j - \alpha_i\right). \tag{4}$$

Analogously, the net fluctuating energy transfer across the gap for two-phase flow can be obtained as:

$$w'_{ij} h_i - w'_{ji} h_j = \left(\varepsilon / z^T_{ij}\right)_{TP} s_{ij}\left(\rho_i h_i - \rho_j h_j\right) = \left(\varepsilon / z^T_{ij}\right)_{TP} s_{ij}\left(\rho_f h_f - \rho_g h_g\right)\left(\alpha_j - \alpha_i\right). \tag{5}$$

The net fluctuating axial momentum transfer across the gap for two-phase flow can be expressed as:

$$f_t w'_{ij} u_i - f_t w'_{ji} u_j = f_t \left(\varepsilon / z^T_{ij}\right)_{TP} s_{ij}\left(\rho_i u_i - \rho_j u_j\right). \tag{6}$$

Eq. (5) implies that the net energy transfer is from subchannel i to j when $\alpha_j > \alpha_i$ since $\rho_f h_f > \rho_g h_g$. This may seem paradoxical since it indicates energy transfer to the higher void subchannel. This will be explained shortly. In terms of Eq. (4), Eq. (5) can be represented as:

$$w'_{ij} h_i - w'_{ji} h_j = \left(\varepsilon / z^T_{ij}\right)_{TP} s_{ij}\left(\rho_f - \rho_g\right)\left(\alpha_j - \alpha_i\right)\frac{\rho_f h_f - \rho_g h_g}{\rho_f - \rho_g} = w'_{i\leftrightarrow j} h_{eff}, \tag{7}$$

where $h_{eff} \equiv \dfrac{\rho_f h_f - \rho_g h_g}{\rho_f - \rho_g} = h_f - \dfrac{\rho_g}{\rho_f - \rho_g} h_{fg} < h_f$. (8)

The apparently paradoxical implication of Eq. (5) can now be explained. For $\alpha_j > \alpha_i$, both net mass and energy are transferred from subchannel i to j from Eqs. (4) and (5). While net vapor is transferred from subchannel j to i, a larger mass of liquid is transferred from subchannel i to j. Now since this net mass carries enthalpy of a value h_{eff} less than saturated liquid, the void fraction of subchannel j is not increasing. Rather, the void fraction decreases since mixing decreases the specific energy content of the coolant in the hot subchannel j.

Eq. (4) indicates that the mixing flow rate is finite whenever a difference in subchannel void fractions exists. This implies that mixing will occur so as to equalize adjacent subchannel void fractions. A body of evidence has been developed, however, which demonstrates that subchannel void fractions do not equalize in rod bundles. In fact, a clear tendency has been demonstrated for void to migrate to that subchannel with the larger cross-sectional area and higher velocity. In practice, the mixing flow rate is reformulated to limit this flow rate as the equilibrium void distribution is approached. Hence Eq. (4) is reformulated as:

$$w'_{i\leftrightarrow j} = \left(\varepsilon / z^T_{ij}\right)_{TP} s_{ij}\left(\rho_f - \rho_g\right)\left[\left(\alpha_j - \alpha_i\right) - \left(\alpha_j - \alpha_i\right)_{eq}\right]. \tag{9}$$

This result can be rewritten in terms of the single-phase mixing rate expressed by Eq. (3) if ρ_i is taken equal to ρ_f. This result is:

$$\left(w'_{i\leftrightarrow j}\right)_{TP} = \left(w'_{i\leftrightarrow j}\right)_{SP}\theta\left[\left(\alpha_j - \alpha_i\right) - \left(\alpha_j - \alpha_i\right)_{eq}\right], \quad (10)$$

where $\theta \equiv \dfrac{\left(\varepsilon/z_{ij}^T\right)_{TP}}{\left(\varepsilon/z_{ij}^T\right)_{SP}}\left(1 - \dfrac{\rho_g}{\rho_f}\right)$. (11)

Correlations for θ and $\left(\alpha_j - \alpha_i\right)_{eq}$ are required to evaluate $\left(w'_{i\leftrightarrow j}\right)_{TP}$ from Eq. (10). Beus[6] developed a two-phase mixing model that suggested the concept of this two-phase multiplier, θ, and demonstrated that it depends strongly on flow regime. This multiplier has been modeled as increasing linearly with quality χ between $\chi = 0$ and the slug-annular transition point χ_c. For qualities greater than χ_c, θ is assumed to decrease hyperbolically from its maximum χ_c. The functions that describe this behavior are:

$$\theta = 1 + \left(\theta_c - 1\right)\left(\chi/\chi_c\right) \quad \text{if } \chi < \chi_c, \quad (12)$$

$$\theta = 1 + \left(\theta_c - 1\right)\left(\frac{1 - \chi_0/\chi_c}{\chi/\chi_c - \chi_0/\chi_c}\right) \quad \text{if } \chi > \chi_c, \quad (13)$$

where $\chi_0/\chi_c = 0.57\ \mathrm{Re}^{0.0417}$ and $\theta_c = 5$. Fig. 1 illustrates this behavior. The quality χ_c at the slug-annular transition point from Wallis[7]'s model is:

$$\chi_c = \left[0.4\left\{\rho_f\left(\rho_f - \rho_g\right)gD\right\}^{1/2}/G + 0.6\right]\Big/\left[\left(\rho_f/\rho_g\right)^{1/2} + 0.6\right]. \quad (14)$$

The remaining parameter $\left(\alpha_j - \alpha_i\right)_{eq}$ can be represented as:

$$\left(\alpha_j - \alpha_i\right)_{eq} = \overline{\overline{\alpha}}\frac{\left(G_j - G_i\right)_{eq}}{\overline{\overline{G}}}, \quad (15)$$

where $\overline{\overline{\alpha}} \equiv \left(\alpha_i A_i + \alpha_j A_j\right)/\left(A_i + A_j\right)$ and $\overline{\overline{G}} \equiv \left(G_i A_i + G_j A_j\right)/\left(A_i + A_j\right)$, and $\left(G_j - G_i\right)_{eq}$ is in practice taken equal to the existing mass flux difference $G_j - G_i$.

3. Modification of COBRA-IV-I

Based on the theories mentioned above, the conservation equations of the COBRA-IV-I code have been modified with the equal volume exchange turbulent mixing and void drift models. The flowchart of the COBRA-IV-I code is shown in Fig. 2 with the modified calculational procedures.

4. Analysis of Experimental Data

Lahey et al.[8] measured the exit mass flow rates and enthalpies in representative corner, side and center subchannels of a 3×3 rod bundle under adiabatic and diabatic conditions. The salient geometrical features of the rod bundle are shown in Fig. 3 with the radial rod power distribution and the subchannel analysis layout of the COBRA-IV-I code. We have analyzed the equilibrium exit qualities of the representative 3 subchannels for 13 diabatic test conditions with the modified COBRA-IV-I code, and compared the predictions with the measured data. The 13 diabatic test conditions and the measured equilibrium exit qualities of the representative 3 subchannels are shown in Table 1, and the predictions of the modified COBRA-IV-I code are shown in Table 2 and Fig. 4, where EM, EV and VD stand for the equal mass, equal volume exchange turbulent mixing models and void drift model, respectively. As shown in Fig. 4, the equal volume exchange turbulent mixing model with void drift predicts the two-phase flow data trends better than the equal mass exchange model, however the equal volume exchange model alone gives the poor predictions.

5. Discussion

To investigate the effect of the void drift model, we have studied the sensitivity of the COBRA-IV-I predictions to the void drift term. Fig. 5 shows the variation of the representative 3 subchannel exit qualities with the void drift correction factor C_{vd} for the test condition 2E2. We have obtained 9 void drift correction factors corresponding to the 9 test conditions among the total 13 diabatic test conditions, and showed their distribution with bundle average exit quality in Fig. 6. As shown in Fig. 6, C_{vd} decreases hyperbolically with bundle average exit quality. Todreas et al.[9] obtained the value of the equilibrium void parameter K_a, equal to $\overline{\overline{\alpha}} C_{vd}$, as 1.4. We have converted C_{vd} to K_a and showed the distribution of K_a with bundle average exit quality in Fig. 7. Fig. 7 shows the good agreement between our results and Todreas et al.'s.

6. Conclusions

It has been known that the equal mass exchange turbulent mixing model of the existing COBRA-IV-I code is poor in predicting the two-phase experimental data trends. To remove this weak point of COBRA-IV-I we have incorporated the equal volume exchange turbulent mixing and void drift models in the code. To evaluate the improvement in the predicting capability we have analyzed the diabatic steam-water two-phase flow data obtained for the 9-rod bundle test under the typical operating conditions of BWR conducted by GE with the modified COBRA-IV-I code. From the analysis results we have found that the equal volume exchange turbulent mixing model with void drift predicts the observed two-phase flow data trends such as the central peaking in equilibrium quality better than the equal mass exchange model. It is also found that the equal volume exchange model, by itself, gives the poor predictions and the void drift model plays an important role in predicting the two-phase flow data trends more correctly. Further works need to be concentrated on the refinement of the void drift model as well as the other two-phase flow models to improve the performance of the COBRA-IV-I code in predicting the two-phase flow data.

References

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Table 1 Test Conditions and Results

Test Point	P (psia)	G_{avg} (Mlb_m/ hr-ft^2)	χ_{avg}	Δh_{sub} (Btu/ lb_m)	$\chi_{measured}$ Corner	Side	Center
2B2	1000	0.530	0.029	149.9	0.003	0.014	0.030
2B3	1000	0.535	0.090	108.7	0.072	0.075	0.104
2B4	1000	0.535	0.176	52.8	0.133	0.180	0.220
2C1	1000	1.060	0.042	57.2	0.029	0.018	0.059
2C2	1000	1.068	0.075	35.1	0.063	0.075	0.100
2D1	1000	0.540	0.110	259.2	0.083	0.105	0.117
2D3	1000	0.540	0.318	124.4	0.260	0.330	0.364
2E1	1000	1.080	0.035	142.9	0.004	0.026	0.051
2E2	1000	1.080	0.106	96.7	0.049	0.097	0.105
2E3	1000	1.060	0.215	29.1	0.160	0.185	0.249
2G1	1000	1.070	0.038	225.9	0.032	0.044	0.043
2G2	1000	1.080	0.090	189.8	0.020	0.068	0.110
2G3	1000	1.070	0.160	146.7	0.074	0.127	0.176

Table 2 Results of COBRA Analysis

Test Point	$\chi_{predicted} - \chi_{measured}$ Corner EM	Corner EV&VD	Side EM	Side EV&VD	Center EM	Center EV&VD
2B2	0.059	0.047	0.011	0.011	-0.003	0.000
2B3	0.052	0.033	0.008	0.009	-0.013	-0.010
2B4	0.087	0.024	-0.012	-0.010	-0.042	-0.033
2C1	0.039	0.029	0.021	0.020	-0.018	-0.016
2C2	0.038	0.015	-0.004	-0.003	-0.025	-0.022
2D1	0.093	0.063	-0.006	-0.002	-0.003	-0.001
2D3	0.151	0.093	-0.032	-0.031	-0.036	-0.027
2E1	0.085	0.067	0.003	0.004	-0.018	-0.016
2E2	0.109	0.064	0.000	0.005	0.003	0.006
2E3	0.108	0.043	0.019	0.021	-0.029	-0.021
2G1	0.089	0.058	-0.015	-0.011	-0.008	-0.006
2G2	0.150	0.101	0.011	0.017	-0.019	-0.017
2G3	0.168	0.106	0.018	0.025	-0.011	-0.008

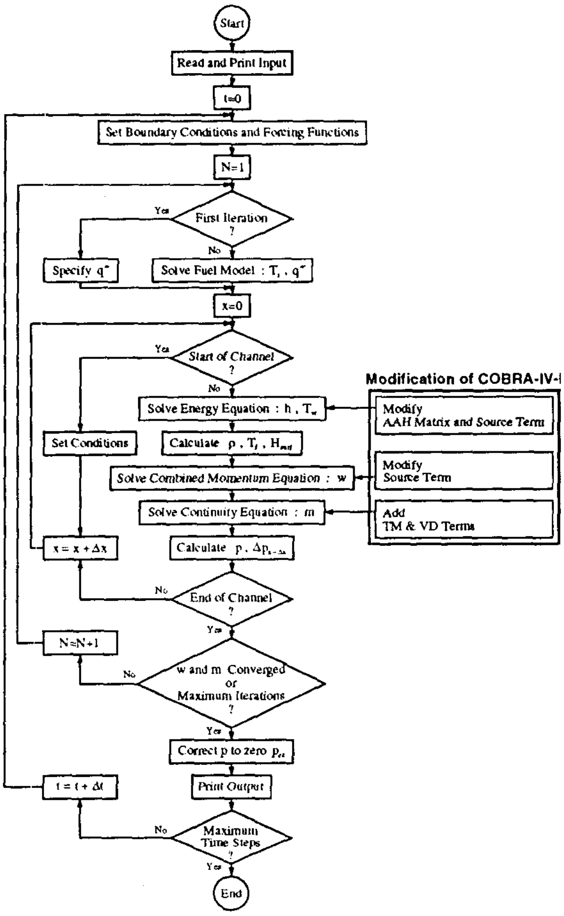


Fig. 2 Flowchart of COBRA-IV-I

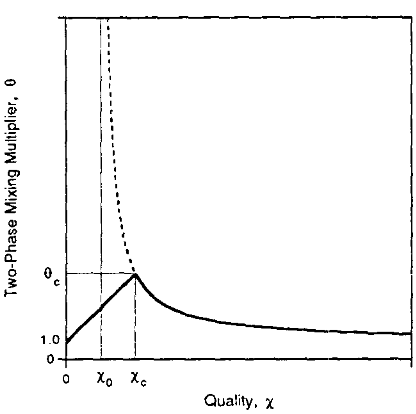


Fig. 1 Variation of Two-Phase Mixing Multiplier with Quality (Beus Model)

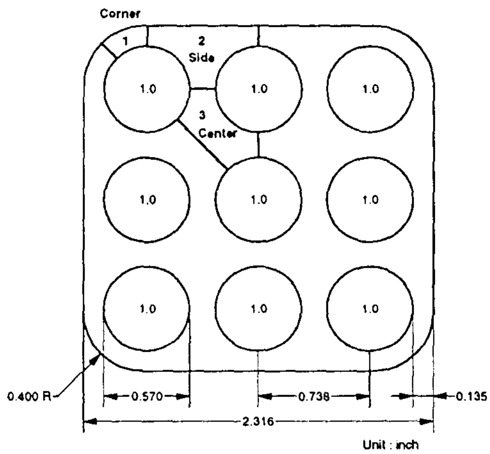
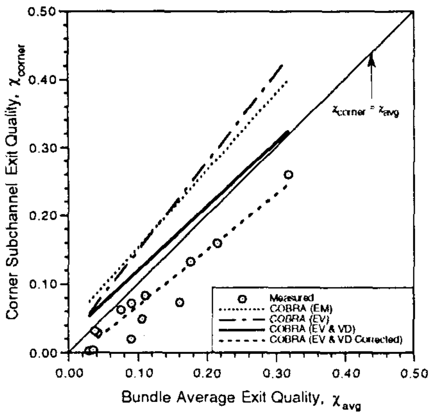
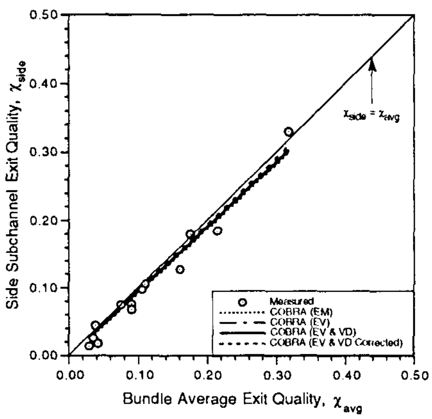


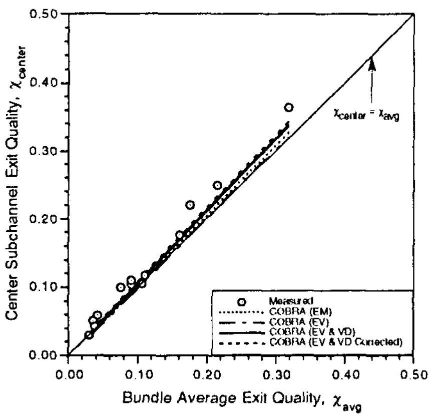
Fig. 3 Cross-Sectional View of GE 9-Rod Bundle



(a) Corner Subchannel



(b) Side Subchannel



(c) Center Subchannel

Fig. 4 Comparison of Measured and Predicted Subchannel Exit Qualities for GE 9-Rod Bundle

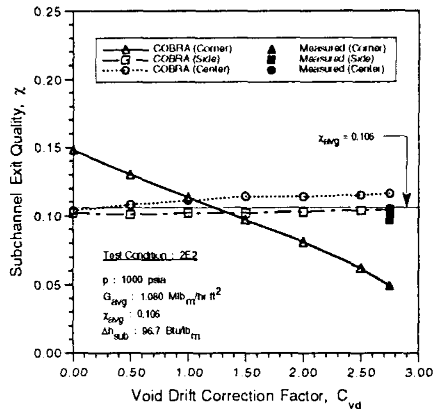


Fig. 5 Variation of Predicted Subchannel Exit Quality with Void Drift Correction Factor

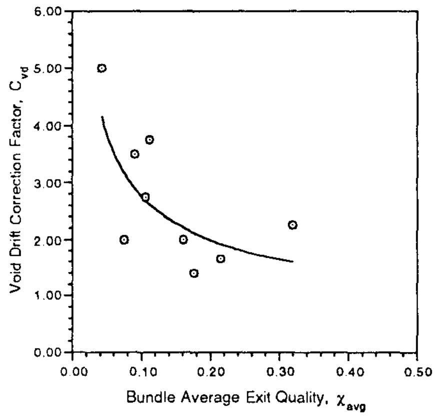


Fig. 6 Variation of Void Drift Correction Factor with Bundle Average Exit Quality

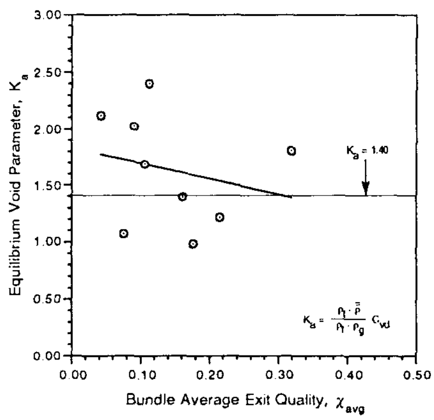


Fig. 7 Variation of Equlibrium Void Parameter with Bundle Average Exit Quality