Experimental analysis of ex-vessel core catcher cooling system performance for EU-APR1400 during severe accident

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1. Introduction

Ex-vessel core catcher facility is one of the possible strategy of high temperature corium retention inside containment building. This system should provide adequate external cooling of molten core and minimizes the risk of radioactive materials spreading into the environment in severe accident scenarios. Initial study by Henry and Fauske(1993)[1] states that in AP600 In-Vessel Retention by External Reactor Vessel Cooling(IVR-ERVC) strategy can prevent catastrophic reactor vessel failure in core melt accident. However, for higher power reactor, the feasibility of the IVR-ERVC strategy is not perfectly known. Therefore, APR1400(Korean Advanced Power Reactor 1400 MWe) for export to Europe, EU-APR1400, adopted ex-vessel core catcher system to comply with European requirement[2],[3].

Ex-vessel core catcher for APR1400 as shown in Figure 1 spreads molten corium to increase total cooling area. It can prevent debris accumulation which could result in re-melting of a solidified mass of corium. Molten core is cooled by directly contacting with water at the upside of the core catcher plate and indirectly at downside through the steel plate to the water inside of coolant channel. In the coolant channel which has a unique design and large scale flow paths, natural circulation is passively activated by buoyancy driven force. Since two-phase flow behavior in a large scale channel is different from that in a small scale channel, the two-phase flow affecting the cooling capability is difficult to be predicted in the large channel. Therefore, cooling experiment in the core catcher coolant path is necessary. Cooling Experiment - Passive Ex-vessel corium retaining and Cooling System(CE-PECS) is constructed in full scale(in height and width) slice of half prototype. It actually simulates steam–water flow in the coolant channel for different decay heat condition of the corium[4].

In this study, thermal power considering of total amount of decay heat 190 kW which corresponds to 40MW of thermal power in the prototype is loaded on the top wall of the CE-PECS coolant channel. Natural circulation flow rate and pressure drops at the two-phase region are measured in various power level. Temperatures of heater block and working fluid in various position along the flow path enable to calculate heat fluxes and heat transfer coefficients distribution. These results are used for evaluating heat removal capability of core catcher facility.

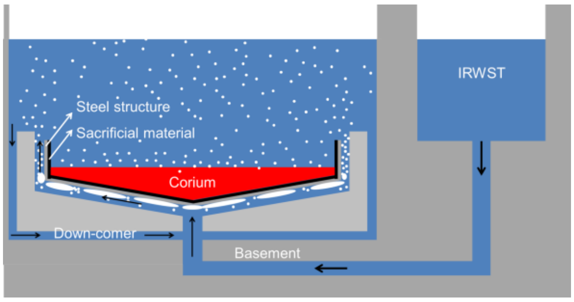

Fig. 1. Natural circulation driven two-phase coolant loop in core catcher system.

2. EXPERIMENT SETUP

Cooling experiment in CE-PECS facility is carried out using prototypic heat load under core melt accident. The maximum power of 299 kW/m^2 is supplied with uniformly heat flux distribution. Under the given thermal power, natural circulation and heat exchange characteristics are observed.

2.1 CE-PECS facility and instrumentations

CE-PECS facility consists of coolant channel(test section), water tank, downcomer, and cooling tower. Test section is composed of horizontal(HB1), 10 ° inclined(HB2, HB3 and HB4), bended(HB5 and HB6) and vertical(HB7) channel whose cross section is 10 cm height and 30 cm width. 8.4-meter height of water tank is positioned at the outlet of the test section to separate vapor from liquid. 4-inch diameter of downcomer pipe connects water tank to test section. Large capacity of heat exchanger condenses the steam at the top of the water tank to maintain atmospheric pressure and the water level. Magnetic flow meter is mounted on the middle of downcomer pipe to measure volumetric flow rate of single phase water. As shown in Figure 2, top wall of the coolant channel is covered by 7 individual copper blocks(remarked as HB1 to HB7), and each contains large number of cartridge heaters. The copper block surfaces directly contact with a coolant water.

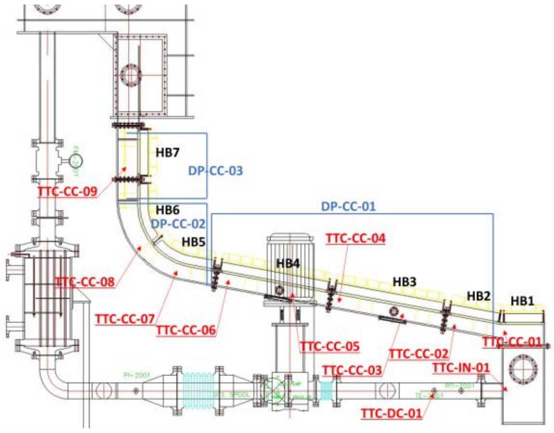

Fig. 2. Test section and measurement positions.

Heat flux distribution on the channel surface is determined by mounted cartridge heater configuration and supplied power level. A couple of thermocouples are inserted in the heating block, one near the cooling surface(2.5 to 4.5 mm), the other one far from the cooling surface(13 to 15 mm). These thermocouples are located in the entire heater blocks in axially 19 position and laterally 3 positions(center and two sides). Coolant temperature is also measured at the center of the channel and downcomer which is indicated by TTC-CC-01 to 09, TTC-IN-01, and TTC-DC-01 in Figure 2. Differential pressure transmitter DP-CC-01, 02 and 03 measures two-phase pressure drop at inclined, bended and vertical channel. In this experiment, every data is acquired in every 1 second.

2.2 Test conditions

Test factors and conditions are shown in Table 1.

Table I: Test condition

Water level	3.1 m
Water surface pressure	Atmospheric
Target inlet temperature	Saturation
Total power	3-100 %
Power distribution	Uniformly on inclined channel

Constant 3.1 m water level and atmospheric pressure at free surface is maintained by secondary heat exchanger during an experiment. Saturation temperature is targeted at the inlet of the test section. However, due to the heat loss along the coolant paths including test section and downcomer, inlet water should be in subcooled condition. Power is given from 5.9 % to 100 % of prototypic heat load. Total thermal power of 190 kW is uniformly distributed on the horizontal and slightly inclined channel except bended and vertical channel. This is conservative condition because heat load is concentrated only on the downward facing heated channel which has significantly low critical heat flux comparing to the vertical channel. 299 kW/m^2 heat flux is followed when 100 % of power is supplied on HB1 to HB4 uniformly.

2.3 Procedure

First of all, the water tank is filled of deionized water up to 3.1 m from the bottom of the channel. Differential pressure transmitter is, then set to be 0. Water in the secondary cooling tower is circulated through heat exchanger by operating the pump. After then SCR power increases gradually until 100 % of target power is reached. Water temperature increases together with time and increase of power. Temperature gradient makes natural circulating flow and once vapor is generated flow rate increases abruptly. Since power is firstly supplied, entire system is heated up until water temperature is maintained in saturation condition with steady states. Almost 2-hour is required to reach a steady state in 100 % power level from the startup. Steady state is achieved when the temperatures of the heater blocks maintain consistent temperature(within ±0.2 °C) more than 5 minutes. Experiment is conducted by decreasing heat flux from high to low step by step. Approximately 1200 seconds(20 minute) is required to reach a steady state from one power level to next power level.

3. RESULTS

3.1 Natural circulation flow rate

The flow boiling natural circulation mass flow rate strongly affects the cooling performance of the core catcher plate and critical heat flux(CHF). In Figure 3, natural circulation flow rate and pressure drop are measured in CE-PECS facility corresponding to various power ratio. DP_inclined, DP_bend, and DP_vertical are measured at DP-CC-1, DP-CC-2, and DP-CC-3 in Figure 2 respectively, and DP_two-phase which is a sum of those three pressure drops, indicates total pressure drop in the test section. Pressure drop obviously increases together with flow velocity. Since natural circulation is driven by buoyant force, amount of the vapor in the channel determines circulating mass flow rate. In this experiment, even though steady boiling condition is achieved, heat loss at the downcomer and water tank makes water temperature subcooled. Therefore, boiling in subcooled water generates less vapor, and even generated vapor can be condensed. In addition, supplied power of heater also cannot transfer entire heat to the coolant and thus amount of vapor in the channel is certainly less than that in perfecty insulated ideal situation. As a result, 12.4 kg/s mass flow rate is lower than 14.9 kg/s which is the calculation result in 100 % power using homogeneous equilibrium model. Friction factor of two-phase region is obtained using properties of homogeneous mixing fluid.

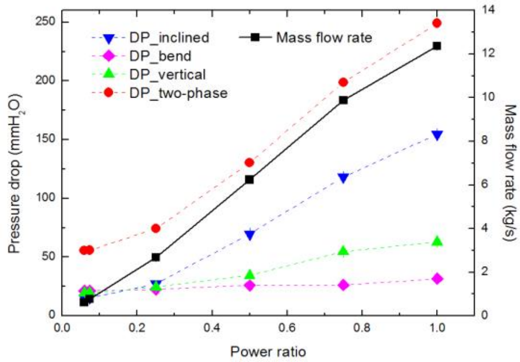

Fig. 3. Two-phase pressure drop and natural circulation mass flow rate

3.2 Heat exchange between wall and coolant

Based on the surface temperature of heater blocks and heat fluxes, heat transfer coefficient is obtained using thermocouple's readings. Figure 4 shows the averaged heat transfer coefficient at horizontal and inclined channel wall in different power level. A pair of thermocouples are installed at center and two sides of the heater block, and each data is obtained by taking average of them. Heat transfer coefficients of the cooling surface tend to increase towards downstream especially in high power. Horizontally downward faced heater block 1 shows lower heat transfer coefficient than 10 ° inclined channel wall. This is because void fraction increases to the downstream, and fluid is accelerated to enhance a convective cooling of the wall. In addition, since downward faced surface shows poor heat transfer than inclined surface[5], lower heat transfer coefficient appears at heater block 1. And it is suggested that channel geometry could makes stagnant flow under the heater block 1 where the flow direction changes 180 °. Water temperature of upstream of the channel is lower than that of the downstream because of the heat loss at the water tank and downcomer. Since bulk temperature increases as passing heated section, bubble generation also becomes more active. Higher convection and phase change enhance the heat transfer of the downstream wall. On the other hand, heat transfer coefficients do not change much in power level less than 25 %, because less vapor generation makes less effect on flow acceleration and/or bubble generation enhancement. Wall temperature and bulk temperature distribution is shown in Figure 5. Saturation temperature is calculated by hydrodynamic head. The highest wall temperature is observed at heater block 1 in spite of the high sub-cooling, which means poor heat transfer. Figure 6 shows the boiling curve at each position along a flow path. The legend after heater block number(HB#-X) means axial position, and the larger number means downstream location. The higher inclination does not directly mean better heat transfer, because of different subcooled temperatures at each location. It shows that heat transfer coefficient improves fast near 150kW/m^{2}K region where vigorous nucleate boiling starts.

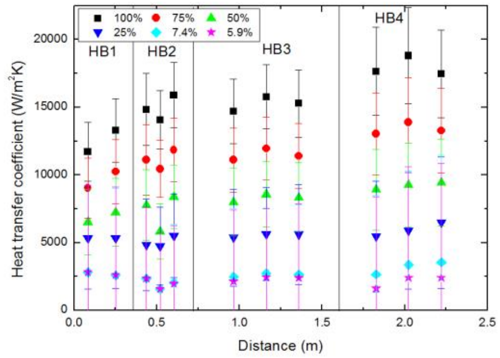

Fig. 4. Averaged heat transfer coefficient at horizontal and inclined channel wall

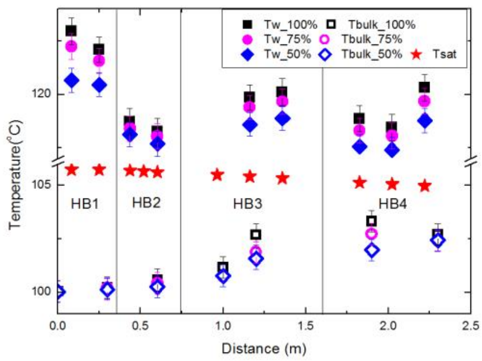

Fig. 5. Temperature distribution along the horizontal and inclined channel in various power

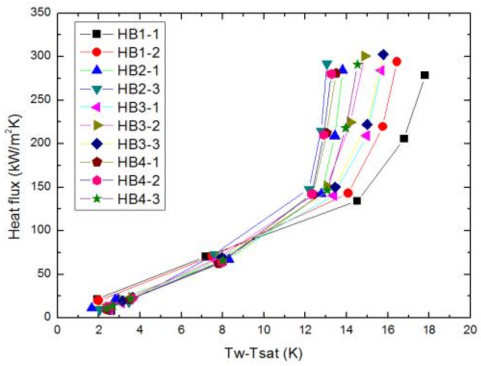

Fig. 6. Boiling curve on the channel center in various position

4. Discussion

4.1 Experimental limitation

Heat flux is distributed as uniformly as possible at the cooling surface. To get the uniformity of the heat flux, 3-D solid heat transfer is calculated using COMSOL multiphysics 5.0. Same amount of power with experiment is supplied, and constant heat transfer coefficient and saturation temperature is given at the cooling surface and ambient. Except the cooling surface, entire copper block is set to be adiabatic. The magnitude of heat transfer coefficient is based on the experimental result. Figure 7 shows the result of the heat flux at block 1 and 3. Because of high thermal conductivity of the copper and installed heater arrangement, it is impossible to distribute heat perfectly uniform on the cooling surface. In the Figure 7, heat flux nearby the thermocouple-installed measuring position is about 4 % higher than averaged heat flux. Figure 8 shows differences between actual supplied power and total power divided by surface area. Normally heat flux calculated by thermocouple readings is lower than supplied heat flux due to the heat loss of the heating system. It shows that heat loss of the heating system is not significant.
In this report, every thermodynamic analysis uses the heat flux calculated by thermocouple readings at each positions.

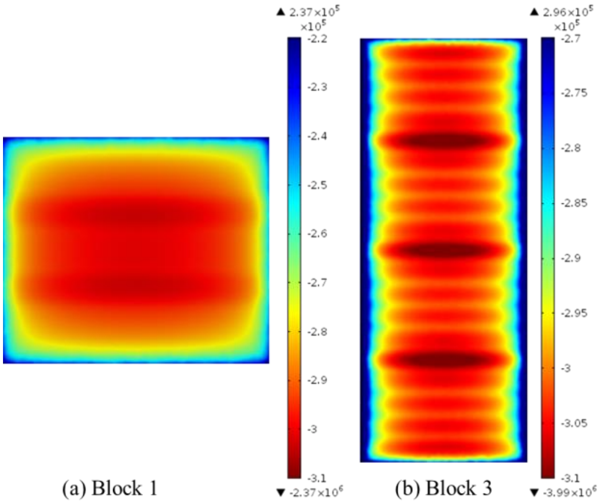

Fig. 7. Heat flux on the surface calculated using COMSOL 5.0 (a) Block 1 (b) Block 3

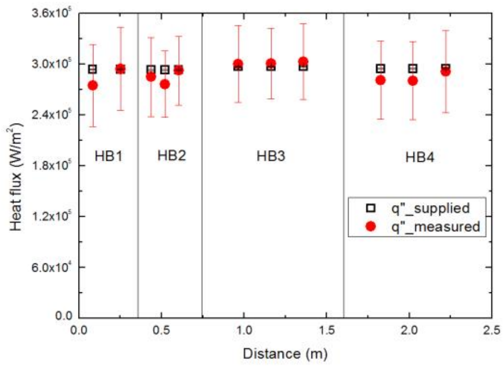

Fig. 8. Heat flux measured by thermocouples and actual supplied power by SCR in 100 % power

4.2 Safety analysis

In core catcher system, total amount of generated steam should remove the decay heat of molten corium in severe accident scenarios. Natural circulation mass flow rate is 12.4 kg/sec for CE-PECS facility for removal of 190 kW power corresponding to 40 MW thermal power in prototype. With adequate natural circulation flow rate, local dry out also should be avoided. This experiment shows that ex-vessel core catcher system is able to cool the expected thermal power (prototypic heat load) without failure. It should be noted that the heat load condition is conservative because total power is concentrated on horizontal and inclined wall, except vertical channel. We should also remember that water temperature at test section inlet is not fully saturated condition due to heat loss.

5. Conclusion

Two-phase natural circulation experiment is carried out in CE-PECS facility. Based on the prototypic condition, 190 kW of total power is supplied to the top of the coolant path. Uniform distribution of heat load on the downward facing heater bock produces ~300 kW/m2 at 100 % power ratio. Although the experiment should consider the heat loss and heat flux uniformity, several noticeable conclusions have been made as followings;
1. Mass flow rate and two-phase pressure drop are measured in various power conditions.
2. Slightly inclined top wall at the downstream of the channel shows better heat exchange performance than horizontal top wall because enhanced convection due to the increase of void fraction improves local cooling. This effect is more clear in high power region.
3. It is expected that natural circulation cooling can adequately remove decay heat without CHF occurrence in ex-vessel core catcher system.

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