Two-Phase Flow Instability in Parallel Sloped Channels

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1. Introduction

PECS (passive ex-vessel corium retaining and cooling system) is a Korean core catcher developed for exporting nuclear power plants. PECS keeps and cools down the molten corium in the structure when the corium is ejected from the reactor vessel by a severe accident. The major mechanism for corium cooling in PECS is a natural convection through the sloped channel under the body.

Since the natural convection accompanies a coolant boiling in the channel, two-phase flow instabilities need to be considered when validating the cooling capability of PECS. The coolant channels of PECS are wide and symmetric for the centerline of PECS. Therefore, multiple channels share the same inlet and outlet in PECS. In this configuration, the two-phase flow instability can cause uneven flow distribution to the multiple channels, which deteriorates the cooling capability of PECS.

In this article, the natural convection in parallel heated sloped channels were tested experimentally by using the experimental facility, VPEX. A two-phase flow instability was observed by the tests depending on the boundary conditions of the inlet subcooling and the heat flux. The cooling capability were also shown when the flow instability exists.

2. PECS and VPEX

Figure 1 shows the schematic of PECS. PECS is composed of the V-shape steel body with the top sacrificial layer to retain the molten corium, and the sloped cooling channels below the body. Upon the corium ejection from the reactor vessel, the sacrificial layer initially protects the steel body from direct contact with the corium. Then, coolant is supplied from IRWST (in-containment refueling water storage tank) to the sloped channel. The coolant circulates through the channel via the downcomer by natural convection, and cools down the steel body and corium. At the same time, the flooded water on top of the core catcher also cools down the corium.

VPEX(variable PECS experimental facility) is a scaled down experimental facility to validate the cooling capability of PECS channels. Heater blocks with cartridge heaters on top of the channel simulates the heat flux from the molten corium.

The special feature of VPEX is a capability of multi-channel experiment. The VPEX channel can be divided into two parallel channels by installing a wall in the channel. The parallel channels of VPEX simulate the symmetric channels of PECS when folded along the axis of symmetry.

Table 1 shows the geometrical similarities of PECS and VPEX. The slope and the length of the cooling channel are the same each other, but the channel width and the downcomers are scaled down.

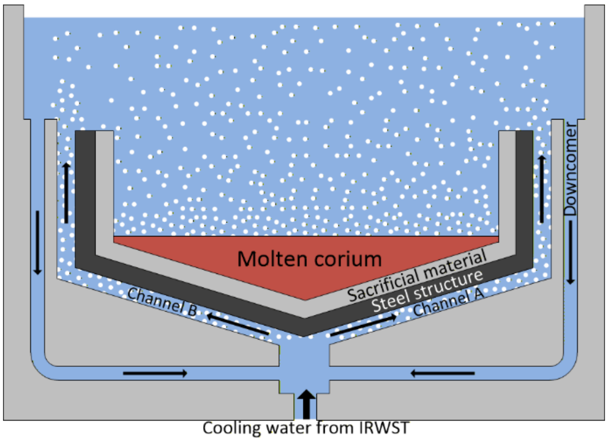

Fig. 1 Schematic of PECS core catcher

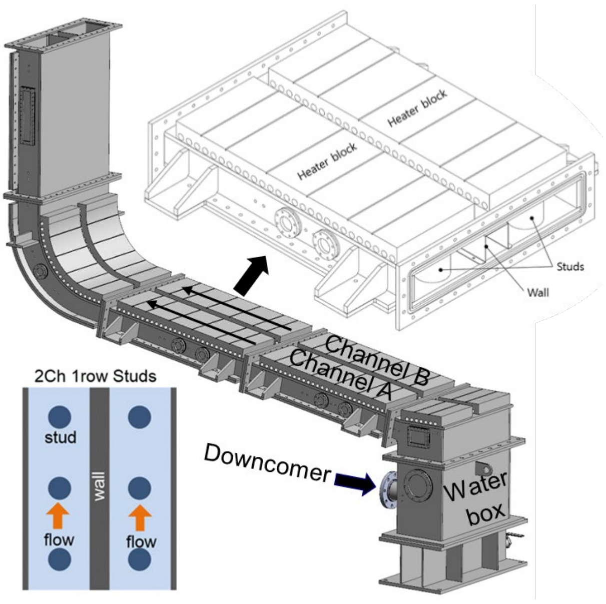

Fig. 2 VPEX 2 Channel Experiment

Table 1 Sloped channel geometry of PECS and VPEX

Variable	PECS	VPEX
Channel angle and length	10°, 2.7m	
Channel width	16 m x 2 (symmetric)	0.3 m x 2
Downcomer diameter	0.15 m	0.1 m
Number of downcomers	13 x 2	2

3. Parallel Channel Experiments

Parallel channel experiments were performed with VPEX test facility for different inlet coolant temperature and for various heat fluxes. Table 2 shows the test matrix of the experiments. The inlet temperatures and the pressures were measured at the channel inlet, waterbox, and the inlet subcooling were calculated for the saturation temperature at the pressure. The inlet subcooling of D1SHRb case was the lowest achievable value in VPEX, because the channel inlet coolant was drawn from the downcomer inlet, at which the saturation temperature is lower than the channel inlet due to the hydraulic head. The minimum inlet subcooling is the same as that in PECS because VPEX and PECS has the same elevations in channels and downcomers.

Figure 3 shows the heat flux distribution of PECS and VPEX. The solid line shows the heat flux distribution of PECS calculated by CFD considering the flow and solidification of molten corium for a typical severe accident scenario. The heat flux distribution was then discretized into 5 sections for the heater blocks of VPEX. The average heat flux of 132 kW/m^2 was varied from 75% to 175% to test the effect of heat flux to the flow instability. Detailed explanation about VPEX facility and the experimental results for single channel tests can be found elsewhere [1,2]. Here, only the multi-channel tests are presented to discuss about the two-phase instability of the parallel channels sharing the same inlet and outlet.

Table 2 Test matrix of multi-channel experiments

Test name	Pressure (bar)	Inlet Subcooling (K)	Average heat flux (kW/m^2)
D1SHRb	1.80 ± 0.05	6.3 ± 0.3	99,132, 166,199, 232
D1WHR		12.6 ± 2.0	
D1CHR		16.3 ± 0.2	

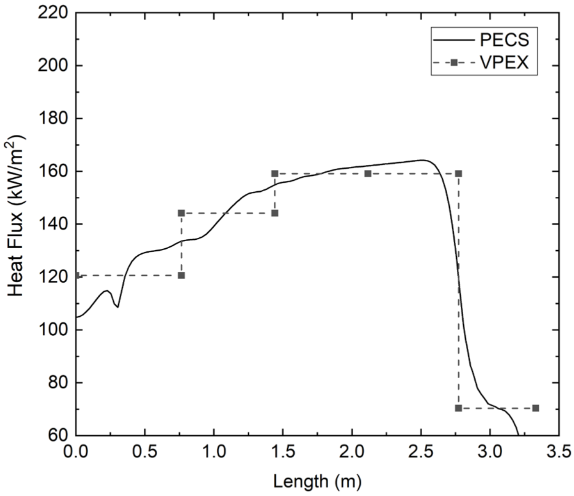

Fig. 3 VPEX heat flux distribution along channel

4. Experimental Results

Figure 4 shows the coolant temperature along the channels for D1SHRb test, in which flow instabilities occur. The test started with the 175% of the reference power (232kW/m^2) and the power was reduced by 25% at each stage, to 75% power at final. The coolant temperature near the channel inlet near the waterbox was represented in red, followed sequentially by blue, green, and purple. If a flow is upward as normally expected in natural convection, the temperature in red is the lowest, and that in purple is the highest. However, in the channel A of the test, the temperature in red was the highest, and that in purple was the lowest, which means the coolant flow was reversed. The flow reversal persisted throughout the test, and the flow oscillation was observed during a short period of the 75% power condition. In the meanwhile, the channel B shows an upward flow throughout the test as expected in natural convection. Since the temperature was not oscillating except the short period during the 75% power, the two-phase flow instability seems static rather than dynamic.

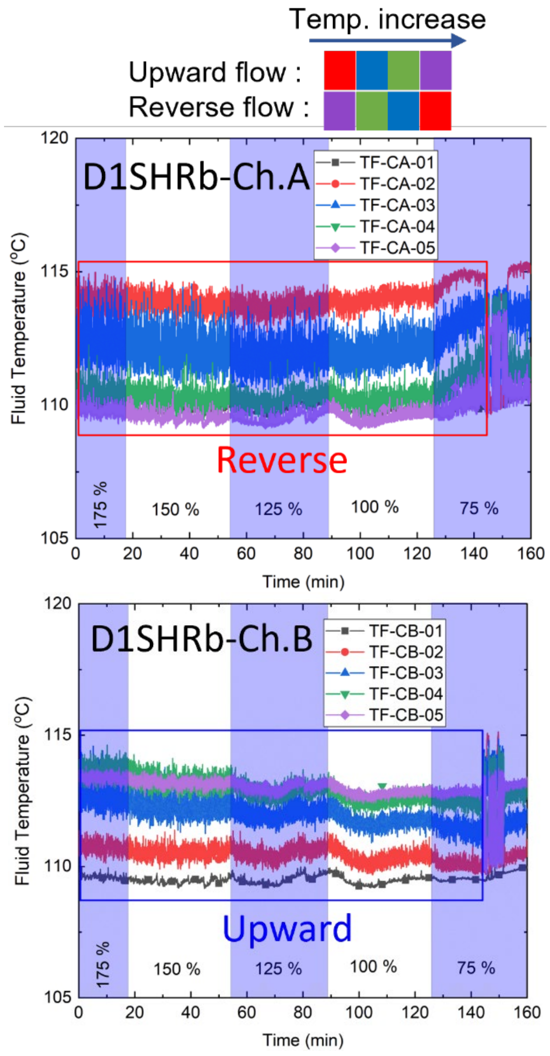

Fig. 4 Fluid temperature along channels during D1SHRa experiment

Figure 5 shows the outlet void fraction at each channel depending on the inlet subcooling. In D1SHRb test, the outlet void fraction is nearly zero for all heat flux conditions because the coolant flow reverses in the channel A. When the inlet subcooling increases, in D1WHR case, the outlet void fraction of both channel are the same until the heat flux of 199 kW/m^2 case, which means no instability occurred in these power. However, the outlet void fractions of the channels deviate at the heat flux of 233kW/m^2, where the flow instability occurs.

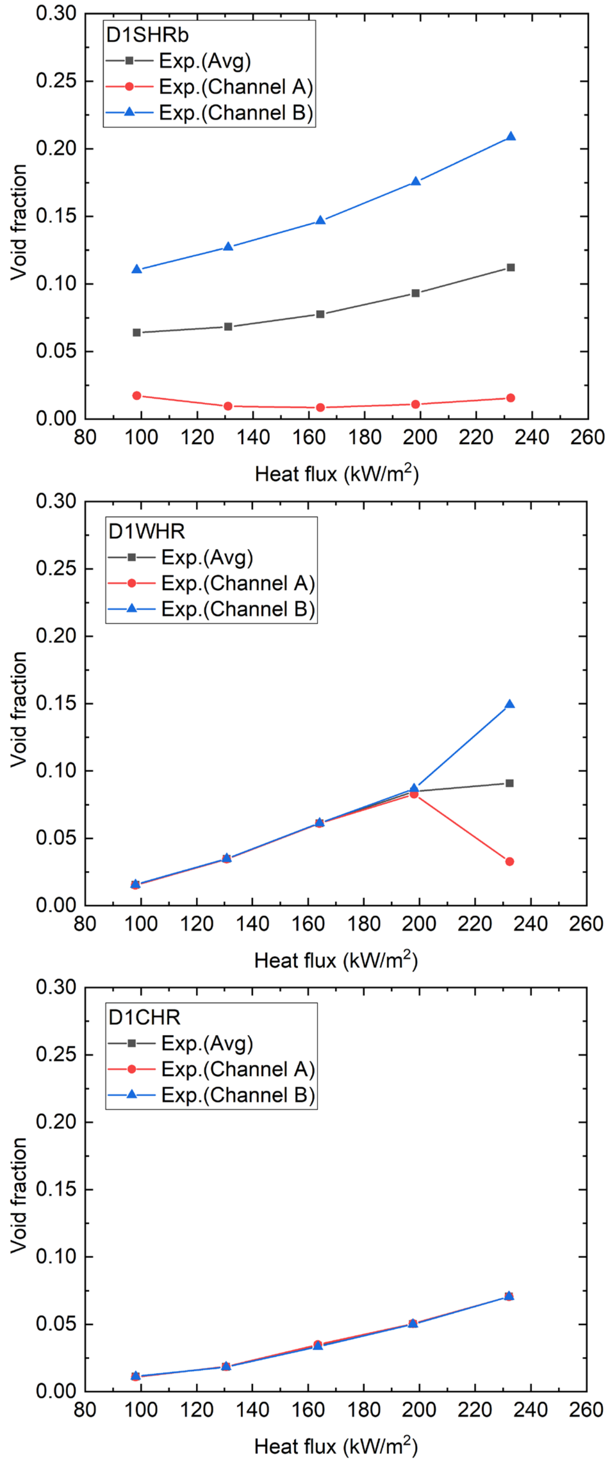

Fig. 5 Outlet void fraction for different inlet subcooling

Table 3 Occurrence of two-phase flow instability

Test cases		D1CHR	D1WHR	D1SHRb
Inlet subcooling (K)		6.3 ± 0.3	12.6 ± 2.0	16.3 ± 0.2
Average heat flux (kW/m^2)	99	X	X	O
	131	X	X	O
	165	X	X	O
	199	X	X	O
	233	X	O	O

In D1CHR case with the highest inlet subcooling, the outlet void fractions in the channels were the same throughout the tests because there was no instability. Therefore, the two-phase flow instability occurs in high heat flux, and low inlet subcooling condition. When an inlet subcooling is sufficiently low, the coolant is near the single-phase condition, in which the two-phase flow instability do not occur.

Table 3 shows the test summary, the occurrence of two-phase flow instability depending on the inlet subcooling and the heat flux. The results shows that both the inlet subcooling and the heat flux affects the occurrence of flow instability, however, the inlet subcooling seems the dominant factor. Nevertheless the flow instability deteriorates the cooling performance of channels, the cooling capability was sufficiently ensured even for 175% of expected power.

Figure 6 shows the channel pressure drop and the buoyancy by the generated steam bubble with respect to the mass flow through the channel. The mass flow rate by natural convection is determined at the intersection of the channel pressure drop and the buoyancy, the driving force. For a given heat flux of 233 kW/m^2, the highest value among the test conditions, only single intersection was shown for each inlet subcooling, which means no static instabilities is expected. Therefore, the cause of the flow instability seems not originated by the single channel characteristics, but by interaction between two channels. Detailed analyses about the instabilities are currently underway.

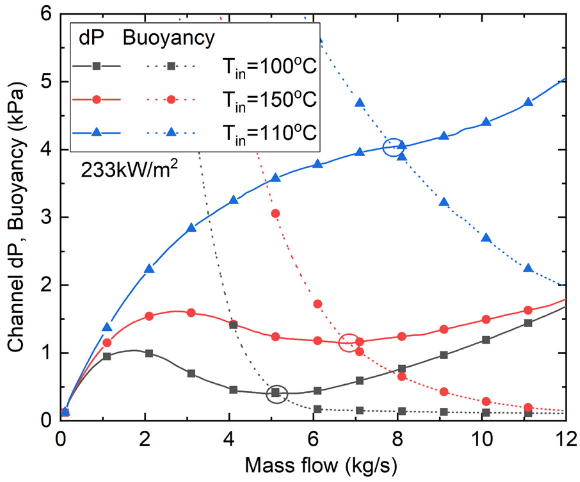

Fig. 6 Channel pressure drop (dP) vs. buoyancy for different inlet temperatures

5. Summary

Natural convection through parallel channels sharing the same inlet and outlet were tested with VPEX test facility, to examine the two-phase flow instability depending on heat flux and inlet subcooling. VPEX was a scaled down test facility to examine the cooling performance of PECS, with a capability of parallel channel experiment with a wall installed in the channel.

Tests were conducted with two parallel channels for different inlet subcoolings and heat fluxes. In the highest inlet subcooling test, D1SHRb, the coolant flow reverses in one channel while it flows forward (upward) in the other channel. The flow reversal was confirmed by the coolant temperature decrease from the channel inlet to the outlet, and also by the disappearance of the outlet void fraction at the channel. On the other hand, the flow reversal tends not shown in higher subcooling cases. The results shows that the two-phase flow instability is generally governed by inlet subcooling rather than heat flux, although the instability is still more probable in a high heat flux condition.

The flow reversal persisted in one channel without fluctuations, which means the instability is static rather than dynamic. However, the operating point of single channel was determined unique by calculation, which means that the instability was originated not by the single channel characteristic but by the multi-channel interaction.

Although the instability deteriorates the overall cooling capability of the channels, the sloped channel provided sufficient cooling even for the 175% of expected heat flux.

Acknowledgement

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