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ASSERT-PV Simulations of Two-Phase Flow in Horizontal and Vertical Subchannels

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Abstract

This is a part of the effort to assess the ASSERT-PV code which is supposedly capable of quantifying the effect of small flow boundary changes in the fuel channel of CANDU reactors. Two independently performed subchannel experiments are simulated by the ASSERT-PV code. The result includes the pressure and the void fraction distributions in each subchannel. It is found that the ASSERT-PV predicts both experimental data quite well by selecting the void diffusion constant properly for the adiabatic two-phase flows.

I. Introduction

The subchannel technique has been efficiently used for predicting distributions of flow and thermophysical properties in fuel rod bundles in the nuclear reactor. The subchannel code such as COBRA (Rowe, 1973) has been used for predicting the critical heat flux and the operating margin of the light water reactors. For heavy water reactors, the subchannel code is known to be capable of analyzing the effect of the fuel bundle and the fuel channel geometry changes (Dam et al., 1994). A unique feature of the subchannel analysis is the model for the lateral exchanges of mass, momentum and energy, by which the multidimensional effect can be taken into account. There are major differences in modeling the lateral exchanges between the horizontal and the vertical flows. The difference occurs due to the gravity. In other words, the gravity may not affect the lateral motion of the flow between vertical subchannels while the gravity may pump the lighter phase to the upper subchannel through the gaps in horizontal subchannels. Due to this reason, modeling of the lateral motion of the flow in horizontal subchannels has been considered to be less straightforward. Nevertheless, the existing subchannel models for the vertical subchannel still leave room for improvement.

In modeling the lateral flow in horizontal subchannels, the effect of gravity has to be considered on top of the mixing and the void drift. The effect of gravity can be reasonably taken into account by using the drift flux parameters. The implementation of the void drift model for the horizontal channel flow, however, is in question since the equilibrium void distribution is changing for different values of mass flow rates due to gravity.

In this work, two dual subchannel experiments, that is, the vertical channel (Tapucu et. al, 1994) and the horizontal channel experiments (Shoukri et. al, 1982), are simulated by the ASSERT-PV code.

II. THE ASSERT CODE

The ASSERT code (Carver et al., 1995) was developed by AECL to address the computation of flow and phase distribution within subchannels of CANDU fuel bundles. Unlike conventional subchannel codes such as COBRA, which are designed primarily to model in vertical fuel bundles and use a homogeneous mixture model of two-phase flow, the ASSERT code uses the drift-flux model (Zuber & Findlay, 1965; Ishii, 1977) that permits the phase to have unequal velocities. ASSERT includes gravity terms that make it possible to analyze the phase separation tendency which could occur in the horizontal flow. During its developmental stage, computational results of the ASSERT code were validated against the real scale 37-element bundle experimental data (Dam et al., 1994)(Kiteley et al., 1994).

The thermal-hydraulic modeling equations used in the ASSERT code were derived from the two-fluid formulation (Judd et al., 1984). Like COBRA-IV computer code, the ASSERT code is based upon subchannels which are divided axially into a number of control volumes. The closure relationships for the governing equations used in the ASSERT code include the equation of state, the relative velocity relationship, the fluid friction, the wall heat transfer and the thermal mixing to primary variables, the phasic flow velocities, the densities, the enthalpies and the pressure.

The transverse interchange models of the ASSERT code are based upon the following partition:

$$w''_{i \to j} = (w''_{i \to j})_{CF} + (w''_{i \to j})_{MIX} + (w''_{i \to j})_{VD} \qquad (1)$$

where

$(w''_{i \to j})_{CF}$: flow diversion due to the imposed transverse pressure gradients,

$(w''_{i \to j})_{MIX}$: turbulent (eddy diffusivity) mixing,

$(w''_{i \to j})_{VD}$: "void drift" due to the tendency to approach equilibrium conditions.

The crossflow is directed flow caused by pressure gradients between the subchannels. The so-called void diffusion includes the second and the third terms in Eq.(1). The second effect can be modeled by the classical Reynolds stress term. Unfortunately, however, it is known that the turbulent mixing alone fail to produce the required results since infinite turbulent mixing implies that subchannel void fractions must be the same for a finite value of crossflow while the observed void distribution is a nonuniform equilibrium distribution (Lahey and Moody, 1993). Therefore, it was hypothesized that net two-phase turbulent mixing is proportional to the nonequilibrium void fraction gradient. This hypothesis implies that there is a strong trend toward the equilibrium distribution and that when this state is achieved, the net exchange due to mixing ceases.

In CANDU reactors, the gravity influences the crossflow since the direction of gravity is perpendicular to the channel flow while the phasic slip is close to unity in the major flow direction. When the phasic slip in the major flow direction is close to unity, the behavior of two-phase flow was found to be quite different from that of the large slip flow. For example, the bubble-to-slug regime transition was found to be more gradual and the thermal-hydraulic information propagation (i.e., characteristics) become slower (Park, 1995). Under this flow condition, the two-phase transverse momentum exchange (i.e., the void drift model) must be more important since the void and enthalpy distributions in the fuel bundle can be strongly influenced by the lateral void drift model. Since, in general, the exit flow quality in CANDU fuel channels are often greater than zero, the void drift model used in the ASSERT code should be validated further under such a flow condition (Park, 1999). Since in two-phase flow, not only the energy and the momentum exchange but also the mass exchange occur between subchannels, the equal volume exchange concept was applied in the ASSERT code. It should be noted that the effect of the transverse exchange on the void distribution in the fuel bundle can be larger as the channel flow rate decreases.

III. Description of Experiments

The cross-sectional view of the horizontal (Shoukri, 1982) and the vertical flow (Tapucu et al., 1994) channels are shown in Figure 1. The experimental operating conditions are summarized in Table 1.

IV. Results and Discussion

The void fraction, the mass flow rate, the pressure and the crossflow for each subchannels are considered. For both of the horizontal and the vertical flow simulations, the inlet condition (e.g., void fraction) has been obtained by adjusting the enthalpy of each phase (i.e., the steam or the water) since the ASSERT does not have air-water flow simulation capability.

IV.1. Vertical Channel Flow

The subchannel pressures of the vertical flow experiment are compared with the experimental data in Figure 2. It was found that the void diffusion constant may change the axial pressure distribution, speically near the inlet region. As can be seen, the void diffusion constant of 0.15 is more favorable.

The diversion crossflow, which is induced by the static pressure difference between subchannels developed at the downstream of the separator between two subchannels, is diminished (i.e., 0.343 meters from the inlet).

What is found in the vertical flow simulations are mostly consistent with the previous simulation result obtained by Tapucu et al. (1994). Most importantly, the void distribution is strongly influenced by the void diffusion constant as shown in Figure 3. Simulated values of the crossflow are shown in Figure 4. As can be seen, the crossflow is not only induced by the interchannel static pressure difference but also due to the mass exchange mechanism between subchannels.

IV.2. The Horizontal Channel Flow

The void fractions in horizontal flow channel are shown in Figures 5 and 6 for two differnet values of mass flow rate. In these simulations, the void diffusion constant is set to be 0.15. For both cases, the void fraction can be predicted quite well by the ASSERT-PV code for adiabatic two-phase flows in horizontal channel.

To examine the separation tendency of each phase in the horizontal subchannels, the fraction of the liquid phase in the upper subchannel is plotted against the total gas flow rate in Figure 7. The general trend is found to be that the liquid in the upper subchannel decreases as the total gas flow rate increases and the equal distribution between phases would never be reached. As the total flow rate increases, the portion of the liquid staying in the upper subcahnnel increases. This is due to the fact that the liquid particles may have less time in the upper subchannel for the gravity separation when the velocity is larger. This tendency is also consistently predicted by the ASSERT-PV code. It should be noted that the liquid staying in the upper subchannel seems to have its asymptote for each value of the total mass flow rate of the two-phase mixture. Different values of these asymptotes can be clearly seen in ASSERT-PV simulations.

V. Concluding Remarks

It is presented that sets of experimental data obtained from the vertical and horizontal flow channels are compared with a part of ASSERT-PV simulation results performed at KAERI. It is found that the ASSERT-PV code can be efficiently used for predicting the void fraction and the other associated thermal-hydraulic parameters by selecting the void diffusion constant properly. Further research should be focused on the mechanistic modeling of the transverse exchange of the vapor phase in the subchannels.

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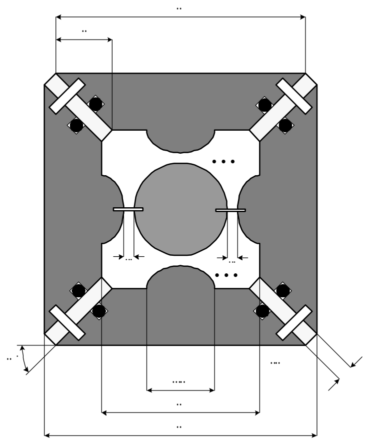
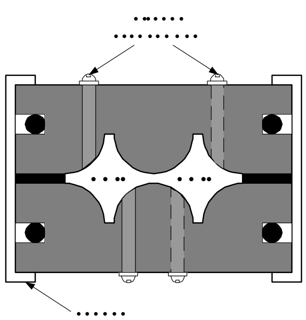
Table 1. Experimental Conditions

	Vertical Flow (Tapucu et al., 1994)	Horizontal Flow (Shoukri et al., 1982)
Working Fluid	Air-water mixture	Air-water mixture
Mass Flux (kg/m^{2}Is)	~3000	950, 1360, 1650
Void Fraction	0 - ~0.6	0- ~0.8
Pressure (MPa)	0.11	0.13
Temperature (πC)	20	20
Subchannel Area ($\lambda 10^4$ m^2)	1.166	1.857
Gap Clearance (m)	0.0017	0.005
Rod Diameter (m)	0.0176	0.015
Wetted Perimeter (m)	0.06039	0.0944
Centroid-to-centroid Length (m)	0.0187	0.0175



(a) Horizontal



(b) Vertical

Figure 1. Cross-sectional View of the Test Sections

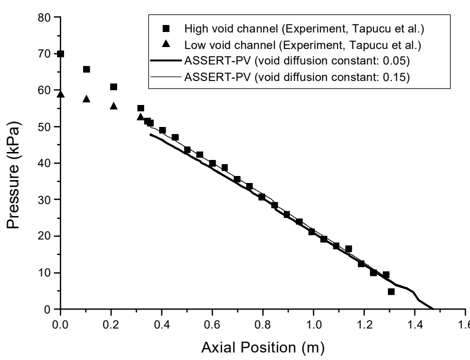


Figure. 2. Pressure Distribution in the Vertical Subchannels

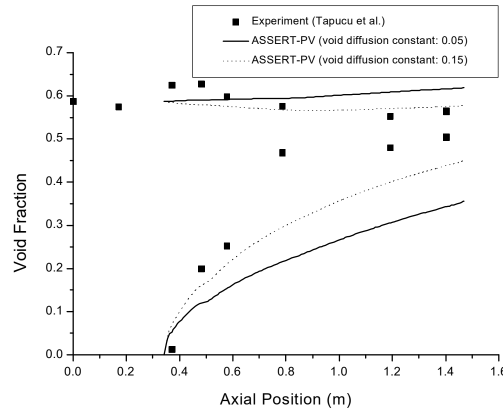


Figure 3. ASSERT-PV Prediction and Vertical Flow Data

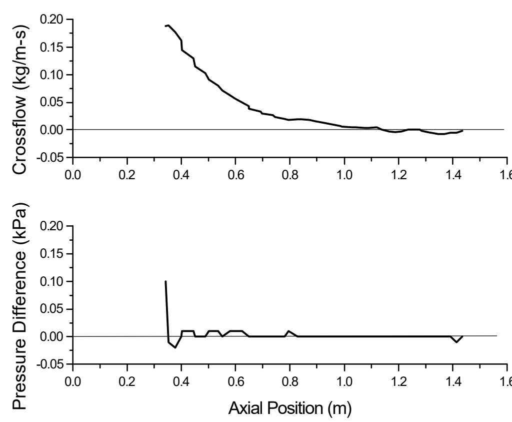


Figure 4. Crossflow Between Vertical Subchannels

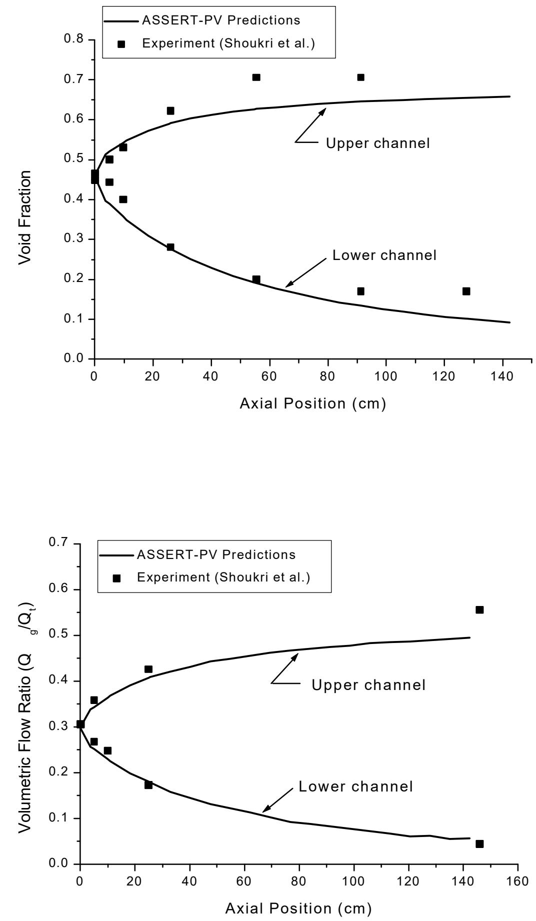


Figure 5. ASSERT-PV Predictions and Horizontal Flow Data (G = 1360 Kg/m^2 s)

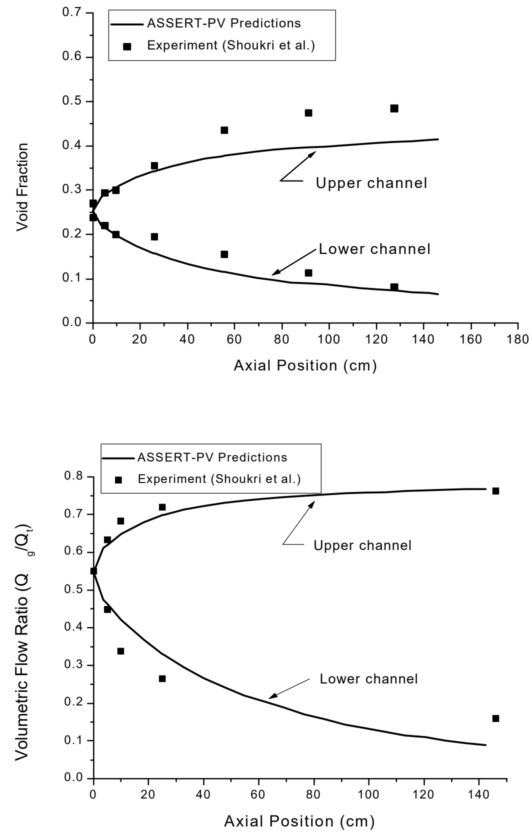


Figure 6. ASSERT-PV Predictions and Horizontal Flow Data (G = 950 Kg/m^2 s)

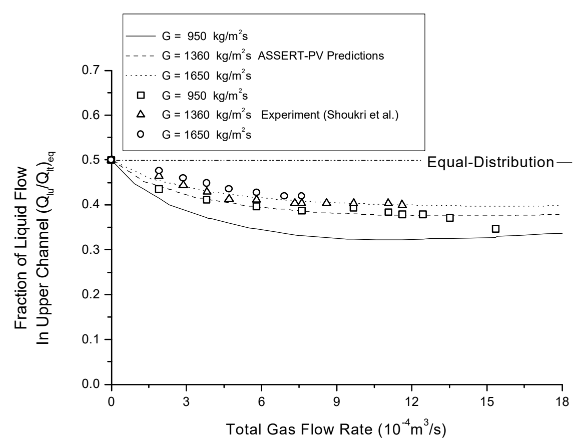


Figure 7. Equilibrium Liquid Flow Distribution in Horizontal Subchannel