Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Calculation of Natural Convection Phenomena in Core Catcher System

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1. Introduction

PECS (passive ex-vessel corium retaining and cooling system) is the Korean core catcher originally developed for EU-APR. When a severe accident occurs and the molten corium is ejected from the reactor vessel, the PECS retain the molten corium and cool down it by the natural convection of coolant suppled from in-containment refueling water storage tank (IRWST).

To validate the coolability of PECS in case of severe accidents, the natural convection phenomena of two-phase flow in PECS channel need to be examined by analyses or by experiments. Variable PECS experimental facility (VPEX) was recently designed and built to investigate the phenomena experimentally, and natural circulation calculator (NCir) code was developed to predict the flow rate of the natural convection and the void fraction along the channel.

In this article, the natural convection phenomena in PECS was examined by comparing the flow rates calculated by NCir code with those from existing experimental results of CE-PECS. The scaling analyses were performed for the new experimental facility, VPEX. In addition, the flow instability in PECS and in VPEX were predicted using the calculation results.

2. PECS and VPEX

Figure 1 shows the schematic of PECS and the validation facility, VPEX. PECS is composed of the V-shape steel body with the top sacrificial layer to retain the molten corium, and the sloped cooling channel under the bottom surface of the structure. When molten corium is ejected from the reactor vessel by a severe accident, the cooling water is suppled from the IRWST and fills the reactor cavity. The coolant is then cooling down the molten corium by the natural convection flow through the channel under the core catcher body, and at the same time, the flooded water on top of the corium.

VPEX is designed to validate the cooling capability of PECS by investigating the natural convection phenomena through the sloped cooling channel. VPEX is composed of the sloped cooling channel, the upper pool, and the downcomer which provides the flow path for flow circulations. On top of the cooling channel, metal blocks with electric cartridge heaters are installed to simulate the heat flux from the molten corium during severe accidents.

Table 1 shows the geometrical values of PECS and VPEX. The slope and the length of the cooling channel are the same each other, however, the channel width was scaled down.

Table 1 Geometry of PECS and VPEX

Variable	PECS	VPEX
Sloped channel	10°, 2.7m	
Total channel width	16 m	0.7 m
Channel width per downcomer	1.3 m	0.3 m
Downcomer diameter	0.15 m	0.1 m

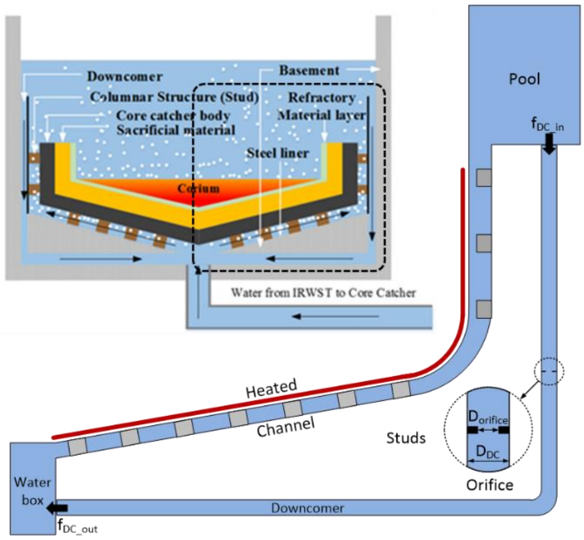

Fig. 1 Schematic of PECS and VPEX

3. Natural Circulation Calculator (NCir)

NCir code were developed to calculate the simple 1-D two-phase natural convection for arbitrary loop geometry. The code calculates the momentum equation over the natural convection loop as

$$-\frac{dP}{dz} = \rho_m u_m \frac{du_m}{dz} + \rho_m g_z + \left(\frac{dP}{dz}\right)_{friction}$$

where subscript m means two-phase mixture. Integrating the equation over the loop, the total pressure drop at the left hand side becomes zero. The density ρ of the water-steam mixture can be calculated by the void fraction which can be expressed generally by

$$\alpha = \left[1 + B\left(\frac{1-x}{x}\right)^{n1}\left(\frac{\rho_g}{\rho_f}\right)^{n2}\left(\frac{\mu_f}{\mu_g}\right)^{n3}\right]$$

where x is steam quality calculated by the inlet enthalpy and the supplied heat to the coolant, μ is viscosity, and subscript g and f are gas and fluid, respectively. The constants B, n1, n2, n3 are given in Table 2.

Table 2 Constants for void faction calculation

Correlation	B	n1	n2	n3
Homogeneous	1	1	1	0
Zivi [1]	1	1	0.67	0
Wallis seperate cylinder model [2]	1	0.72	0.4	0.08
Lockhart and Martilelli [3]	0.28	0.64	0.36	0.07
Thom [4]	1	1	0.89	0.18
Baroczy [5]	1	0.74	0.65	0.13

NCir code provides user inputs for the geometry of the natural circulation loop, heat flux, and the boundary condition such as the inlet subcooling and the pressure. The code also provides the options of correlations used for the void fraction calculation and the two-phase friction calculation. Among the options for the two-phase friction calculation, the methods of Muller-Steinhagen & Heck was used for the results shown in this article [6].

With the provided user input file, the code calculates the mass flow rate of natural circulation, and the void fraction along the channel. The code also calculate the pressure drop of each section of the loop.

4. Calculation Results

4.1 Comparison with CE-PECS results

Figure 2 shows the experimental facility, CE-PECS, which is similar to VPEX but has narrower single cooling channel and one downcomer. Series of experiments were conducted to investigate the natural convection phenomena of PECS to check the basic coolability of PECS cooling channel, however, the effect of different channel width, uneven heat flux, and the flow instability could not be tested due to the fixed channel geometry of the facility.

Figure 3 shows the heat flux shape along the channel used in the CE-PECS tests. The shape A is increasing heat flux along the channel, whereas the shape B is decreasing.

Figure 4 shows the comparison of NCir calculation with the CE-PECS test case T7-1. The case T7-1 is the test with 100% heat flux of the shape A and with pool water height of 3.06 m. The calculation results fits the experimental data well for some of the void fraction correlations. The homogeneous, Lockhart-Martinelli, Thom, and Baroczy correlations fits the experimental data quite well, however, Zivi and Wallis correlations underpredict the experimental results. The results also depends on the calculation methods of two-phase friction, however, the influence of two-phase friction calculation is much smaller than that of void fraction correlation.

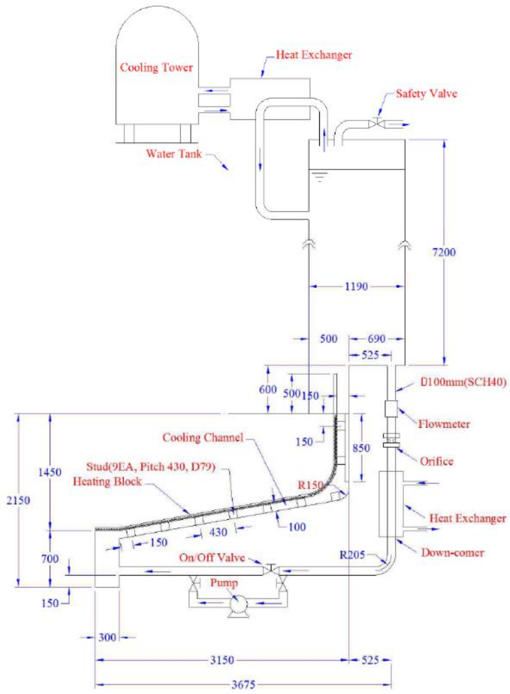

Fig. 2 CE-PECS experimental facility

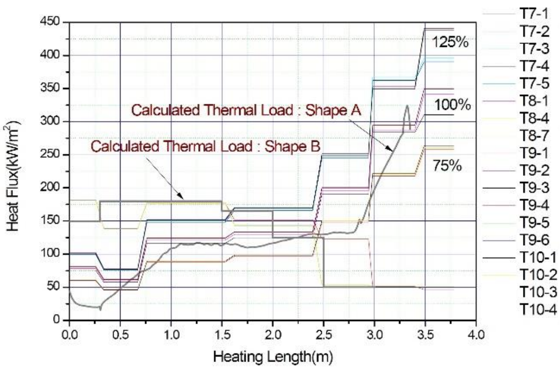

Fig. 3 Heat flux of CE-PECS along the channel

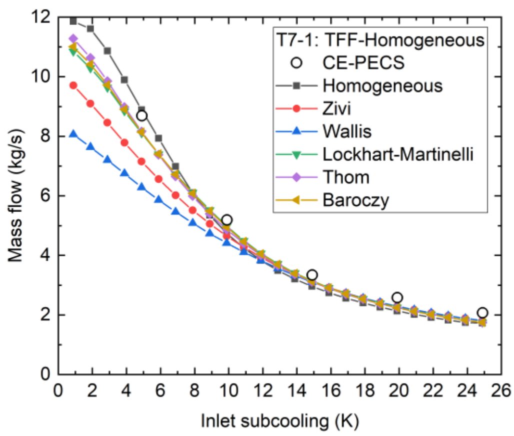

Fig. 4 Comparison of NCir calculation and CE-PECS experimental results (case T7-1)

4.2 Scaling analyses of VPEX

Figure 5 shows variable channel configuration of VPEX experimental facility. VPEX has been designed such that the channel geometry can be modified by the internal structures such as the studs and the center wall. Without the center wall, the VPEX channel become a 70 cm wide single channel. On the other hands, double channel experiments can be conducted by installing the wall at the center of the channel. With the variable channel geometry of VPEX, the effect of the channel width, uneven heat flux distribution, and two-phase flow instability between two parallel channels can be evaluated experimentally.

For each channel geometery of VPEX, the frictional loss at the downcomer region should be changed to satisfy the scaling analyses between PECS and VPEX. Instead of changing the whole downcomer pipes, the orifice diameter installed at the downcomer section was replaced to fulfill the required frictional loss at the downcomer region.

Figure 6 shows the calculation results with different channel geometry without installing orifice, and with the orifices with proper opening diameter. In the calculations, the Lockhart-Martinelli correlation was used for the void fraction calculation. Without the orifice, the frictional loss at the downcomer section is relatively smaller than that of PECS, therefore, the mass flow rate of natural circulation becomes much higher than that of PECS. On the other hands, the flow rates becomes identical to that of PECS with the orifice diameters satisfying the scaling analyses results for each channel geometry.

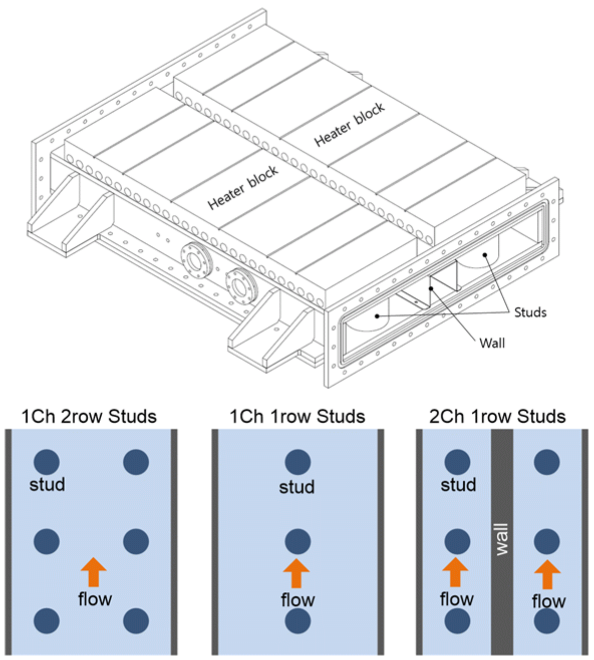

Fig. 5 Channel configuration of VPEX

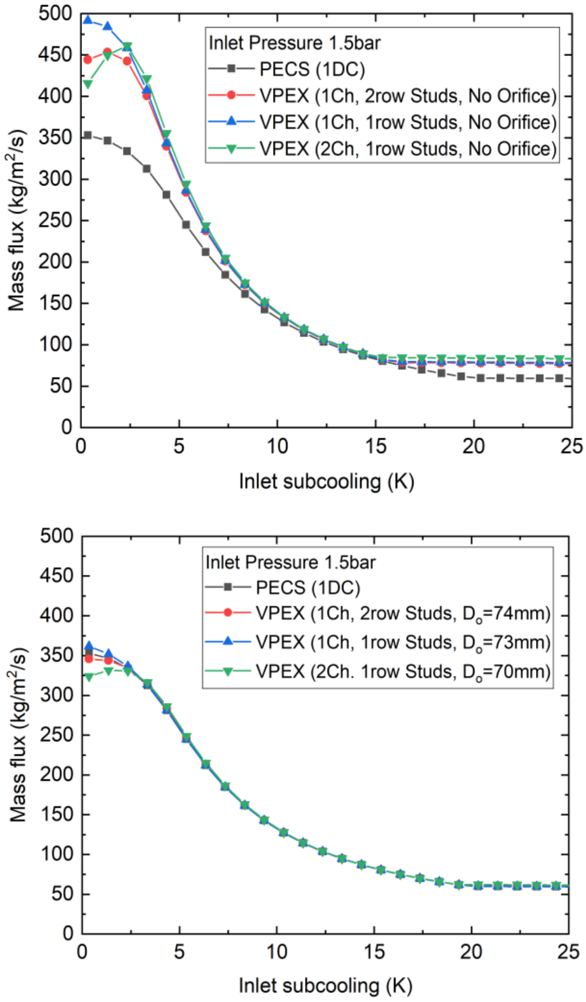

Fig. 6 Determining orifice diameter for each channel geometry

4.3 Two-phase flow instability

Figure 7 shows comparison of the density wave oscillation (DWO) model and the PECS/VPEX natural circulation loop. The flow resistance at the channel inlet of the DWO model corresponds to the sum of the flow resistances in the downcomer region in the PECS/VPEX loop, and the channel outlet of the DWO model becomes the outlet of heating channel. The inlet and the outlet pressure are kept constant because the upper pool is exposed to an atmospheric condition.

The Ledinegg instability and the DWO instability can be examined on the map drawn with the non-dimensional numbers, the subcooling number (N_{sub}) and the phase change number (N_{pch}) defined as

$$N_{pch} = \frac{Q}{\dot{m}_{in}(h_g - h_f)} \frac{\rho_f - \rho_g}{\rho_g}$$

$$N_{sub} = \frac{h_f - h_{in}}{h_g - h_f} \frac{\rho_f - \rho_g}{\rho_g}$$

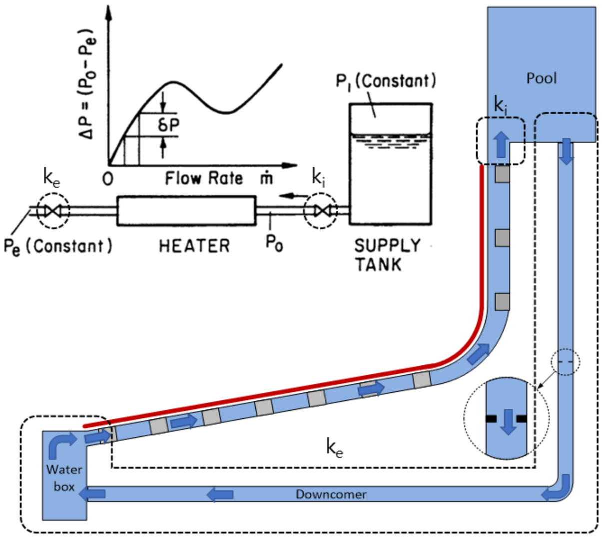

Fig. 7 DWO in PECS and VPEX

The instability criteria are [7]

DWO instability:

$$N_{pch} - N_{sub} < \frac{\tau}{2}\left(1+\frac{2}{N_{sub}}\right) - \frac{5}{2} + \left\{\left[\frac{\tau}{2}\left(1+\frac{2}{N_{sub}}\right) - \frac{5}{2}\right]^2 + \tau\right\}^{1/2}$$

Ledinegg instability:

$$N_{pch} > 2N_{sub} - \tau, \qquad \tau = \frac{2(K_i+K_e)}{K_e+1}$$

Figure 8 shows the instability map drawn with the calculation results for the PECS and for the VPEX. The high subcooling makes the flow to be kept in single phase, therefore, no instability occurs with high subcooling condition. Also, the low heat flux of 140kW/m^2, Ledinegg or DWO instability are not probable because of the mild boiling phenomena at the heater surface. With higher heat flux, the DWO instability is probable for certain subcooling region. The region of DWO instability seems relatively larger in PECS rather than VPEX. On the other hands, the region of Ledinegg instability is larger in VPEX than PECS. If the subcooling approaches to zero, which means the coolant is already in saturation condition from the inlet, the two-phase instability does not occur.

In the APR1000, the target plant for the validation of PECS, the maximum heat flux expected at the upper surface of the cooling channel is less than 200kW/m^2. The DWO instabilities is not expected to occur for VPEX in this low heat flux region, however, it is possible in PECS because the unstable region is larger in PECS system. To observe the DWO instability expected in the PECS system, the experiment with higher heat flux is required for the VPEX system.

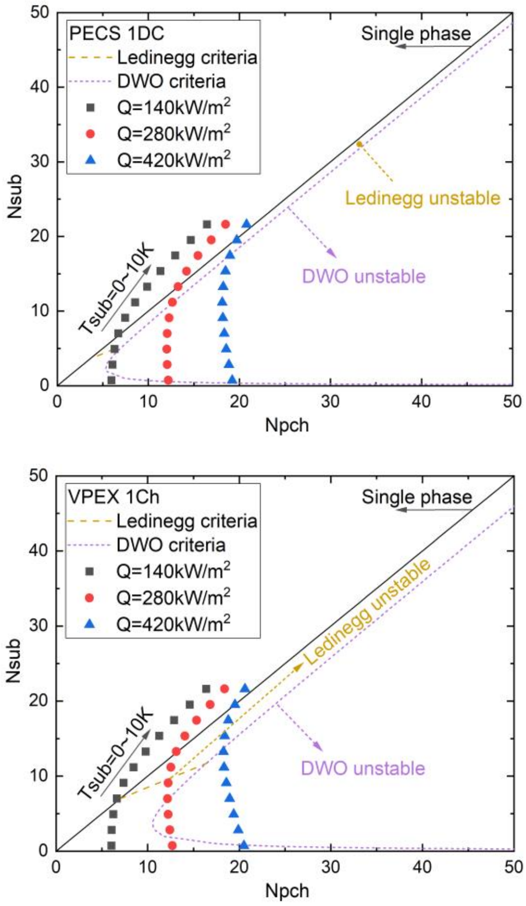

Fig. 8 DWO and Ledinegg instability map for PECS and VPEX

5. Summary

Natural circulation calculator (NCir) code were developed to examine the natural convection phenomena expected in PECS core catcher and VPEX experimental facility. The code calculates the circulation mass flow and the void fraction in the arbitrary shaped natural convection loop.

The code calculation was validated with the existing CE-PECS experimental results and showed good agreement with proper selection of void fraction correlation.

Considering the various channel geometries of VPEX, the scaling analyses were conducted to determine the orifice diameter for each channel configuration, and the result showed that the VPEX could simulate the natural convection in PECS properly.

The possibility of two-phase flow instability in PECS and VPEX were examined using flow instability map, and the results showed the condition in which the Ledinegg and the DWO instabilities could occur.

The NCir code will be used for analyzing the planned experiments using VPEX, also for comparison with the other analyses result using CFD code or those using system code such as MAAP5.

Acknowledgement

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (Ministry of Trade, Industry and Energy) (No.KETEP-20217810100040).

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