Effects of Additives on CHF Behaviors for ERVC-IVR Strategy with FIRM Facility

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ABSTRACT

In-vessel retention of molten corium through external reactor vessel cooling (IVR-ERVC) is a severe accident management strategy. The effectiveness of IVR-ERVC strongly depends on the critical heat flux (CHF). This study conducted CHF experiments using the FIRM facility, which is a 2-D large scale model with SA508 steel as the heated surface material, to investigate the effects of coolant additives including boric acid (BA: H_3BO_5) or/and trisodium phosphate (TSP: Na_3PO_4) on the CHF behaviors. Preliminary results were obtained. The CHF of BA was reduced compared with that of DI water because of the loose, irregular Fe_2O_3 oxide layer formed on the heated surface and the reduction was 4.1 % for the case of using BA 3000ppm.The CHF for TSP solution with lower concentration of 1000ppm was enhanced by 4.0%, which is mainly due to the increase wettability of coolant. However, a CHF reduction of 6.4% is observed for the case of using TSP with a much higher concentration of 3500ppm caused by the increase of two phase flow instability by the surfactant with high concentration under high mass flow condition. The CHF values for the mixed solution of CHF and TSP showed the same variation trend with that of the TSP solution, which indicates the TSP has a dominated effect on the CHF behavior. In addition, it suggests the coolant which contains BA and TSP with certain concentration could provide additional thermal margin for the IVR-ERVC strategy.

KEYWORDS
Critical heat flux, trisodium phosphate, boric acid, FIRM, SA508 steel

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) [1]. This strategy has been adopted by some operating nuclear power plants and proposed for some advanced LWRs such as AP1000 of the US and APR 1400 of Korea[2]. The strategy gives sufficient thermal margin for small and medium-sized reactor. However, it is uncertain that the IVR-ERVC provides sufficient thermal margin for large reactors (more than 1000MWe). The coolability limit, i.e., the critical heat flux (CHF) of coolant boiling on the reactor vessel outer surface, is one of the most important criteria by which to judge the success of IVR-ERVC strategy. Reactor Pressure Vessel (RPV) can lose integrity due to the sudden increase of the vessel surface temperature and the molten corium can leak out if the decay heat from the molten corium exceeds its CHF.

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Therefore, the apprehensive understanding of CHF phenomenon is one of the most important interests for power plant safety under accident situations.

When the IVR-ERVC strategy being conducted under severe accident conditions, the cooling water of the in-containment refueling water storage tank (IRWST), which contains boric acid (BA:H_3BO_3), is injected into the reactor cavity by an external reactor vessel cooling (ERVC) system and a cavity flooding system (CFS, a passive feature) to manage severe accidents. As the CFS begins to operate, IRWST water flows through the hold-up volume tank (HVT), which contains trisodium phosphate (TSP:Na_3PO_4), and the TSP is dissolved into the cooling water. Thus, the coolant injected into the reactor cavity from the IRWST through the HVT contains BA and TSP. The reactor vessel is made of SA508 Grade3 Class 1 (SA508, low alloy carbon steel). Corrosion of the steel surface is affected by the environment under accident conditions: the composition of the water and the degree of contact with the water.

In connection with the CHF on the outer surface of reactor vessel wall, many researchers have carried out IVR-ERVC experiments such as ULPU, KAIST, SULTAN, and, etc. T.G. Theofanous et al. [3, 4] conducted CHF experiments at the ULPU-2000 facility to identify the coolability limit of the AP600 of the USA and the Lovisa plant of Finland. T.N. Dinh et al. [5] conducted CHF experiments at the ULPU-2400 facility to identify the coolability limit of the AP 1000 of the USA. All the ULPU experiments are conducted using a large scale two-dimensional test section with copper as heated surface material and DI as coolant. Y.H. Jeong et al.[6]conducted the KAIST-CHF experiments to investigate the coolability limit of the APR1400 of Korea by a two-dimensional slice test section using SS304 steel as heated surface material and TSP as additive. SULTAN experiments are conducted by S. Rouge[7] to investigate CHF data of a large-scale test section at inclined aluminum plates using DI as coolant.

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 the realistic severe accident conditions such as reactor vessel material and coolant additives(Table 1). It is evident that CHF limit is crucial to the safety of a nuclear plant under severe accident conditions especially for large reactors with an uncertain safety margin. Therefore, an experimental CHF study using a large scale test section which reflects the actual accident conditions can be more important.

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

Mesh	KAIST-CHF	ULPU	SULTAN	Severe accident condition
Heater material	SS304	Copper	Aluminum	SA508
Additives	TSP	None	None	TSP, BA, etc.
Pressure	1 bar	1.3bar	1-10bar	More than 1 bar

In this study, CHF experiments are conducted using FIRM facility which is a large scale 2-D test model with SA508 as heated surface material. BA and TSP, which are adopted in a nuclear power plant presently, are used to investigate the effects of coolant additives on CHF behaviors.

2. EXPERIMENTAL WORK

2.1. Experimental Apparatus

The FIRM system is a large scale two-dimensional test facility with SA508 steel as the heated surface material which is designed and built by State Nuclear Power Technology Research and Development

Centre. As shown in Figure 1, the FIRM facility consists of the following sub-system: (1) primary experimental loop; (2) the auxiliary system. The former includes the test section, the pre-heated vessel, the circulating pump and the upper tank; the latter consists of cooling system, coolant-supply/treatment, measurement and control system. With these systems, FIRM is capable of simulating the ERVC-IVR process using DI water/BA solution/ TSP solution.

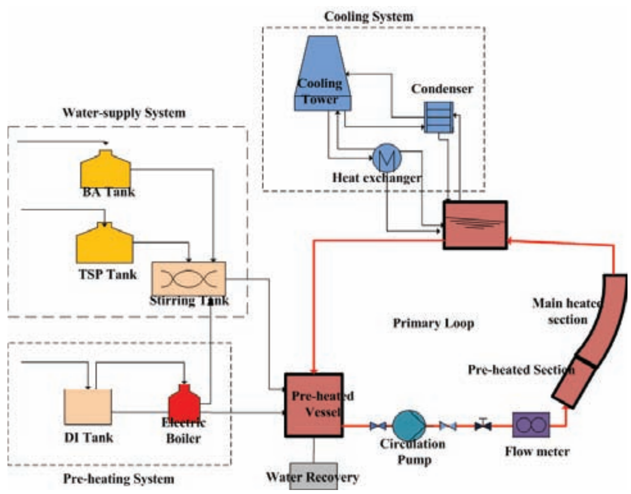

Figure 1. Schematic Diagram of FIRM System

The test section of FIRM is a large scale 2-D slice test section, which consists of the heated block and the flow chamber as depicted in Figure 2. The heat block includes the main heated block and the pre-heated block. The main heated block is designed an arc structure of 30 degrees with an outer radius of 2380mm to simulate the real lower plenum of a RPV and is made of T1 oxygen-free copper welded by a 2.5mm thick SA508 steel layer; the width of the heated surface is 150mm. The pre-heated block is designed to assure the subcooling and void fraction of coolant. The chamber is utilized to simulate the cavity between the reactor vessel and thermal insulation structure. Electrical cartridge heaters embedded in the heated block are used to simulate the decay heat of corium with a total heat power approximately to 600kW and a maximum heat flux of 2.4MW/m^2. Two arrays of thermal couples are applied to measure the temperature near the heated surface. The first array is 5mm away from the surface, and the second is 12mm. Forced circulation of the working fluid is driven by the circulating pump in the primary experimental loop. The maximum flow rate of the forced circulation is 80m^3/h. The overheated water and vapour produced in the test section will flow into upper tank, and cooled down by cooling system, which is composed of a condenser, a cooling tower, and a heat exchanger. The pre-heated vessel is used to keep the thermal balance of the primary experimental loop and ensure a suitable subcooling. Key system parameters including mass flow rate and inlet subcooling can be adjusted to cover the real cases of a nuclear plant.

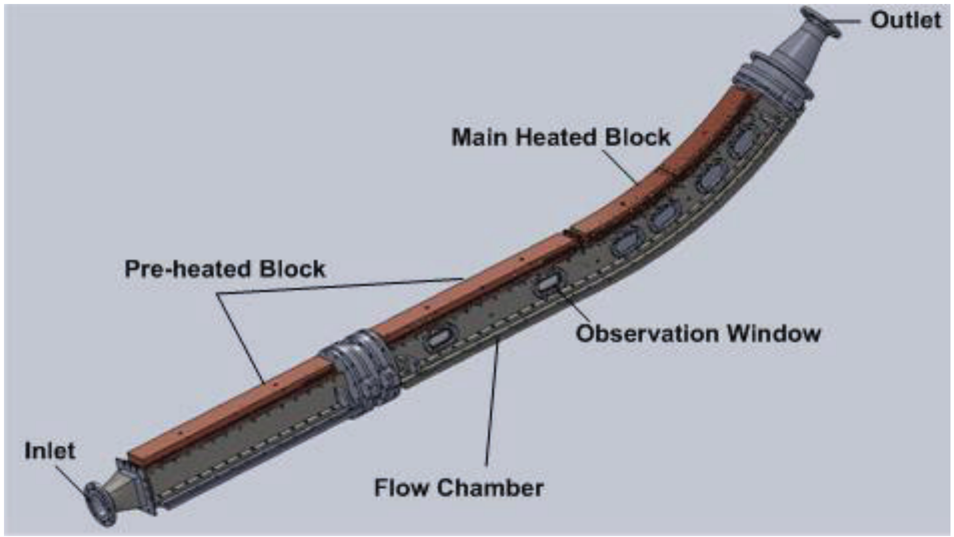

Figure 2. Schematic Diagram of the Test Section

2.2. Working Fluid

As mentioned above, the coolant used by the IVR-ERVC strategy under severe accident condition contains BA and TSP. Therefore, BA and TSP are considered as the coolant additives in this study. To investigate the individual effect of each solution, experiments using BA solutions with different concentrations and TSP solutions with different concentrations were conducted. To identify the combined effects of BA and TSP, experiments were conducted with mixture solutions of BA and TSP. And for comparison, CHF experiment with DI water was also performed.

2.3. Experimental Procedure and Data Processing

For the FIRM facility, all CHF experiments were conducted through the following procedure:
(1) Prepare the scheduled working fluid consisting of BA and /or TSP using the coolant supply system.
(2) Fill the primary experimental loop with coolant.
(3)Turn on all devices in the experimental loop, the data acquisition system and the power supply system.
(4) Heat up the working fluid in the primary experimental loop by the pre-heated vessel and adjust the mass flux to a scheduled level.
(5) Heat pre-heated region and main heated region of test section up to actual thermal load which is calculated by the heat flux distribution under severe accident conditions according to the principle of power shaping[4].
(6) Gradually raise heat flux level of the test section by adding the electrical power step by step until CHF occurs.
(7) Reduce the heating power loaded on the test section immediately and calculate the heat flux according the electrical heating power.

The heat flux level on the test section was calculated through dividing the effective electrical power applied to the test section by the heated area, and the electrical power of the previous step before the CHF occurrence is used to calculate the CHF value from a conservative point of view.

The overall uncertainty in CHF mainly includes uncertainties from direct parameter measurement such as the temperature and electrical power measurements and uncertainties from indirect calculation such as heat loss. The temperature (K-type thermocouples) measurement uncertainty was estimated to be less than 1K. The uncertainties of voltage and current which were used to calculate the electrical power were both estimated as 0.05%. The geometric uncertainty of the heater area in the main heated region was less than 1.0%. To estimate the heat loss to external surroundings, conservative calculations were performed at various heat flux conditions with the help of computer code (ANSYS 13.0). Heat loss to the surroundings was less than 1.0%.Taking into account all these factors, the uncertainty in CHF was around 3.6%.

3. RESULTS and DISCUSSION

Preliminary flow boiling CHF experiments were conducted in FIRM facility with DI water and coolant containing different additives (BA and/or TSP) under the inlet subcooling condition of 15K and mass flux conditions of around 500kg/m^{2}s. Effects of additives are investigated by comparing CHF results of coolant containing different additives with those of DI water. For future research, systematic CHF experiments will be performed to investigate more key factors effects in next stages.

3.1. CHF Behavior

In order to approach to the CHF occurrence, the heating power is increased step by step. For each power level, the heat flux is hold till the temperature of the heated block approaches to a steady state. The step increment of heating power is gradually decreased when approaching to CHF in order to catch the boiling crisis more precisely. As shown in Figure 3, a sudden temperature increase of over 50K per minute is observed by a near-surface thermal couple of testing position.

Despite of no direct visual image of local bubble behaviour on heated surface due to the design constraint, an overall visualization of the bubble in the chamber is obtained, as shown in Figure 4, from which a flow type of slug or churn flow is observed at a near CHF power level. The flow type indicates the boiling crisis of CHF can be explained using the Departure from Nucleate Boiling (DNB) mechanism instead of the dry-out mechanism.

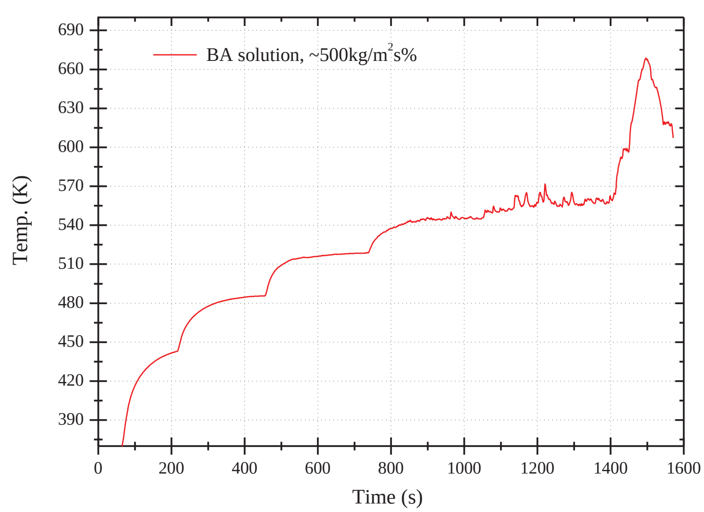

Figure 3. Temperature History of a Thermal Couple 12mm away from Heated Surface and Occurrence of CHF

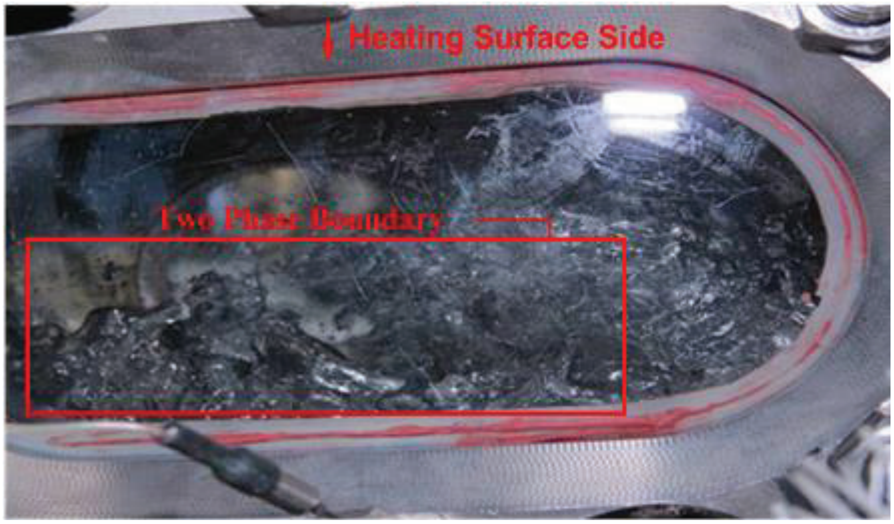

Figure 4. Visualization of Bubble Behavior in the Chamber

3.2. Effect of BA on CHF Behavior

Previous researches have proved that CHF is related to inclining angle of the heated surface in ERVC-CHF process. The Preliminary experiments give CHF results of BA solution and DI water at the upper region (θ=81°) of the reactor vessel outer wall under mass flux of about 500 kg/m^{2}s, as shown in Figure 5. The results show that, the CHF value of DI water at this degree is 1.53MW/m^2 and the CHF value of DI water with BA 2000ppm (boron concentration) is comparable to that of DI water. While the CHF values for DI water with BA 2500ppm and BA 3000ppm are lower than that of DI water and the reductions are 1.7% and 4.1% respectively.

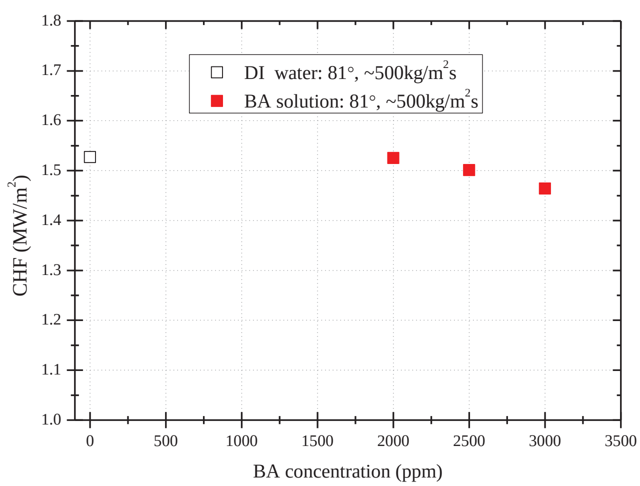

Figure 5. CHF Results for Boric Acid with Different Concentrations

This CHF reduction is mainly due to the heated surface change. SA508 material is easily oxidized in an aqueous environment, thus during the boiling process of CHF experiments with DI water, the heated surface material is oxidized and a layer of Fe_3O_4 (black color and generated at high temperature with water) is formed, which can be seen in Figure 7 that the heated surface is covered by a layer of black attachment after the DI water experiment. It had been reported that Fe_3O_4 particles of the heated surface work as magnetite nanoparticles which will improve the hydrophilicity and surface wettability of the heated surface[8], such a factor is favorable to enhance the heat transfer during the flow boiling. After adding BA into DI water, the pH value of coolant changes. The steel oxidation varies according to the pH of the working fluid because acid solutions have more hydronium ions(H_3O+) which accelerate the oxidation reaction. However, the oxidation product in acid environment should be ferric oxide, Fe_2O_3, as shown in Figure 8, the heated surface become light brown in certain parts. Differing from Fe_3O_4 layer, the irregular Fe_2O_3 layer is loose and has relatively greater heat resistance, which could worsen the heat transfer in CHF situation. Thus, the CHF values of coolant containing BA are lower. However, to further confirm the foregoing analysis, research on the surface morphology and component of different oxidation layer by SEM images or EDAX analysis will be performed in the subsequent researching works.

Figure 6. Heated Surface before Experiments

Figure 7. Heated Surface After Experiments with DI Water

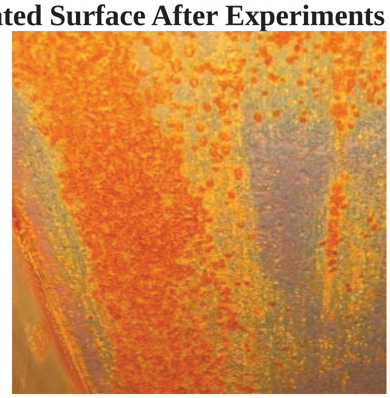

Figure 8. Heated Surface After Experiments with BA

3.3. Effect of TSP on CHF Behavior

The CHF results of TSP solutions and DI water at the upper region (θ=81°) under mass flux of about 500 kg/m^2s are shown in Figure9. It can be seen that, for the TSP solution with a concentration of 500ppm, the CHF value is only 0.7% enhanced comparing with that of DI water and the CHF enhancement ratio is 4.0% for 1000ppm TSP solution. However, when the TSP concentration increases to a much higher value of 3500ppm, the CHF value decreases and shows a reduction of 6.4%. Therefore, the TSP solution of lower concentration can enhance the CHF, while a higher concentration leads to a CHF reduction.

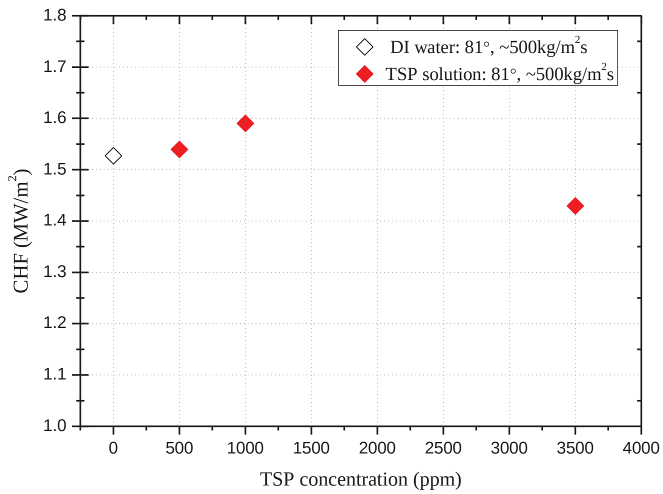

Figure 9. CHF Results for TSP Solutions with Different Concentrations

The SA508 steel is easily oxidized to form a thick layer of Fe_2O_3 on the heated surface under acid environment of baric acid experiments. Conversely, the oxide layer is thinly formed and is a relatively dense and regular layer under alkaline conditions of TSP experiments, as shown in Figure 10, which is a totally different surface topography from that of BA experiments. Therefore, the CHF reduction caused by loose Fe_2O_3 layer is not significant for the TSP case.
Besides the surface morphology, CHF behaviors can be affected by other factors, such as surface tension and wettability of the coolant. According to the study of Jeong et al.[9], the main effects of TSP are a decrease of surface tension and an increase of wettability, which feature is not distinct for the BA solution. They have showed that the surface tension decreased with increase of TSP concentration. TSP surfactant doesn't affect other properties except for surface tension in low enough concentrations; and increase of wettability is due to the decrease of surface tension. This is followed by phenomena like the decrease in bubble diameter, breakup of bubbles and avoidance of bubble coalescence, and thus CHF is enhanced when the TSP concentration is low (500ppm, 1000ppm). However, when the TSP concentration increases to a much higher level of 3500ppm, the possibility of flow instability occurrence rapidly increases with the decrease of surface tension especially under a high mass flux of 500 kg/m^2s. In this case, CHF occurs by instability of the large slug. Once the instability occurs around the unstable and wavy slugs, the surface is dried out, having no leeway to be rewetted. Then, the CHF occurs. Therefore, in an unstable state under high mass flux and higher concentration followed by decrease of surface tension, the CHF value can decrease. In fact, there are some uncertainties in the results still, and more studies need to be performed in future.

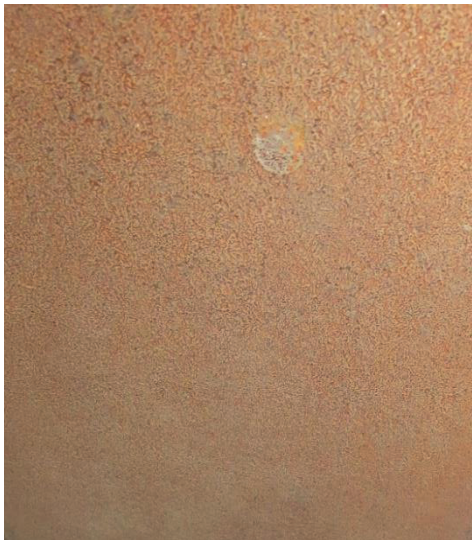

Figure 10. Heated Surface after Experiments with TSP Solution

3.4. Combined Effects of BA and TSP

The CHF results of the mixed solutions of BA and TSP are shown in Figure 11. The mixed solutions have a same BA concentration of 2500ppm and different TSP concentration of 500, 1000 and 3500ppm. It can be seen that, the CHF values of TSP 500ppm and 1000ppm are enhanced by5.6 % and 7.3% respectively, while reduced by 4.7% for the TSP 3500 ppm case. The variation trend of CHF is similar to the results of TSP, which means that TSP dominates the CHF enhancement rather than BA.

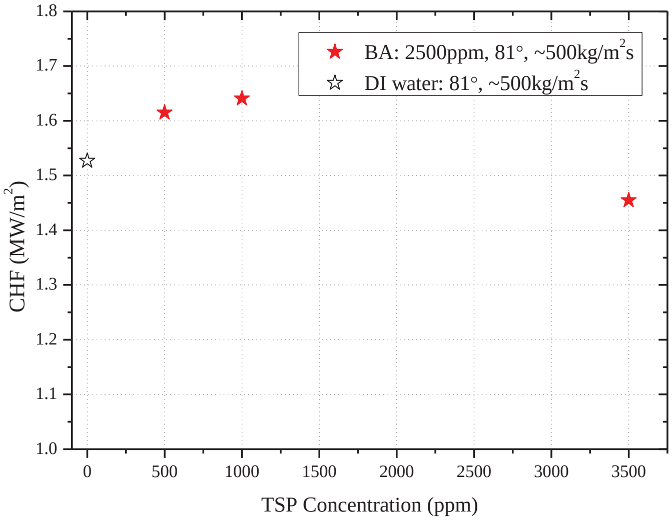

Figure 11. CHF Results for the Mixed Solution of BA and TSP

Based on these results, it may be concluded that, under severe accident conditions, the thermal margin for the IVR-ERVC strategy could have a change due to the coolant additives of TSP and BA comparing with DI water. However, whether the thermal margin increases or decreases is depending on the specific concentrations of coolant additives.

4. CONCLUSIONS

The CHF experiments using a large scale 2-D test section with real RPV surface material SA508 steel as heated surface material and coolant containing additives of BA or/and TSP were conducted to investigate the CHF behaviors for the IVR-ERVC strategy. The significant findings according to the preliminary experimental results can be summarized as follows:

(1)Temperature history of a thermal-couple near heated surface shows a sudden increase of around 50K per minute when the CHF is achieved. And the slug or churn flow on the CHF occurrence indicates a DNB mechanism for the boiling crisis.

(2) The CHF value of BA is lower than that of DI water, and for the case of using BA 3000ppm, the CHF reduction is 4.1 %. The CHF reduction is mainly due to the loose, irregular Fe_2O_3 layer formed on the heated surface.

(3) The CHF values for TSP solution with lower concentration of 500ppm and 1000ppm are enhanced due to the increase wettability of coolant. However, the DHF value for using TSP 3500ppm is reduced due to the increase of instability of two phase flow caused by the surfactant with a high concentration under a much high mass flow condition.

(4) CHF values for the mixed solution of BA and TSP show the same change trend with that of TSP solution, which indicates the TSP has a decisive effect on the CHF behavior. In addition, it suggests the coolant which contains TSP and BA could have different thermal margin for the IVR-ERVC strategy compared with DI water.

(5)Much more research works should be conducted in future to analyze such factors influencing CHF as heated material morphology, coolant surface tension, wettability and so on.

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