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Scaling Analysis of Natural Circulation Flow Loop

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1. Introduction

Various safety systems are designed and adapted in nuclear power plants to prevent postulated accidents, to enhance the life time and economic benefit, and to increase a 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 as recently presented by Rempe *et al.* [1]. 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 [2]. 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 [3].

An ex-vessel core catcher under consideration, which is one of the engineered corium cooling system, is a passive system consisting of an inclined engineered cooling channel made of a single channel between the body of the core catcher and the inside wall of the reactor cavity [4]. Under severe accident conditions, water is supplied from the IRWST to the engineered cooling channel. The water in the inclined channel absorbs the decay heat transferred from the corium through the carbon steel structure of the core catcher body and boils off as steam. The latter is subsequently released into the free volume of the containment above the corium spreading compartment. Water continues to flow from the IRWST to the cooling channel as a result of buoyancy-driven natural circulation. The engineered cooling channel is designed to provide effective long-term cooling and stabilization of the corium mixture in the core catcher body while facilitating steam venting. To maintain the integrity of the ex-vessel core catcher, however, it is required that the water coolant be circulated at a sufficiently high rate through the inclined cooling channel for decay heat removal by downward facing boiling of the water circulated from the IRWST. KAERI are performing constructing and performing the real scaled experimental facility to quantify the boiling-induced natural circulation flow rates in the inclined heating channels.

Generally, boiling-induced natural circulation flow experiments in the cooling channels should be scaled the real prototypic system down. Therefore the scaling analysis should be performed to design the scaled-down experimental facility and to maintain the characteristics of the real natural circulation flow. In this study, the scaling analysis was performed by solving the natural circulation flow loop equation for the cooling channel in the ex-vessel core catcher.

2. Analysis of two-phase natural-circulation flow

The two-phase flow is analyzed to predict the natural circulation mass flow rate occurring in the engineered corium cooling system [3]. 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 and vapor mass flow rate 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 by using force balances, that is, the pressure difference along the vertical 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 flow path, and flow loss due to two phase retardation such as the velocity difference between the liquid and vapor 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 due to two phase retardation is ignored since the two-phase pressure loss is usually much smaller than other loss terms [5]. If the energy losses are ignored through the flow channel, the energy equation can simply be represented by a balance between the flow enthalpy change and the heat input 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 one- or two- phase flow in dynamic equilibrium state can be described by equation (4), assuming only the liquid or the vapour phase to be flowing in the original channel with their respective mass flow rates

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$$\left(-\frac{dP}{dz}\right)_{fr}=\frac{f_v}{2D_h}\rho_m u_m^2 \tag{4}$$

The friction factor, *f*, depends on the Reynolds number of each phase. The values of *C* and *m* for evaluating the friction factor given by equation (5) depend on the type of flow taking place inside the channel.

$$f_a=C\,\mathrm{Re}_a^{-m}=C\left(\frac{\rho_a u_a D_h}{\mu_a}\right)^{-m} \tag{5}$$

The values of *C* and *m* are 64 and 1 for *Re* less than 2300, and 0.316 and 0.25 for *Re* greater than 2300.

The mixture quality is defined as the flow enthalpy change due to the wall heat input as given by equation (6).

$$x\equiv\frac{h-h_f}{h_{fg}}=\frac{(h_{inlet}+\Delta h)-h_f}{h_{fg}}=\frac{(h_{inlet}-h_f)+\frac{1}{\dot{m}}\int q''\xi dz}{h_{fg}} \tag{6}$$

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. Butterworth [6] has shown that several of the available void-fraction correlations can be cast in the general form given by equation (7).

$$\alpha=\left[1+B_B\left(\frac{1-x}{x}\right)^{n_1}\left(\frac{\rho_g}{\rho_f}\right)^{n_2}\left(\frac{\mu_f}{\mu_g}\right)^{n_3}\right]^{-1} \tag{7}$$

The values of the various constants in this relation corresponding to different correlations are listed in Table I [7].

As the void fraction is calculated by equation(7), the mixture density can be also obtained by equation(8).

$$\rho_m=\alpha\,\rho_g+(1-\alpha)\rho_f \tag{8}$$

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 (9).

$$\oint\left(-\frac{dP}{dz}\right)dz=\oint\rho_m u_m\frac{du_m}{dz}dz+\oint\rho_m g_z\,dz+\oint\left(-\frac{dP}{dz}\right)_{fr}dz+\oint\left(-\frac{dP}{dz}\right)_{fo}dz=0 \tag{9}$$

If the form loss term in Eq.(9) is formulated by the mixture velocity , the only unknown in Eq.(9) is the mixture velocity with the assistance of Eq. (4) through (8). Each term in Eq. (9) is numerically integrated along with the natural-circulation flow loop by assuming the initial mixture velocity. A final mixture velocity the initial mixture velocity is found by solving Eq.(9), then the natural circulation mass flow rate can be calculated by Eq.(1).

Table I: Valued of the constants used in Eq.(7)

Correlation or Model	B_B	n_1	n_2	n_3
Homogeneous model	1	1	1	0
Zivi model [8]	1	1	0.67	0
Wallis Separate Cylinder Model [9]	1	0.72	0.4	0.08

3. Target System and Scaling Methodology

The newly engineered corium cooling system, that is, an ex-vessel core catcher, has been considered as one of severe accident mitigation measures for an APR1400 [4]. The proposed ex-vessel core catcher concept can be adapted for both existing reactors and advanced light water reactors. It is a passively actuating device that can arrest and stabilize the molten core material inside the reactor cavity. The primary goal of the proposed ex-vessel core catcher is to reliably accommodate and rapidly stabilize the corium, including the entire core inventory and reactor internals that is injected into the cavity following a postulated severe accident. To achieve this important goal, the proposed core catcher design employs the combined effects of several key design components to: (i) direct the paths of relocation of the corium once the accident proceeds to the ex-vessel stage, (ii) retain the corium within the ex-vessel core catcher, (iii) promote spreading of the corium over the entire floor area of the core catcher, and (iv) provide effective long-term cooling of the corium so as to quickly achieve and maintain a stabilized corium configuration. These key design components include: (1) a composite layer of sacrificial material and protective material, (2) a corium spreading compartment, and (3) an engineered corium cooling system with passive natural circulation. The ex-vessel core catcher in an APR1400 is a passive corium cooling system consisting of an inclined engineered cooling channel made of a single channel between the body of the core catcher and the inside wall of the reactor cavity. If the severe accident in a nuclear power plant occurs and the reactor vessel fails, the molten corium ejected from the reactor vessel is relocated in the body of the ex-vessel core catcher. The water from the IRWST is supplied to the engineered cooling channel between the outside of the core catcher body and the reactor cavity wall. The supplied water in the inclined channel should sufficiently remove the decay heat transferred from the corium by boiling off as steam. A buoyancy-driven natural circulation flow through the cooling channel and down-comers is intended to provide effective long-term cooling, and to stabilize thermally the molten corium mixture in the core catcher body. In general, an increase in the natural circulation mass flow rate of the coolant leads to an increase in the critical heat flux on the hot wall, thus enhancing the thermal margin. Therefore, it should be ensured and quantified that the water coolant is circulated at a sufficiently high rate through the inclined cooling channel for decay heat removal to maintain the integrity of the ex-vessel core catcher system.

Figure 1 shows a schematic drawing of the prototypic ex-vessel core catcher. As shown in Fig. 1, the ex-vessel core catcher has a rectangular cross section with 16m width and 6m horizontal length. The cooling channel of the ex-vessel core catcher is made between the core catcher body and inside wall of the reactor cavity and the gap size of the cooling channel is 0.1m. Seven short columnar structures, called studs, each with a dimension of 0.113m diameter and 0.1m height, are placed in the cooling channel gap to support the static and dynamic loading on the core catcher body. The gap of the cooling channel is determined appropriately such that the cooling channel also has an inclination angle of 10 degrees to facilitate the steam venting. Each down-comer, which has a 0.15 m diameter and 1.3m distance, is provided to generate the natural circulation flow.

Figure 2 shows a schematic drawing of the experimental facility for the natural circulation flow simulation of the prototypic ex-vessel core catcher. As shown in Fig. 2, the horizontal length of the experimental facility is 3 m, that is, the half section of the core catcher is simulated. The gap size of the cooling channel is 0.1m as is the gap between the prototypic core catcher body and concrete body. Seven short columnar structures, called studs, each with a dimension of 0.079m×0.1m (diameter×height), are placed in the cooling channel gap, and the diameter are scaled to coincide with flow blockage ratio of the prototypic ex-vessel core catcher. The gap of the cooling channel is determined appropriately such that the cooling channel also has an inclination angle of 10 degrees as is the actual core catcher system to facilitate the steam venting. A water tank is also installed to supply static pressure to the cooling channel.

The experimental facility is prepared to simulate the unit down-comer section with 1.3m width. However, the width of the cooling channel of the experimental facility is only 0.3 m. Therefore the scaling analysis should be required. To meet the natural circulation mass flux between the prototypic core catcher and experimental facility, the diameter of the should be adjusted. Due to the experimental flexibility, the diameter of the down-comer set as 0.1 m, and the new orifice is provided in the down-comer section to match the pressure drop through the flow path in the down-comer with prototypic core catcher. The proper orifice diameter is selected by following scaling analysis.

The form loss term in the down-comer region of the equation (9) can be rearranged by equation (10). In equation (9), the circulation mass flow rate is normalized by the cooling channel area.

$$\oint\left(-\frac{dP}{dz}\right)_{fo} dz = \frac{K_{total}}{2}\rho_{inlet}u_{inlet}^2$$
$$= \frac{K_{total}}{2}\rho_{inlet}\left(\frac{\dot{m}}{\rho_{inlet}A_{dn}}\right)^2 = \frac{K_{total}}{2\rho_{inlet}}\left(\frac{\dot{m}}{A_{ch}}\right)^2\left(\frac{A_{ch}}{A_{dn}}\right)^2 \qquad (10)$$

To match the circulation flow condition of the experimental facility with that of the prototypic core catcher, the circulation mass fluxes of two systems should be same. If the circulation mass flux in the experimental facility is same as in the prototypic core catcher, the equation (11) should be satisfied.

$$\left[K_{total}\left(\frac{A_{ch}}{A_{dn}}\right)^2\right]_{\text{Prototypic}} = \left[K_{total}\left(\frac{A_{ch}}{A_{dn}}\right)^2\right]_{Experimental} \qquad (11)$$

The ratio of total form loss factor in the experimental facility to in the prototypic core catcher is inversely proportional reciprocally to the squared area ratio of the cooing channel to the down-comer as shown in equation (12). Considering the experimental facility and prototypic core catcher geometries, the total form loss factor in down-comer region of the experimental facility should be 3.71 times larger than in the prototypic core catcher.

$$\frac{\left[K_{total}\right]_{Experimental}}{\left[K_{total}\right]_{\text{Prototypic}}} = \frac{\left[(A_{ch}/A_{dn})^2\right]_{\text{Prototypic}}}{\left[(A_{ch}/A_{dn})^2\right]_{Experimental}} = 3.71 \qquad (12)$$

4. Results and Discussion

The equation (9) can be solved numerically to get the K-factors and circulation mass flow rates of the prototypic and experimental facility. Figure 3 shows the assumed heat flux distribution imposed by the molten corium in the core catcher which was estimated considering the natural convection of the molten corium in the core catcher. Figures 4 and 5 show the calculated circulation mass flow rates and mass fluxes of the prototypic and experimental facility. As shown in Figs 4 and 5, the circulation mass flow increases as the inlet subcooling decreases because the quality at the exit of the cooling channel increases as the inlet temperature increases. In Figs. 4 and 5, the experimental facility has no orifice. As shown in Fig. 5, the circulation mass flux of the experimental facility without orifice is higher than of the prototypic core catcher system. This is why the area ratio of the cooling channel to the down-comer in the experimental facility is smaller than in the prototypic system, that is, the down-comer sizing in the experimental facility is overestimated compared to the prototypic one. As shown in Figs. 4 and 5, the circulation mass flow rates and mass fluxes are varied with void fraction models, that is, homogeneous, Wallis Separate Cylinder [9], and Zivi models [8]. The Wallis Separate Cylinder model [9] estimates the lowest void fraction for a given mixture quality, so the induced mass flow rate and mass flux are also the lowest as can be seen from Figs. 4 and 5.

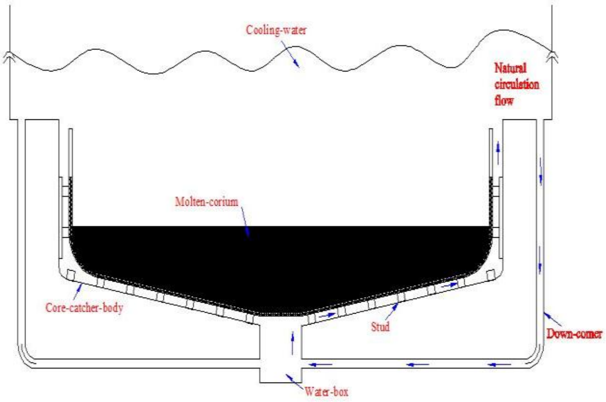

Fig. 1. Schematic of the prototypic core catcher system

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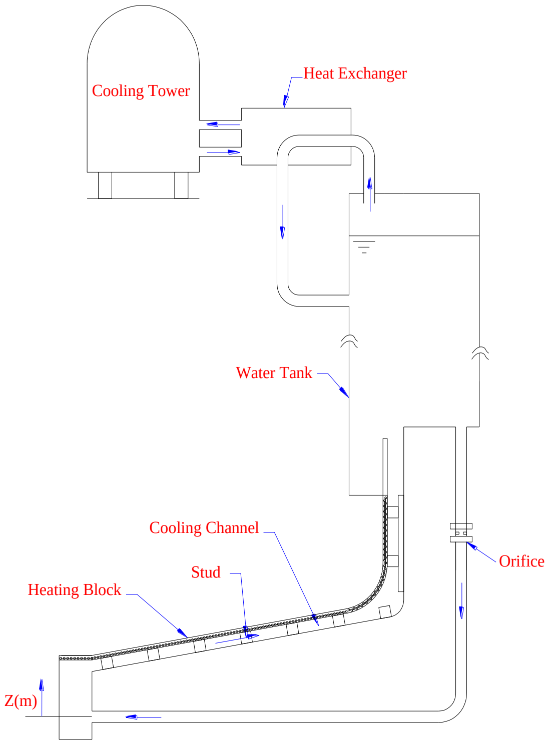

Fig. 2. Schematic of the experimental facility.

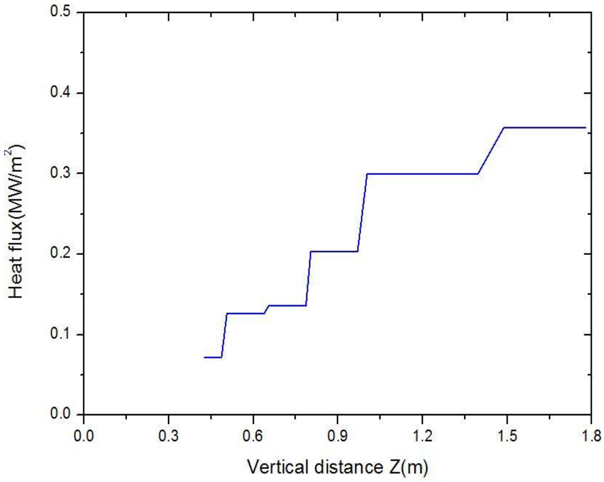

Fig.3. Heat flux distribution imposed on the cooling channel

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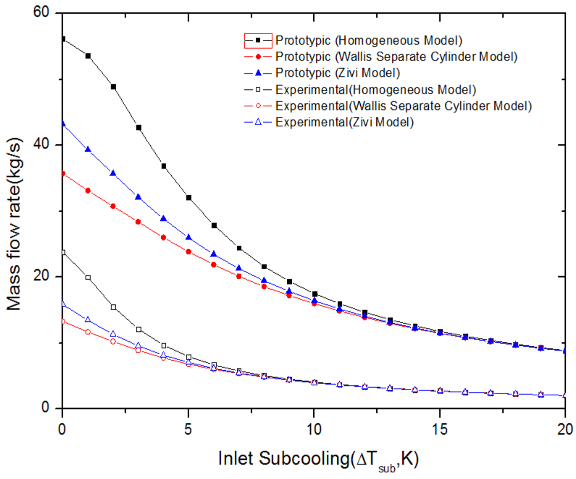

Fig. 4.The calculated mass flow rate in the experimental facility without orifice with respect to the inlet subcooling and void fraction model

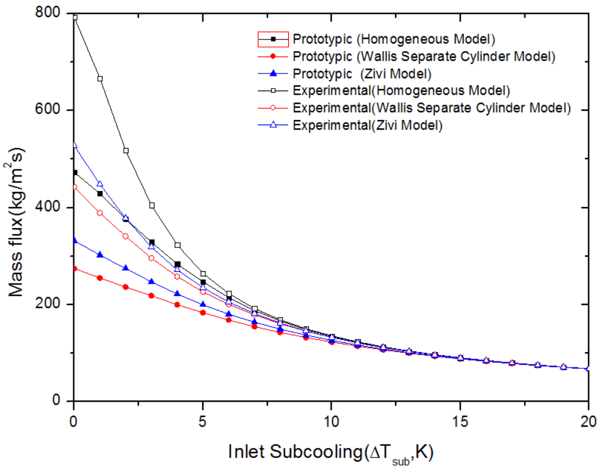

Fig. 5.The calculated mass flux in the experimental facility without orifice with respect to the inlet subcooling and void fraction model

Figure 6 shows the calculated total form loss factors in the experimental facility without orifice and in the prototypic down-comer regions with respect to the inlet subcooling. As shown in Fig. 6, the form loss factor is independent of the void fraction models and slightly changed by the inlet subcooling. In Table II, shows the averaged total form loss factors in the experimental facility without orifice and in the prototypic down-comer regions are summarized. The total form loss factor in the prototypic down-comer region is calculated as 2.4, therefore, the total form loss factor in the experimental down-comer region should be 8.9 as shown in equation (12). As the calculated total form loss factor in the experimental down-comer region without orifice is calculated as 2.9, the form loss of the orifice should be 6.0, so the orifice diameter is selected as 0.067m. Figure 6 also shows the calculated total form loss factors in the experimental facility with orifice with respect to the inlet subcooling.

Figure 7 shows the calculated circulation mass flux of the prototypic and experimental facility with an orifice whose diameter is 0.067m. As shown in Fig. 7, the circulation mass flux in the experimental facility with the orifice exactly coincide with in the prototypic core catcher system even though the different void fraction models are applied. This is why the quality and void fraction at the exit of the cooling channel in the experimental facility with the orifice are same as in the prototypic core catcher as shown in Figs. 8 and 9.

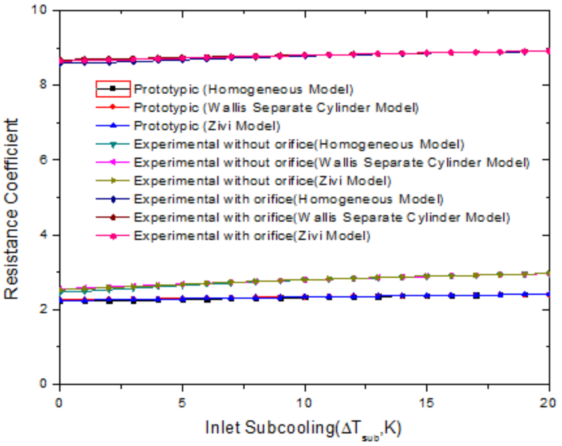

Fig 6. Form loss factor in the down-comer region with respected to the inlet subcooling and void fraction model

Table II: Total form loss factors of the prototypic and experimental facility

Parameters	Prototypic	Experimental
Channel width	1.3(m)	0.3(m)
Down-comer Dia.	0.15(m)	0.1(m)
K_{total} without orifice	2.4	2.9
K_{total} target	2.4	2.4x3.71=8.9

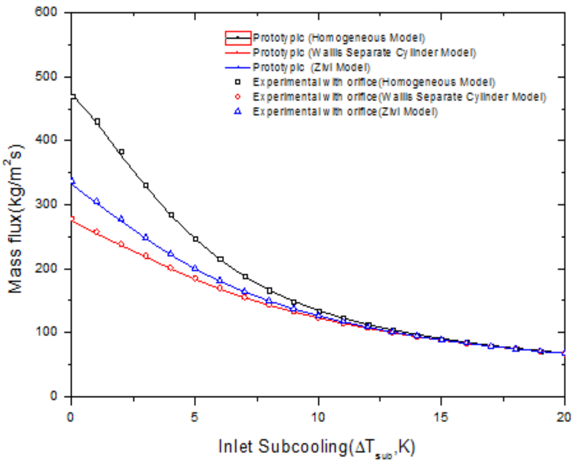

Fig.7. The calculated mass flux in the experimental facility with orifice with respect to the inlet subcooling and void fraction model

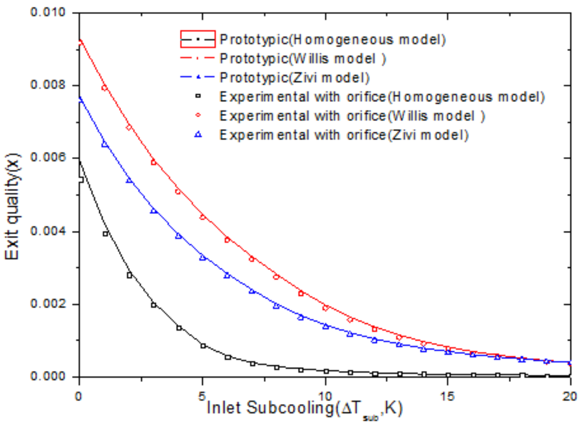

Fig.8. The exit quality in the experimental facility with orifice with respect to the inlet subcooling and void fraction model

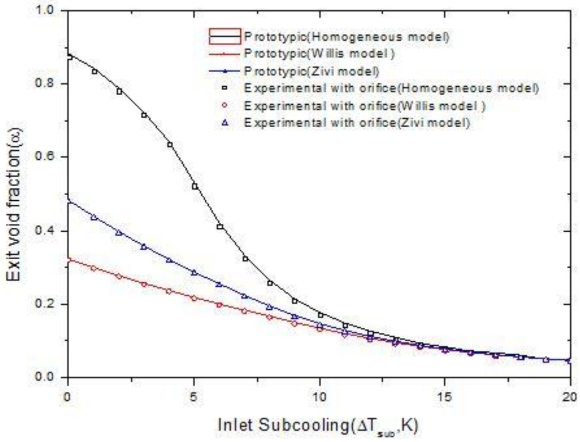

Fig.9. The exit void fraction in the experimental facility with orifice with respect to the inlet subcooling and void fraction model

5. Conclusion

The scaling analysis was performed by solving the natural circulation flow loop equation for the cooling channel in the ex-vessel core catcher. The boiling-induced natural circulation flow in the cooling channel of the core catcher has been modeled by considering the conservation of mass, momentum and energy in the two-phase mixture, along with the two-phase friction drop and void fraction. The resulting governing system has been solved numerically to predict the natural circulation flow rate that would be induced in the channel by the downward-facing boiling process for given flow area and inclination of the channel relative to the gravitational field.

In order to compensate the geometric discrepancy between the experimental facility and prototypic core catcher system, the orifice was selected by the scaling analysis with relation of total form loss factor in the down-comer region and area ratio of the cooing channel to the down-comer. The circulation mass flux, the quality, and void fraction at the exit of the cooling channel in the experimental facility with selected orifice exactly coincided with in the prototypic core catcher system even though the different void fraction models were applied. In conclusion, the scaling analysis methodology for the natural circulation flow loop was proposed and successfully verified.

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