Design of Hemispherical Downward-Facing Vessel for Critical Heat Flux Experiment

Jin S. Hwang, Kune Y. Suh*
Department of Energy Systems Engineering, Seoul National University
599 Gwanak-Ro, Gwanak-Gu, Seoul, 151-744, Korea
Corresponding author: kysuh@snu.ac.kr

1. Introduction

The in-vessel retention (IVR) is one of major severe accident management strategies adopted by some operating nuclear power plants during a severe accident. The recent Shin-Gori Units 3 and 4 of the Advanced Power Reactor 1400 MWe (APR1400) have adopted the external reactor vessel cooling (ERVC) by reactor cavity flooding as major severe accident management strategy [1-3]. The ERVC in the APR1400 design resorts to active flooding system using thermal insulator. The Corium Attack Stopper Apparatus Spherical Channel (CASA SC) tests are conducted to measure the critical power and critical heat flux (CHF) on a downward hemispherical vessel scaled down from the APR1400 lower head by 1/10 on a linear scale. CASA is designed through scaling and thermal analysis to simulate the APR1400 vessel and thermal insulator. The heated vessel of CASA SC represents the external surface of a hemisphere submerged vessel in water. The heated vessel plays an important role in the ERVC experiment depending on the configuration of oxide pool and metallic layer. Hand calculation and computational analysis are performed to produce high heat flux from the downward facing hemisphere in excess of 1 MW/m^2.

2. Design of heated vessel

2.1. Final design of heated vessel

CASA apparatus is designed to measure the heat transfer coefficient and CHF in view of IVR-ERVC. Fig. 1 shows the design process of hemispherical heated vessel. This design process has examined the number, space and arrangement of heaters. Its final design is concerned with a metal layer and an oxide pool in a molten pool by using 120 and 165 cartridge heaters, respectively, as shown in Fig. 2.

The cartridge heater is 15.8 mm in diameter, and 60 mm long heated with 3 kW power. The heated section is integrated to protect the cartridge heaters and wires in the hemispherical section from coolant penetration, and to reduce thermal resistance. The hemispherical heated section is 500 mm in diameter scaled linearly down to 1/10 of APR1400.

The test factors include the in-core instrumentation (ICI) tube, inlet subcooling, gap size, oxide pool heat flux, mass flow rate and natural circulation condition. A uniform heat flux method is adopted in each heated region (metal layer and oxide pool). The various heat fluxes in oxide pool region are adopted as key variables for the saturated condition at the inlet.

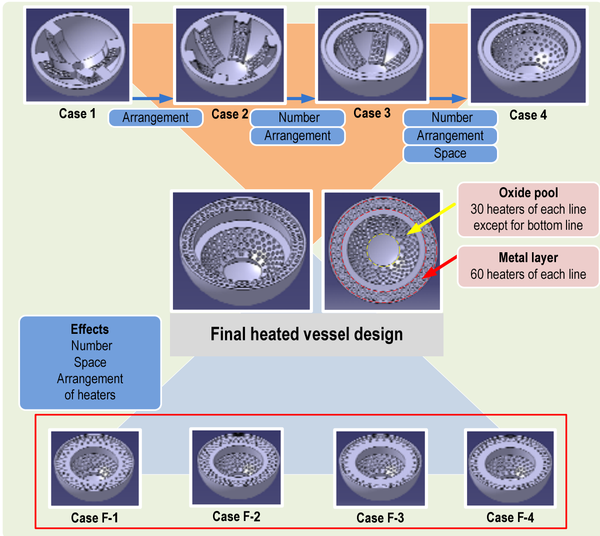

Fig. 1. Design process of hemispherical heated vessel

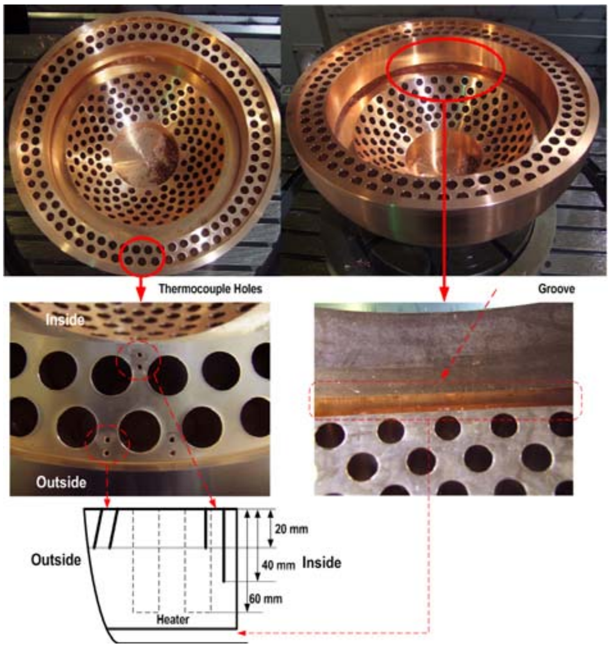

Fig. 2. Photos of heated vessel

The heated section is divided into two regions to obtain heat flux in excess of 2 MW/m^2 in the metal layer. Also, Fig. 2 shows the number and position of holes for the heater rods. They are manufactured at tolerance of 3/100, as shown in Fig. 2. In order to determine the local wall heat flux and temperature, the metal layer has twenty-four thermocouple holes and additional two holes of thermocouples in the oxide pool. Twenty-six type-K thermocouples and thermocouples holes are 1.5 mm and 1.6 mm in diameter, respectively. The thermal insulator is put into the groove whose width is 10 mm between the metal layer and oxide pool.

2.2. Thermal analysis of heated vessel

Thermal analysis is made to study inner temperatures and heat fluxes on the outer surface in the integrated hemispherical heated section resorting to finite element analysis code. The temperature and heat flux data are obtained according to heat transfer coefficient, heat power ratio as well as external heated vessel surface temperature. Assuming that the heat transfer coefficient is 10,000 W/m^{2}K, copper was chosen as heated vessel material for the heat power ratios of 30%, 50% and 70%. The finite element analysis code results are shown in Fig. 3 of temperature and heat flux.

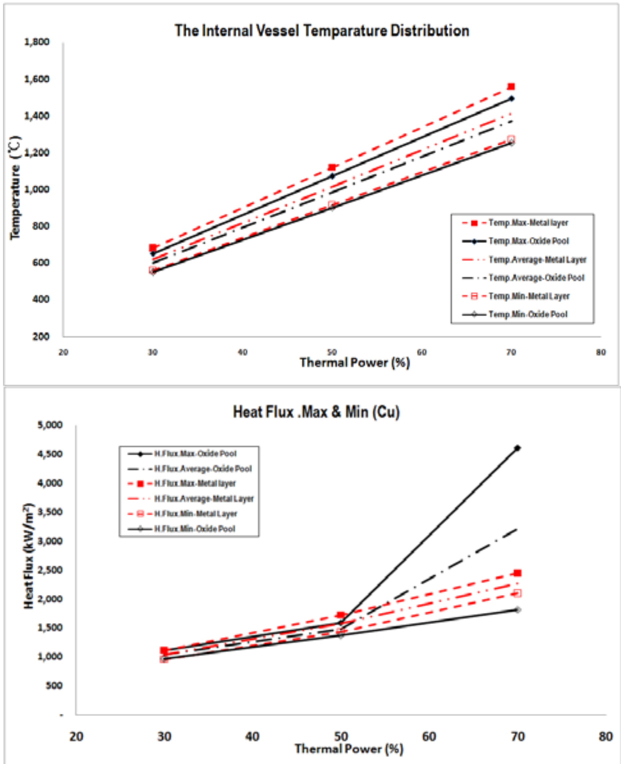

Fig. 3. Deviation distribution of temperature and heat flux in heated vessel with thermal power

3. Conclusion

The internal average temperature in stainless steel heated vessel was higher than in others. Further, the difference in maximum and minimum temperatures was also large. Stainless steel had difficulty in heat transfer due to its low thermal conductivity. On the other hand, the copper heated vessel had the low internal average temperature thanks to its high thermal conductivity and heat transfer than those of aluminum. Thus, the integrity of the heated section could be maintained in the case of copper.

The heat flux increased generally with thermal power ratio. Stainless steel, aluminum, and copper shared similar trends and heat flux distributions as heated vessel materials. In particular, the heat flux of copper exceeded 2.4 MW/m^2 in the metal layer and 2.2 MW/m^2 in the oxide pool when the thermal power ratio was 70%.

In addition, the heat flux in the oxide pool was 1732.5 kW/m^2 for the 70% thermal power ratio in hand calculation with a 29.24% error. However, the heat flux and internal temperature in the metal layer were 2520 kW/m^2 and 426.1^{o}C, respectively, for the 70% thermal power ratio in hand calculation. The heat flux and temperature in the metal layer resulted in 0.68 and 0.02% in error analysis. It was thus considered that the heated vessel design in CASA apparatus may well yield enough heat flux.

ACKNOWLEDGMENTS

This work was performed under the auspices of the Brain Korea 21 Program awarded to the Department of Energy Systems Engineering, Seoul National University by the Ministry of Education, Science & Technology.

REFERENCES

[1] J.L. Rempe, K.Y. Suh, F.B. Cheung, S.B. Kim, In-Vessel Retention of Molten Corium- Lessons Learned and Outstanding Issues, Nuclear Technology, Vol. 161, No. 210, pp. 210-267, 2008.

[2] J. Yang, F.B. Cheung, J.L. Rempe, K.Y. Suh, S.B. Kim, Critical Heat Flux for Downward-Facing Boiling on a Coated Hemispherical Vessel Surrounded by an Insulation Structure, Nuclear Engineering & Technology, Vol. 38 (2), pp. 139-146, 2006.

[3] T.G. Theofanous, C. Liu, S. Addition, In-Vessel Coolability and Retention of a Core Melt, DOE/ID-10460, Santa Barbara, CA, USA, 1996.