Preliminary Study of CANDU Moderator Thermal Hydraulics using the CUPID Code

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1. Introduction

When the moderator cooling system fails, moderator may act as to remove decay heat which occurs in fuel. During loss of coolant accident (LOCA), the film boiling occurs in the Calandria tube (CT) because the hot pressure tube would deform into contacting with the calandria tube. And lower subcooling would decrease the margin of the CT to dryout. So, it is important to estimate a local subcooling of the moderator inside the Calandria vessel. However, in order to predict the internal temperature the study of empirical experiments and calculations are needed because only the inlet/outlet temperature can be measured in real reactor [1].

In this study, the internal flow of the moderator was predicted by using the CUPID code, which has been developed in KAERI. The CUPID adopts three-dimensional, transient, two-phase and three-field model, and includes various physical models and correlations of the interfacial mass, momentum and energy transfer for the closure relations of the two-fluid model [2]. The CUPID code shows single-phase and two-phase flow through two-phase flow calculations of virtual can be applied.

2. Mathematical Model of the CUPID Code

2.1 Governing Equations

To simulate two-phase flow, CUPID code adopts a transient two-fluid, three-field model. The three-fields represent the liquid, droplet and vapor. Each fields the mass, energy, and momentum equations are established separately and each field are linked by the interfacial mass, energy, and momentum transfer models. The continuity, momentum, energy and conduction equations for the k-phase are given by

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla \cdot (\alpha_k \rho_k \underline{u}_k) = \Omega_k \qquad (1)$$

and $\Omega_g = \Gamma_v + \Gamma_{wall} = -\Omega_l$

The momentum equation for the *k*-field is;

$$\frac{\partial}{\partial t}(\alpha_k \rho_k \underline{u}_k) + \nabla \cdot (\alpha_k \rho_k \underline{u}_k \underline{u}_k) = \qquad (2)$$
$$-\alpha_k \nabla P + \nabla \cdot [\alpha_k(\tau_k + \tau_k^T)] + \alpha_k \rho_k \underline{g} + \underline{M}_{ik}$$

where $\underline{M}_{ik}$ is the interfacial momentum transfer term. To consider the turbulent flow, the standard ($k-\varepsilon$) turbulence model was used and it is assumed that the continuous liquid and droplet fields are in a thermal equilibrium. The energy equations for the gas and liquid fields are;

$$\frac{\partial}{\partial t}(\alpha_g \rho_g e_g) + \nabla \cdot (\alpha_g \rho_g e_g \underline{u}_g) =$$
$$-P\frac{\partial}{\partial t}\alpha_g + E_g^D - P\nabla \cdot (\alpha_g \underline{u}_g) + Q_{ig} - Q_{gl} + q_{wg}$$
$$\frac{\partial}{\partial t}[(1-\alpha_g)\rho_l e_l] + \nabla \cdot [(\alpha_l \underline{u}_l + \alpha_d \underline{u}_d)\rho_l e_l] =$$
$$-P\frac{\partial}{\partial t}(1-\alpha_g) + E_l^D - P\nabla \cdot (\alpha_l \underline{u}_l)$$
$$-P\nabla \cdot (\alpha_d \underline{u}_d) + Q_{il} + Q_{gl} + q_{wl}$$

where E_k^D includes the conduction, turbulent energy source, and viscous dissipation that are represented in terms of a diffusion. Q_{ig} and Q_{il} are the interfacial energy transfer terms. Q_{gl} is the heat transfer rate per unit volume at the non-condensable gas-liquid interface.

2.2 Frictional pressure drop model

To simulate the two-phase flow in complicated geometry, such as tube bundle region, a porous media approach is adopted. Pressure drop model for a porous media zone is needed to accurately simulate the flow behavior. In the tube bundle region, the frictional pressure drop for the cross flow according to the flow direction is introduced as follows [3];

$$PLC = \frac{\Delta P}{N_f \cdot \rho \cdot v_{fs}^2/2} = 4.54 \cdot Re^{-0.172} \qquad (5)$$

Eq. (5) is implemented into the CUPID code as linear form as follows;

$$M_i = -\frac{\Delta P}{\Delta L} = \frac{4.54 \cdot Re_{tube}^{-0.172}}{pitch} \cdot \rho \frac{(\varepsilon V)}{2} \cdot u_i \qquad (6)$$

where i is the flow direction.

3. Result and discussion

3.1 Low flow condition

In this calculation, the coolant injection is reduced to 2.0kg/s, and thermal power is 100 kW [4]. Fig. 1 shows a transition by natural convection at the upper region, which due to thermal stratification by the buoyancy. The buoyancy as the internal heat generation is relative higher than momentum. In the natural convection regime, the hot spot occurs at the top of the Calandria vessel. The local maximum temperature in this calculation is 75.8 ℃, and outlet average temperature is 67.05℃. The difference between the local maximum temperature and the average exit temperature increases as the injection flow rate decreases. Thus, it is predicted that further decreasing of the injection flow may lead to a boiling from the top of the Calandria tank.

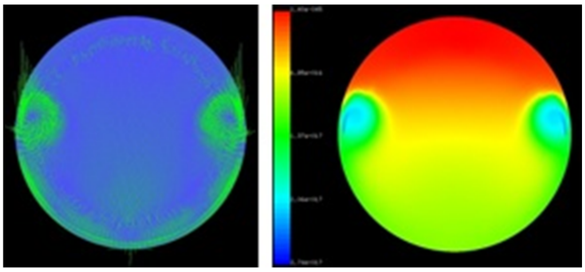
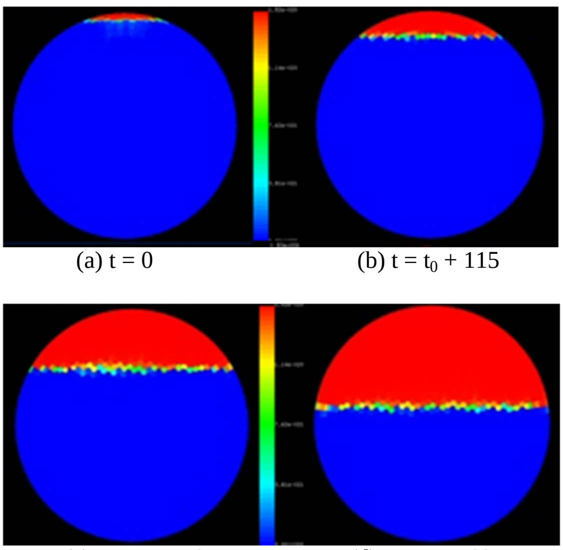


Fig. 1 Velocity and temperature distribution of low flow

3.2 Two-phase flow

To simulate two-phase flow of hypothetical in the moderator tank, the total inlet mass flow rate is 0.7 kg/s, which is about 30% of the nominal case and the power is supplied the same as the previous two cases. In previous studies, The CUPID code evaluated predicts the flow pattern changes and thermal stratification process. If the injection flow into the vessel is further decreased, the thermal stratification due to the buoyant force is accelerated and the subcooling of upper region is reduced. Therefore, a local boiling is expected to occur as in Fig. 2.

Fig. 2 shows the void fraction of two-phase flow. A boiling occurs at the top of the fluid region, and the interface between the upper superheated vapor and the lower subcooled liquid gradually moves downward.



(a) t = 0 (b) $t = t_0 + 115$

(c) $t = t_0 + 140$ (d) $t = t_0 + 160$

Fig. 2 Void fraction of two phase flow

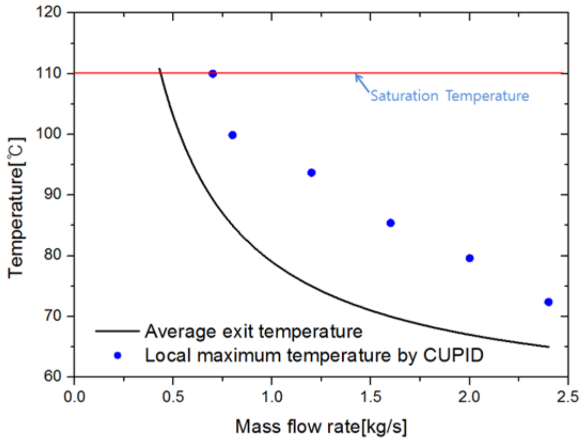


Fig. 3 The maximum temperature versus the inlet flow rate and average outlet temperature

Fig. 3 shows the average outlet temperature obtained from the CUPID calculations and the local maximum temperature versus the inlet flow rate. This can be used to predict the local subcooled margin in the Calandria vessel.

5. Conclusions

In this study, the CUPID code was validated using the moderator experimental results had been performed at STERN Lab., first. The results showed good agreement with both the experiments and the previous researchers' results. And a qualitative two-phase flow condition and the result evaluated. As result, The CUPID code might be said that can be applied to both single phase and two-phase flow analyses.

ACKNOWLEDGMENTS

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