CHF Experiment of RPV Lower Head with Real Surface Material for ERVC-IVR Strategy

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ABSTRACT

In-vessel retention of molten corium through external reactor vessel cooling (IVR-ERVC) is a severe accidents management strategy. FIRM(Key Factor of Improving ERVC-CHF experiMent) facility which is a two dimensional full scale model is built to investigate CHF behavior with SA508 Grade 3 Class 1 as surface material of the heater.

CHF behaviors with SA508 steel (that is the prototype surface material of RPV) as the surface material are quite different from those with copper or stainless steel as the surface material. Currently there are few experiments, especially at full scale, considering the effects of surface material. CHF behaviors are investigated at atmospheric pressure in deionized water a with real surface material in present study in FIRM facility. Preliminary results are obtained and influences of key factors like inclining angle of the surface on CHF are discussed. The aging effect of SA508 steel in DI water is invstigated. The test result will provide a profound understanding of CHF behaviors with real RPV material under IVR-ERVC condition.

KEYWORDS
Critical heat flux, SA508 steel, ERVC-IVR

1. INTRODUCTION

In-vessel retention (IVR) of molten corium through external reactor vessel cooling (IVR-ERVC) is a severe accidents management strategy for light water reactor (LWR). It was first introduced by Theofanous [1] and adopted by Lovissa [2] reactors firstly and then by Westinghouse advanced light water Reactor (AP600 [3] and AP1000 [4]), also by Korean Advanced Power Reactor APR1400 [5] and Chinese Advanced Passive pressurized water reactor CAP1400 [6]. To implement the IVR strategy, the reactor cavity is flooded with cold water, which removes the decay heat as it boils and flows by natural circulation in the gap between the vessel outer surface and the vessel insulation (see Figure 1). The maximum heat removal capability is limited by the critical heat flux (CHF) on the wall cooled by water. At the CHF point, a sudden increase of RPV surface temperature and deterioration of heat transfer rate will occur, which set an constrain for nominal power of nuclear plants.

To verify the effectiveness of ERVC-IVR strategy, experiments are carried out to indentify the CHF on RPV outer surface. A series of ULPU experiments [2,7] are conducted using a large scale two-dimensional test section with copper as heating surface to verify ERVC-IVR strategy for Loviisa, AP600 and AP1000. KAIST-CHF experiments are conducted by Y.H. Jeong et al. to investigate the coolability limit of the APR1400 of Korea [8] using two-dimensional slice test section with SS304 steel as the heating surface. No real surface material (SA508) of RPV is used in any of these experiments which might lead to a distinct deviation of CHF behavior from the real case. It had been proved that SA508 steel showed very different CHF behaviors from the other cases (stainless steel or copper, etc.) [9]. It is evident that CHF limits is crucial to safety of nuclear plants in severe accidents. While the safety margin of the removal capability of decay heat is not sufficient for higher power plant like 1400 MW, so a large scale CHF test with real surface material which reflect the actual accident conditions is necessary.

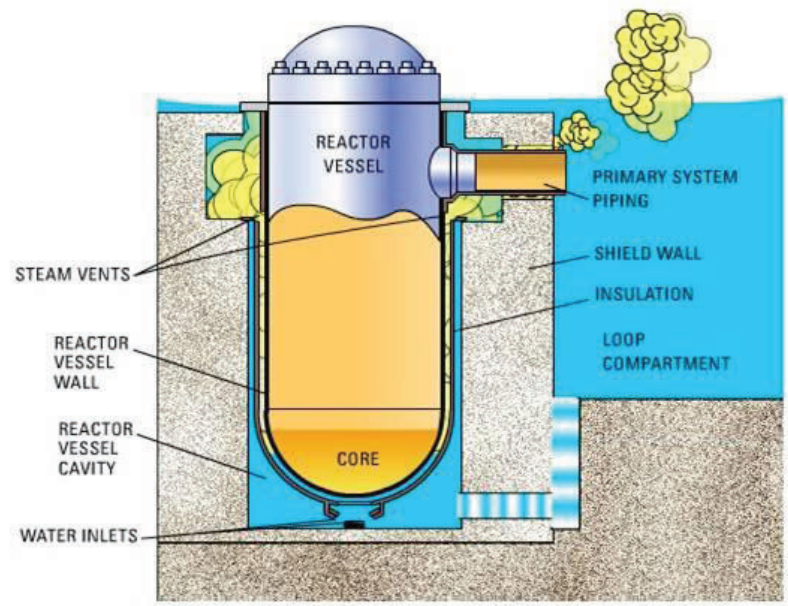

Figure 1. Schematic of ERVC-IVR strategy.

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In present study, the experimental facility of FIRM (Key **F**actor of **I**mproving E**R**VC-CHF experi**M**ent) using a large scale, two-dimensional test section with SA508 Grade 3 Class 1 as surface material of the heater is built to investigate the IVR-ERVC process of high power nuclear plants. The maximum heat flux of the test section is as high as 2.4 MW/m^2. CHF behavior are investigated at atmospheric pressure in both deionized water and tap water. Preliminary results are obtained and influences of key factors like inclining angle of the surface and subcooling degree of the inlet water are discuss. The ageing effect of the SA508 steel heating surface is investigated.

2. EXPERIMENTAL FACILITY

2.1. GENERAL

FIRM is a large scale two-dimensional test facility with SA508 steel as the heating surface which is designed and built by State Nuclear Power Technology Research and Development Center (SNPTRD). As depicted in Figure 2, FIRM test system consist of the following sub-system: (1) primary loop; (2) the auxiliary system. The former includes the test section, additional pre-heated section, the pre-heated vessel, the circulating pump and the upper tank; the latter consist of cooling system, chemistry-water-supply/treatment, measurement and control system. With these systems, FIRM is capable of simulating the ERVC-IVR process in DI water/ tap water/ boric acid solution/ trisodium phosphate solution. Key system parameters like mass flow rate, subcooling degree of inlet water can be adjusted to cover all the real cases. High maximum heat flux which is up to 2.4 MW/m^2 is designed to simulate power plants of high power.

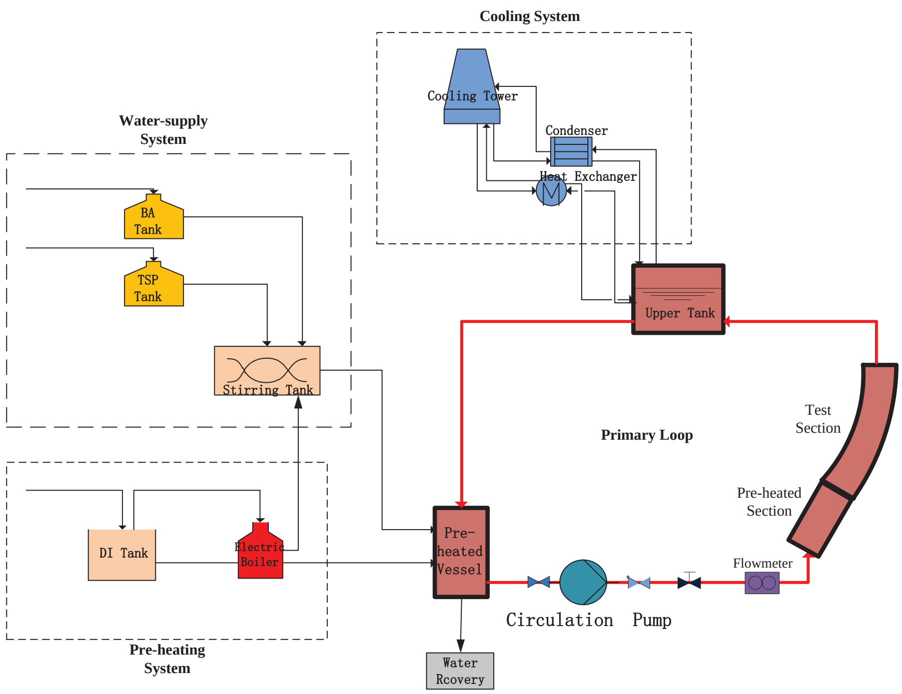

Figure 2. Schematic diagram of FIRM test system.

2.2. PRIMARY LOOP AND TEST SECTION

Test section of FIRM consists of a heat block and a chamber as depicted in Figure 3. The outer radius of the heating surface is 2380mm which is the scale of a real RPV lower head; the width of the two-dimensional slice of heating surface is 150mm. In FIRM, a 30° arc of test section which is one-third of a full length of reactor vessel lower head, is used instead of a full length test section in consider of easy manufacturing and assembling. While it's notable that CHF is sensitive to the upstream condition. Once the vapour is generated by boiling, it remains by gravity within the two-phase boundary layer long the downward facing heating surface, and the flow velocity and the phase distribution within this boundary layer depends very much on the cumulative quantities of steam generated in all upstream positions. Hence the upstream local features of two-phase flow like subcooling and void fraction need to be assured. So that pre-heating section are applied. To conduct a full length test of the 90° arc of RPV lower head, a rotating mechanism is built, by which the test section can be set to three different positions.

Due to the high thermal resistance of steel, simulation of real surface material (SA508) in ERVC-CHF experiments of large scale is one of the most tough technical problems, especially in a high surface flux design. In FIRM, a Cu-Fe composite heating block (seen in Figure 4) manufactured by explosive welding is applied to simulate the surface condition of the real case, of which the SA508 layer is 2.5 mm thick.

The decay heat of the corium in the severe accident is simulated by the cartridge heaters embedded in the heater block in FIRM. 340 cartridge heaters (9.5 mm diameter), the maximum heat power of which is 1685 W, are used to provide a maximum surface heat flux of 2.4 MW/m^2. In order to simulate the power shape distribution of the decay heat of the corium, 29 separate heat sections which can be controlled individually, are applied. Test section are divided to 20 individual sections, of which 10 sections are backup heat sections.

Two arrays of thermal couples are applied to survey the near-surface of heating block, of which the first array is 5mm away from the surface, and the second is 12mm.

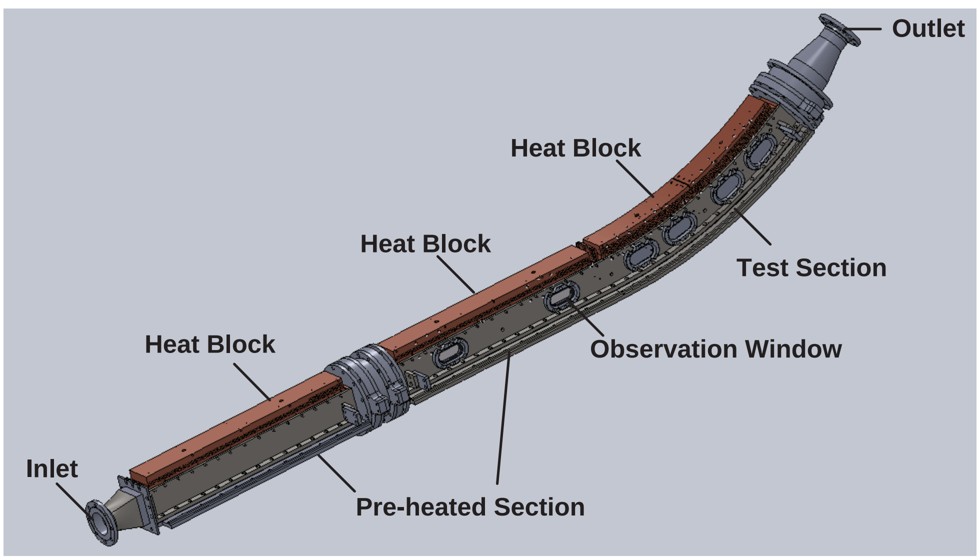

Figure 3. Schematic diagram of test section and pre-heated section.

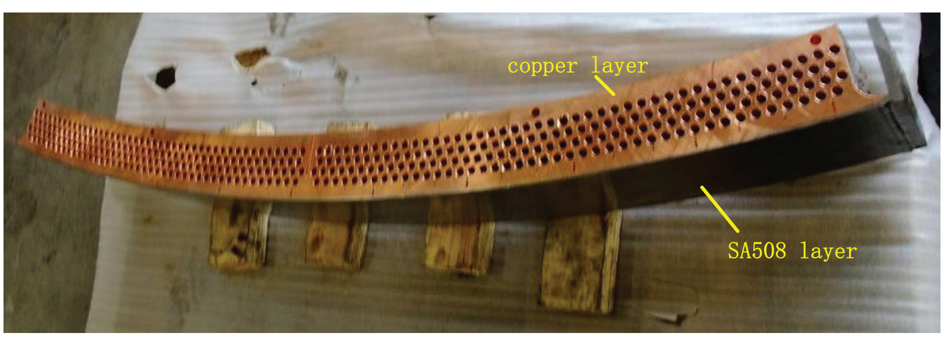

Figure 4. Heating block of test section.

Forced circulation of the working fluid is driven by the circulation pump in the primary loop. The maximum mass flow rate of the forced circulation is 80m^3/h. The overheated water and vapor produced in test section will be flow into upper tank, and cooled down by cooling system, which is consisted of a condenser, a spray, and a heat exchanger. The pre-heated vessel heated by cartridge heaters is used to keep the thermal-balance of the primary loop and ensure suitable subcooling. Key system parameters including mass flow rate and inlet subcooling can be adjusted to cover the real case of nuclear plant.

3. EXPERIMENTAL PROCEDURE

As a two-dimensional test facility, the principle of power shaping is adopted [3] in FIRM to assure the consistency of the two-phase flow conditions at the testing position between the 2-D test section and the 3-D hemispherical geometry of RPV lower head.

The axial symmetry of RPV lower head allows a 'pie' segment representation of the hemisphere, and by the principle of power shaping, a uniform 2-D slice is adopted to represent the 'pie ' segment. We set

$$q_{p,cr}(\theta_m) = q_{e,cr}(\theta_m)$$

in which, $q_{e,cr}(\theta_m)$ is the critical heat flux of the experiment test position of θ_m, $q_{p,cr}$ is the one of prototype, and require:

(i) that the superficial vapor velocities match up with those of prototype for all $\theta > \theta_m$

(ii) that for $\theta < \theta_m$ the vapor flow rates build up gradually, so as to smoothly approach the vapor required at $\theta = \theta_m$, while allowing a 'natural' development of the boundary layer in all of the upstream region. By satisfying these requirements, we ensure that the two-phase boundary layer is properly driven in a broad neighborhood of the location consideration θ_m as well as the downstream region.

The power shaped heat flux can be derived as:

$$q_e(\theta) = \begin{cases} q_p(\theta)\dfrac{\sin\theta}{\sin\theta_m} & \theta < \theta_m \\ q_p(\theta) - \dfrac{\cos\theta}{\sin^2\theta}\displaystyle\int_0^\theta q_p(\theta')\sin\theta' d\theta' & \theta > \theta_m \end{cases}$$

In each individual heating sections the power shaped heat flux is transform to an equivalent average value via energy conservation.

For each test run, primary loop parameters including mass rate of the flow and inlet temperature are first adjusted and stabilized to the target value by the pre-heated vessel, variable-frequency pump and control valve. Then heating power is gradually increased until CHF occurs. The heating flux distribution of all heating sections are hold all through the heating period, which means the power levels of all heating sections are proportionally increased.

The step increment of heating power is gradually decreased when approaching to CHF in order to catch the boiling crisis more precisely. Once CHF point is approached, the power level is quickly decreased to a low level (not switch off, in case of a major leaking of test section) that will alleviate the boiling crisis. The power step which CHF phenomena occurs and the last power step before it occurs set the upper and lower limit of CHF value respectively. From a conservative-point-of-view, the last power step before CHF phenomena is used to calculate the resulted CHF value.

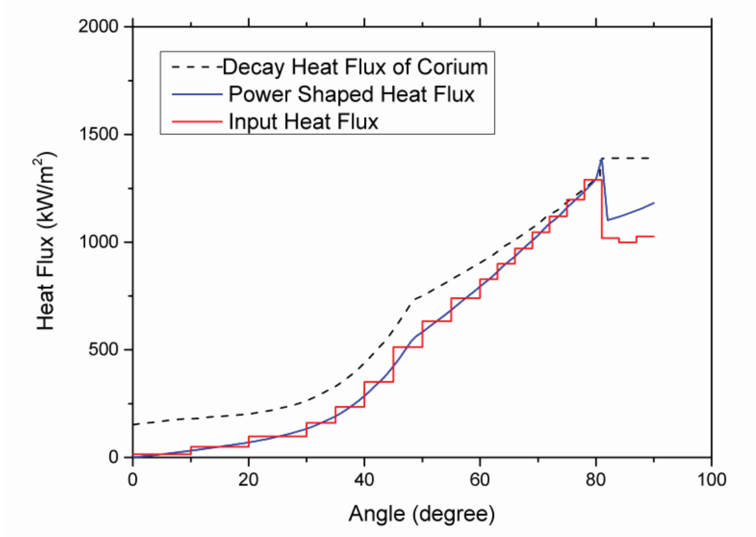

Figure 5. Heat flux input of testing position 81° .

4. RESULTS

Experiments are conducted in FIRM with DI water in present stage. CHF behaviors of different inclining positions are investigated with subcooling of 15° and flow rate of 40 t/h (mass flux about 500 kg/m^{2}s). A total amount of 30 test runs are conducted including 22 shakedown test runs. Aging effect of surface material is investigated by comparing CHF results of different aging periods. For future research, experiments of tapped water, boric acid and tri-sodium phosphate and more key factors influences like subcooling and flow rate are planned in next stages.

4.1. CHF BEHAVIORS

In order to approach to CHF point, the heating power is increased step by step. For each power level, the heat flux is hold until the temperature of the heating 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 6, a sudden temperature increase (over 50℃/min) are observed in near-surface thermal couples of testing position.

Despite of no direct visual image of local bubble behavior on heating surface due to design constraint, an overall visualization of the bubble in the chamber is obtained, 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 is through the Departure from Nucleate Boiling (DNB) mechanism instead of the dry-out mechanism.

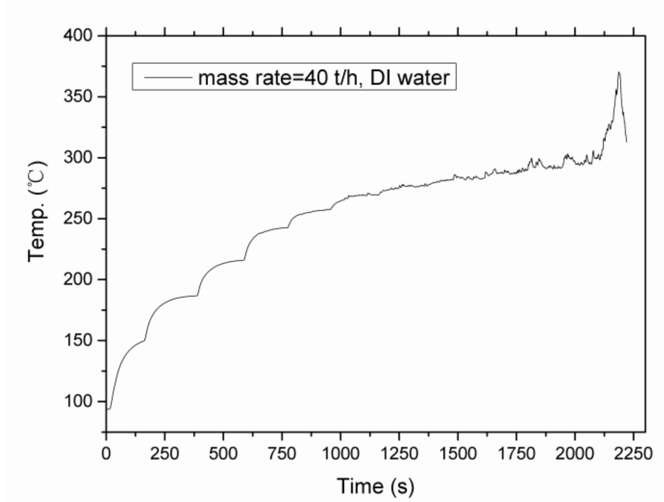

Figure 6. Temperature history and occurrence of CHF.
(near-surface thermal couple of 12mm away from surface)

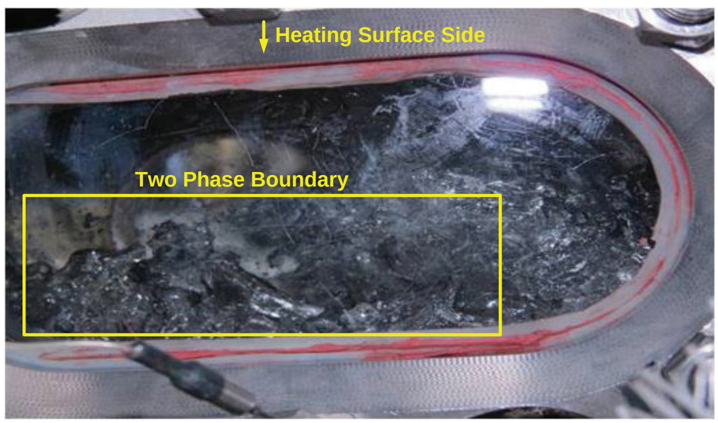

Figure 7. Visualization of bubble behavior on the heating surface.

4.2. AGING EFFECT OF SA508 HEATING SURFACE

The aging effect of surface material SA508 is investigated in FIRM, which is the CHF variation along with time. CHF values of a fresh heating surface that is newly polished and surface of different aged periods are measured in DI water. As shown in Figure 10, a significant CHF enhancement is observed in the fully aged surface condition, which is aged over a year (in air of room temperature, 15 shakedown CHF tests and 20 DI water CHF tests, about 1h each run). CHF of the fully aged surface is enhanced about 12.4% and 10.9% respectively comparing to the fresh surface and aged surface over a week time (in air of room temperature and few runs of CHF experiments in DI water, about 1h each run). While for stainless steel SS316, as shown in Figure 10, no distinct CHF variation is observed [10].

The aging effect is related to the process of corrosion of surface material. SA508 material is oxidized in an aqueous environment, thus during the boiling process of CHF experiments the heating surface material is oxidized and a layer of Fe_3O_4 (black color and generated at high temperature with water) is formed. It can been seen in Figure 9 that the fully aged heating surface is covered by a layer of black attachments. It had been reported that Fe_3O_4 particles of the heating surface work as magnetite nanoparticles which will change the thermal conductivity of fluid [11] and improving hydrophilicity and surface wettability of the surface [12]. Thus the a fully aged SA508 heating surface will enhance CHF significantly.

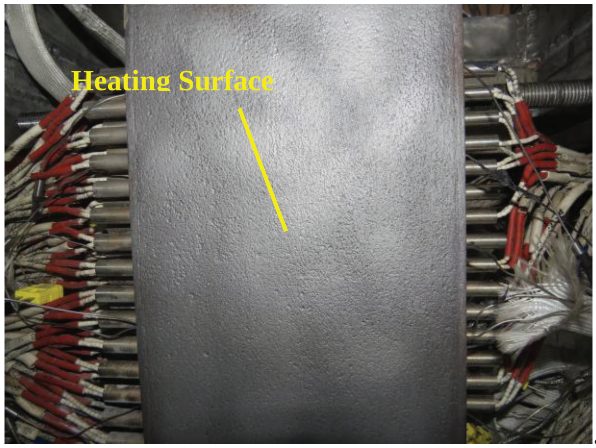

Figure 8. Fully aged heating surface.

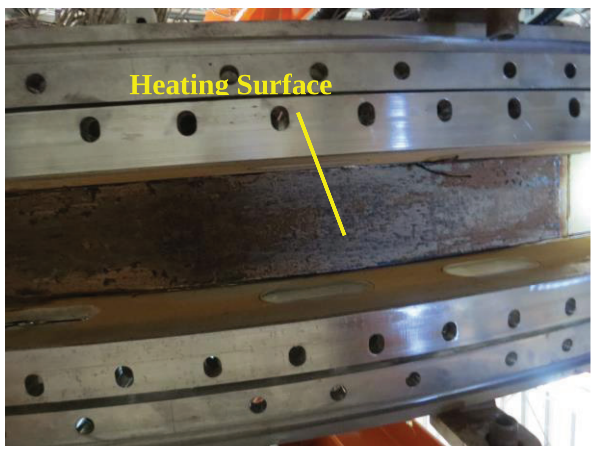

Figure 9. Fresh heating surface newly polished.

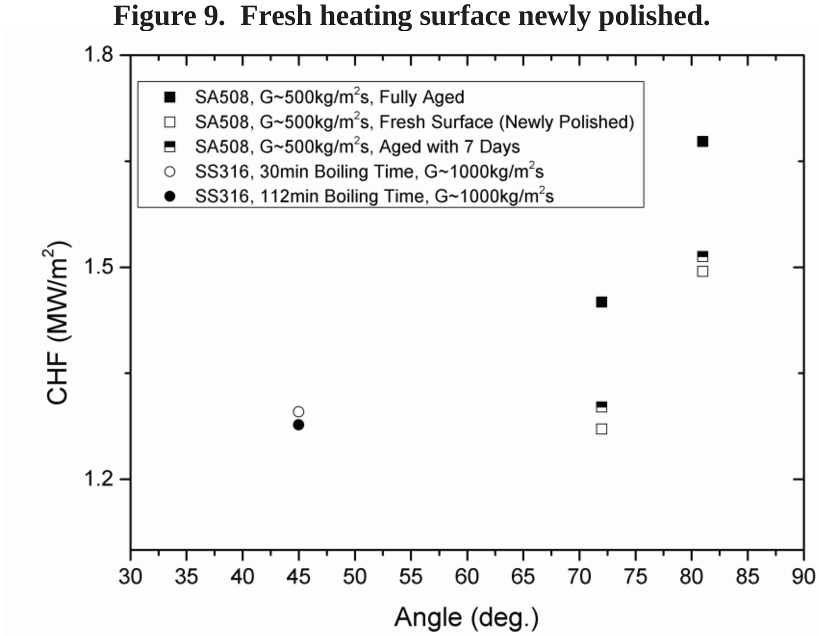

Figure 10. Fully aged heating surface.

4.3. CHF LIMITS OF DIFFERENT ANGLE

Previous researches have proved that CHF is related to inclining angle of the heating surface in ERVC-CHF process. Influences of key factors like inclining angle of the surface are investigated in FIRM test facility. Preliminary results are obtained and present results are compared with those of copper (ULPU-III) [3] and stainless steel [11]. CHF relationship with inclining angle shows a similar pattern in all three materials, as shown in Figure 11. CHF limits increase along with inclining angle; the variation of CHF with inclining angle appears to be composed of two linear regions-the lower region (0~57°) and the upper region(57~90°), which denotes different flow regimes in respective regions in present study. The material of SA508 will lead to a significant increase in CHF limits comparing to copper and SS316 stainless steel, which can be attributed to the enhancing effect of Fe_3O_4 generated in the heating surface working as the magnetite nanoparticles. In the position of 81° , CHF limit of SA508 is enhanced by 32.1% and 17.8% comparing to that of copper and SS316 (linear fitted results) respectively.

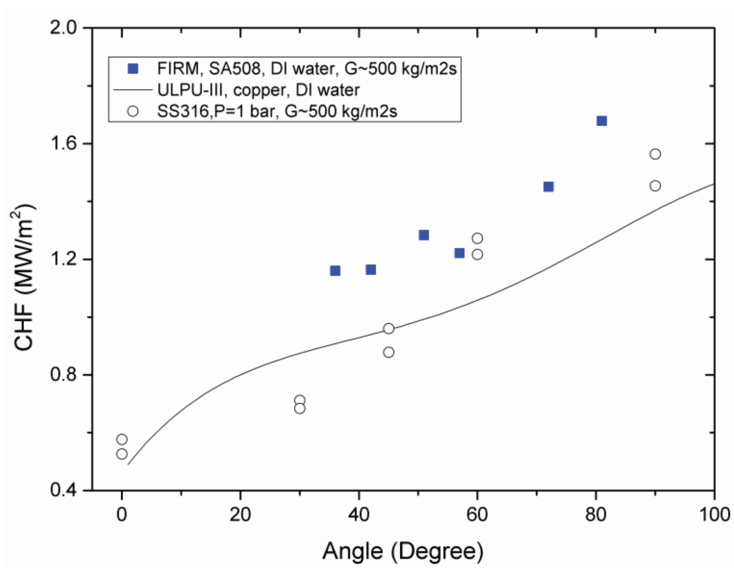

Figure 11. CHF limits v.s. downward facing angle of different surface material.

5. CONCLUSION

Experiments are carried out to study CHF behaviors in a large scale test section with real surface material in atmospheric pressure in FIRM facility. In present research stage, DI water is used as the working fluid and preliminary results are obtained. Conclusions are mainly obtained as following:

1) Temperature history of near-surface thermal couples shows a sudden increase (over 50℃/min) when CHF point is achieved. When the power level approaches to CHF power level, a flow type of slug/ chum flow is observed, which indicates a DNB mechanism for the boiling crisis.
2) Aging effect is observed in SA508 material which shows a great difference with SS316. CHF of the fully aged surface is enhanced about 12.4% and 10.9% respectively comparing to the fresh surface and aged surface over a week time (in air, room temperature and few runs of CHF experiments in DI water). The enhancement is contributed to oxidization process of SA508, that is the generations Fe_3O_4 on the surface work as magnetite nanoparticles.

3) CHF relationship with inclining angle shows a similar pattern in all three materials, SA508, SS316, copper. The material of SA508 will lead to a significant increase in CHF limits comparing to the other two. In the position of 81°, CHF limit of SA508 is enhanced by 32.1% and 17.8% comparing to that of copper and SS316 (linear fitted results) respectively.

Present study obtained the CHF results of RPV lower head with real surface material by using DI water as the working fluid. While in the real case, the working fluid is boric acid and trisodium solution which will also affect the CHF behaviors. Even though, the experiment results of deionized water are important which is a basic experiment of the full scale experiment and is of great importance in safety validation. For experiments of following stages, influences of more key factors like flow mass rate and inlet subcooling will be investigated; and also effects of chemical additives like boric acid, trisodium phosphate will be considered.

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