Prediction of Flow Instability of Natural Convection in Sloped Channel

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1. Introduction

A core catcher is the system to retain and to cool down the molten corium safely when it is ejected from the reactor vessel during severe accidents. Although there are many kinds of core catcher design, all of them rely on the natural convection of coolant to remove the heat from the molten corium.

PECS (passive ex-vessel corium retaining and cooling system) is the core catcher developed for the Korean nuclear power plants (NPPs). The domestic NPPs have used in-vessel retention by external reactor vessel cooling (IVR-ERVC) strategy for molten corium cooling, however, the core catcher was developed to satisfy the various needs of foreign NPP market.

The typical phenomenon of the PECS operation is a two-phase natural convection through the sloped wide channel. Since it is a complicated two-phase phenomenon, a proper validation is required for future licensing procedures to show the cooling performance of the PECS during severe accidents. Among the expected phenomena in the PECS system, a two-phase flow instability is one of the most important phenomena deteriorating the cooling performance in the channel.

A validation facility of the PECS is designed to examine the cooling performance of the PECS sloped channel, and the validation tests are planned to be performed. Before the actual experimental tests, various types of two-phase flow instabilities are listed and explained, and then the possibilities of occurrences in PECS validation facility are evaluated.

2. PECS Core Catcher and Validation Facility

Figure 1 shows the schematic of PECS [1]. The PECS is composed of the V-shape steel structure body to retain the molten corium, and the sloped cooling channel under the bottom surface of the steel structure. A sacrificial material covers the upper surface of the steel structure to protect the steel from the direct contact to the molten corium. The steel structure has studs on the bottom surface, to secure the cooling channel between the bottom surface and the basement. Multiple downcomers are embedded in the concrete wall to allow the path for the coolant circulation by the natural convection.

The molten corium ejected from the reactor vessel by a severe accident hit the upper sacrificial layer on the core catcher, and starts spreading over the structure. At the same time, the molten corium reacts with the sacrificial layer, delaying the direct contact of the corium to the steel structure until the coolant is supplied.

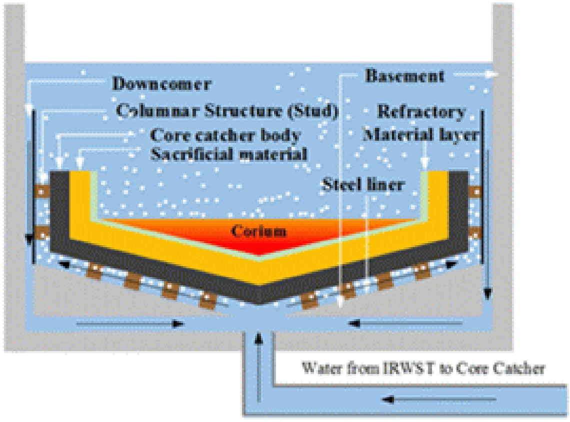

Fig. 1 Schematic of Korean core catcher

After the cooling water is supplied from the IRWST through the pipe connected to the bottom of the core catcher channel, the water box, the coolant flows through the sloped channel between the core catcher structure and the basement and cools down the molten corium indirectly. The flow circulates through the sloped channel and the downcomers, and at the same time, the coolant removes the heat from the upper surface of the corium by a boiling heat transfer.

Figure 2 shows the schematic of the validation facility of PECS. The validation facility scales down the sloped cooling channel and the loop for the natural circulation of PECS. The channel width is narrowed down for the tests, and the water tank on top of the channel resembles the upper pool of the PECS. The facility simulates the region including one downcomer, and the channel width were adjustable between 300 mm to 700 mm, using internal structures.

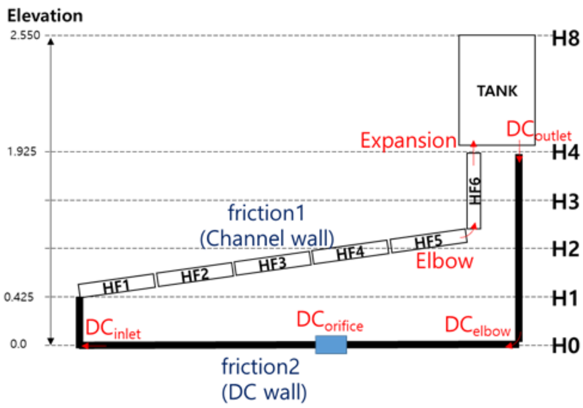

Fig. 2 Schematic of PECS validation facility

Table 1 Types of two-phase flow instabilities

Type	Instabilites	Causes
Static	Ledinegg	Negative slope of channel characteristic curve
	Flow pattern transition	Flow pattern transition from one regime to another
	Geysering	Periodic adjustment of metastable condition
	Natural circulation	Certain region of channel gathers bubble
Dynamic	Acoustic oscillation	Resonance of pressure wave
	Density wave oscillation	Delay and feedback effect of flow, density and pressure drop
	Pressure drop oscillation	Dynamic interaction between channel and compressible volume

3. Two-phase flow instabilities

Table 1 shows the different types of two-phase flow instabilities, which are categorized into the static or the dynamic instability [1]. The static instability means that the system has multiple equilibrium states, therefore the flow state moves among the different equilibrium points. On the other hand, the dynamic instability is the flow oscillation due to interactions and delayed feedbacks between the inertia and the compressibility of the two-phase mixture.

Ledinegg instabilities occurs due to the channel characteristics and the flow supply characteristics. The operating point of the channel is determined at the intersection point of the demand curve of the channel and the supply curve. If the curves have multiple points of intersection, the flow condition can change from one point to another.

Flow pattern transitions occurs when the flow condition is near the shifting point of two different flow regime. For example, the flow condition is near the transition points between bubbly and slug flow regime, the flow can be shifted between the flow regimes, which induces the flow instability.

Geysering means the instability by an abrupt evaporation of coolant. The process breaks down into boiling delay, expulsion of vapor, and liquid returning [2]. Among the three processes, the boiling delay takes much longer than the other processes, therefore, the period of the geysering is equal to the boiling delay, which is similar to the time required to heat the subcooled water in the channel to the saturation temperature.

Natural circulation instability occurs when the channel has a part in which bubbles can accumulates. The PECS and its validation facility has smooth channel shape, therefore, the bubble accumulation is not probable.

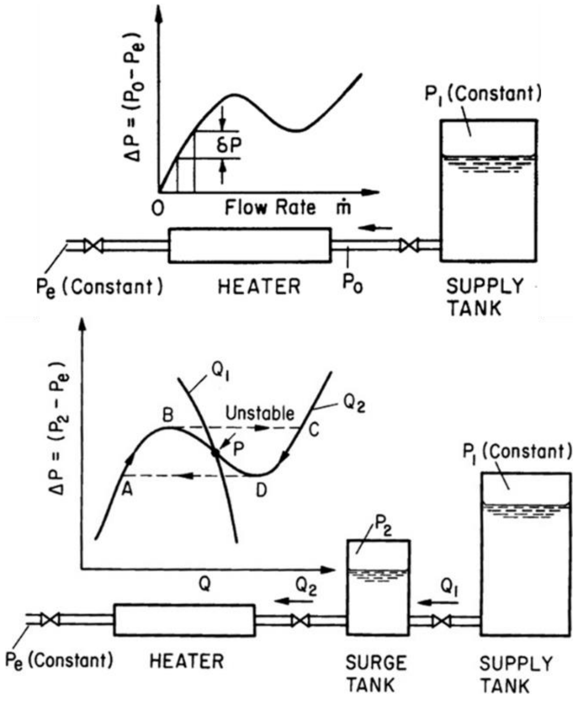

Fig. 3 Mechanism of DWO (upper) and PDO (lower)

Among the dynamic instabilities, acoustic oscillation is not considered in the system because the resonance frequency is too high for this large system.

Figure 3 shows the mechanisms of the density wave osccilation (DWO) and the pressure drop oscillation. The density wave oscillation starts when the exit pressure drop decreases suddenly from its steady-state. The decrease of the exit pressure drop causes the inlet pressure, P_0, decrease. Then, the inlet velocity increases by the pressure difference, P_i-P_0, increases. Since the P_e is constant, the increased inlet velocity results in an increase of P_0 because the pressure drop at the channel increases. Because P_i is also constant, the increase of P_0 results in the decrease of inlet flow velocity. Therefore, the flow velocity oscillates periodically.

The pressure drop oscillation occurs when a compressible volume is in the system. While the system operates at a point P, when the pressure of the surge tank increases a little, the flow entering the surge tank increases and the flow exiting the tank decreases by the characteristic curve Q_1 and Q_2. Then, the water is accumulated in the surge tank, and then the pressure P_2 increases upto point B. By the curve Q_2, the pressure difference cannot increase further, then the operating point moves abruptly to C. At the point C, the flow increases a lot, and then the pressure difference decreases. The operating point moves to the point C, and then abruptly to the point A. By the flow decrease, the surge tank level increases, then the operating point shifts to B again. The PDO is the flow oscillation by the operating point tracing B-C-D-A-B. The PDO occurs when the channel characteristic curve has negative slope, so-called N-shape.

4. Analyses Results

4.1 Flow Pattern Transition

Figure 4 shows the RELAP5 model of the PECS validation facility. The average heating power from the upper wall of the channel is 160 kW/m^2, and the water level is 2.35 m. The channel width in this analysis were set to be 300 mm, and the overall friction balance between the channel and the downcomer were set to be the same as the actual PECS cooling channel.

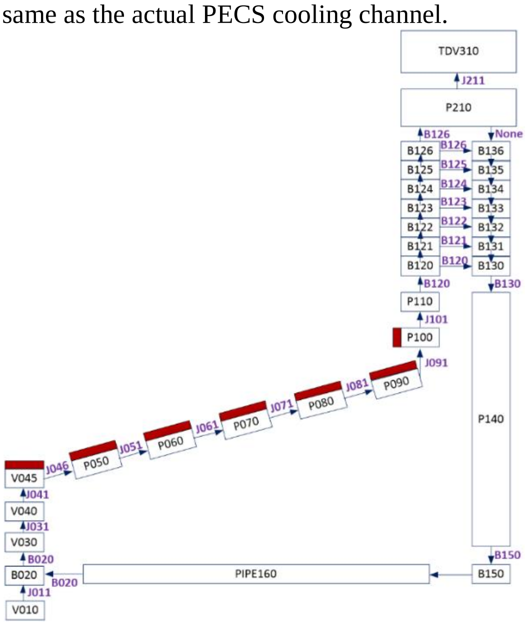

Fig. 4 PECS validation facility model

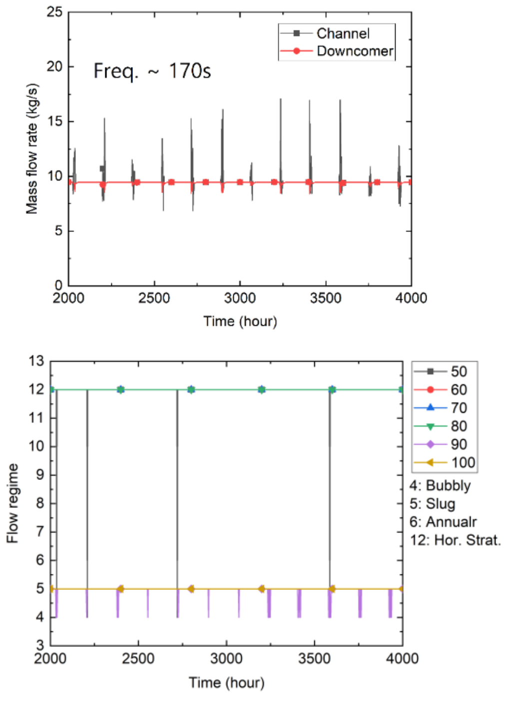

Fig. 5 Flow rate (upper) and flow regime in channel (lower)

Figure 5 shows the mass flow rate of the analyses and the corresponding flow regime in the channel. The downcomer flow rate is constant over the time, however, the flow rate at the channel shows periodic peaks, which are considered to be the result of a flow instability. The flow regime at the of the channel is either a slug flow or a horizontal stratified flow, however, the flow periodically becomes a bubbly flow, which induces the periodic flow peaks. The cause of this periodic change of the flow regime is that the void generation and removal at each section of the channel is not constant over the time. The void is generated at the wall of a channel section is accumulated for a certain amount of time, and then removed from the section when the void fraction becomes sufficiently high. After the void escape the section, the flow regime becomes a bubbly flow because the void fraction is low at that time.

4.2 Pressure Drop Oscillation

To examine the possibility of PDO occurrence in the PECS validation facility, a simple calculation model was developed using momentum and energy conservation equation for a closed loop with heated section. For the PECS validation system shown in Fig. 2, the pressure drop at the heated channel section can be written as

$$\Delta P = \Delta P_{acc} + \Delta z \left(\frac{dp}{dz}\right)_{fric}.$$

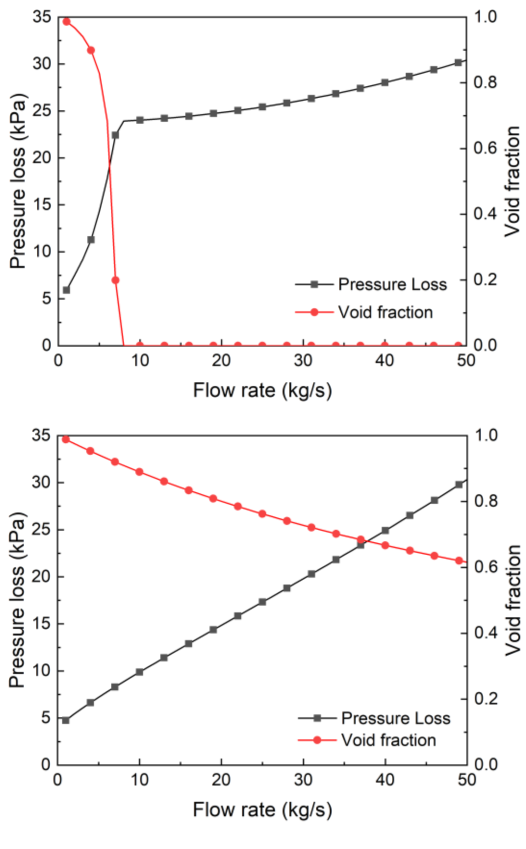

Fig. 6 Void fraction and pressure drop at the channel: inlet subcooling of 6K (upper) and 0K (lower)

Here the ΔP_{acc} is the pressure drop by density changes of the fluid, and the following frictional pressure drop were calculated using Lockhart & Martinelli correlation [3][4].

The pressure drop at the regions except the channel is some of the pressure drop at each section such as

$$\Delta P_{DC,sum} = \Delta P_{inlet} + \Delta P_{outlet} + \Delta P_{DC,elbow} + \Delta P_{DC,orifice} + \Delta P_{DC,wallfriction}$$

Solving the energy and the momentum equation over the PECS validation system, the mass flow rate and the corresponding void fraction can be calculated at the channel. With those results, the pressure drop with respect to the flow rate can be estimated, which is the characteristic curve of the channel.

Figure 6 shows the pressure drop and the outlet void fraction of the channel with respect to the flow rate. When the inlet subcooling is 6 K, the pressure drop increases fast with the flow rate while the mass flow rate is less than 8 kg/s however, the negative sloe of pressure drop over the flow rate is not shown, which means that the PDO is not probable. When the inlet subcooling is 0, which means that the inlet is in saturated condition, the pressure drop gently increases over the entire flow rate range. Therefore, no PDO is expected regardless of the inlet subcooling. This is because the pressure drop over the entire coolant loop was relatively smaller than the hydrostatic head by gravity. PDO is plausible in the smaller system in which the pressure drop across the channel is comparable to the hydrostatic head, or the horizontal system without no gravitational loss.

4.3 Density Wave Oscillation and Ledinegg Instability

Figure 7 shows the model to analyze the possibility of DWO in the PECS validation facility. The flow resistance at the channel inlet can be modeled as the sum of the flow resistance in the downcomer region, and then the inlet and outlet pressure are kept constant because the upper pool of the facility is exposed to an atmospheric condition.

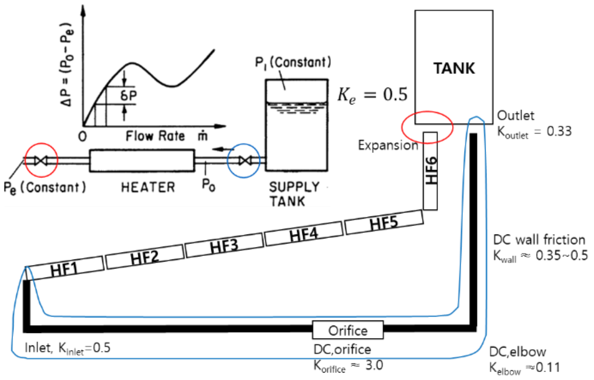

Fig. 7 DWO in PECS validation facility

The Ledinegg instability and the instability by density wave oscillation can be examined on the map drawn with the non-dimensional numbers, the subcooling number (N_{sub}) and the phase change number (N_{pch}). The two nondimensional numbers are defined as

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

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

The criteria in which the instabilities occur are [5]

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:

$$N_{pch} > 2N_{sub} - \tau$$

where $\tau = \frac{2(K_i + K_e)}{K_e + 1} \approx 6.8$ for the current flow loop

Figure 8 shows the instability map drawn with the calculation results at the PECS validation facility with the conditions in Table 2. In all of the power conditions, the high subcooling makes the flow to be the single phase, which means there's no two-phase instability. If the power small, from 100 to 200 kW/m^2, the DWO is not probable. With the power of 300 kW/m^2, the DWO is probable with a certain range of the subcooling, 1 to 4 K. Also, Ledinegg instability can occur with high heat flux and moderate subcooling condition. If the subcooling is very small, no Ledinegg instability is expected to occur. On the other hand, if the subcooling is too high, the flow becomes single-phase, therefore no instability is probable.

Table 2 Analyses Conditions

Conditions	Value
Reference heat flux (kW/m^2)	100, 160, 200, 300
System pressure (bar abs)	1.49
Inlet subcooling (K)	0~20

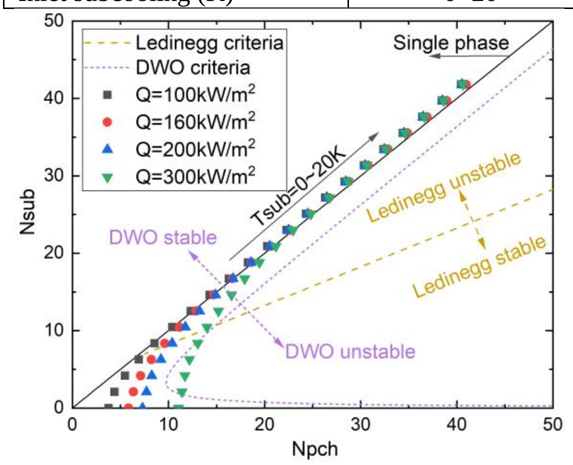

Fig. 8 DWO and Ledinegg instability map

5. Summary

For the PECS validation facility, probable two-phase flow instabilities are listed and explained. Among the static and dynamic flow instabilities, the flow pattern transition, the pressure drop oscillation (PDO), the density wave oscillation (DWO), and the Ledinegg instabilities were examined.

The flow pattern transition in the channel were observed with the RELAP5 calculation simulating the PECS validation facility. The flow pattern shifted from slug or horizontally stratified flow to bubbly flow, and the flow rate showed peaks at the time of the transition.

The PDO were observed when the channel characteristic curve shows negative slope at certain region, however, the negative slope were not shown in the system regardless of the subcooling, because of the relatively small pressure drop over the flow loop compared to the hydrostatic head.

The Ledinegg instability and the DWO were examined on the map drawn with the phase change number and the subcooling number with the expected experimental conditions. The DWO and Ledinegg instabilities were probable in a certain range of subcooling with a high surface heat flux condition.

The current expectations of the instability occurrence facilitate a better understanding on the two-phase flow in a heated channel. The current analyses will be validated when the experimental results are available.

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