The experimental study to support IVR strategy

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Introduction

For alleviating the severe accident damage in nuclear power plant, In-vessel retention (IVR) is used on the severe accident management strategy in light water reactor. The criterion of IVR effectiveness is the safety margin, the value that between the melt pool heat flux and the critical heat flux on the lower head, matching the design requirements. For ensuring the safety margin, the heat flux of the molten pool and the critical heat flux of external reactor vessel cooling (ERVC) should be investigated.

For studying this two key problems, we set up HELM (Heat transfer behavior of mEtal Layer experiMent) facility and FIRM (key Factor of Improving ERVC-CHF experiMent) facility to test the correlation at high Rayleigh number of the metal layer (10^8<Ra<10^{12}), because of the thermal focus effect, and to indentify the CHF on RPV outer surface respectively.

Experiment facility

HELM facility

HELM apparatus includes the test section and the auxiliary system. The test section is composed of five parts, in the middle of which is a changeable cylindrical part with an inner diameter of 1000 mm. The five parts from the top are the expansion tank, the cooling plate, the cylindrical side wall, the heating plate and the adjustable support respectively. The auxiliary system consists of recirculation cooling water system, measuring instrument and data acquisition system, control console, and electricity supply. The recirculation cooling water system is designed to provide cooling for the cooling plate and the sidewall. Four refrigerating circulators, with a cooling capacity of 21kW and stability of ±0.1℃, are used in the recirculation cooling water system. The basic instrumentation in the measurement system includes multipoint thermocouples, Pt100 RTDs, Pt1000 RTDs and mass flow meters. The accuracy of the multipoint thermocouples, RTDs, and mass flow meters are ± 0.5℃, ±(0.1+0.0017|t|) and ±0.1% respectively.

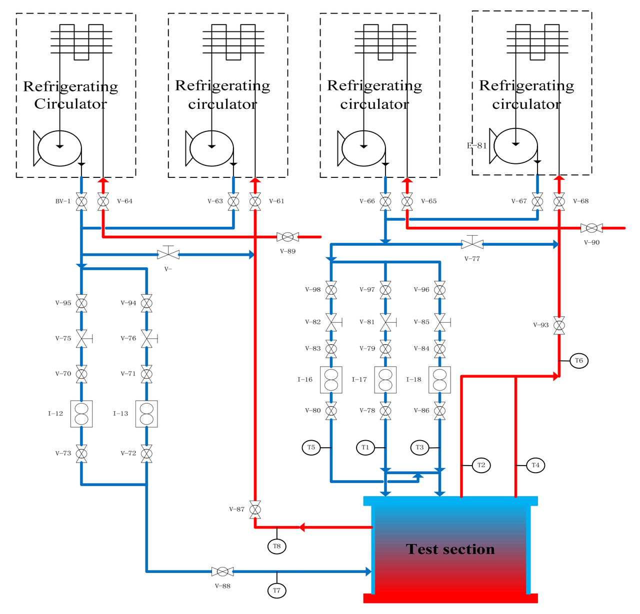

Figure 1 Schematic diagram of HELM test system


Figure 2 Picture of HELM facility

FIRM facility

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.

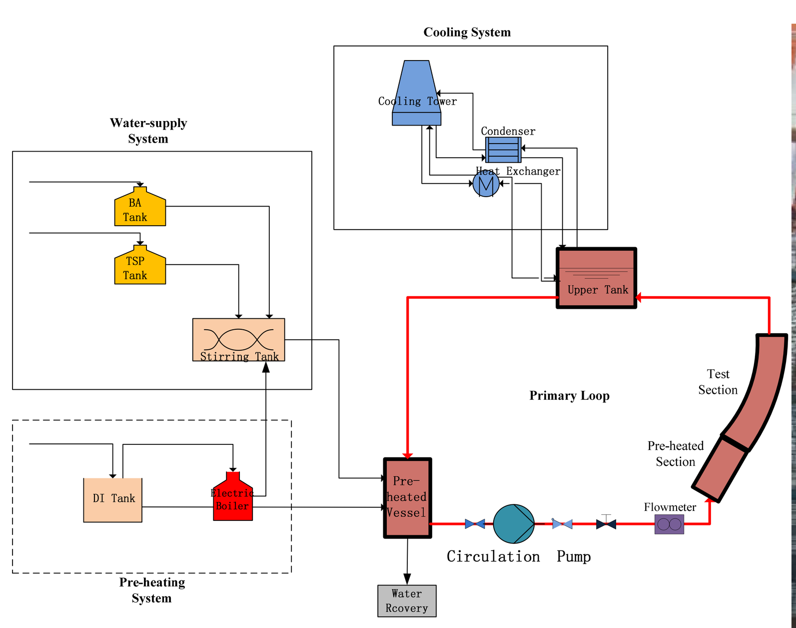

Figure 3 Schematic diagram of FIRM test system

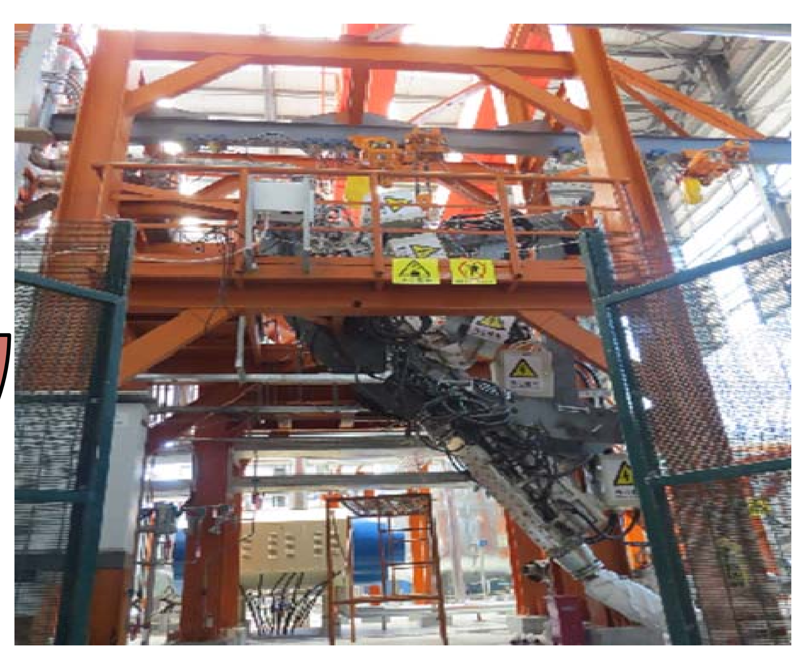
Figure 4 Picture of FIRM facility

Results

HELM result

The experiments, designed in three stages initially, were started in May 2012. Each stage was classified by the middle replaceable cylindrical part with heights of 150 mm, 400 mm, and 1000 mm of the test facility heights and the input power were adjusted for reaching high Ra number. In the logarithmic graph, log (NuRa) is good linearly varied with log (Ra). The result also shows that the aspect ratio has no noticeable effect on the relation between Nu and Ra. Since the experiment results with water are consistent, the data of high Ra range are still need to be compared with other research data. By comparison of these data in high Ra range, a good agreement is reached as shown in Figure 5. The comparison of predicted temperature differences across the top and bottom boundary layers is shown in Figure 6. The experiment data has a good agreement with the prediction, and are higher than the predicted upward values and lower than the predicted sideward values. It must be pointed out that "heat focus" effect in sidewall is more dangerous, so the little higher values provide safer prediction for designing. It is considered that the coupling of the experiment I results and the C-C correlation can accurately and safely predict the heat flow distribution of the metal layer.

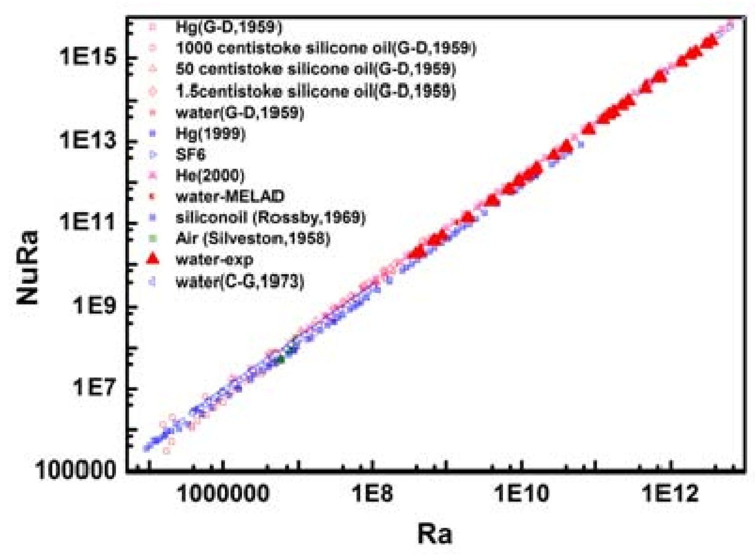

Figure 5 Comparison of the present experiment data and other experiment data using different fluids

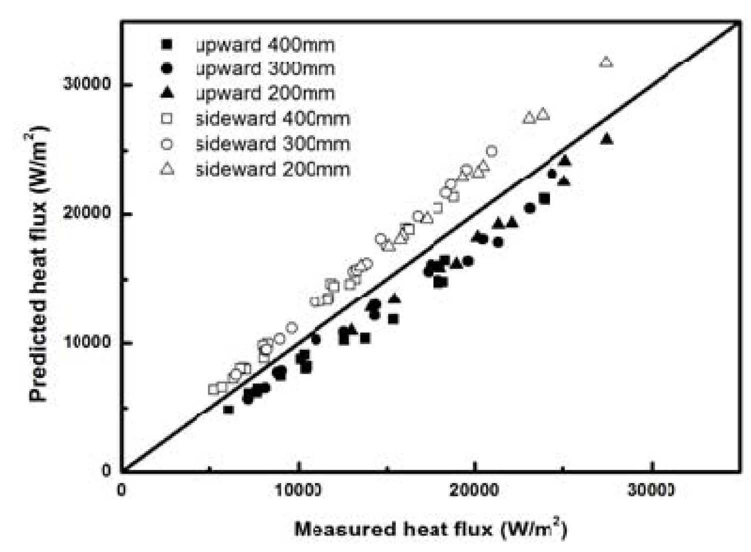

Figure 6 Comparison of predicted heat fluxes on the upward and sideward

FIRM result

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. CHF relationship with inclining angle shows a similar pattern in all three materials, as shown in Figure 7. Visualization of bubble behavior on the heating surface shown in Figure 8. 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 (0~42°) and the upper region(42~90°), 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.

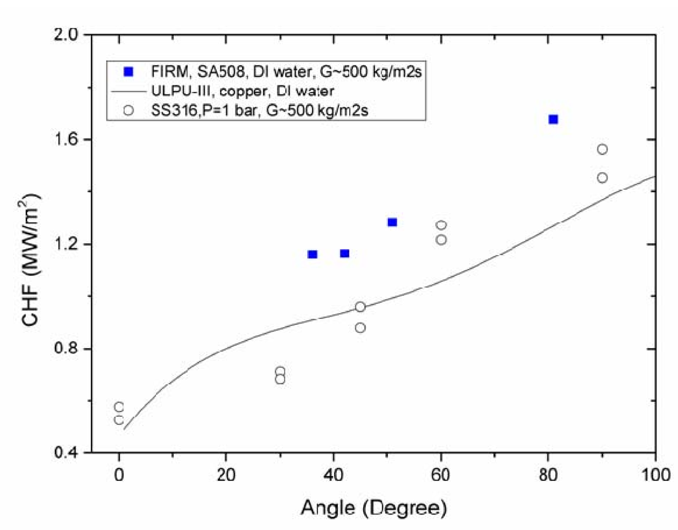

Figure 7 CHF limits v.s. downward facing angle of different surface material

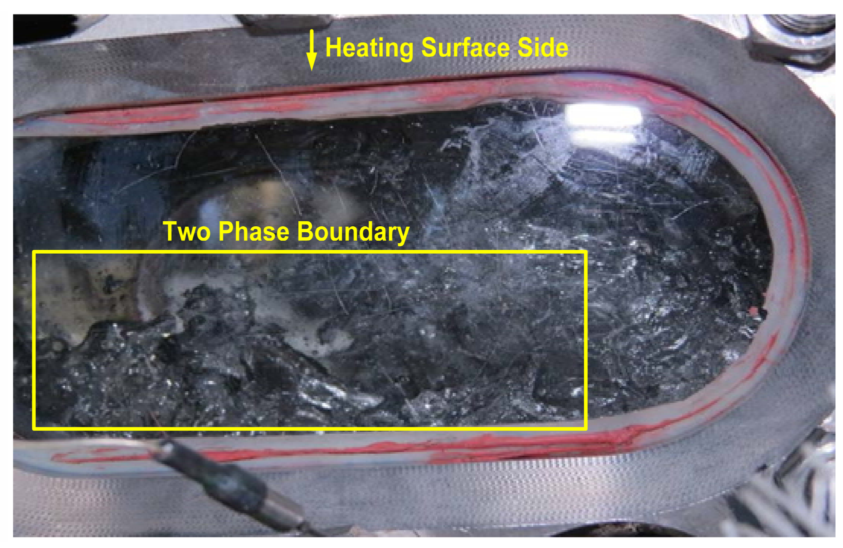

Figure 8 Visualization of bubble behavior on the heating surface

Conclusions

- The HELM facility reached high Ra number at 10^{12} in the high power reactor working condition. Experiment I provides the test data at high Ra number for engineering application. The predicted sideward values shared of the whole heat flow from oxide pool to the metal layer are higher than experiment results, which means this method can safely predict the heat flow distribution of metal layer in high Ra number conditions.
- Experiments are studied CHF behaviors in a large scale test section with real surface material in FIRM facility. 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.