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The effect of the advanced drift-flux model of ASSERT-PV on critical heat flux, flow and void distributions in CANDU bundle subchannels

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ABSTRACT

This paper studies the effect of the drift flux model of the subchannel code ASSERT-PV on critical heat flux (CHF), void fraction and flow distribution across fuel bundles. Numerical experiments and comparison against measurements were performed to examine the trends and relative behaviour of the different components of the model under various flow conditions.

The drift flux model of ASSERT-PV is composed of three components: (a) the lateral component or diversion cross-flow, caused by pressure difference between connected subchannels, (b) the turbulent diffusion component or the turbulent mixing through gaps of subchannels, caused by instantaneous turbulent fluctuations or flow oscillations, and (c) the void drift component that occurs due to the two-phase tendency toward a preferred distribution.

This study shows that the drift flux model has a significant impact on CHF, void fraction and flow distribution predictions. The lateral component of the drift flux model has a stronger effect on CHF predictions than the axial component, especially for horizontal flow. Predictions of CHF, void fraction and flow distributions are most sensitive to the turbulent diffusion component of the model, followed by the void drift component. Buoyancy drift can be significant, but it does not have as much influence on CHF and flow distribution as the turbulent diffusion and void drift.

1. Introduction

This paper constitutes a part of the effort to systematically review and upgrade all thermalhydraulic closure relationships used in an earlier version of the ASSERT-PV code (Carver et al., 1990). It examines the effect of the drift flux model of ASSERT-PV on critical heat flux (CHF) prediction. More specifically, it looks at how the drift flux model influences local void fraction and flow distribution across a bundle. Qualitative numerical experiments and quantitative comparisons against experimental data were performed to examine the trends and relative behaviour of the different components of the drift flux model under various flow conditions.

This work is prompted by the observed significant impact of the drift flux modelling on CHF predictions. CHF predictions are greatly influenced by the local thermalhydraulic conditions across the fuel bundle subchannels and by the CHF prediction method. The former is in turn affected by the ASSERT-PV advanced drift flux model via flow and void fraction distribution across fuel bundles.

1.1. ASSERT-PV code

ASSERT-PV is a computer code that has been developed to model the subchannel flow and phase distribution in horizontal Canada uranium deuterium (CANDU®[1]) pressurized heavy water reactor fuel channels (Carver et al., 1990; Hammouda et al., 2001; Rao et al., 2014a). The code has been designed to be general enough to accommodate other geometries and orientations. These include single subchannels of different shapes, and multiple subchannels of CANDU PHWR, PWR and BWR designs, in both vertical and horizontal orientations. As well, the code can accommodate a range of fluids, including single- and two-phase heavy water, light water, various Freons, and two-phase air-water. ASSERT-PV (Carver et al., 1990; Hammouda et al., 2001; Rao et al., 2014a) is based on ASSERT-IV (Rowe et al., 1988), which, in turn originated from the COBRA-IV computer program (Wheeler et al., 1976; Stewart et al., 1977); ASSERT has been enhanced to meet the specific requirements

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[1] CANDU® is a registered trademark of Atomic Energy of Canada Limited (AECL).

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for the thermalhydraulic analysis of two-phase flow in the horizontally oriented CANDU fuel.

ASSERT uses the subchannel approach to model single- and two-phase flow in rod bundles. Subchannels are defined by the coolant flow areas between rods, which are bounded by the rods and imaginary planes linking adjacent rod center lines. Subchannels are divided axially into control volumes, which communicate axially in the same subchannel, and laterally across fictitious boundaries with control volumes in neighboring subchannels. The code is based on a five-equation, advanced drift-flux thermalhydraulic model that accounts for the thermal and mechanical non-equilibrium and transverse flow found in CANDU-type fuel channels. The thermalhydraulic conservation equations used in ASSERT are derived from the two-fluid equations (Ishii, 1975). Heat transfer, friction, and the exchange of mass, momentum and energy between subchannels affect the distribution of flow and enthalpy among individual subchannels. In addition to the conservation equations, ASSERT uses a number of closure relationships to model wall-to-fluid heat and momentum transfer and inter-subchannel mass, momentum and energy exchanges due to turbulent mixing, void drift and buoyancy drift (Carver et al., 1990; Hammouda et al., 2001; Rao et al., 2014a). The governing equations are given in Table 1. ASSERT uses a staggered grid numerical solution scheme based on a pressure-velocity algorithm (Carver et al., 1990; Hammouda et al., 2001; Rao et al., 2014a). ASSERT has a built-in capability to systematically determine CHF occurrence, based on its prediction of local subchannel flow and rod heat-flux conditions.

1.2. Subchannel mixing

Inter-subchannel turbulent mixing can result in the lateral transfer of momentum and thermal energy in single-phase flow and of mass, momentum and thermal energy in two-phase flow. The transfer of mass in two-phase flow is modeled via the use of a void diffusion coefficient, based on the assumption that the phasic diffusion rates are equal. This results in a "diffusion velocity" component of the relative gas-phase velocity. The inter-subchannel thermal energy and momentum transfer rates due to turbulent mixing appear as source terms in the momentum and energy equations of ASSERT-PV. In general, conservation equations of axial and transverse momentum consider two major components: (a) diversion cross flow, caused by transverse pressure difference, and (b) mixing, caused by turbulent fluctuations in flow and pressure.

The essence of the drift flux concept and modelling is based on the experimental observation that the vapour phase in a two-phase system has a strong tendency to seek the more open and higher velocity regions of a given geometry. In general, subchannel analysis accounts for this phenomenon in special ways. The unique feature of subchannel analysis is contained in the treatment of the transverse (or lateral) interchange of mass, momentum, and energy between subchannels. These interchanges are arbitrarily decomposed into three components (Lahey and Moody, 1993):

1. diversion cross-flow, caused by pressure difference between connected subchannels,
2. turbulent mixing through gaps of subchannels, caused by instantaneous turbulent fluctuations or flow oscillations, and
3. transverse void drift that occurs due to the two-phase tendency toward a preferred distribution.

For the CANDU reactors the fuel channels are horizontally oriented. Therefore, modelling of the relative velocity takes a paramount importance in the successful application of the ASSERT-PV code to horizontal bundles and channels. In ASSERT-PV the relative velocity is modeled to comprise the following effects (Carver et al., 1987):

1. relative velocity due to cross-section averaging,
2. local relative velocity due to gravity separation, and
3. turbulent diffusion of void, both between neighboring channels and towards a preferred phase distribution pattern.

As pointed out by Lahey and Moody (1993), the phenomenon of void drift is still not completely understood in two-phase flows. Therefore, to carry out meaningful two-phase flow analysis, and predict accurately two-phase data trends void drift models must be *synthesized*.

The advanced drift flux model described and analyzed in this paper has been the foundation for the earlier code version (Carver et al., 1990) and more recent code development from ASSERT-PV 3.0 (Hammouda et al., 2001) to ASSERT-PV 3.2 (Rao et al., 2014a). The model slightly evolved through these code developments, resulting in differences in recommended sub-model selection and model coefficients. However, the fundamental equations, and the observations made of the effect or sensitivity of each model component, remain equally applicable to all code versions.

Note that in this paper no attempt is made to modify existing models, since the purpose of the study is to analyze and observe the behaviour of the drift flux model components for the proper (expected) trends and its influence on bundle subchannel CHF predictions. The latter has not been investigated before in the CANDU community in subchannel analyses using the ASSERT-PV code and to the authors' knowledge was not investigated elsewhere in general. The value of this work is most significant to developers of subchannel codes who need to know where efforts should be focused in order to improve sub-models and set recommendations for model coefficients of the drift flux model.

2. The Zuber and Findlay drift flux model

Since the basis of the "advanced" drift flux model of ASSERT-PV (Carver et al., 1990; Hammouda et al., 2001; Rao et al., 2014a) is the well-known Zuber and Findlay (1965) model, an outline of this model is given in this section.

The basic drift flux model of Zuber and Findlay (1965) is general, and in principle can be applied to any two-phase flow regime. The specification of the drift flux parameters (e.g., C_o, V_{gj}, etc.) are often empirical and flow regime dependent. This, however, limits the applicability or the extension of the model to specific flow regimes.

In general, the drift flux model takes into account both the effect of non-uniform flow and concentration (e.g., void fraction) profiles as well as the effect of the local relative velocity between the phases. The general expression of the drift flux relationship proposed by Zuber and Findlay can be represented by

$$\bar{V}_v = \frac{\langle j_v \rangle}{\langle \alpha \rangle} = C_0 \langle j \rangle + \frac{\langle \alpha V_{gj} \rangle}{\langle \alpha \rangle}, \tag{1}$$

where V_v, j_v, α, C_0, j, and V_{gj} are the local vapour velocity, local vapour volumetric flux, local void fraction, distribution parameter of non-uniform flow and concentration profiles, local mixture volumetric flux, and local drift velocity for local relative velocity between the phases, respectively. The symbol $\langle\rangle$ defines the average value of a variable F over the cross-sectional area A as

$$\langle F \rangle = \frac{1}{A} \int_A F dA, \tag{2}$$

and the *bar* over a variable defines a weighted mean value as

$$\bar{F} = \frac{\langle \alpha F \rangle}{\langle \alpha \rangle} = \frac{\frac{1}{A}\int_A \alpha F dA}{\frac{1}{A}\int_A \alpha dA} \tag{3}$$