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The prediction of Critical Heat Flux(CHF) on the outer wall of System-Integrated Modular Advanced Reactor

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1. Introduction

In 2012, South Korea obtained Standard Design Approval (SDA) for System-integrated Modular Advanced Reactor (SMART), a small modular nuclear reactor system. It has been 15 years since Korea embarked on its development in 1997. Until now, Korea has retained a total of 4 nuclear reactors, including High-Flux Advanced Neutron Application Reactor (HNANRO) in 1995 and SMART, which resulted from the development of indigenous reactor technology. Unlike Pressurized Water Reactor (PWR), Korea's SMART includes all components of the primary system in one pressure vessel. For this reason, if station blackout (SBO) events occur, SMART is likely to cause more severe accidents than the conventional reactor. When a nuclear meltdown, one of the serious accidents, occurs, and if the process of cooling is done by Ex-Vessel Cooling system (EVCS), this study explored as to whether EVCS is proper for SMART by calculating Critical Heat Flux (CHF) depending on the angle of reactor vessel.

If the coolant is lost due to Loss-of-Coolant Accident (LOCA) and SBO in the reactor core, a core is melt due to decay heat. When the core meltdown occurs, corium is accumulated at the lower plenum of the reactor and transfers heat to the bottom of vessel as shown in Figure 1. Then heat is transferred to the outer wall of vessel, causing Nucleate Boiling at the outer wall of vessel. A rising heat flux caused by corium could reach CHF and do damage to vessel due to Departure from Nucleate Boiling (DNB), so such incidents should be prevented.

Thus, to prevent such event, Ex-Vessel Cooling System is employed. In particular, when a core meltdown occurs, In-Vessel Melt Retention (IVMR) is designed to bring coolant from the outside and cool vessel by using the coolant flow around the vessel. Although IVMR is a passive method, it is safe to remove heat.

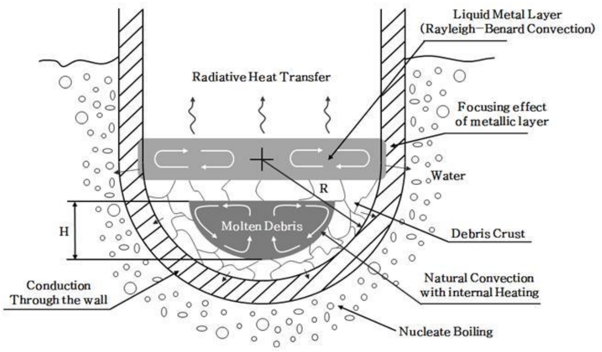

Fig 1. The situation of when the core melting

In other words, when nuclear accidents like a core meltdown occur, EVCS should be operated in order to prevent DNB caused by decay heat under the condition of Nucleate Boiling.

2. Literature review

When a core meltdown occurs by directly using SMART, the value of Critical Heat Flux(CHF) cannot be obtained in the cooling of the outer wall by means of EVCS for in-vessel retention. So this study will explore the value of CHF in SMART-330 by finding correlation conducted by the previous research and applying it to SMART.

2.1 ULPU

ULPU experiments, which are performed by University of California at boiling facility regarding in-vessel retention, is designed to find the value of CHF in a higher core temperature in an attempt to set limits to coolant for the actual size of reactor vessel. A total of five experiments were performed, and Configuration Ⅱ, Ⅲ, Ⅴ were used in this study.

CHF correlation of Configuration Ⅱ is as follows.

$$q_{CHF}(\theta) = 500 + 13.3\theta\ [kW/m^2],\quad 0^\circ \le \theta \le 15^\circ \quad (1)$$

$$q_{CHF}(\theta) = 540 + 10.7\theta\ [kW/m^2],\quad 15^\circ \le \theta \le 90^\circ \quad (2)$$

The value comes from AP-600 reactor and Configuration Ⅲ is also conducted on AP-600. In the case of Configuration Ⅲ, an insulator was added to figure out the cooling capacity by insulators. The correlation of the below experiment is as follows.

$$q_{CHF}(\theta) = 490 + 30.2\theta - 0.888\theta^2 + 1.35 \times 10^{-3}\theta^3 - 6.65 \times 10^{-5}\theta^4\ [kW/m^2] \quad (3)$$

Meanwhile, Configuration Ⅴ was performed on AP 1000 and the CHF correlation was as follows.

$$q_{CHF}(\theta) = 0.069 + 0.0067\theta^{0.656} \times {\rho_g}^{0.5} \times h_v \times [9.8 \times \sigma \times (\rho_f - \rho_g)]^{0.25} [kW/m^2] \quad (4)$$

2.2 SULTAN

SULTAN experiment, which was performed at the SULTAN facility (CEA France) adopted the full-size experimental technology of an analytical approach. Rather than an experiment on IVR, this experiment was also designed to figure out the characteristics of two-dimensional flow in forced circulation conditions, measure the value of CHF and assess CATHARE code, a standard flow code.

Table Ⅰ: Condition of SUTAN

	Parameter	Range
Geometry	Inclination	Vertical to Horizontal
	Heated Length	2 or 4m
	Hydraulic gap	3 to 15cm
Thermal-Hydraulic	Pressure	0.1 to 0.6MPa
	Flow rate	10 to 2000kg/sec/m^2 for gap 15cm 20 to 5000kg/sec/m^2 for gap 3cm
	Heat flux	0 to 1 or 2 MW/m^2 (600kW)
	Inlet subcooling	0 to 50℃

The correlation for this is as follows.

$$q_{CHF}(\theta) = A_0 + A_1 \times X + A_2 \times X^2 + A_3 \times sin\theta + A_4 \times sin\theta^2 \; [kW/m^2] \; (5)$$

$A_0 = 0.65444 - 1.2018 \times lnG - 0.008388/0.2^2 + 0.00179 \times G + 1.36899 \times 0.089/0.2 - 0.077415 \times 0.089/0.2^2 + 0.024967 \times 0.2 \times (lnG)^2$
$A_1 = -0.086511 \times (lnG)^2 + 0.000179 \times 0.089 \times lnG$ $A_2 = 9.28489 \times 0.089$ $A_3 = -0.0066169 \times (lnG)^2 + 11.62546 \times 0.089 \times 0.2 + 0.855759 \times X \times lnG$ $A_4 = -1.74177 \times 0.2 + 0.182895 \times lnG - 1.8898 \times X + 2.2636 \times 0.089$

$$x(\theta) = \left(h_{in} + \int_0^{\theta} \frac{q''_{act}(\theta)}{\dot{m}} A_{heated}(\theta) d\theta - h_f\right)/h_{fg} \; (6)$$

3. Choice the Correlation

Of the above-mentioned experiments, CHF Correlation for this study is correlation of SULTAN experiment. In the case of ULPU, since parameters of CHF Correlation varied depending on the angle of vessel, the experiment was regarded as being unsuitable. Parameters of CHF Correlation used in SULTAN experiment includes flow rate of coolant, subcooling, pressure, hydraulic gap and inclination. After making a comparison between several parameters and conditions for SULTAN experiment, the conclusion was made that SMART was applicable to SULTAN experiment. The below Table 2 shows why CHF Correlation of SULTAN experiment is suitable for the application of SMART (Heat Flux in SMART is the value of Heat Flux at the inner wall of reactor and it also varies depending on the angle. However, this study found the value under the assumption that the value only changes by decay heat. Additionally, SMART used the insulation size of APR1400 – Figure 2 and Table 3).

Table Ⅱ: Compare SULTAN to SMART condition

	Parameter	Range (SULTAN)	Range (SMART)
Geometry	Inclination	0° to 90°	0° to 90°
	Heated Length	2 or 4m	
	Hydraulic gap	3 to 15cm	8.9cm
Thermal-Hydraulic	Pressure	0.1 to 0.6MPa	0.2MPa
	Flow rate	10 to 2000kg/sec/ m^2 for gap 15cm	100kg/sec/ m^2
	Heat flux	0 to 1 or 2 MW/m^2 (600kW)	0.78MW/ m^2
	Inlet sub-cooling	0 to 50℃	45℃

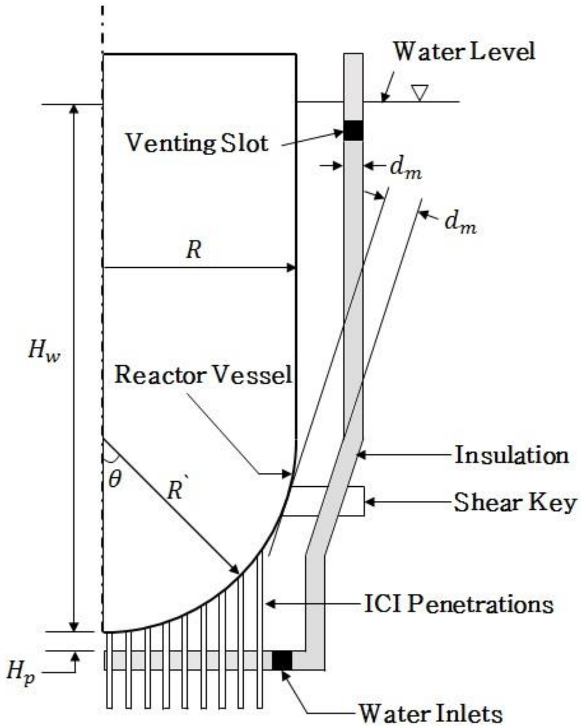

Fig 2. Design of APR-1400's vessel and insulation

Table Ⅲ: Condition of APR1400

	APR1400
Outer radius of reactor vessel	2.572m/2.612m
Radius of bottom	2.536m
Gap(location)	55°
Gap(size)	0.089m
Distance(head-bottom)	0.1207m
Water level of Inner Pool	7.141m
Diameter of ICI Tubes	0.0765m
Size of Shear Key	H 0.203m W 0.610m
Area of Flow Inlet	1.79m^2/1.86m^2
Area of Venting Slot	1.62m^2

4. Result of research

The value of CHF in SMART measured by SULTAN CHF Correlation is as follows.

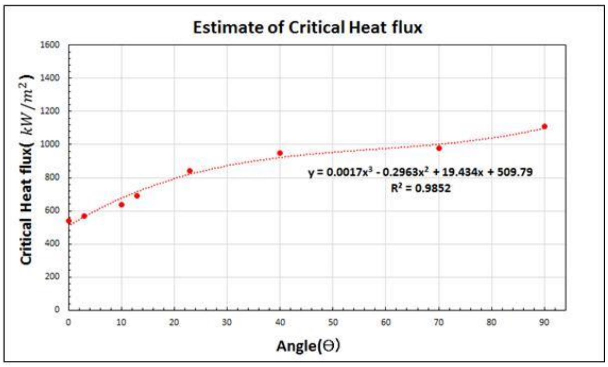

Fig 3. The result of CHF at SMART

In addition, CHF Correlation in SMART found in the graph is as follows.

$$q_{CHF}(\theta) = 0.0017\theta^3 - 0.2963\theta^2 + 19.434\theta + 509.79\ [kW/m^2]\quad (7)$$

Based on the correlation, this study found that the minimum of CHF was about 0.5MW/m^2 , the maximum of CHF was 1.1MW/m^2 in the angel of 90° and the error range, about 15%.

5. Conclusion

For in-vessel retention of SMART-330, this study examined the feasibility of SMART-330 by conducting a literature search of CHF correlation for the conventional commercial reactor at the outer wall of pressure vessel. The findings of the study showed that the correlation equation for SULTAN experiment was the most suitable for SMART-330. Accordingly, when the value of mass flow rate is 100kg/s and pressure is 0.2MPa, a correlation equation is simply as follows.

$$q_{CHF}(\theta) = 0.0017\theta^3 - 0.2963\theta^2 + 19.434\theta + 509.79\ [kW/m^2]\ (8)$$

As a result, the minimum value was about 0.5MW/m^2 and the maximum was 1.1MW/m^2at the angel of 90°. Additionally, when core meltdown occurs, the maximum value of heat flux was 0.78MW/m^2 at 10,000sec after started the melting core in the reactor. (The result of heat flux was calculated heat transfer correlation inside oxide pool with number of Ra) When operating Ex-Vessel Cooling System at the outer reactor, the maximum value of CHF was about 1.1MW/$m^2$and it was larger than 0.78MW/m^2, the value of heat flux in the outer reactor. Therefore, this study proved that Ex-Vessel Cooling System was applicable to SMART-330.

NOMENCLATURE

Γ=lnG
G : flow velocity(kg/s/m^2)
Θ : inclination angle
E : gap(m)
P : outlet pressure(MPa)
X : thermodynamic quality

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