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CHF Experiments under Realistic Severe Accident Condition for IVR-ERVC Strategy

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Abstract

This study describes critical heat flux (CHF) experiments using a 2-D curved test section with trisodium phosphate (TSP : Na_3PO_4) and boric acid (BA : H_3BO_5). The CHF values of TSP solution, BA solution, and TSP + BA solution were enhanced by as much as 50% for all experimental conditions except the condition of 150 mm radius with BA solution. The enhancement can be explained by wettability enhancement and decrease of bubble departure diameter. This CHF enhancement could provide additional thermal margin for the IVR-ERVC strategy.

1. Introduction

In-vessel retention of molten corium through external reactor vessel cooling (IVR-ERVC) is a strategy to manage severe accidents of light water reactor (LWR). This IVR-ERVC strategy has been adopted by some operating nuclear power plants and has been proposed for some advanced LWRs such as AP1000 of the U.S. and APR1400 of Korea. The strategy gives sufficient thermal margin for small and medium-sized reactors. However, it is not certain that the IVR-ERVC provides sufficient thermal margin for large reactors (more than 1000 MWe) without additional enhancements of critical heat flux (CHF) [1].

Studies regarding CHF on the reactor vessel outer surface have been conducted by many researchers to examine the feasibility of the IVR-ERVC strategy [2-7]. No study has demonstrated that the CHF values have a sufficient margin for severe accident conditions. However, these studies do not reflect realistic severe accident conditions such as coolant additives, reactor vessel materials, pressure, and so on, that could provide additional thermal margin for the IVR-ERVC strategy. In particular, coolant additives could play an important role in external reactor vessel cooling; thus, the effect of additives on the CHF should be evaluated.

In a severe accident, coolant which comes from the in-containment refueling water storage tank (IRWST) through the hold-up volume tank (HVT) is injected into the reactor cavity to flood the reactor vessel (Fig. 1). In the IRWST, boric acid (BA : H_3BO_5) is dissolved in the water to a concentration of 4000 ppm, and in the HVT, trisodium phosphate (TSP : Na_3PO_4) is dissolved to a concentration of 5000 ppm. Thus, the coolant injected into the reactor cavity from the IRWST through the HVT contains 4000 ppm of BA and 5000 ppm of TSP.

In the present study, we conducted CHF experiments using a 2-D curved test section with TSP and BA to find the additional thermal margin for the IVR-ERVC strategy. Body text formatting

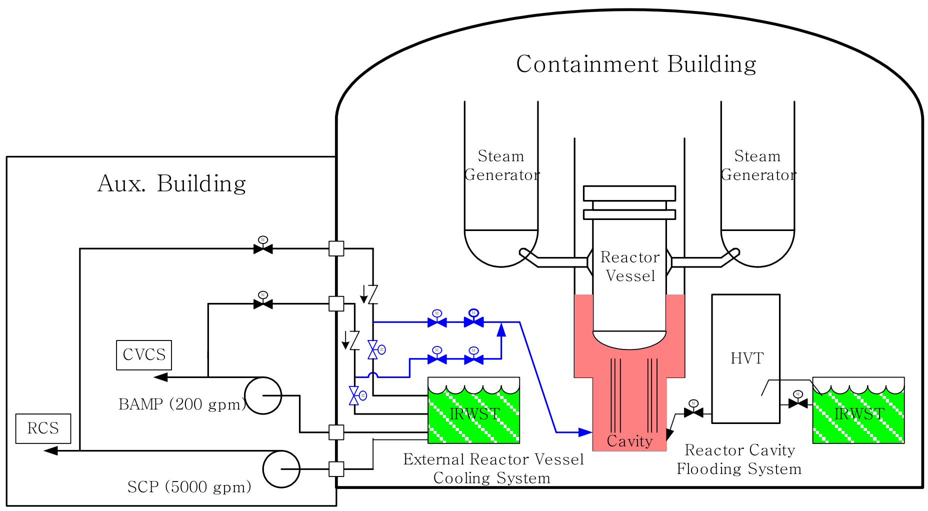


Fig. 1. Cavity Flooding System

2. Previous Work

There have been many studies to examine the CHF value on the reactor vessel wall outer surface [2-7]. T.G. Theofanous et al. conducted CHF experiments at the ULPU-2000 facility to identify the coolability limit of the AP600 of the U.S. and the Lovisa plant of Finland. In configuration Ⅰ, the CHF experiments of the lower region of the reactor vessel outer wall (0°<θ<30°) were conducted in pool boiling conditions. In configurations Ⅱ and Ⅲ, the CHF experiments of the overall inclination angle (0°<θ<90°) were conducted under natural convection conditions. The maximum CHF value at the upper region end (θ=90°) was about 1.6 MW/m^2 [2, 3].

T.N Dinh et al. conducted CHF experiments at the ULPU-2400 facility to identify the coolability limit of the AP 1000 of the U.S. In configurations Ⅳ and Ⅴ, they modified the flow path of the coolant and examined the effects of the modification. They found that a smooth flow path could enhance the CHF value considerably, and the CHF values of the upper region were in a range from 1.8 to 2.0 MW/m^2 [4].

Y.H. Jeong et al. conducted the KAIST-CHF experiments to investigate the coolability limit of the APR1400 of Korea. The maximum CHF value was 1.4 MW/m^2. Their CHF results were lower than those of the ULPU. They concluded that the lower CHF was due to the difference in the material and the geometry of the test section [5].

S. Rouge et al. conducted the SULTAN experiments to investigate CHF data of a large-scale test section at inclined plates. In the SULTAN experiments, gap size and heater length varied case by case. A CHF correlation was developed considering the experimental results. This yielded information about gap size effect and high exit quality on the CHF. However, in the SULTAN experiments, the test section had uniform heat flux distribution, which is unlike the actual heat load of the lower head [6, 7].

Examining the studies about the CHF on the reactor vessel outer surface that have been conducted up to now, we can see that no experiment accurately reflects severe accident conditions (Table 1).

Moreover, there have been few studies about the effects of TSP and BA on the CHF in flow boiling conditions [8, 9].

Y.H. Jeong et al. conducted flow boiling CHF experiments with a circular tube using TSP under atmospheric pressure. They found that TSP solutions showed decrease in contact angle, which leads to high wettability and low surface tension. Their results show that CHF was enhanced up to 48% at very low mass flux (100-300 kg/m^{2}s) and CHF decreased at high mass flux. They concluded that the CHF enhancement at very low mass flux was due to increasing wettability, and the decrease of CHF at high mass flux was due to instability of the liquid slug flow [8].

J. Lee et al. conducted flow boiling CHF experiments with a circular tube using TSP and BA under atmospheric pressure. They found that the CHF was enhanced by as much as 21.4% by using TSP, and the CHF enhancement ratio decreased with the increase of mass flux. In the case of BA, they found that the CHF was enhanced by as much as 12.4%, and the trend of CHF enhancement was similar to that of the TSP case [9].

Table 1. Experimental conditions of KAIST-CHF, ULPU and SULTAN experiments

	KAIST-CHF	**ULPU**	**SULTAN**	**Severe accident condition**
Heater material	SS304	Copper		SA508

Additives	TSP	None	None	TSP, BA, etc.
Pressure	1 bar	1.3 bar	1~10bar	More than 1 bar

3. Experiments

3.1 Experimental Apparatus

CHF experiments were conducted using the IVR-ERVC CHF experimental loop shown in Fig. 2. This experimental loop consists of a CRN3-25 pump, an electromagnetic flow meter, a 2-D slice test section, a condenser for cooling of coolant, a surge tank with an overhead liquid reservoir, and a preheater to control the inlet condition of the coolant. The test section is divided into two parts to simulate the actual thermal load of severe accident conditions and the focusing effect of the metal layer of the core melt [3, 10]. One part is the pre-heated region which consists of three different thickness heaters and simulates the actual thermal load. The other part is the main-heated region in which the CHF occurs and the focusing effect is simulated. A schematic diagram of the test section is shown in Fig. 3, and the flow channel geometry is shown in Fig. 4. The dimensions of the test section and the experimental conditions are listed in Table 2.

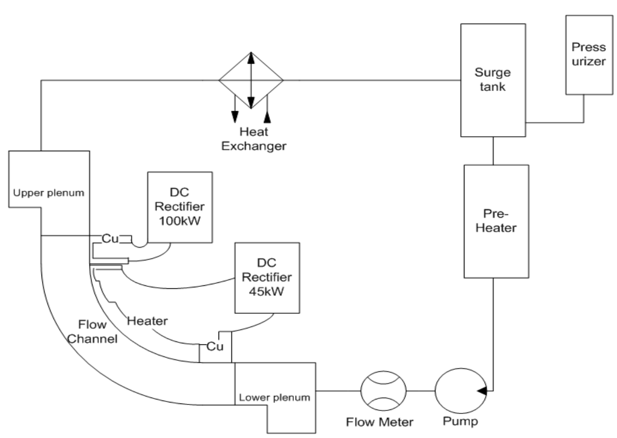
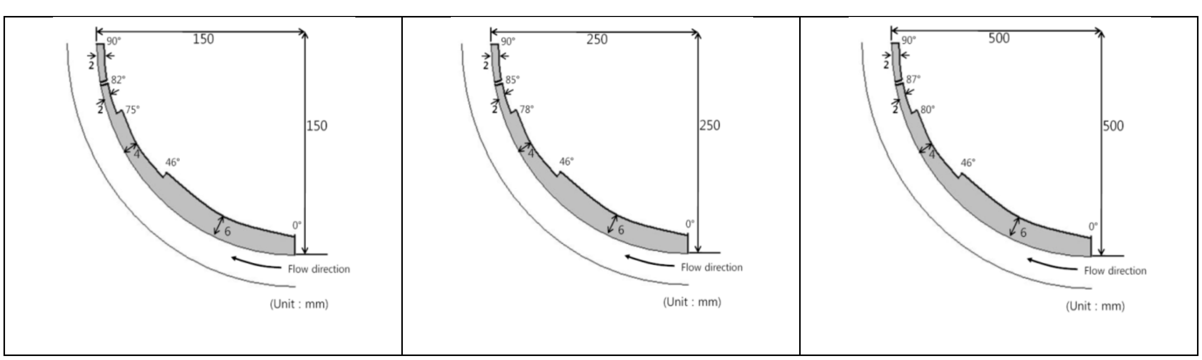


Figure 2. Schematic diagram of IVR-ERVC CHF experimental loop



Radius : 150mm Material : SS304	Radius : 250mm Material : SS304	Radius : 500mm Material : SS304

Figure 3. Schematic diagram of test section

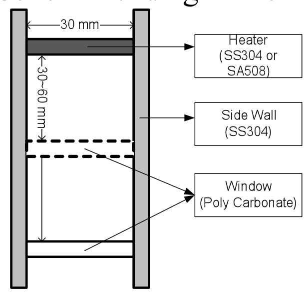


Figure 4. Flow channel geometry

Table 2. Test matrix of IVR-ERVC CHF experiments

Test Matrix			
Test Section			
Radius	150 mm	250 mm	500 mm
Material	SS304	SS304	SS304
Width	30mm	30mm	30mm
Gap Size	30mm	30mm	60mm
Coolant			
DI water			
Additives	TSP 5000 ppm, BA 4000 ppm, TSP 5000 ppm+BA4000 ppm		
Mass flux	100, 210, 300 kg/m^{2}s		
Inlet subcooling	2 K		
Pressure	101.3 kPa		

3.2 Experimental Procedure

All CHF experiments were conducted under atmospheric pressure. Heat losses to surroundings were less than 2%. The procedure of the IVR –ERVC CHF experiments are as follows:

⊖ Fill the experimental loop with coolant

⊜ Circulate coolant with heating by preheater to remove non-condensable gas and to make scheduled inlet condition.

⊛ Heat pre-heated region of test section by DC heating up to actual thermal load which is calculated by heat flux distribution under severe accident conditions (Fig. 5) and then maintain.

④ Heat main-heated region of test section by DC heating up to CHF occurrence.

⑤ Heat flux of main-heated region is calculated by the following equation :

$$q'' = I2RA \quad ,$$

where I is current, R is electrical resistance, and A is area of the main-heated region.

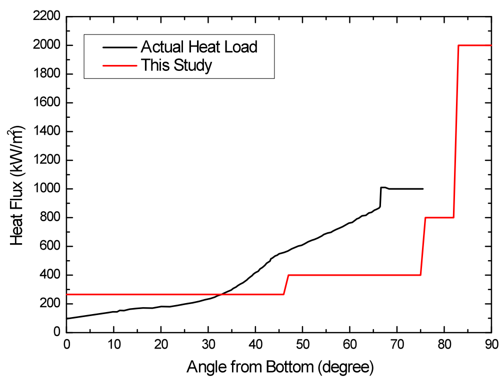


Figure 5. Heat flux distribution of heater of test section

4. Experimental Results and Discussion

4.1 Comparison with other experiments

The CHF values of DI water were varied from 1.17 MW/m^2 to 1.5 MW/m^2 at the 150 mm radius test section, and from 1.07 MW/m^2 to 1.41 MW/m^2 at the 500 mm radius test section. These CHF values showed reasonable values compared to other experimental data [2-7], and this indicated that our IVR-ERVC CHF experimental loop worked properly.

The CHF values of DI water with TSP 5000 ppm were varied from 1.58 MW/m^2 to 1.73 MW/m^2 at the 150 mm radius test section, and from 1.64 MW/m^2 to 1.74 MW/m^2 at the 500 mm radius test section. These CHF values were higher than those of the KAIST-CHF experiments conducted by Jeong et al [5]. In our experiments, the test section was divided into two parts, while the test section of the KAIST-CHF experiments was undivided, and this could give a more accurate thermal load. The radius of our test section was smaller than that of the KAIST-CHF experiments. The separation of the heater and the smaller size of the heater resulted in lower exit quality and thus higher CHF values.

Our CHF values using TSP 5000 ppm were also higher than those of the experiments conducted by Jeong et al. [8] and those of the experiments conducted by Lee et al [9]. In our experiments, the flow channel was rectangular with one side heating while the experiments conducted by Jeong et al. and Lee et al. using circular tube. The difference in geometry of flow channel could result in higher CHF values.

The CHF values of DI water with BA 4000 ppm were varied from 0.97 MW/m^2 to 1.17 MW/m^2 at the 150 mm radius test section, and from 1.35 MW/m^2 to 1.53 MW/m^2 at the 500 mm radius test section. These CHF values were higher than those of the experiments conducted by Lee et al [9], and this could be explained by the difference in geometry of flow channel. Fig. 6 shows a comparison of our CHF values with other experimental CHF value using TSP and BA.

4.2 The effect of additives on the CHF

In the case of using TSP 5000 ppm, the CHF values were enhanced under all experimental conditions by as much as 50% (Fig. 7). TSP decreases the surface tension of the solution, and this decreases the contact angle and bubble departure diameter. The decrease in the contact angle means an increase in wettability, and the decrease in bubble departure diameter means an increase in nucleate boiling. These two factors result in CHF enhancement.

The CHF enhancement ratio was observed to decrease with increasing mass flux (Fig. 8). Lee et al. also found that the CHF enhancement ratio decreased with increasing mass flux [9]. The flow patterns under all conditions were examined by using Hewitt and Roberts's map [11], and the flow patterns were churn, slug or bubbly-slug flow (Fig. 9). In these flow regimes, the mechanism of CHF is departure from nucleate boiling (DNB). Ho et al. proposed a theoretical CHF model under low pressure, low mass flux, and low quality [12]. A schematic diagram of the CHF developing process under low pressure, low mass flux, and low quality is shown in Fig. 10. Their CHF model was based on the liquid sublayer dryout model proposed by Lee and Mudawwar [13], and it assumes that the CHF occurrence is triggered by Kelvin-Helmholtz (KH) instability. The KH instability results from velocity shears between two media. These media need not even be of different densities. Any time there is a non-zero curvature, the flow of one fluid around another will lead to a slight centrifugal force, which in turn leads to a change in pressure, thereby amplifying the ripple. The most familiar example of this is wind blowing over calm water. Tiny dimples in the smooth surface will quickly be amplified to small waves, and finally, to frothing white-caps. If there is some restoring force T_g, the instability will arise if

$$\Delta V2 \geq 2(\rho f + \rho g)\rho f \rho g \; Tg(\rho f - \rho g)1/2$$

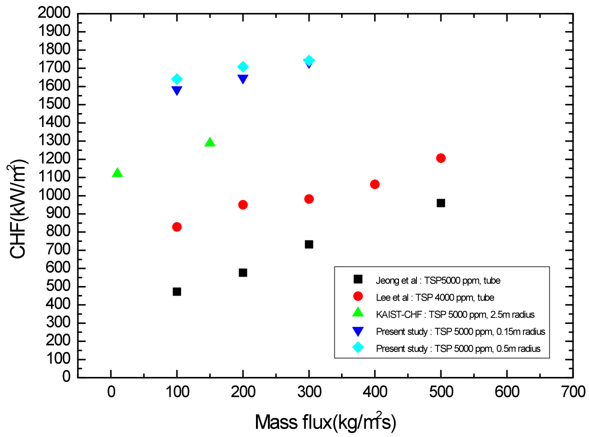
where ΔV is the velocity difference between two phases [14].

An increase in mass flux causes an increase in ΔV, and this means more occurrence of the KH instability, which could break the liquid film between vapor and surface. Hence, the CHF enhancement decreases with increasing mass flux.

In the case of using BA 4000 ppm, the CHF values decreased compared to those of DI water at the test section of 150 mm radius, and the CHF values were enhanced by as much as 15% at the test section of 500 mm radius. There was no big difference in flow patterns between 150 mm and 500 mm. The CHF enhancement at the 500 mm radius test section can be explained by enhanced wettability. Lee et al. also found that the CHF value was enhanced by BA, and they concluded that CHF enhancement by BA is due to a decrease in contact angle and increased wettability [9]. The trend of CHF enhancement at the 500 mm radius test section can be explained by KH instability as TSP. However, the decrease in CHF values at the 150 mm radius test section cannot be explained in the present study, and further study is needed to understand this.

In the case of using both TSP 5000 ppm and BA 4000 ppm, the CHF values were enhanced under all experimental conditions by as much as 35%. The CHF enhancement and the trend of the CHF enhancement ratio were similar to the results of TSP. This means that TSP dominates the CHF enhancement rather than BA.

From the aforementioned results, under severe accident conditions, a coolant which contains TSP and BA could have a wider thermal margin for the IVR-ERVC strategy than DI water.



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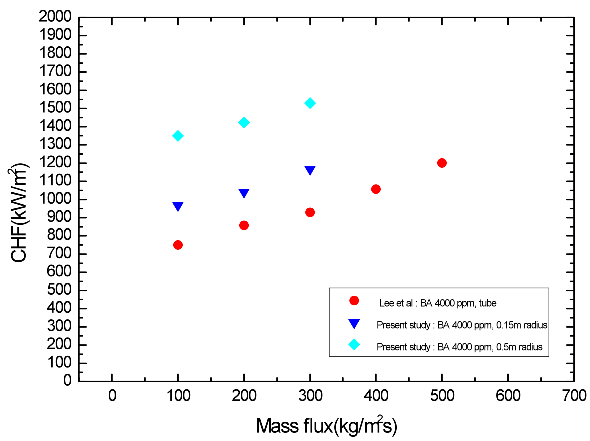
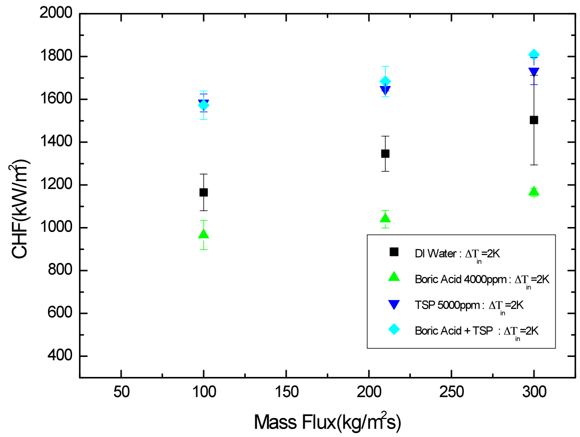


(b)

Figure 6. Comparison of the CHF value with other experimental CHF value using (a) TSP and (b) BA



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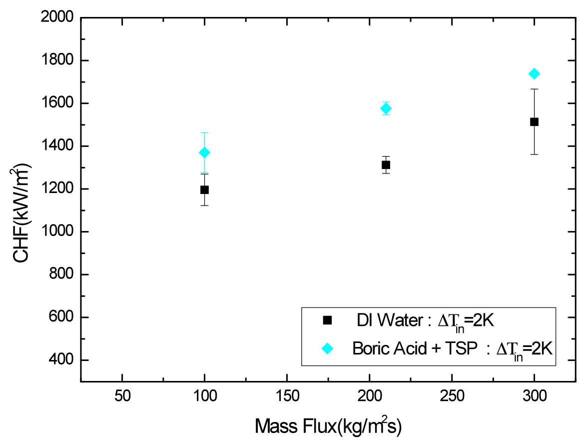

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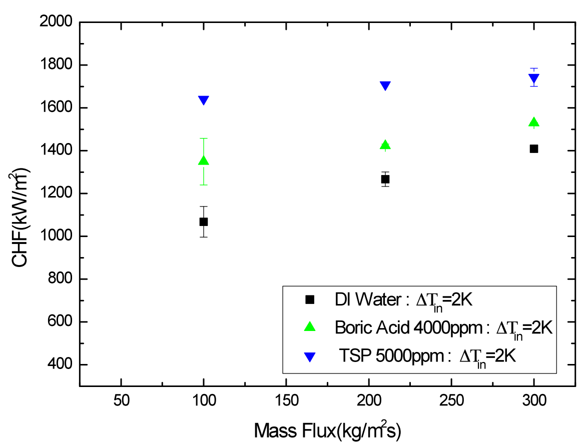
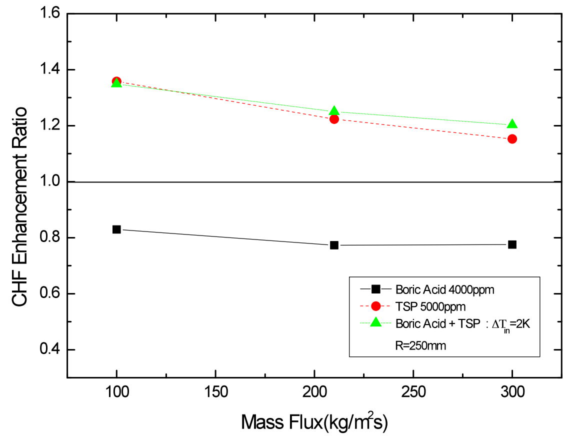


(c)

Figure 7. The CHF value with (a) 150 mm, (b) 250 mm, and (c) 500 mm radius of test section



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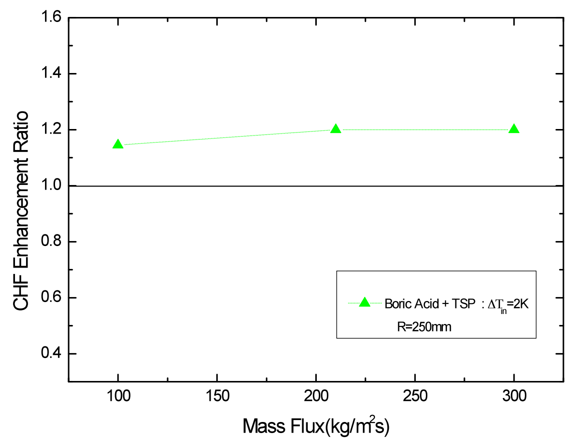

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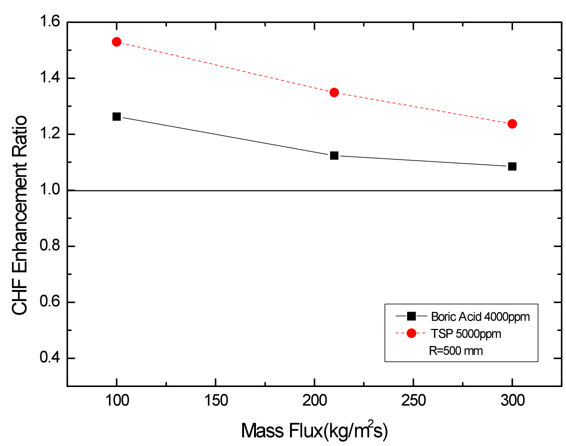
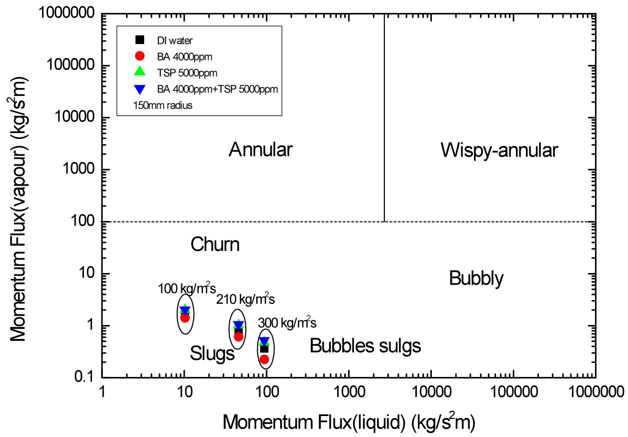


(c)

Figure 8. The CHF**R** with (a) 150 mm, (b) 250 mm, and (c) 500 mm radius of test section



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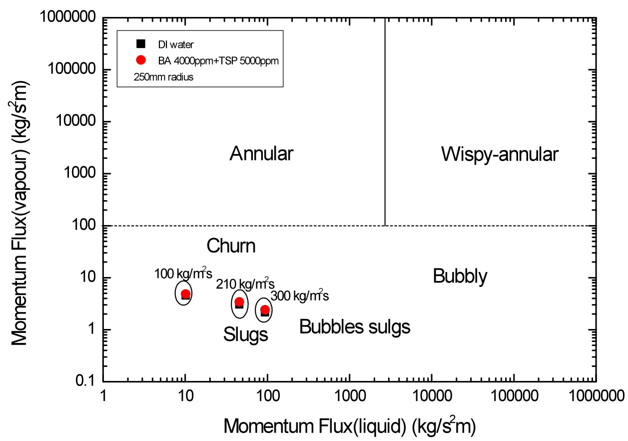

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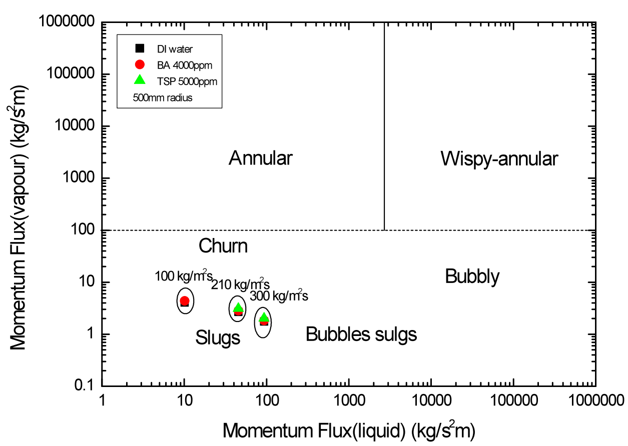

(c)

Figure 9. Flow patterns **at** (a) 150 mm, (b) 250 mm, and (c) 500 mm radius of test section

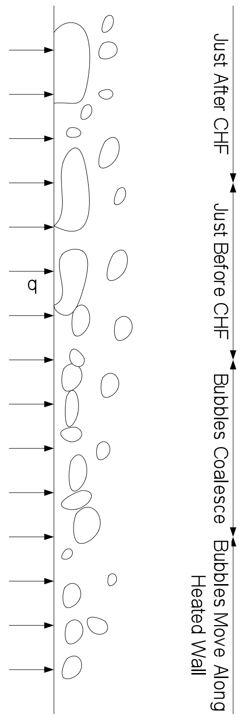

Figure 10. Schematic of a CHF developing process under low pressure, low mass flux, and low quality conditions [12].

5. Conclusion

The CHF experiments using a 2-D curved test section with TSP and BA were conducted under atmospheric pressure to evaluate the additional thermal margin for the IVR-ERVC strategy. The significant findings may be summarized as follows:

- In the case of using TSP 5000 ppm, the CHF values were enhanced under all experimental conditions by as much as 50%. The decrease in contact angle due to TSP means an increase in wettability, and a decrease in the bubble departure diameter means an increase in nucleate boiling. These two factors result in CHF enhancement.
- An increase in mass flux causes an increase in ΔV, and this means more occurrence of the KH instability, which could break the liquid film between vapor and surface. Hence, the CHF enhancement decreases with increasing mass flux.
- In the case of using BA 4000 ppm, the CHF values were lower than those of DI water at the test section of 150 mm radius, and the CHF values were enhanced by as much as 15% at the test section of 500 mm radius. The decrease in CHF values at the 150 mm radius test section cannot be explained in the present study, and further study is needed to understand this.

- In the case of using both TSP 5000 ppm and BA 4000 ppm, the CHF values were enhanced under all experimental conditions by as much as 35%. The CHF enhancement and the trend of the CHF enhancement ratio were similar to the results of TSP. Hence, a coolant which contains TSP and BA could have a wider thermal margin for the IVR-ERVC strategy than DI water.

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