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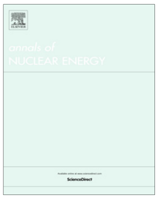

Technical note

Improvement of TASS/SMR code using a simple correlation for subcooled boiling flow prediction

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ABSTRACT

SMART, which was an advanced integral type small modular PWR, was developed by KAERI (Kim et al., 2014). To analyze the thermal hydraulic phenomena including behaviors at the SMART specific components, the TASS/SMR code which can predict a heat transfer for various thermal hydraulic conditions, has been developed. Information of the void distribution in a subcooled boiling flow is important in predicting the inception of a two-phase flow and an onset of the critical heat flux condition. The TASS/SMR code adopts an energy partitioning method and a critical enthalpy correlation determining a point of net vapor generation for subcooling conditions. A range of the subcooling degree investigated is 1.5–50.6 K to validate the method for a subcooled boiling flow prediction. The TASS/SMR code predicts well the void distribution along the height for the subcooled boiling flow conditions compared with the experimental data. The predicted location of the onset of void generation is simulated well at most investigated conditions and delayed slightly at the very high subcooling condition.

1. Introduction

SMART (System-Integrated Modular Advanced ReacTor), which was an advanced integral type small modular PWR (Pressurized Water Reactor), was developed by KAERI (Kim et al., 2014). The main components such as the steam generators (SGs) and reactor coolant pumps (RCPs) are located in the reactor pressure vessel (RPV), as shown in Fig. 1. It has a compact size compared to a conventional PWR, and can produce an electricity of 100 MW, or an electricity of 90 MW and a desalinated water of 40,000 tons per day, concurrently. The performance and safety of the SMART plant should be analyzed using a system analysis code. To analyze the thermal hydraulic phenomena at the SMART plant, the TASS/SMR code, which can predict a heat transfer for various thermal hydraulic conditions in the core has been developed (Lee et al., 2009).

With increasing heat flux, bubbles generated in the fuel aggregate heat transfer in the core and form a transient vapor film, which lead to a sharp rise of the fuel surface temperature. This is called a departure from nucleate boiling (DNB). The rapid increase of the fuel surface temperature leads to the fuel surface damage. A void distribution in a subcooled boiling flow is important in predicting an inception of a two-phase flow and an onset of the critical heat flux condition. The subcooled boiling is the early stage of the departure from nucleate boiling, which is a key phenomenon related to a nuclear reactor safety (Okawa et al., 2007; Zhang et al., 2015). Many models are developed to predict the void distribution under a subcooled boiling flow.

The void distributions assuming the simple relation of local vapor quality to the thermal equilibrium qualities was developed at the point of net vapor generation (Saha and Zuber, 1974). Research activities for a subcooled boiling flow at low pressures have been done focused on the safety analysis of research reactors operation with atmospheric pressure (Bibeau and Salcudean, 1994; Rogers et al., 1987; Tu and Yeoh, 2002), and an improvement of best estimate system analysis code (Koncar and Mavko, 2003). Multi-dimensional calculations were carried out to predict the void fraction in a subcooled boiling flow (Kljenak and Mavko, 2006; Krepper and Rzehak, 2011). These models were generally mechanistic models compared with conventional one-dimensional models. In addition, Bosma et al. (2004) showed that subcooled nucleate boiling occurring at a core region in the pressurized water reactors caused the accumulation of boron compounds on fuel surfaces that led to an unexpected deviation in axial power distribution. Lo (1996) proposed population balance equations for the CFD code to take into account a non-uniform bubble size distribution in two-phase flows. Recently, an interfacial area transport and bubble number density transport equations were applied, respectively, into CFD codes for the prediction of subcooled boiling flows (Yao and Morel, 2004; Yeoh and Tu, 2005).

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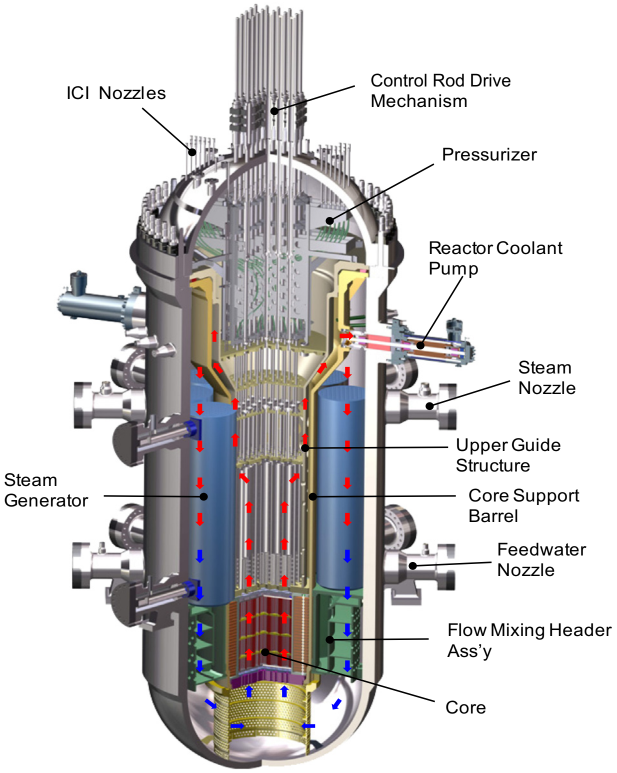

Fig. 1. Schematic diagram for the SMART reactor vessel.

The use of CFD codes has been recently extended to analyze a multi-dimensional two-phase flow to improve the limitation of one-dimensional analysis code. An accurate simulation of a subcooled boiling flow is important for the performance, and safety of nuclear power plants (Yun et al., 2012). However, a one dimensional system analysis is widely used to analyze the overall system behaviors of nuclear power plants for various conditions including accidents. In the present work, a simple model to predict subcooled boiling flow is examined in the TASS/SMR code, which was developed to analyze thermal hydraulic phenomena for the integral reactor, SMART.

2. Implementation of subcooled boiling model

The TASS/SMR code was developed for an analysis of the design based accidents in an integral type reactor reflecting the characteristics of the SMART design (Chung et al., 2015). The governing equations are six one-dimensional conservation variables to predict a two-phase condition well.

Mass conservation

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

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

$$A\frac{\partial}{\partial t}(\alpha\rho_n) + \frac{\partial}{\partial x}\left(\frac{\rho_n}{\rho_g}x_f W_m\right) = 0 \tag{3}$$

Momentum conservation

$$A\frac{\partial}{\partial t}\left(\frac{W_m}{A}\right) + \frac{\partial}{\partial x}\left[\left(\frac{x_f^2}{\alpha\rho_g} + \frac{(1-x_f)^2}{(1-\alpha)\rho_l}\right)\left(\frac{W_m^2}{A}\right)\right] = -A\frac{\partial P}{\partial x} - K_f\Phi^2\frac{W_m|W_m|}{2\rho_l A} - K_g\frac{W_m|W_m|}{2\rho_m A} + \rho_m a_{ext}A \tag{4}$$

Energy conservation

$$A\frac{\partial}{\partial t}(\rho_m e_m) + \frac{\partial}{\partial x}[\{x_f h_g + (1-x_f)h_l\}W_m] = \dot{q}_w \tag{5}$$

$$A\frac{\partial}{\partial t}(\alpha\rho_g h_g) + \frac{\partial}{\partial x}(x_f h_g W_m) = \Gamma_g h_{sg} + \dot{q}_{wg} + \dot{q}_{ig} \tag{6}$$

Here,

$$\rho_m = \alpha(\rho_s + \rho_n) + (1-\alpha)\rho_l \tag{7}$$

$$\rho_m e_m = \alpha(\rho_s e_s + \rho_n e_n) + (1-\alpha)\rho_l e_l \tag{8}$$

$$x_f = \frac{\alpha\rho_g}{\rho_m} + \frac{\alpha\rho_g(1-\alpha)\rho_l}{\rho_m W_m}v_r A \tag{9}$$

$$v_r = \mathrm{v}_g - v_l \tag{10}$$

where ρ W, A, α, v, P, e, and h denote density, mass flow rate, area, void fraction, velocity, pressure, internal energy and enthalpy, respectively. Also, subscript m, r, g, n, and l denote mixture, relative, gas, non-condensable and liquid, respectively. It is also assumed that a non-condensable gas is a thermal equilibrium between a gas and steam, and distributes homogeneously.

Considering a subcooled boiling flow, a vapor phase and liquid phase coexist at different temperatures. Thus, the governing equations describing thermal non-equilibrium and non-homogeneous velocity should be implemented to model a subcooled boiling flow. In TASS/SMR code, a subcooled boiling is implemented in the wall evaporation model ($\dot{q}_w$, and $\dot{q}_{wg}$ in Eqs. (5) and (6)), which determines the wall evaporation rate using a heat flux partitioning and the drift flux model, which determines the differential velocity between the steam and liquid phases (Chexal and Lellouche, 1991). Heat flux partitioning assumes that a total heat transferred from a heated wall is partitioned into a latent heating and a sensible heating of bulk fluid. A critical enthalpy correlation determining the point of net vapor generation is adopted to improve a void distribution prediction under a subcooled boiling flow. Saha and Zuber introduces that a critical enthalpy for a bubble detachment is function of a fixed Nusselt number at low flow rate and fixed Stanton number at high flow rate (Saha and Zuber, 1974). These equations are modified since the trend of the bulk liquid temperature at the onset of significant void is opposite those predicted by Saha and Zuber's correlation (Rogers et al., 1987). The data cited by Saha and Zuber were fitted to two correlations depending on the Peclet number of 52000 (Ha, 2004).

$$h_{cr} = \begin{cases} h_f^{sat} - \frac{St\,Pe^{0.124}C_{pf}}{0.0287} & \text{for } Pe \geqslant 52000 \\ h_f^{sat} - \frac{St\,Pe^{1.08}C_{pf}}{918.525} & \text{for } Pe < 52000 \end{cases} \tag{11}$$

where St, Pe and C_{pf} are the Peclet number, Stanton number, and liquid specific heat, respectively. In the TASS/SMR code, the critical enthalpy for the onset of subcooled boiling is adopted Eq. (11).

3. Validation of subcooled boiling model

The developed subcooled boiling model in the TASS/SMR code is validated. The simulations have been performed and the results are compared with the experimental data. The selected experimental data are the KIT and FRIGG test results (Kalitvianski, 2000; Gingrich, 2007).

3.1. KIT subcooled boiling test

The test section of the KIT has a pipe with an inner diameter of 11.7 mm or 12.23 mm with a constant height of 1.5 m, and is

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