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FLOW BOILING CRITICAL HEAT FLUX ENHANCEMENT ON THE 2-D SLICE FOR BORIC ANCID AND TSP SOLUTION

Hae Min Park[1], Sun Heo[2], Chanyi Song[2] and Yong Hoon Jeong[1]
[1] Nuclear and Quantum Eng., Korea Advanced Institute of Science and Technology
335 Gwahak-ro, Yuseong-gu, Daejeon, Republic of Korea
[2]Nuclear Engineering and Technology Institute, Korea Hydro & Nuclear Power Co.
25-1, Jang-dong, Yuseong-gu, Daejeon, Republic of Korea

Abstract

The critical heat flux (CHF) on the reactor vessel external wall was measured using the small scale two-dimensional slice test section. The radius of the curvature and the channel area of the test section were 0.15 m and 0.03 m×0.03 m, respectively. The objectives are to assess the effects of additives (TSP, boric acid) and heated material (SA508) in inclination angle 90° and to investigate flow boiling CHF enhancement resulting from various working fluids of 5000 ppm tri-sodium phosphate (TSP, $Na_3PO_4 \cdot 12H_2O$) solution, 4000 ppm boric acid solution and mixture solution of TSP and boric acid. Boric acid solution didn't show CHF enhancement and TSP and mixture solution showed CHF enhancement (20~34%).

Introduction

In-vessel retention through external reactor vessel cooling (IVR-ERVC) is important strategy to prevent the release of molten corium outside the primary pressure boundary during severe accident. The cooling method of IVR-ERVC is heat removal of molten corium arrested at the lower head of reactor pressure vessel, through external reactor vessel wall. The coolability limits is standard of success of IVR-ERVC and it is considered that IVR-ERVC successes when the coolability limit is larger than the heat load on lower head. The coolability limits defines critical heat flux (CHF) and CHF may be increased by the composition of coolant and heated material. IVR-ERVC strategy uses the coolant dissolved tri-sodium phosphate (TSP, $Na_3PO_4 \cdot 12H_2O$) solution and boric acid (H_3BO_3) solution and the material of reactor vessel lower head is SA508 Grade 3 Class 1. To assess the effects of additives (TSP, boric acid) and heated material (SA508, Gr.3, Cl.1), critical heat flux (CHF) experiments were conducted under various conditions.

This study examines water flow boiling CHF enhancement with 5000 ppm TSP solution, 4000 ppm boric acid solution, mixture of 5000 ppm TSP and 4000 ppm boric acid solution and SA508, Gr.3, Cl.1 heater. CHF experiments were conducted at atmospheric pressure, at a mass flux of 100~300 kg/m^2s and at an inlet subcooling of 2 K. Results were compared with reference deionized (DI) water CHF data using Type 304 stainless steel (SUS304) heater.

Especially, the top region of the head is the main concern of this study. If the metal layer is formed on the top of the oxide pool, the heat flux is highest on the interface of the metal layer and the vessel wall by focusing effect. We had special interests in APR1400 and the experimental loop was prepared for the 1/16 scale two-dimensional and two phase flow experiments for IVR-ERVC strategy.

1. Previous experimental studies

Flow boiling CHF experiments with boric acid solution and TSP solution were conducted by Korea Advanced Institute of Science and Technology (KAIST). Jeong et al. performed experiments with TSP solution in SS316 circular tube and found the CHF enhancement effect by surfactant TSP solution. They measured CHF data at four concentrations of 0.05%, 0.2%, 0.5% and 0.8% under various condition (inlet subcooling, 25~50 K; mass flux, 100~500 kg/m^2s). Maximum increase in CHF was about 48% at low mass flux (~100 kg/m^2s). TSP solution caused a decrease in surface tension and an increase of CHF. Juno Lee conducted CHF experiments of SS316 circular tube with boric acid solution at four concentrations of 0.2%, 0.4%, 0.6% and 0.8%. CHF enhancement was found as maximum 14% at low mass flux (~100 kg/m^2s). Boric acid also caused a decrease in contact angle. However, the coupling effect between TSP solution and boric acid solution must be concerned.

To identify the coolability limit for APR1400, KAIST-CHF experiments were conducted. In KAIST-CHF experiments, the real scale two-dimensional slice test section was used. The radius of the curvature was 2.5 m and the length was ~4.0 m. The width of the heater was 10cm and the gap size was 15 cm. The CHF on the top of lower head (90°) was only measured. The lower parts of heater (thickness 2~6 mm) had the heat flux distribution of step function which was same with actual heat load during severe accident in APR1400. KAIST-CHF experiments have been conducted under various mass flux (10~150 kg/m^2s) and inlet subcooling (14 K) conditions. The CHF was measured using TSP solution (5000 ppm in weight percentage) and the CHF increase as 30~80 kW/m^2 was confirmed. The CHF enhancement effect of TSP solution at low mass flux was larger than at relatively high mass flux.

To identity the coolability limit for AP600 and the Loviisa plants, the ULPU experiments were conducted using the large scale two-dimensional test section (R=1.76 m). In configuration III, the heater block was constructed from A508 ASTM standard class 3 steel (SA508) instead of copper. CHF was not measured, however the nucleate boiling maintained on the CHF level of copper heater block. The possibility of CHF enhancement about low carbon steel was confirmed.

2. Experimental apparatus

To investigate the effect of working fluid and heated material on CHF for a small scale two dimensional slice, an experimental water loop and test section were constructed. Figure 1 shows a schematic diagram of experimental water loop. The experimental water loop used in this study consisted of test section, heat exchanger, surge tank, preheater, pump, flow meter, lower plenum, test section and upper plenum.

Preheater had roles of inlet subcooling control and water reservoir. And through pump the condition of mass flux can be controlled and forced circulation was used in this study. Lower and upper plenum simulated the APR1400 design. Lower plenum was designed as injection of upward flow path and the length of upper plenum were 0.425 m, long enough to simulate the side vessel wall. Through lower plenum, water was injected to test section and steam was generated in test section. The generated steam was condensed to water again in heat exchanger. The condensed water was gathered in surge tank. All of the connection parts were made of Type 304 stainless steel pipe of 1 inch.

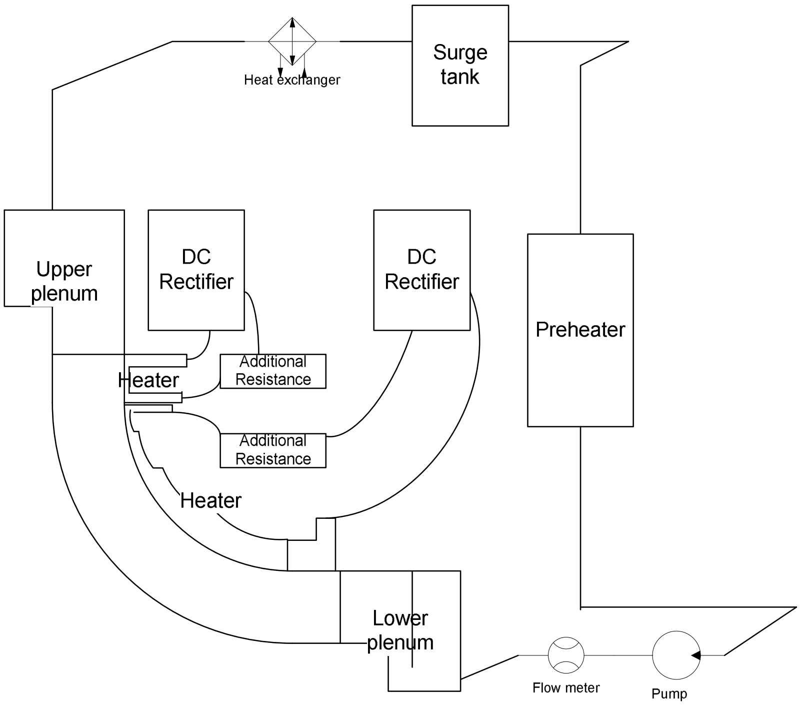

Figure 1 Schematic diagram of the experimental loop

2.1 Test section

The material of test section was Type 304 stainless steel (SUS304) used in KAIST-CHF experiments and SA508, Gr.3, Cl.1 which is the material of reactor vessel lower head. The radius of curvature was 0.15 m, 1/16 scale of the APR1400 design. The total length of test section was 0.235 m and the shape was quarter-circle as shown in Figure 2. The width and gap size were 3 cm. The heater section was insulated by the teflon and silicon sheet. Details are described as follows.

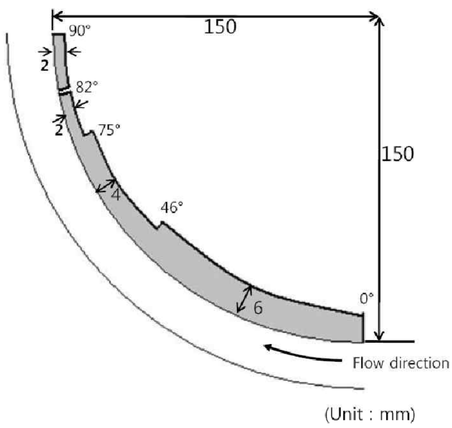

Figure 2 Test heater section geometry

The test section was divided two parts. One part (inclination angle 0~82°) was the pre-heated region by direct current (DC) heating and had a connection with a 45 kW capacity dc rectifier. This part was divided three parts (thickness 2~6 mm) and simulated the actual heat load of the APR1400 design during severe accident. No occurrence of CHF was confirmed through ULPU configuration II correlation. In pre-heated region, the heat fluxes were 280 kW/m^2 on a 6 mm thick region, 420 kW/m^2 on a 4 mm thick region and the maximum heat flux was 839 kW/m^2 on a 2 mm thick region. Figure 3 shows heat flux distribution of test heater section. To control and maintain stably heat flux of the pre-heated region, an additional resistance was added in the circuit for DC heating. Another part of test section was main heated section. In this heated section, CHF was occurred. Using a 100 kW capacity DC rectifier, this part also applied DC heating. The main heated section was vertical plate of which the width was 3 cm and the length was 2 cm. The heater thickness was 2 mm for SUS304 and 1 mm for SA508. The maximum heat flux was higher than 2 MW/m^2. This heater plate also was connected to additional resistance for stable control of heat flux.

Table 1. The experimental conditions of this study

Dimension of test section	**Radius**	0.15 m
	Gap size	0.03 m
	Width	0.03 m
Heating method		DC heating
Circulation method		Forced circulation
Pressure		Atmospheric pressure
Mass flux		100~300 kg/m^{2}s
Heater material		SUS304, SA508
Inlet subcooling		2 K
CHF point		90°
Working fluid		DI water, boric acid, TSP solution, mixture of borid acid and TSP solution

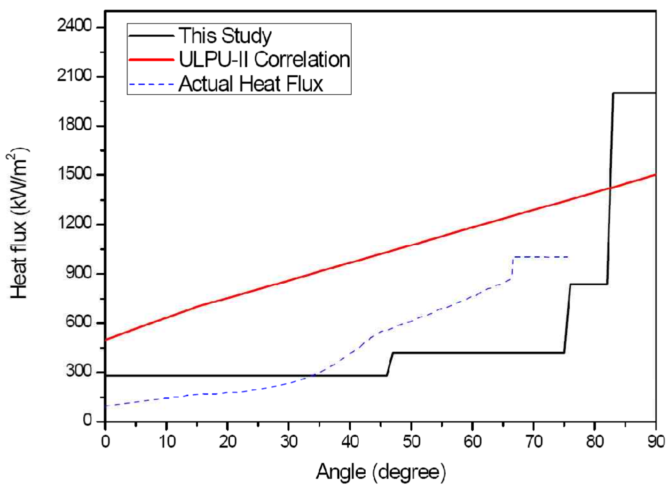

Figure 3 Heat flux distribution of test heater section

Figure 4 shows flow channel geometry. The flow area of this study was 0.03 m × 0.03 m. The gap size between heater and window was 0.03 m. This was same as that of the first campaign of SULTAN experiments and less than that of the KAIST-CHF and ULPU experiments. The experimental conditions of this study are summarized in Table 1.

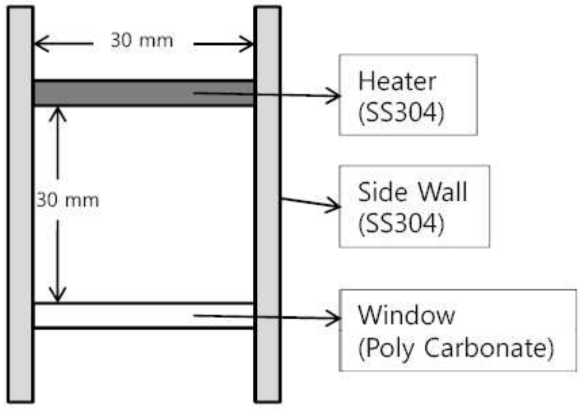

Figure 4 Flow channel geometry

2.2 Working fluid

TSP and boric acid are used in nuclear power plant for maintaining high pH level during severe accidents. It is noticed that boric acid concentration is 4000 ppm in weight percentage in In-containment Refueling Water Storage Tank (IRWST) and TSP concentration is 5000 ppm in weight percentage in coolant injected to reactor cavity. Considering the coolant used for IVR-ERVC strategy, the experiments were performed with the following three working fluids.

1. 0.4% boric acid solution

2. 0.5% TSP solution

3. Mixture of 0.4% boric acid and 0.5% TSP solution

To investigate individual effects of each solution on CHF, the experiments with 0.4% boric acid solution and 0.5% TSP solution were conducted under various conditions of mass flux and exit quality. To identity coupling effects of boric acid and TSP, the experiments with the mixture solution of 0.4% boric acid and 0.5% TSP were conducted.

2.3 Experimental methodology

To measure the CHF on two-dimensional slice, the experimental conditions were controlled and the CHF value was measured by the measurement system and data acquisition system (DAS). The measurement system consisted of seven thermocouples, a flow meter (electro-magnetic type) and a power meter (WT210) and was connected to the DAS. Three K-type thermocouples measured the surface temperature of the preheated region and two K-type thermocouples measured the surface temperature of the main heater region. Two T-type thermocouples measured the inlet and the outlet temperature of the test section. Experimental errors in the temperature measurement were estimated to be ±0.5 ℃ for the K-type thermocouple and ±0.5 ℃ for the T-type thermocouple. The flow rate was measured by a flow meter (±0.5%) and the voltage and the current by a power meter. The DAS consisted of an Agilent 34980A data acquisition/control unit and a personal computer.

The typical procedure of experiments was the following.

1. Install thermocouple sets on the test section to detect the CHF.

2. Fill the experimental loop with working fluid.

3. Turn on the preheater and pump and heat up working fluid in the experimental loop to a scheduled inlet subcooling

4. Turn on the 100 kW dc rectifier, flow meter and data acquisition system and adjust heat flux of the pre-heated region and mass flux at a scheduled level

5. Turn on the 45 kW dc rectifier and gradually raise heat flux level of main heated region until the CHF was detected. The increase rate of the heat flux was limited within 1% of the previous heat flux, near CHF conditions (from 80% of CHF)

6. Shut down the dc rectifier as soon as possible after the onset of the CHF

The heat flux level on the test section is calculated as the following joule's equation.

$$\begin{aligned} q' &= \frac{I^2\ R_{heater}}{A_{heater}} \\ &= I^2\left(\rho\frac{L_{heater}}{w_{heater}\ t_{heater}}\right)\left(\frac{1}{w_{heater}\ L_{heater}}\right) \\ &= I^2\frac{\rho}{w_{heater}\ t_{heater}^2} \end{aligned} \quad (1)$$

The heat flux is in terms of the current, electrical resistivity, width and thickness of the test section. The measured CHF data include the uncertainties of each instrument. The root-sum square (RSS) error is given by the individual uncertainties of the independent measured data. For the power meter, the uncertainty of current is 1.0 % and that of voltage is 0.2 %. And the geometric uncertainty in heater area is 1.0 %. Thus, the overall uncertainty of the heat flux is 1.4 %. The heat loss from the heater was about 0.3 %. Therefore the overall uncertainty in CHF is 1.7 %.

3. Results and discussion

Through this study, the CHF data of 3 points were measured on vertical plate for each working fluid (DI water, boric acid solution, TSP solution and mixture of boric acid and TSP solution) and SA508 heater. The pressure at test section was ~1.15 bar due to hydraulic head by accumulated water along test section and surge tank. Inlet subcooling condition was 2 K. And mass flux conditions were 100, 210 and 300 kg/m^{2}s.

As shown in Figure 5, the CHF with TSP solution and mixture of boric acid and TSP solution increase and the CHF with boric acid decrease, compared with the CHF data with deionized (DI) water.

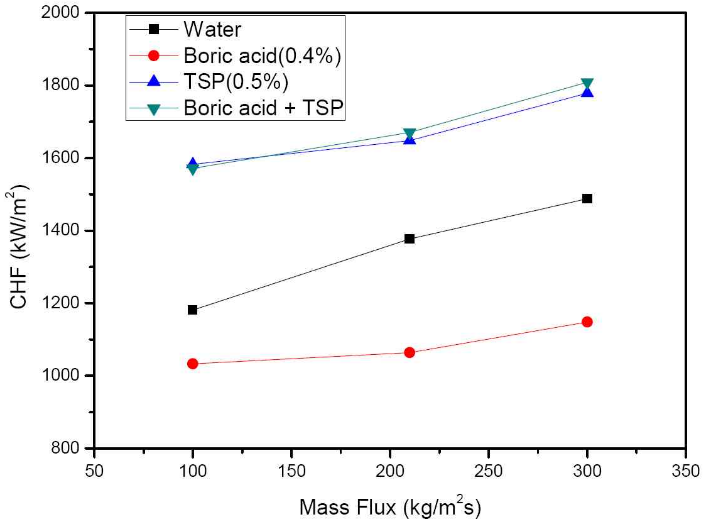

Figure 5 CHF data according to working fluid

In case of boric acid, CHF was decreased at all mass flux condition. Maximum decrease was ~340 kW/m^2 at high mass flux (~300 kg/m^{2}s) and minimum decrease was ~150 kW/m^2 at low mass flux (~100 kg/m^{2}s). In Juno Lee's experiments, boric acid solution caused an enhancement effect of CHF at high inlet subcooling condition (25~50 K). However, CHF for boric acid solution decrease at low inlet subcooling condition (2 K) in this study.

In case of TSP solution, the CHF enhancement effect was confirmed. CHF enhancement was found as maximum 34% at low mass flux (~100 kg/m^{2}s) and more than 20% at all mass flux conditions (100~300 kg/m^{2}s) as compared to the CHF with DI water. As confirmed in wettability measurement experiments of Jeong et al., TSP solution caused a decrease in contact angle and an increase in CHF.

In CHF experiments with Mixture of boric acid and TSP solution, the CHF enahancement was also confirmed. The tendency of CHF was much similar with the CHF results of TSP solution. As shown in Figure 5, the CHF for mixture of boric acid and TSP solution was almost same with that for TSP solution under the same experimental conditions. Maximum increase was 33% (~400 kW/m^2) at low mass flux (~100 kg/m^{2}s) and the increase of CHF was more than 21% (~300 kW/m^2) at all experimental conditions (100~300 kg/m^{2}s). For additives effects on CHF with mixture of boric acid and TSP solution, the effect of TSP solution was dominant, regardless of boric acid. Under the working fluid of DI water, CHF experiments were performed using test section of SA508. The CHF results for SA508 heater are shown in Figure 6 and compared with that for SUS304 heater under the same experimental conditions. The tendency of the SA508 data was same with that of SUS304 data about mass flux and exit quality, as shown in Figure 6 and 7. However the CHF data of SA508 were higher than that of SUS304. The extent of CHF enhancement was high at relatively low mass flux and high exit quality. Maximum increase was 17% (~200 kW/m^2) at low mass flux (~100 kg/m^{2}s).

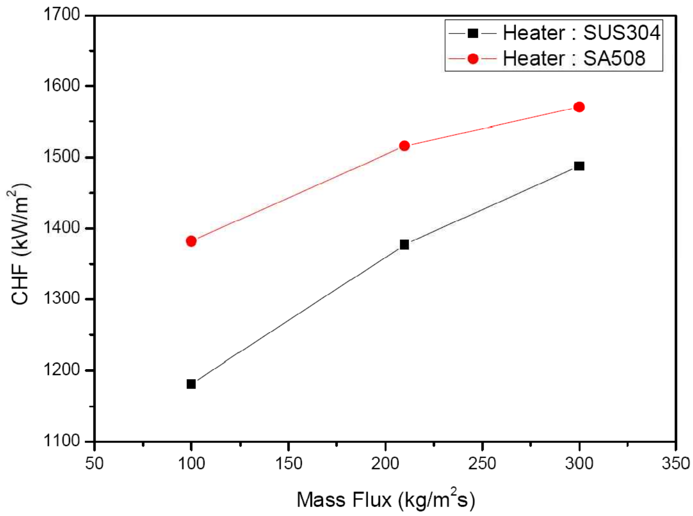

Figure 6 CHF data according to heater material (mass flux)

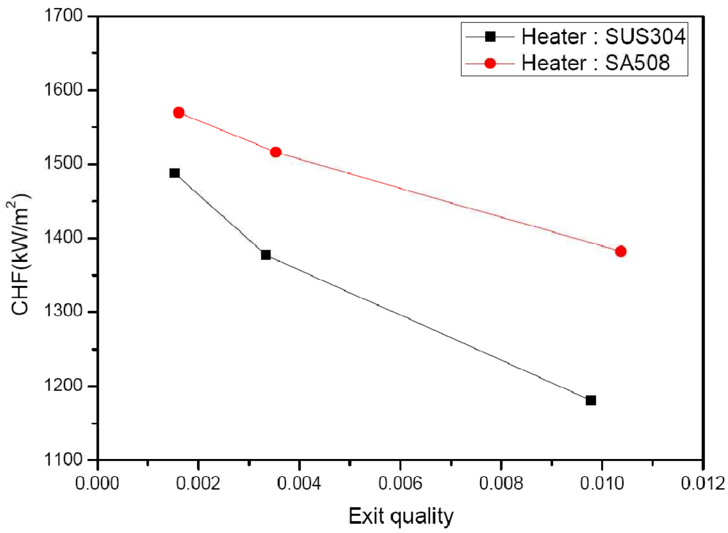

Figure 7 CHF data according to heater material (exit quality)

4. Conclusion

Through this study, CHF experiments for IVR-ERVC using a small scale two-dimensional slice test section were conducted. Basically, the effect of additives (boric acid solution, TSP solution and mixture of boric acid and TSP solution) and heated material (SUS304 and SA508) on CHF phenomenon was investigated. The comparison with DI water experiments of SUS304 heater was examined.

For working fluid of boric acid, CHF was decreased on the contrary to flow boiling CHF with SUS316 tubes. In case of TSP solution, the CHF results of this study were consistent with SUS316 tube experiments. TSP solution caused a decrease in contact angle and an increase in CHF. In CHF experiments with Mixture of boric acid and TSP solution, the CHF results were almost same with TSP solution data. For additives effects on CHF with mixture of boric acid and TSP solution, the effect of TSP solution was dominant, regardless of boric acid. Maximum increase was 33% (~400 kW/m^2) at low mass flux (~100 kg/m^2s).

Enhanced (~17%) CHF was observed for SA508 heater under low mass flux (~100 kg/m^2s). The extent of CHF enhancement was high at relatively low mass flux and high exit quality.

Especially, this study confirmed the CHF enhancement factor on the external wall of reactor vessel lower head during severe accident.

5. References

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