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CHF Experiments for IVR-EVC using 2-D Slice Test Section

Yong-Hoon Jeong, Won-Pil Baek* and Soon Heung Chang

Department of Nuclear and Quantum Engineering
Korea Advanced Institute of Science and Technology
* Korea Atomic Energy Research Institute

ABSTRACT

This paper presents the first campaign of KAIST CHF experiments on IVR-EVC using real-scale (APR1400) 2-dimensional slice test section. In this study, we used forced flow Through this experiments, the effect of mass flux on CHF at 90^o area has been investigated and the gap effect on CHF has also been investigated by comparing the previous experimental data (such as ULPU and SULTAN) and SULTAN correlation.
Generally, the measured CHF on 90^o area are smaller than that of ULPU experiments. This is seems to be due to the gap size effect, i.e. as the gap size is increased the corresponding CHF is increased. Because the gap size of this study (15 cm) is greater than that of ULPU (23.75 cm), the CHF of this study is generally smaller than that of ULPU. And, clearly, as the mass flux increases the corresponding CHF increases.
For using SULTAN correlation, the gap size effect can be predicted and this correlation can be used to assess various design alternatives of APR1400 EVC design.

1. Introduction

The purpose of this paper is to make available the first experimental data to make comparison with other experimental data (ULPU, SULTAN). As the management of severe accidents, reactor outer vessel wall is submerged by water pool and decay heat from inside corium pool can be removed through boiling on the reactor vessel outer wall. In this situation, critical heat flux (CHF) is an important thermal-hydraulic phenomenon which should be considered in designing and operating such in-vessel retention through external vessel cooling (IVR-EVC) devices. For this IVR-EVC strategy to work, it is necessary that the thermal load created by natural convection of the heat generating pool on the inside, be below what could cause a boiling crisis on the outside. Especially, if the metal layer is formed on the top of the melt pool, heat flux is focused on the interface of metal layer and vessel wall [1]. This region is the main concern of this study.

In this study, we have special interests in APR1400 design, and the test loop is prepared for real scale 2-dimensional simulation of IVR-EVC of APR1400.

2. Background

To identify the coolability limit for the AP600 (USA) and Loviisa (Finland) plants, ULPU experiments have been conducted [1, 2]. Configuration I experiment is focused on the boiling mechanism and CHF on the bottom of the lower head (near 0^o), and configuration II and III are focused on the CHF along the lower head from bottom to top of the head (0^o ~ 90^o).

- ✧ Configuration I : to investigate CHF behaviours between 0^o and 30^o
- ✧ Configuration II: to clarify CHF behaviours for overall inclination angles between 0^o and 90^o
- ✧ Configuration III: to identify the effect of the change in flow geometry (riser and exit restriction) and composite effect of the change in flow geometry and the material of heated surface (copper & ASTM stand class 3 steel)

With two kinds of experimental methods (uniform heating and peak heating) several kinds of experiments were performed. And, based on their experimental results, they developed correlations.

ULPU experiments have been conducted under fixed gap size (23.5 cm). So, the effect of gap size and other flow constraints have not been studied. When we using the ULPU experimental data as a reference CHF data for various design alternatives of other plants such as APR1400, we cannot examine the gap size effect on the CHF. There must be the experimental data for various gap size to examine the coolability limit of APR1400 design alternatives.

On the other hand, SULTAN experiments has been conducted by CEA to enhance boiling mechanisms at inclined plates and identify the coolability of large facility under natural convection [3, 4]. The objectives of the facility are as follows:

- ✧ To provided database to verify analysis code for system, which has large thermal hydraulic diameter under low pressure
- ✧ To measure boundary thickness, the distribution of void fraction in channel, temperature distribution in working fluid, pressure drop and CHF
- ✧ To investigate the transition to channelling flow regime.

CHF correlation was also developed considering experimental data under the cooperation of CEA and DINCE (Department of Nuclear Engineering and Energy Conversion) [5].

In SULTAN experiments, gap size and heater length are varies with case by case. So, it is possible to give information about gap size effect on CHF. However in SULTAN experiments, the heat flux distribution is uniform, and this can lead the CHF data with high exit quality comparing with real accident conditions.

3. Experiments and Results

Figure 1 shows a schematic of the experimental loop used in this study. We used pump to supply water flow through flow channel. However, natural circulation was used in ULPU and SULTAN experiments.

Using 200 kW capacity DC rectifier, direct current is applied to the two end of heater section. The heater thickness is varies along inclination angle by four steps to varies heat flux distribution (Fig. 2). The maximum heat flux is given through 1 mm region because the corresponding resistance is maximum at 1 mm region, and the other hand, the minimum one is given through 6 mm region because the corresponding resistance is minimum at 6 mm region. As shown in figure 3, when the maximum heat flux is about 1.6 MW/m^2 on 1 mm region, the minimum heat flux is about 266 kW/m^2 on 6 mm region.

Flow area of this study is 15 cm × 10 cm (Fig. 4) and that of ULPU experiments is 23.75 cm × 16.25 cm. The gap size is 15 cm and this is equal to that of SULTAN and less than that of ULPU 23.75 cm.

The difference of test conditions and geometry of this study, ULPU experiments and SULTAN experiments are summarized in table 1.

Through the first campaign of this study, we got 6 points of CHF data on 90^o area and those are plotted in figure 5 and 6.

The subcoolings of those 6 points are about 13 ~ 14 ^{o}C, and mass flux is varied from 33 to 210 kg/m^{2}sec. As shown in figures, CHF increases as the corresponding mass flux is increases. However, generally the magnitude of CHF is less than that of ULPU experiments and the increasing slope also less than that of ULPU.

When we get the test conditions of this study into SULTAN correlation, we get the CHF predictions as shown in figure 6. As shown in the figure, SULTAN predicted CHF values are greater than this experiment’s data and smaller than that of ULPU. If we use correction factors for SULTAN correlation, it can be used for CHF prediction under various design alternatives of vessel outer wall and insulation design. For, SULTAN correlation had been developed using various flow conditions (subcooling, mass flux) and channel geometry (gap size, channel length, inclination angle). The details of SULTAN correlation is like flowing:

$$q_{CHF} = A_0(s,P,G) + A_1(s,G)\cdot x + A_2(s)\cdot x^2 + A_3(s,P,G,x)\cdot\Theta + A_4(s,P,G,x)\cdot\Theta^2 \qquad (1)$$

where,

$$A_0 = b_0 + b_1 s\ln(G) + b_2/P^2 + b_3 G + b_4 s/P + b_5 s/P^2 + b_6 P(\ln(G))^2$$

$$A_1 = b_7(\ln(G))^2 + b_8 s\ln(G)$$

$$A_2 = b_9 s$$

$$A_3 = b_{10}(\ln(G))^2 + b_{11}sP + b_{12}x\ln(G)$$
$$A_4 = b_{13}P + b_{14}\ln(G) + b_{15}x + b_{16}s$$

b_0 = 0.65444,	b_1 = -1.2018,	b_2 = -0.008388,	b_3 = 0.000179
b_4 = 1.36899	b_5 = -0.077415	b_6 = 0.024967	b_7 = -0.086511
b_8 = -4.49425	b_9 = 9.28489	b_{10} = -0.0066169	b_{11} = 11.62546
b_{12} = 0.855759	b_{13} = -1.74177	b_{14} = 0.182895	b_{15} = -1.8898
b_{16} = 2.2636			

Generally, it can be conformed that as the gap size increases, the corresponding CHF increases. It can be explained by the magnitude of friction that can be formed between vapor slug and channel wall. For lage channel gap, there is less friction than that of small gap.

5. Conclusions

In this study, a series of CHF experiments for IVR-EVC of APR1400 using 2-D slice test section. Through this study, CHF and its trend on various mass flux condition is studied. And, the effect of channel gap size is studied also. Important findings from this study are summarized as follows:

a) The CHF on the vessel wall increases as mass flux increases and as channel gap size (gap between vessel wall and insulation) increases.

b) CHF value in this study is generally smaller than that of ULPU under same condition except gap size. It is because of gap effect on friction between vapor slug and channel walls.

c) SULTAN correlation can be a valuable CHF correlation for estimating various flow conditions and channel geometry of IVR-EVC alternatives. For, SULTAN correlation had been developed using various flow conditions (subcooling, mass flux) and channel geometry (gap size, channel length, inclination angle).

Nomenclature

G	mass flux	kg/m^{2}s
P	pressure	MPa
q_{CHF}	critical heat flux	MW/m^2
s	channel gap size	m
x	local thermodynamic quality	-
Θ	sinθ	-
q	inclination angle above horizontal	-

References

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Table 1 Experimental conditions of this study, ULPU experiments and SULTAN experiments

	This study	ULPU	SULTAN
Scale	R = 2.5 m	R = 1.76 m	L=4.0 m
Flow channel	15 cm × 10 cm	23.75 cm × 16.25 cm	3~15 cm × 15 cm
Circulation	Forced circulation	Natural circulation	Natural Circulation
Heating method	DC heating	Heater Block	DC Heating
Subcooling	13 ~ 14 ^{o}C	~ 10 ^{o}C	0 ~ 50 ^{o}C
CHF points	90 ^{o}	0 ~ 90^{o}	10, 45, 90 ^{o}

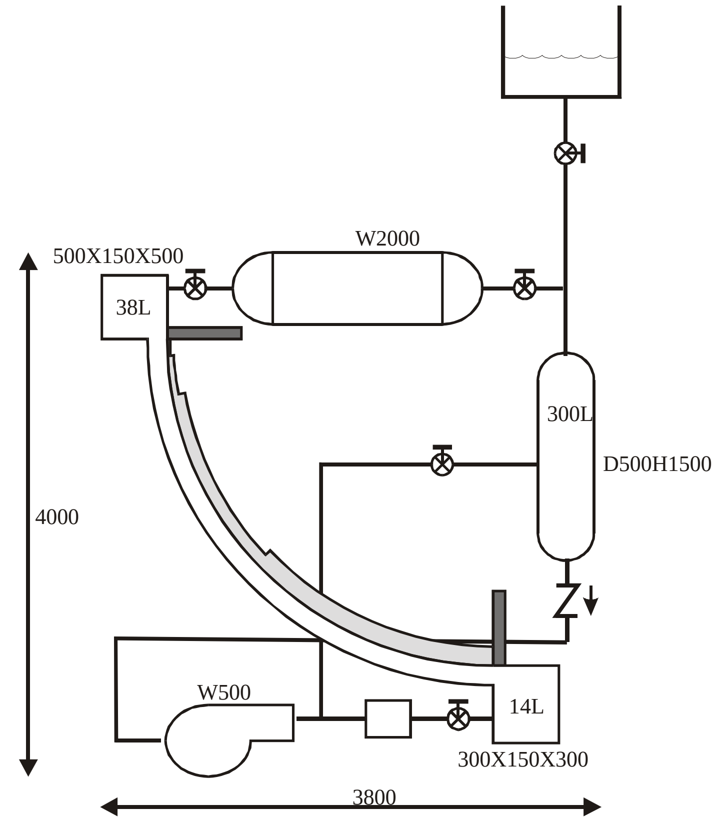

Fig. 1 Schematic diagram of the experimental loop

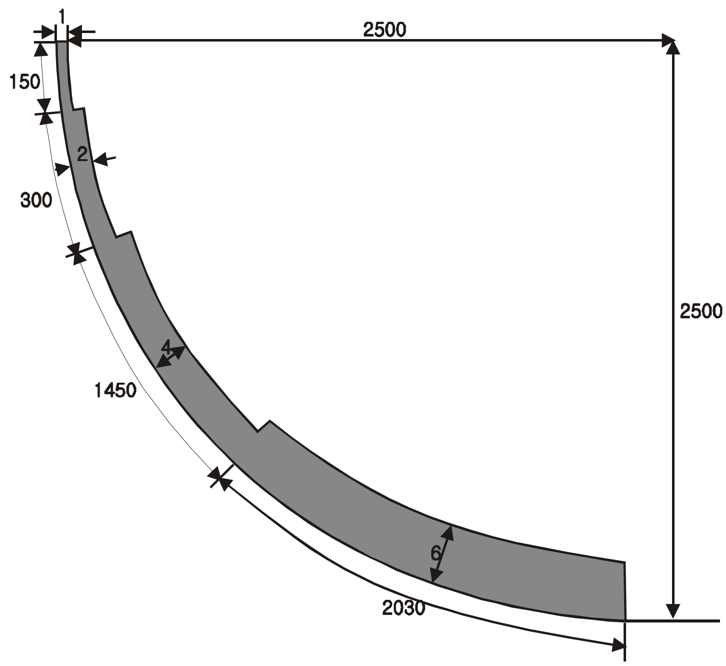

Fig. 2 Test section geometry (heater part)

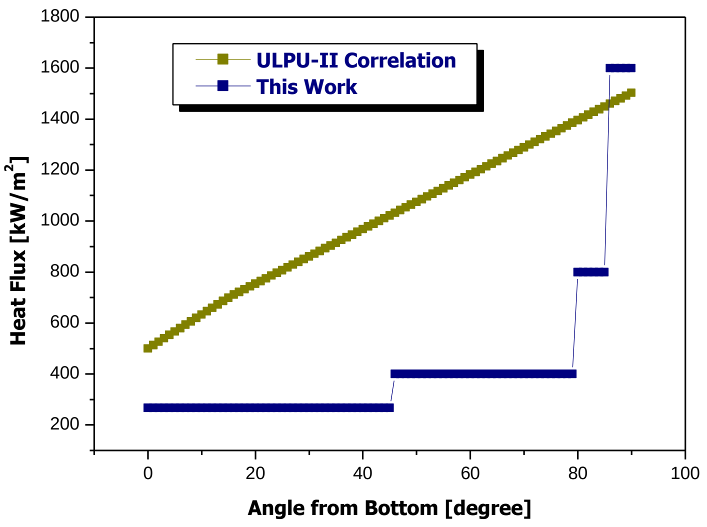

Fig. 3 Heat flux distribution (when the maximum heat flux is 1.6 MW/m^2)

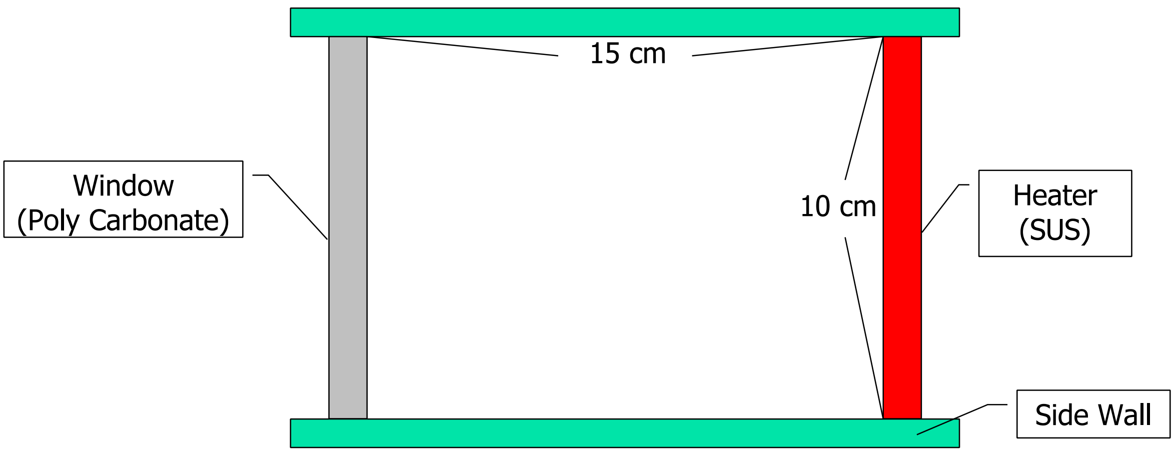

Fig. 4 Flow channel geometry

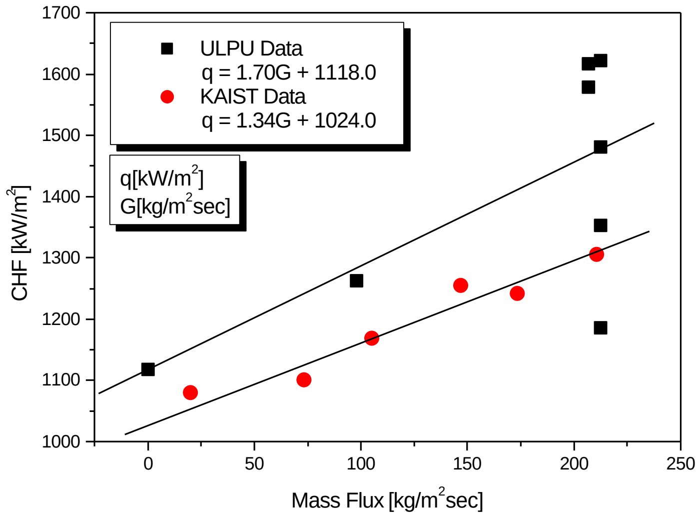

Fig. 5 CHF data according to mass flux (comparison with ULPU-II data)

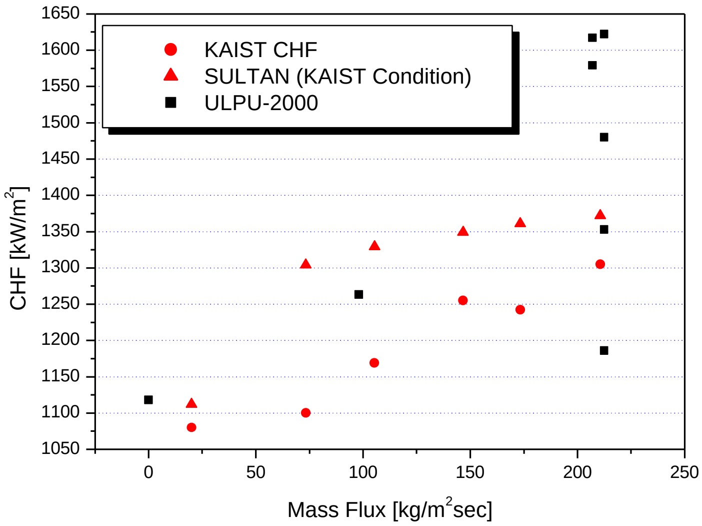

Fig. 6 Comparison of KAIST, SULTAN, and ULPU data