Experimental CHF Study on the Pressure Effect in the 2-D Slice Test Section

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1. Introduction

For severe accident mitigation, a number of nuclear power plants use the in-vessel retention through external reactor vessel cooling (IVR-ERVC) strategy which removes the decay heat of the molten corium. The critical heat flux (CHF) is one of the most important criteria by which to judge the success of the IVR-ERVC strategy. The CHF on the external vessel wall is also affected by a pressure condition of the containment. During severe accident, the pressure in containment is higher than the atmospheric pressure due to coolant loss from the primary loop. Therefore, the effects of pressure conditions should be clarified.

2. Experimental Apparatus

To investigate the effect of pressure on CHF on a downward facing surface in the rectangular channel, an experimental water loop constructed in Park et al. (2013) [1] and SUS304 and SA508 test sections were used. Fig. 1 shows a schematic diagram of experimental water loop.

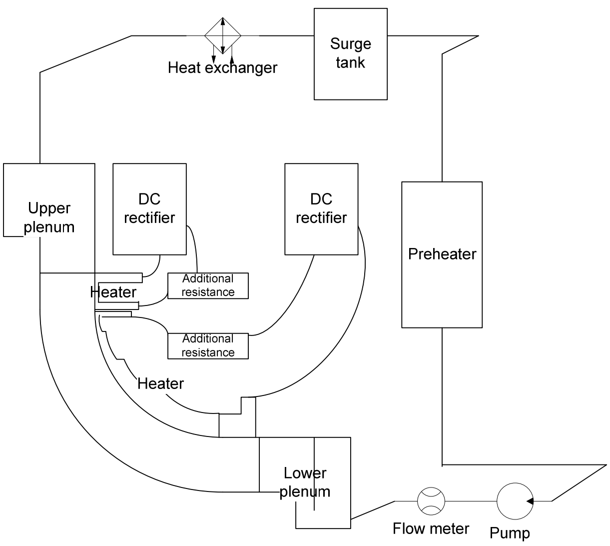

Fig. 1. Schematic diagram of the experimental loop

In this study, the design of the surge tank was modified, in order to make the pressurized conditions. The surge tank have an air injection valve and a venting valve to control the pressure condition.

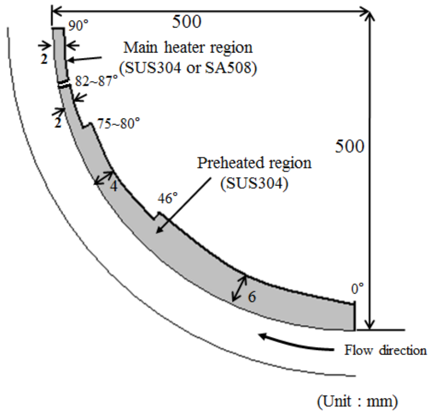

Fig. 2. Test heater section geometry

The geometry and structure of the test sections were the same with those used in Park et al. (2013). In this study, the 0.5 m test section was only used. The heater materials of both SUS304 and SA508 and the additives of the mixture of boric acid and tri-sodium phosphate (TSP) were considered. And the flow boiling CHF experiments were conducted under 2 bar condition. The experimental conditions of this study are summarized in Table I.

Table I: The experimental conditions of this study

Dimension of test section	**Radius**	0.5 m
	Gap size	0.06 m
	Width	0.03 m
Heater material		SUS304, SA508
Pressure		Atmospheric pressure, 2 bar
Mass flux		100, 300 kg/m^2s
Inlet subcooling		2 K
CHF point		90°
Working fluid		DI water, Mixture solution of 2.5 wt% boric acid and 0.5 wt%TSP

3. Results and Discussion

It is expected that the CHF is enhanced under pressurized conditions in comparison with the CHF under atmospheric pressure. To confirm that tendency, the CHF was measured under the pressure conditions of 2 bar only in the R=0.5 m test section and the 6 CHF points in each pressure condition were acquired. The experimental conditions were the same with those for the atmospheric pressure. The mass fluxes were 100-

300 kg/m²s and the inlet subcooling condition was 2 K. The working fluid used in this experiment series was DI water and mixture solution of 2.5 wt% boric acid and 0.5 wt% TSP.

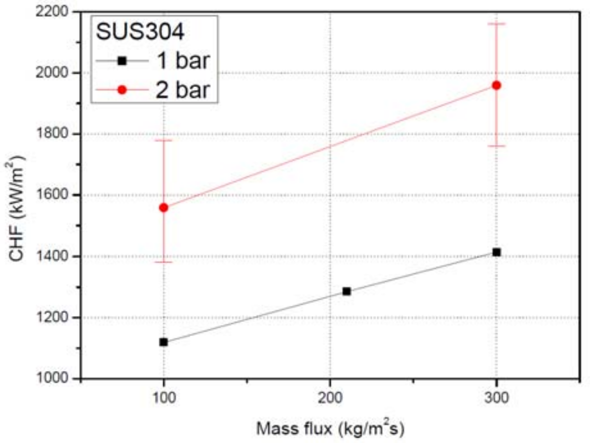

Fig. 3. Pressure effect on the CHF on SUS304 surface with DI water

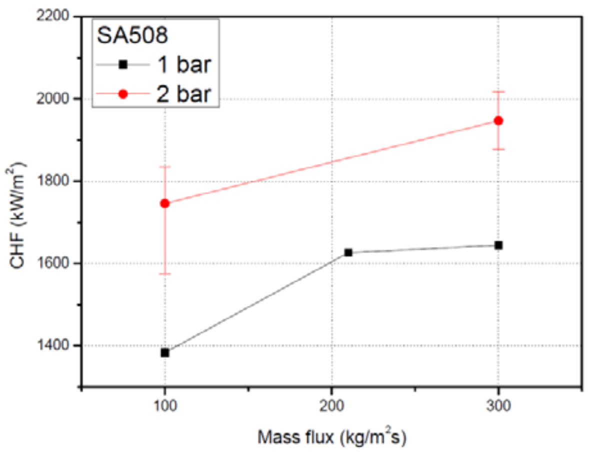

Fig. 4. Pressure effect on the CHF on SA508 surface with DI water

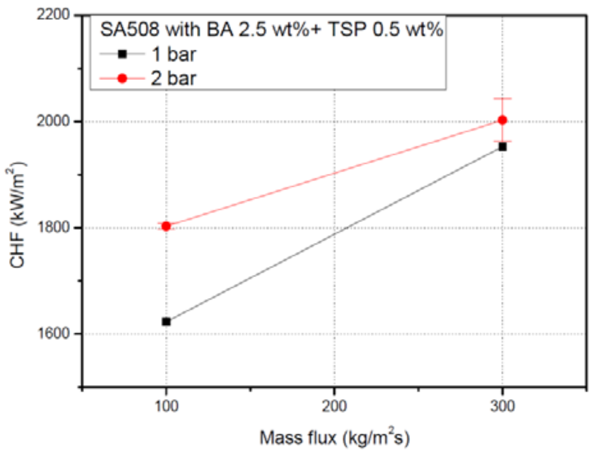

Fig. 5. Pressure effect on the CHF on SA508 surface with mixture solution of boric acid and TSP

To investigate the effect of pressure, the experimental results for 2 bar were compared with those for the atmospheric pressure in each condition. And the effect of heater material alone and the combined effects of heater material and additives were discussed under pressurized conditions.

3.1 Comparison with 1 bar Data

To discuss the effect of pressure only for the various circumstances, the CHF data under atmospheric pressure condition (1 bar) were compared with those under the pressure conditions of 2 bar.

As shown in Fig. 3, the CHF on the SUS304 surface increased as the pressure increased when the working fluid of DI water was used. The same tendency of CHF on the SA508 surface with SUS304 cases was appeared, as shown in Fig. 4. The CHF data for the heater material of SA508 and the working fluid of the mixture solution of 2.5 wt% boric acid and 0.5 wt% TSP are plotted in Fig. 5 and also compared with those for atmospheric pressure condition. This case also appeared the CHF enhancement.

The pressure characteristic for the CHF which was confirmed was the same with general relationship which means the CHF is enhanced as the pressure increases. The mechanism of the CHF enhancement is reduction of void fraction due to the higher vapor density by pressurizing.

3.2 Comparison with the Existing Model

The CHF enhancement tendency by increasing the pressure, which was confirmed in this study, was compared with that of the existing CHF model suggested by Cheung and Haddad (1997) [2], as the following equation.

$$q''_{CHF} = B\rho_g h_{fg}\left[\frac{\sigma u_l}{\rho_l \delta_0}\left(1+\frac{\rho_g}{\rho_l}\right)\left(\frac{\rho_g}{\rho_l}\right)^{-1.6}\right]^{1/3}$$

Based on that equation, the CHF increase ratio was calculated, according to the property of fluid and vapor of DI water. Because the constant, *B*, is unknown, the absolute CHF value was not calculated and the only ratio can be calculated. The properties of DI water under 2 bar are slightly different from those under 1 bar, except for vapor density. Therefore, the CHF increase ratio is strongly dependent on the vapor density and approximately proportional to the vapor density. According to the calculated value of the ratio, the CHF under 2 bar is about two times higher than that under 1 bar condition. As shown in Fig. 6, there was disagreement between the experimental results and the CHF model of Cheung and Haddad (1997).

It is regarded that the constant, *B*, should be specified and different in terms of the corresponding pressure conditions. It is necessary that the existing model is modified and considers other relationship which can clearly reflect the CHF tendency as the pressure condition increases or decreases.

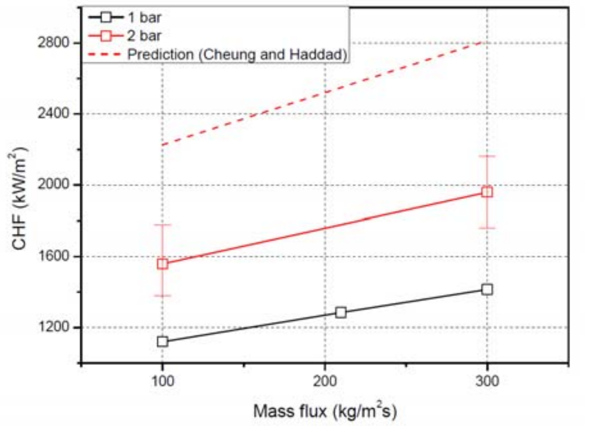

Fig. 6. Comparison between the experimental results and the existing CHF model

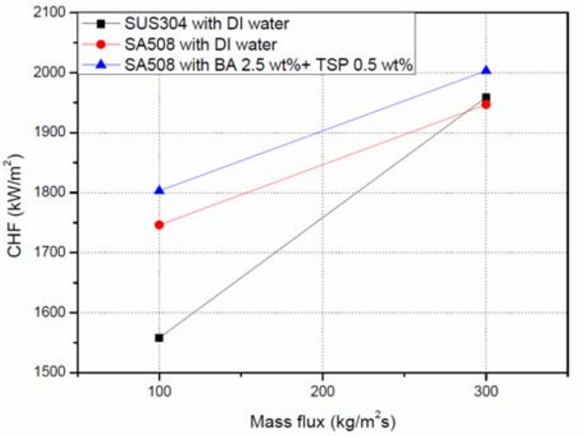

Fig. 7. Effect of heater material and additives in 2 bar condition

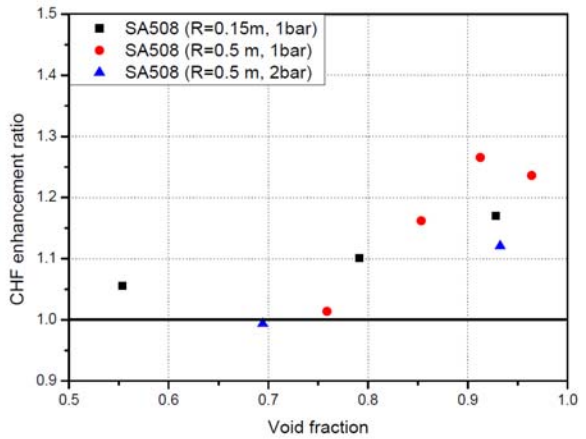

Fig. 8. CHF enhancement ratio according to void fraction

3.3 Heater Material Effect

The CHF data on a SA508 surface were compared with those on a SUS304 surface in each pressure condition, to discuss the effect of heater material and additive under pressurized conditions.

According to the CHF data for the atmospheric pressure, the CHF enhancement on a SA508 surface is expected by improvement of the wettability. Under relatively low mass flux condition (100 kg/m^{2}s), the effect of the CHF enhancement was also confirmed by using SA508 test section in 2 bar condition in comparison with the SUS304 case, as shown in Fig. 7. However, the CHF increase in the SA508 test section did not appear and the CHF on a SA508 surface is the same level with that on a SUS304 surface under relatively high mass flux condition (300 kg/m^{2}s). The possible reason is the reduction of void fraction by pressurizing. The values of void fraction was calculated from thermodynamic exit quality at the CHF point for atmospheric pressure and 2 bar condition and the CHF enhancement ratios in terms of the void fraction are plotted in Fig. 8, in comparison with SUS304 cases with DI water. In a condition of relatively low void fraction, the liquid occupy approximately a half volume and the surface is wetted enough to ignore the improvement of the wettability of SA508 surface. The lower mass flux condition is, the higher void fraction is. Therefore, it resulted in the high CHF enhancement in relatively low mass flux conditions and the low CHF enhancement in relatively high mass flux conditions. In other words, the effect of the wettability improvement on the CHF can be minimized in relatively high mass flux and low void fraction.

3.3 Combined Effect of Heater Material and Additive

The CHF on a SA508 surface with mixture solution of 2.5 wt% boric acid and 0.5 wt% TSP was compared with the CHF on SA508 and SUS304 surface with DI water to clarify the combined effect of heater material and additive as shown in Fig. 7. According to the previous section for the combined effect of heater material and additive in atmospheric pressure condition, it is expected that the CHF is enhanced by the effects of steel oxidation and additive deposition. In the 2 bar condition, the CHF was also enhanced in comparison with SUS304 case and SA508 case.

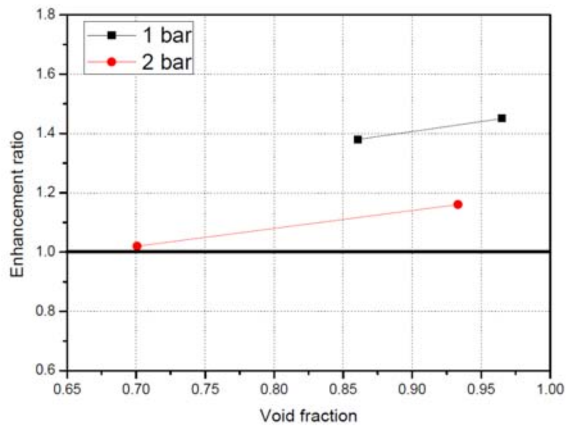

Fig. 9. CHF enhancement ratio of boric acid 2.5 wt%+TSP 0.5 wt% cases compared with SUS304 cases with DI water

However, the CHF enhancement ratio in 2 bar case was lower than that in atmospheric pressure case. Fig. 9 show the CHF enhancement of additive mixture cases compared with SUS304 cases for each pressure condition. Although the wettability improvement by steel oxidation and additive deposition is evident, the effect on CHF enhancement can be reduced in relatively low void fraction conditions. In the void fraction of ~0.7, the CHF enhancement ratio was nearly 1.

3. Conclusions

For the pressure effect, the R=0.5 m test section was used under the pressure of 2 bar. The CHF for pressurized conditions was enhanced in comparison with 1 bar data, as the general relationship. However, there was disagreement between the experimental results and the existing CHF model. For the effect of heater material and additive, although the CHF enhancement was also confirmed, the CHF enhancement rate was decreased in comparison with 1 bar cases because the effect of the wettability improvement on the CHF can be reduced in relatively low void fraction.

REFERENCES

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[2] F. B. Cheung and K. H. Haddad, “A Hydrodynamic Critical Heat Flux Model for Saturated Pool Boiling on a Downward Facing Curved Heating Surface”, Int. J. Heat and Mass Tran., Vol. 40, pp. 1291-1302, 1997.