Prediction of Natural Circulation Flow with Inclined Downward Facing Heating Channel

Kwang Soon Ha [a*], Rae Joon Park [a]
[a] *Korea Atomic Energy Research Institute, 1045 Daedeok-daero, Yuseong-gu, Daejeon, Korea*
[*]Corresponding author: tomo@kaeri.re.kr

1. Introduction

Various safety systems have been designed and adapted in nuclear power plants to prevent postulated accidents, to enhance the life time and economic benefit, and to increase public acceptance of the plants. Postulated severe core damage accidents have a high threat risk for the safety of human health and jeopardize the environment. Versatile measures have been suggested and applied to mitigate severe accidents in nuclear power plants. To improve the thermal margin for the severe accident measures in high-power reactors, engineered corium cooling systems involving boiling-induced two-phase natural circulation have been proposed for decay heat removal [1]. The boiling-induced natural circulation flow is generated in a coolant path between a hot vessel wall and cold coolant reservoir. In general, an increase in the natural circulation mass flow rate of the coolant leads to an increase in the critical heat flux (CHF) on the hot wall, thus enhancing the thermal margin [2].

To predict the natural circulation flow, the boiling-induced natural circulation flow in a real-scaled experimental cooling channel is modeled and solved by considering the conservation of mass, momentum and energy in the two-phase mixture, along with the two-phase friction drop and void fraction.

2. Analysis method and results

The two-phase flow is analyzed to predict the natural circulation mass flow rate occurring in the engineered corium cooling system [1]. Assuming the flow to be at a steady state in the coolant channel, the mass, momentum, and energy equations can readily be formulated. Since no mass is being added to the flow from outside the channel other than at the inlet, the overall mass flow rate is the sum of the liquid ($\dot{m}_f$) and vapour ($\dot{m}_g$) mass flow rate with mixture density(ρ_m) and velocity(u_m) as given by equation (1).

$$\dot{m} = \rho_m u_m A = \dot{m}_f + \dot{m}_g \qquad (1)$$

The momentum equation is rearranged using force balances, that is, the pressure (P) difference along the z-direction can be represented as the sum of the inertia force, gravitational force, wall friction loss induced by the flow, form loss by the geometric change of the flow path, and flow loss due to two phase retardation such as the velocity difference between the liquid and vapour phase, as given by equation (2).

$$-\frac{dP}{dz} = \rho_m u_m \frac{du_m}{dz} + \rho_m g_z + \left(-\frac{dP}{dz}\right)_{fr} + \left(-\frac{dP}{dz}\right)_{fo} + \left(-\frac{dP}{dz}\right)_{tp} \qquad (2)$$

In this study, the flow loss from two-phase retardation is ignored since the two-phase pressure loss is usually much smaller than other loss terms. If the energy losses are ignored through the flow channel, the energy equation can be represented simply by a balance between the flow enthalpy (h_m) change and heat input ($\dot{Q}$) through the heated channel wall, as given by equation (3).

$$\rho_m u_m A \frac{dh_m}{dz} = \left(\frac{d\dot{Q}}{dz}\right)_{in} \qquad (3)$$

The wall friction loss induced by a one- or two-phase flow in a dynamic equilibrium state can be described assuming only the liquid or the vapour phase to be flowing in the original channel with their respective mass flow rates.

The mixture quality (x) is defined as the flow enthalpy change due to the wall heat input, as given by equation (4). A method for predicting the void fraction is essential for predicting the acceleration and gravitational components of the pressure gradient in the two phase flow.

$$x \equiv \frac{h - h_f}{h_{fg}} = \frac{(h_{inlet} + \Delta h) - h_f}{h_{fg}} = \frac{(h_{inlet} - h_f) + \frac{1}{\dot{m}}\int q''\xi dz}{h_{fg}} \qquad (4)$$

Butterworth [3] has shown that several of the available void fraction correlations can be cast in a general form. In this study, a homogeneous model is used.

If the momentum equation is integrated over the entire circulating flow loop from the inlet to the outlet and then back to the inlet, the result must be zero as shown in equation (5).

$$\oint\left(-\frac{dP}{dz}\right)dz = \oint \rho_m u_m \frac{du_m}{dz}dz + \oint \rho_m g_z\, dz + \oint\left(-\frac{dP}{dz}\right)_{fr} dz + \oint\left(-\frac{dP}{dz}\right)_{fo} dz = 0 \qquad (5)$$

If the form loss term in equation (5) is formulated by the mixture velocity, the only unknown in equation (5) is the mixture velocity with assistance of the wall friction and form loss equations. Each term in equation (5) is numerically integrated along with the natural circulation flow loop by assuming the initial mixture velocity. A final mixture velocity that satisfies equation (5) can be obtained using trial-and-error method. If the mixture velocity is found by solving equation (5), then the natural circulation mass flow rate can be calculated by equation (1).

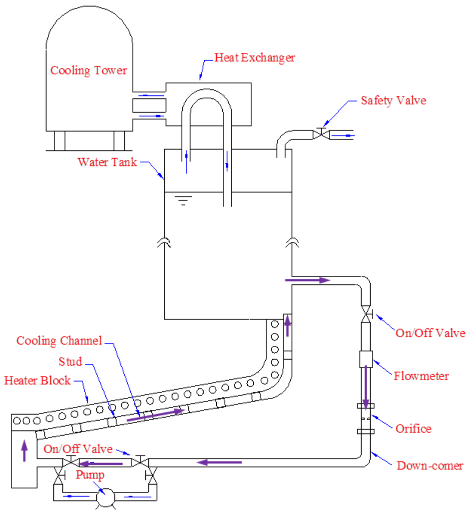

Fig. 1 Schematics of real-scaled natural circulation experimental facility

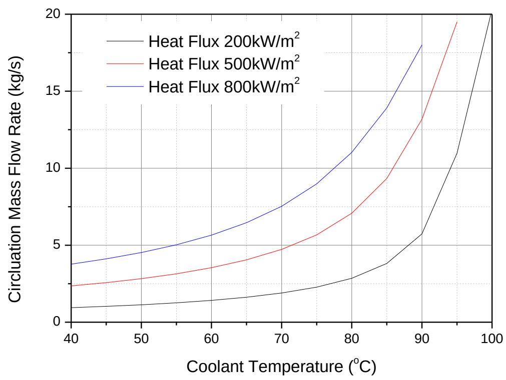

Fig. 2 Circulation mass flow rate along with coolant temperature and heat flux

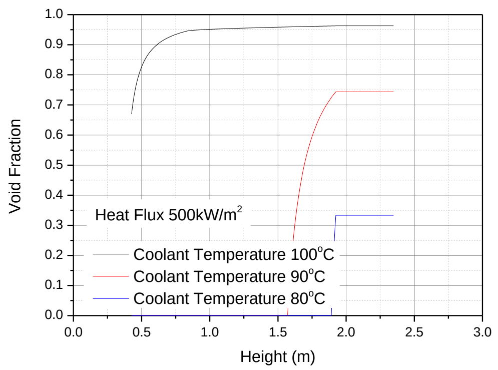

Fig. 3 Void fraction along with coolant temperature (heat flux 500kW/m^2)

As shown in Fig. 1, the target cooling channel is made of a single channel between the downward-facing heating block and wall [4]. The width of the cooling channel gap is 0.3m, and the horizontal length is 3m. The gap size of the cooling channel is 0.1m and the gap inclines 10 degrees to facilitate the steam venting. Short columnar structures (studs, 0.07m width × 0.1m length × 0.1m height) are placed between the heating block and wall, which is used to support the static and dynamic loading on the cooling channel. A down-comer, which has a 0.1m diameter, is provided to generate the natural circulation flow. A water tank is also installed to supply static pressure to the cooling channel.

In equation (4), the form loss term by the geometric change of flow path is modeled by considering a the discharge from a tube in the inlet and entrance of the water tank, an elbow in the tube, studs in the cooling channel, and a thick-edged orifice [5].

Figure 2 shows the calculated circulation mass flow rates along with the coolant temperature and uniform heat flux. As the coolant temperature and heat flux increase, the circulation mass flow rate also increases. Figure 3 shows the void fraction distribution with channel height according to the coolant temperatures at a uniform heat flux of 500kW/m^2. In the high sub-cooling cases, the boiling point is retarded on the height, and the circulation mass flow rate then decreases.

3. Conclusion

The boiling-induced natural circulation flow in a real-scaled experimental cooling channel was modeled and solved by considering the conservation of mass, momentum and energy in the two-phase mixture to estimate the natural circulation flow rate. The circulation mass flow rates and void fractions using a homogeneous void fraction model were calculated along with the coolant temperature and wall heat flux. It is expected that the more accurate void fraction model and related experimental data on the downward facing heating channels should be required to verify the calculated natural circulation flow rate.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science, ICT, and Future Planning) (No. NRF-2012M2A8A4025893).

REFERENCES

[1] K.S. Ha, F.B. Cheung, J.H. Song, R.J. Park, and S.B. Kim "Prediction of Boiling-induced Natural Circulation Flow in Engineered Cooling Channels", *Nuclear Technology* Vol.181, pp.196-207, 2013.
[2] S. Rouge, "SULTAN Test Facility for Large-Scale Vessel Coolability in Natural Convection at Low Pressure", *Nul. Eng. and Design* , Vol.69, pp.185-195, 1997.
[3] D. Butterworth, "A Comparison of Some Void-Fraction Relationships for Co-Current Gas-Liquid Flow", International Journal of Multiphase Flow. Vol.1, Issue 6, pp.845-850, 1975.
[4] B.W. Rhee, K.S. Ha, R.J. Park, and J.H. Song, "A Study on the effect of various design parameters on the natural circulation flow rate of the ex-vessel core catcher cooling system of EU-APR1400", Proc. of ICAPP12, Chicago, USA, June 24-28, pp. 87-93, 2012.
[5] I.E. Idelchik, Handbook of Hydraulic Resistance, 3rd Ed., Begell House, New York, 1994.