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KAERI Activities on the Cooling Performance of Ex-vessel Core Catcher

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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 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]. A 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].

Recently, a 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 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 a 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 thermally stabilize 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 (CHF) 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.

KAERI has performed various researches to validate the cooling performance of an ex-vessel core catcher. First, a scaling analysis was performed to design the scaled-down experimental facility and maintain the characteristics of the real natural circulation flow by solving the natural circulation flow loop equation for the cooling channel in the ex-vessel core catcher. Second, boiling-induced natural circulation flow experiments in the cooling channels of the ex-vessel core catcher were investigated. Finally, a new correlation was developed to estimate the natural circulation mass flow rate with the inclined downward facing heating surface.

2. Ex-vessel core catcher system

The newly engineered corium cooling system, PECS (Passive Ex-vessel corium retaining and Cooling System), that is, an ex-vessel core catcher, has been considered as one of the 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 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 a severe accident occurs in a nuclear power plant and the

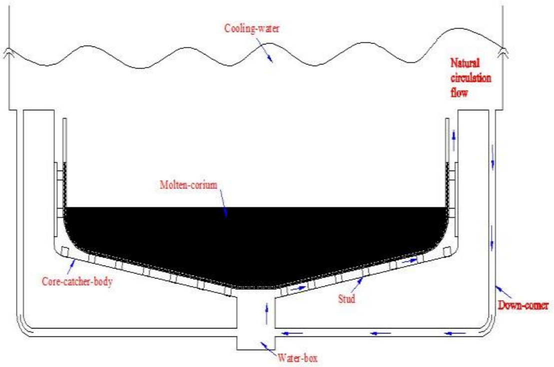

Fig. 1. Schematic of the prototypic core catcher system

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 thermally stabilize 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 a 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 dimensions of 0.113m in diameter and 0.1m in 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.

3. Scaling analysis

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

The two-phase flow is analyzed to predict the natural circulation mass flow rate occurring in the engineered corium cooling system [2]. 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).

$$\dot{m} = \rho_m u_m A = \dot{m}_f + \dot{m}_g \tag{1}$$

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 the flow path, and the flow loss due to two phase retardation such as the velocity difference between the liquid and vapor phase, as given by equation (2).

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

In this study, the flow loss due to two phase retardation is ignored since the two-phase pressure loss is usually much smaller than the 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).

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

If the momentum equation (2) 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 (4).

$$\oint \left(-\frac{dP}{dz}\right) dz = \oint \rho_m u_m \frac{du_m}{dz} dz + \oint \rho_m g_z \, dz + \oint \left(-\frac{dP}{dz}\right)_{fr} dz + \oint \left(-\frac{dP}{dz}\right)_{fo} dz = 0 \tag{4}$$

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

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, a half section of the core catcher is simulated. The gap size of the cooling channel is 0.1 m, as is the gap between the prototypic core catcher body and concrete body. Seven short columnar structures, called studs, each with dimensions of 0.079m×0.1m (diameter×height), are placed in the cooling channel gap, and the diameter is 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 was prepared to simulate the unit down-comer section with a 1.3m width. However, the width of the cooling channel of the experimental facility is only 0.3 m. Therefore, a 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 is 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 a prototypic core catcher. The proper orifice diameter is selected through the following scaling analysis.

The form loss term in the down-comer region of equation (4) can be rearranged by equation (5). In equation (4), the circulation mass flow rate is normalized by the cooling channel area.

$$\oint\left(-\frac{dP}{dz}\right)_{fo} dz = \frac{K_{total}}{2}\rho_{inlet}u_{inlet}^2 = \frac{K_{total}}{2}\rho_{inlet}\left(\frac{\dot{m}}{\rho_{inlet}A_{dn}}\right)^2 = \frac{K_{total}}{2\rho_{inlet}}\left(\frac{\dot{m}}{A_{ch}}\right)^2\left(\frac{A_{ch}}{A_{dn}}\right)^2 \quad (5)$$

To match the circulation flow condition of the experimental facility with that of the prototypic core catcher, the circulation mass fluxes of the two systems should be same. If the circulation mass flux in the experimental facility is the same as in the prototypic core catcher, equation (6) should be satisfied.

$$\left[K_{total}\left(\frac{A_{ch}}{A_{dn}}\right)^2\right]_{Prototypic} = \left[K_{total}\left(\frac{A_{ch}}{A_{dn}}\right)^2\right]_{Experimental} \quad (6)$$

The ratio of total form loss factor in the experimental facility to that 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 (7). Considering the experimental facility and prototypic core catcher geometries, the total form loss factor in the down-comer region of the experimental facility should be 3.71-times larger than in the prototypic core catcher.

$$\frac{\left[K_{total}\right]_{Experimental}}{\left[K_{total}\right]_{Prototypic}} = \frac{\left[(A_{ch}/A_{dn})^2\right]_{Prototypic}}{\left[(A_{ch}/A_{dn})^2\right]_{Experimental}} = 3.71 \quad (7)$$

Equation (4) can be solved numerically to obtain the K-factors and circulation mass flow rates of the prototypic and experimental facility. Table I shows the averaged total form loss factors in the experimental facility without an orifice and in the prototypic down-comer regions. The total form loss factor in the prototypic down-comer region is calculated as 2.4, and therefore, the total form loss factor in the experimental down-comer region should be 8.9, as shown in equation

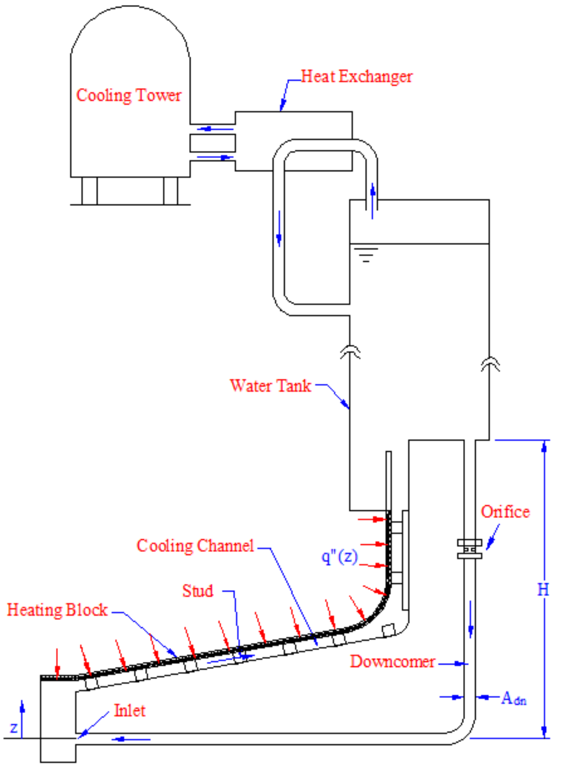

Fig. 2. Schematic of the experimental facility.

(7). As the calculated total form loss factor in the experimental down-comer region without an orifice is calculated as 2.9, the form loss of the orifice should be 6.0, and thus the orifice diameter is selected as 0.067m. Figure 3 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 coincides with the prototypic core catcher system even though 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.

Table I: 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

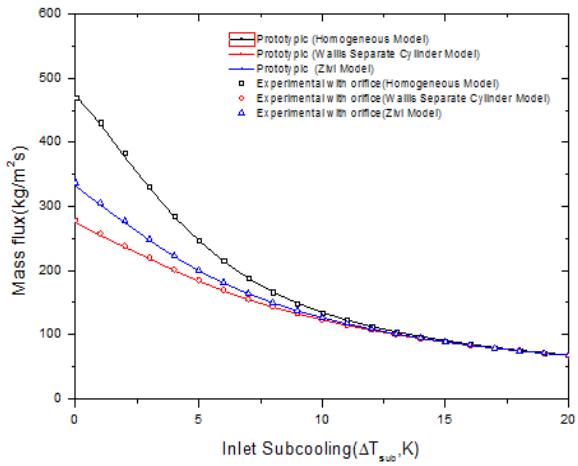

Fig. 3. The calculated mass flux in the experimental facility with an orifice with respect to the inlet subcooling and void fraction model

Fig. 4. Photograph of cooling experimental facility.

4. Cooling experiment

Boiling-induced natural circulation flow experiments in the cooling channels of the ex-vessel core catcher, the so-called CE-PECS (Cooling Experiments for PECS), are investigated. A scaling analysis was applied to design the test facility compared with the prototypic core catcher cooling system.

As shown in Fig. 4, the experimental cooling channel is made of a single channel simulating the actual cooling channel between the core catcher body and inside wall of the reactor cavity. The width of the cooling channel and the heating block is 0.3 m, and the horizontal length is 3 m. The gap size of the cooling channel is 0.1m, as is the gap between the core catcher body and concrete body. Seven short columnar structures, called studs, each with dimensions of 0.079m×0.1m (diameter× 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, as is the actual core catcher system to facilitate the steam venting. A down-comer, which has a 0.1 m diameter, is provided to generate a natural circulation flow. A water tank is also installed to supply static pressure to the cooling channel. The measuring parameters during the test are the input power using a power-meter, the total circulation mass flow rate of the coolant using a flow meter, the local coolant temperature using T-type thermocouples, the local heated wall temperature using K-type thermocouples, the local pressure using pressure transducers, the water level in the coolant tank using a level transmitter, the estimated void fractions using vertical differential pressure transmitters, and a visualization of the flow pattern in the coolant channel using a camera.

Two kinds of tests were carried out. One is the basic natural circulation (NC) test with a transient inlet subcooling condition (i.e., rising inlet coolant temperature), and the other is a steady state NC test with the inlet subcooling (i.e., inlet coolant temperature) kept constant at the desired condition. In the prototype PECS, the real plant condition will be more like the first case, i.e., NC with transient inlet subcooling condition as the coolant is expected to rise continuously up to the saturation condition due to the continued heating from the corium heat source. However, for the future use of the experimental data for validating the computer codes to be used for licensing purposes, steady state experiments were also carried out.

The steady state NC test is one with the inlet subcooling kept constant using the heat exchange installed on the downcomer. For this test, a heat exchanger is installed in the returning line of the down-comer. The heat exchanger installed on the downcomer section may affect the NC flow rate by the induced pressure drop. The steady and unsteady results are the same, and therefore, the pressure drop by the heat exchanger is certainly negligible. The natural circulation mass flux reaches up to 270kg/m^2·sec at 5K of inlet subcooling. If the water level height is quite low, and a high heat flux exists, the steady state NC flow rate is found to be larger than those of the basic NC test results. This is thought to be caused by the inlet coolant increasing rate being relatively high compared to all other cases. In summary, it can be concluded that except those cases where the rate of inlet coolant temperature rise exceeds 0.05K/sec, the basic NC test results match those of the quasi-steady test results. In spite of this discrepancy, the test results of the basic NC test is thought to be used safely as the basic NC test results fall on a more conservative side than the steady state NC test results.

To maintain the integrity of the ex-vessel core catcher, it is necessary that the coolant be circulated at a rate along the inclined cooling channel sufficient to avoid CHF (Critical Heat Flux) on the heating surface of the cooling channel. A series of forced circulation CHF tests using the pump were carried out to estimate the CHF for a range of channel mass flux and inlet coolant subcooling. This is an alternative method devised to replace the natural circulation critical channel power test where the heating power needs to increase monotonously until a critical heat flux condition is reached anywhere in the cooling channel. The critical heat flux test was performed under the NC flow condition measured from the basic and steady state tests. For a given operating condition such as the given thermal load and water subcooling, the critical heat flux did not occur even at the zero recirculation flow rate. In this case, the CCFL (Count Current Flow limitation) type of critical heat flux was found to occur at the heat flux level corresponding to 1.4-times the given heat flux distribution.

5. Correlation development

A new correlation has been developed to estimate the natural circulation mass flow rate with the inclined downward facing heating surface when considering the mass, momentum, and energy conservation equations. By the loop integration of the momentum equation (4) through the natural circulation loop, the dimensionless numbers were extracted to correlate the natural circulation mass flow rate with the heating power, inlet sub-cooling, inlet pressure, etc. as shown in equation (8) .

$$C_1 \exp\left(-\frac{C_2 Dt}{Po}\right) = Mf^2\left[1+B_B\left(\frac{Mf}{Po-Dt\cdot Mf}\right)^{n1}\left(\frac{\rho_g}{\rho_f}\right)^{n2}\left(\frac{\mu_f}{\mu_g}\right)^{n3}\right] \quad (8)$$

In equation (8), three dimensionless numbers were introduced, that is, a dimensionless mass flow rate, Mf, which is defined in terms of the mass flow rate, the density of the liquid, height of the heating section, and cross section area of the liquid path; dimensionless heating power, Po, defined as latent heat, heating power, density of liquid, height of the heating section, and cross section area of liquid path; and finally a dimensionless sub-cooling, Dt, defined as water sub-cooling at the heating channel inlet, specific heat capacity, and the latent heat, as shown in equations (9) through (11).

$$Mf = \frac{\dot{m}}{\sqrt{g_z\, H}\;\rho_f\; A_{dn}} \quad (9)$$

$$Po = \frac{\dot{Q}/h_{fg}}{\sqrt{g_z\, H}\;\rho_f\; A_{dn}} \quad (10)$$

$$Dt = \frac{C_{p,f}\;\Delta T_{sub}}{h_{fg}} \quad (11)$$

Equation (8) is an implicit formula on the circulation mass flow rate, and is dependent of the void fraction model, that is, the two-phase flow regime, heating power, inlet sub-cooling, and inlet pressure, which affect the coolant properties such as the density and viscosity. C_1 and C_2 in equation (8) can be set by the known data obtained experimentally or numerically, and the values are dependent on the geometrical form factor and void fraction model.

The developed correlation was verified using the numerical results on the natural circulation flow loop with the inclined downward facing heating channel, which simulated the ex-vessel core catcher in the APR1400. Figure 5 shows the dimensionless mass flow, Mf, along with dimensionless inlet sub-cooling, Dt, and dimensionless heating power, Po, compared with the developed correlations and the numerical simulation results. As shown in Figure 5, the developed correlations predicted well the numerical simulation

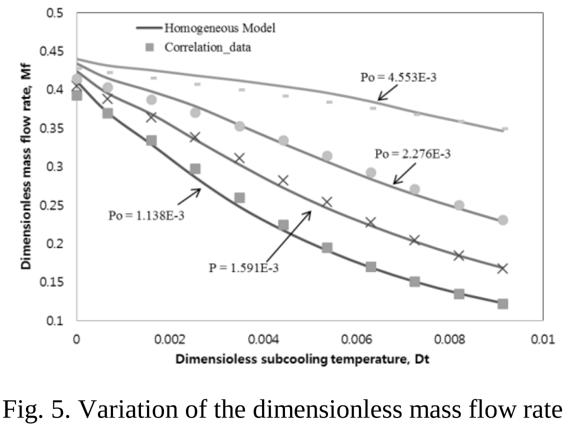

Fig. 5. Variation of the dimensionless mass flow rate along with dimensionless sub-cooling at pressure 1.29 bar (homogeneous model)

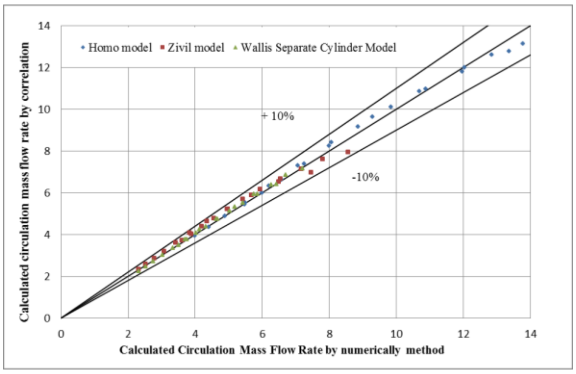

Fig. 6. Error bounds of developed correlations with numerical simulation results

results at different heating powers, inlet sub-cooling, and void fraction correlations. Figure 6 shows that the errors of the results with the developed correlations are bounded within 10 percent, and this therefore shows that the circulation mass flow rate can be calculated using a numerical method or based on the developed correlation.

6. Conclusion

KAERI has performed various researches to validate the cooling performance of the ex-vessel core catcher. First, the scaling analysis was performed to design the scaled-down experimental facility and maintain the characteristics of the real natural circulation flow by solving the natural circulation flow loop equation for the cooling channel in the ex-vessel core catcher. Secondly, boiling-induced natural circulation flow experiments in the cooling channels of the ex-vessel core catcher were investigated. And finally, a new correlation has been developed to estimate the natural circulation mass flow rate with the inclined downward facing heating surface.

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, which would be induced in the channel by the downward-facing boiling process for the given flow area and inclination of the channel relative to the gravitational field.

To compensate the geometric discrepancy between the experimental facility and prototypic core catcher system, the orifice was selected by the scaling analysis with the relation of the 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 the selected orifice coincided exactly with the prototypic core catcher system even though the different void fraction models were applied. In conclusion, a scaling analysis methodology for the natural circulation flow loop was proposed and successfully verified.

In the experiment, the effect of the water level, heat flux, heat flux distribution, core catcher vertical side-wall length, and coolant temperature were studied. A natural circulation test was carried out in two stages, one with freely increasing coolant temperature without the heat exchanger, i.e., transient test, which is to be referred to as the basic test from now on, and the other with a controlled coolant temperature using the heat exchanger, i.e., a steady state test. As a result, the NC (natural circulation) flow rate increases with the heat flux and inlet coolant temperature, and the effect of the water level and the length of the vertical side-wall were not noticeable. As for the effect of varying heat flux distribution, the NC flow rate was a little increased with the that with a larger heat load to the end part of the cooling channel. A series of forced circulation CHF tests using the pump were also carried out to estimate the CHF for a range of channel mass flux and inlet coolant subcooling. For a given operating condition such as the given thermal load and water subcooling, the critical heat flux did not occur even at the zero recirculation flow rate, that is, the CCFL (Count Current Flow limitation) type of critical heat flux was found to occur at the heat flux level corresponding to 1.4-times the given heat flux distribution.

The natural circulation flow correlation with inclined downward facing heating channel was developed by considering the mass, momentum, and energy conservation equations by three dimensionless numbers, that is, the dimensionless numbers of mass flow rate, heating power, and inlet sub-cooling. The natural circulation flow rates of the target system, which was applied for the cooling channel of the core catcher in an APR1400, were modeled and calculated using a numerical method based on conservation equations to obtain two correction factors, and the results were compared with the developed correlations. The dimensionless mass flow rate obtained by the developed correlation agreed well with the heating power, inlet sub-cooling, and void fraction model compared with the numerical simulation results.

As the two correction factors in the developed correlation depend on the boiling initiation point and form loss through the circulation loop, a more detailed mechanical modeling of the two correction factors should be required. The experimental data related to the natural circulation mass flow rate will be used to verify the developed correlation.

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