CCFL Model of the SPACE Code and Its Validation

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1. Introduction

Countercurrent flow between steam and water can occur in several internal structures of reactor system such as the upper core support plate, the entrance to the tube sheet in the steam generator inlet plenum and the downcomer annulus, during a large break loss of coolant accident (LBLOCA). For example, the countercurrent flow limitation (CCFL) at the upper core plate may prevent cooling water from penetrating into the core during the reflood phase of LBLOCA. Therefore, the studies of CCFL phenomena are essential to the safety analyses of nuclear reactor. In order to validate the CCFL model newly developed for the SPACE code, the code is currently under assessment for various separate effect experiments. Especially, a simulation of the countercurrent two phase flow of Dukler's air/water flooding test has been performed so far. The main feature of the CCFL model and its application results will be presented in this paper.

2. CCFL Model

2.1 General Description

Countercurrent flow is defined as the two phase flow pattern in which the gas phase flows upward while the liquid phase flows downwards. This flow configuration cannot be preserved if any flow rate exceeds a criterion known as the CCFL. If either liquid or gas flow is supplied such that this criterion is exceeded, the flow pattern changes to a chaotic flow regime from a stable countercurrent flow. As a consequence, the onset of CCFL determines the maximum rate at which one phase can flow countercurrently to another phase. In order to accurately predict the onset of flow limitation for all structural configurations, a general CCFL model is added in the SPACE code. The CCFL model can be invoked by a user option. If the calculated flow at the junction exceeds the limiting value given by the CCFL correlation, the three-field momentum equations are replaced with the CCFL equation, the sum momentum equation and the droplet momentum equation. Through coupling of these equations, the downward liquid velocity is calculated such that it satisfies the CCFL correlation and other momentum equations for a given vapor upflow and an upstream void fraction.

2.2 Model Implementation

The CCFL correlation for a specific geometry provides the amount of liquid delivery for a given vapor upflow. The basic correlation implemented in the SPACE code is suggested by Bankoff [1]. The Bankoff correlation is given by:

$$H_g^{1/2} + mH_l^{1/2} = C$$

Where, H_g is the dimensionless gas flux and H_l is the dimensionless liquid flux. The Bankoff relationship is sufficiently general so that either Wallis scaling for diameter dependence, Kutateladze scaling for surface-tension dependence, or a combination of the two can be implemented. The flexibility of the Bankoff correlation is provided by defining a variable length scale in the determination of the dimensionless flux as follows:

$$H_k = j_k \left[\frac{\rho_k}{gw(\rho_f - \rho_g)} \right]^{1/2}$$

Where, j_k is the superficial velocity ($\alpha_k U_k$), ρ_k is the density of each phase k, and w is the interpolative length scale given by $w = d^{1-\beta} L^{\beta}$, where d is the junction hydraulic diameter and L is the Laplace capillary constant. The Bankoff correlation reverts to Wallis scaling for β=0 and to Kutateladze scaling for β=1. For between 0 and 1, the Bankoff scaling applies.

If the countercurrent flow exists and if the liquid downflow exceeds the limit imposed by the CCFL model, the Bankoff's CCFL equation written in terms of new-time phasic velocities is solved in conjunction with the sum momentum equation derived from the vapor, liquid and droplet momentum equations, and the droplet momentum equation. The sum equation eliminates the interface friction terms from the momentum equations, as follows:

$$\begin{aligned}
&\alpha_g \rho_g \left(\frac{\partial \mathbf{U}_g}{\partial t} + \left(\mathbf{U}_g \nabla\right) \mathbf{U}_g \right) + \alpha_l \rho_l \left(\frac{\partial \mathbf{U}_l}{\partial t} + \left(\mathbf{U}_l \nabla\right) \mathbf{U}_l \right) \\
&+ \alpha_d \rho_d \left(\frac{\partial \mathbf{U}_d}{\partial t} + \left(\mathbf{U}_d \nabla\right) \mathbf{U}_d \right) = \rho_m \mathbf{B} \\
&- F_{wg}(\mathbf{U}_g) - F_{wl}(\mathbf{U}_l) - F_{wd}(\mathbf{U}_d) + \left(\Gamma_{l,E}(\mathbf{U}_l - \mathbf{U}_g) + \Gamma_{d,E}(\mathbf{U}_d - \mathbf{U}_g)\right) \\
&+ \left(\Gamma_{l,C}(\mathbf{U}_g - \mathbf{U}_l) + S_D(\mathbf{U}_d - \mathbf{U}_l)\right) + \left(\Gamma_{d,C}(\mathbf{U}_g - \mathbf{U}_d) + S_E(\mathbf{U}_l - \mathbf{U}_d)\right) \\
&- C_{g,gd} \alpha_g \alpha_d \rho_{m,gd} \frac{\partial(\mathbf{U}_g - \mathbf{U}_d)}{\partial t} - C_{g,gl} \alpha_g \alpha_l \rho_{m,gl} \frac{\partial(\mathbf{U}_g - \mathbf{U}_l)}{\partial t} \\
&- C_{g,lg} \alpha_l \alpha_g \rho_{m,\mathrm{lg}} \frac{\partial(\mathbf{U}_l - \mathbf{U}_g)}{\partial t} - C_{g,dg} \alpha_d \alpha_g \rho_{m,dg} \frac{\partial(\mathbf{U}_d - \mathbf{U}_g)}{\partial t}
\end{aligned}$$

The droplet momentum equation is written by:

$$\frac{\partial \mathbf{U}_d}{\partial t}+\left(\mathbf{U}_d\nabla\right)\mathbf{U}_d=-\frac{1}{\rho_d}\nabla P-\frac{F_{dg}}{\alpha_d\rho_d}(\mathbf{U}_d-\mathbf{U}_g)+\mathbf{B}$$
$$-\frac{F_{wd}}{\alpha_d\rho_d}(\mathbf{U}_d)-C_{g,dg}\alpha_d\alpha_g\rho_{m,dg}\frac{\partial(\mathbf{U}_d-\mathbf{U}_g)}{\partial t}$$
$$+\frac{1}{\alpha_d\rho_d}\left(-\Gamma_{d,C}\mathbf{U}_d+\Gamma_{d,C}\mathbf{U}_g+S_E\mathbf{U}_l-S_E\mathbf{U}_d\right)$$

Finally, the three equations can be expressed in the following matrix form.

$$\begin{bmatrix} m11 & m12 & m13 \\ m21 & m22 & m23 \\ m31 & m32 & m33 \end{bmatrix}\begin{bmatrix} U_g^{E(n)} \\ U_l^{E(n)} \\ U_d^{E(n)} \end{bmatrix}=\begin{bmatrix} 0 \\ \varepsilon^E A^E \\ \dfrac{\varepsilon^E A^E}{\rho_d} \end{bmatrix}(P_{own}^{n+1}-P_{nei}^{n+1})+\begin{bmatrix} S_{ccfl} \\ S_{gld} \\ S_d \end{bmatrix}$$

Once the explicit velocity and the pressure coefficient are obtained from the above equation, the other numerical solution procedure follows the same algorithm as in the Semi-Implicit scheme of the SPACE code.

3. Application Results

The CCFL model implemented in the SPACE code is assessed for Dukler's air/water flooding test [2], which is conducted to study the interaction between a falling liquid film and an upflowing gas in the core. The facility consists of a 0.051m diameter, 3.96m long, vertically oriented cylindrical plexiglass pipe, air injection and water drain nozzles installed on the pipe. The water is injected into the pipe from the upper section and the air blower pumps the air into the pipe from the lower section. The test geometry is modeled using the pipe and branch components. Three CCFL models were used for the test, but the one that appeared to be best for the test was a Wallis form. The user input data was given by 0.82 for the gas intercept and 1.0 for the slope. A comparison of the measured and calculated water downflow versus air flow injection rates for given liquid injection rates is shown in Figure 1. As shown, a good agreement with the data is observed. At the higher air injection rates, however, the code calculated liquid downflow is less than the data. A possible reason for the under-predicted liquid downflow is that the values for the gas intercept and slope do not fit the data. In order to determine optimal constants for the Wallis correlation, some simulations were performed with changed variables. The resulting constants were 0.84 for the gas intercept and 1.0 for the slope. As shown in Figure 2, the calculated results are in a better agreement with the flooding correlation of Wallis. Thus the code is working properly based on the intercept and slope values input to the model.

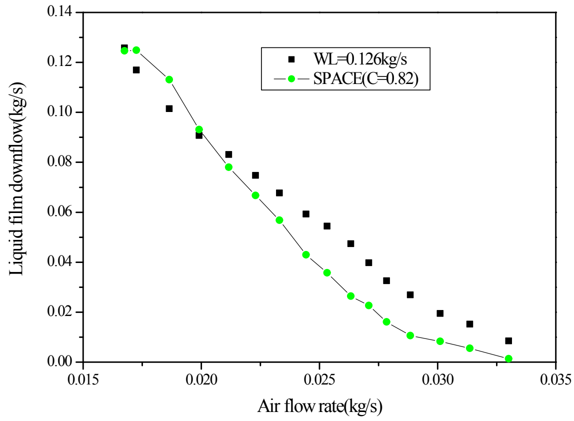

Figure 1. Liquid Downflow Rate Versus Air Flow Rate

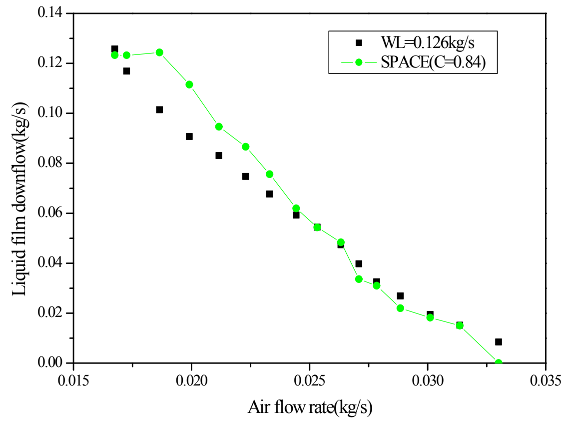

Figure 2. Liquid Downflow Rate Versus Air Flow Rate

4. Conclusions

The CCFL calculation module was incorporated into the SPACE code. As an effort for validation, the CCFL model was assessed for Dukler's air/water experiment. Overall, the calculated results agreed well with the measured data. It is concluded that the SPACE code with the CCFL model predicts the complex phenomena of countercurrent flow properly.

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REFERENCES

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