TURBULENT CONVECTION EXPERIMENT TO SUPPORT IVR STRATEGY

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ABSTRACT

This paper is mainly to research the metal layer heat transfer through studying the correlations of the heat transfers. The Globe-Dropkin (G-D) [1] correlation ($1.5 \cdot 10^5 < Ra < 6.8 \cdot 10^8$) and Chu-Churchill (C-C) [2] correlation have been widely used to calculate the heat flux in the metal layer. However, with the increase of reactor power, both the Ra and the rate of heat transfer below the bottom of metal layer of the molten pool will increase, and in this case the Ra even can reach 10^{11} to 10^{12} for the high power reactor. Accordingly, the application scope of G-D correlation is not suitable for the high power reactor. Meanwhile, there is an ongoing debate about the correct correlation in the field. Therefore, the experiment purpose is to test and validate the G-D correlation at high Ra of the metal layer ($10^8 < Ra < 10^{12}$) with the Heat transfer behavior of mEtal Layer experiMent (HELM) facility. If the experiment results can't fit well with the G-D correlation, an appropriate correlation should be set up at high Ra for the high power reactor which can predict the heat flow distribution using experiment I result and C-C correlation in metal layer.

The experiments are divided into two parts. Each part concerns 39 runs and 47 runs experimental conditions respectively. Its corresponding results are obtained that the Nusselt number is found to be proportional to Ram in the range $3.93 \cdot 10^8 < Ra < 3.57 \cdot 10^{12}$ at middle Prandtl number (Pr=7 for water). Furthermore, the experiment results can predict the relationship between axial and radial heat transfer well.

KEYWORDS
High Rayleigh number, natural convection, metal layer, heat transfer

1. INTRODUCTION

A severe accident in a nuclear power reactor can be defined as an event that involves the melt-down of a reactor core. IVR is an important severe accident management strategy that has been adopted by the nuclear power plants in operation as well as the novel reactors, for examples, AP1000. The characteristics of the heat transfer process and the quantity of heat flux in metal layer are both the critical problems for devising the appropriate in-vessel retention (IVR) strategy. Turbulent convection occurs in the metal layer when the Rayleigh number (Ra) becomes sufficient high.

In the last phase of core degradation, the molten pool will form in the lower head of the reactor pressure vessel (RPV), mainly consisting of UO_2, ZrO_2, Zr and stainless steel. A molten light metal layer, composed mainly of Fe and Zr, will lie above the crust of the oxidic pool. This study can apply on the light metal layer of the two layer structure and three layer structure. The two layer structure: a metal layer on the top and an oxidic layer on the bottom, and the three-layered structure (bottom-to-top): molten "heavy" metal – molten oxides – molten "light" metal are controversial.

In this paper, the light metal layer is the research subject. Our research is mainly focused on the relationship of the heat transfer in the metal layer. Natural convection heat transfer in the metal layer has been the subject of extensive experimental and numerical investigation over the years. In particular, nuclear reactor safety has impelled research in the thermal convection for the heated layers during the past four decades. The research in the area of heat transfer is of paramount importance in the evaluation of core damage accidents. The Globe-Dropkin (G-D) [1] correlation, which is valid for $1.5\bullet10^5<Ra<6.8\bullet10^8$, has been widely used to calculate the heat flux in the upper surface of the metal layer. The predicted aspect ratio of the metal layer and the heat transfer from the oxidic pool to the metal layer for the high power reactor are larger than those for AP1000, the temperature difference in metal layer will be higher. As a result, the Rayleigh number of the metal layer for the high power reactor (10^{11}-10^{12}) was found to be much larger than that for AP1000 ($\sim10^{10}$), far more than the valid range of the G-D correlation ($1.5\bullet10^5$-$6.8\bullet10^8$). Some experiments have shown that the Nu-Ra relation can have different slopes for 'soft' and 'hard' turbulence on the logarithmic scale [3]. There is an ongoing debate about the correct correlation in the field. So the study is to set up an appropriate correlation. We summarize some of most well-known correlations, given in the form $Nu=CRa^nPr^m$, in Table I.

Table I. Correlations for Rayleigh-Bénard convection

References	Nu	Ra range
G-D [1]Nodal	$0.069Ra^{1/3}Pr^{0.074}$	$1.5\bullet10^5\sim6.8\bullet10^8$
C-G [4]	$0.8138Ra^{0.278}$	$2.8\bullet10^5\sim1.1\bullet10^8$
Castaing et al. [5]	$0.23Ra^{2/7}$	
Cioni et al. [6]	$0.14Ra^{0.26}$	
Niemela et al. [7]	$0.124Ra^{0.309}$	$10^6\sim10^{17}$

Therefore, the main objective of our research is to test and validate the correlation at high Rayleigh number of the metal layer ($10^8<Ra<10^{12}$) by HELM. If the experiment results can't fit well with the G-D correlation, an appropriate correlation should be set up which can predict the heat flow distribution using experiment result and C-C correlation in metal layer.

2. EXPERIMENT DESIGN

The heat transfer coefficient for geometrically similar containers is subject to the influence of a same set of factors, with the exception of L and ΔT. The heat transfer data are correlated in terms of the Nusselt number and the Rayleigh number:

$$Nu=hL/k\,,\ Ra=g\beta\Delta TL^3/\nu\alpha \tag{1}$$

Where k is thermal conductivity, β is the coefficient of thermal expansion, g is the gravitational acceleration, ν is the kinematic viscosity and α is the thermal diffusivity. The thermo-physical properties are evaluated at the mid-plane temperature, which is average temperature between the two surfaces. L and ΔT are respectively the layer depth and the temperature difference, and h is the heat transfer coefficient based on ΔT. Since Ra ∞ L^3, we can obtain a Ra in the range of 10^{11}, as observed, by increasing L. To achieve the research purpose, the height of the test sections is altered, with the layer depth=150 / 400 / 1000 mm. The Rayleigh number ranges from $10^8 \sim 10^{12}$.

The G-D correlation ($Nu=0.069Ra^{1/3}Pr^{0.074}$) is widely used for estimating the safety of RPV in severe accident. The MELAD [8] experiment studied the metal layer heat transfer phenomenon for AP600, using water as simulated fluid. In addition, the metal melt in the metallic layer and water are Newtonian fluid, so water is a suitable working fluid and would not have any adverse effect in modeling the correlation. Furthermore, experiments with water are more economical and practical. Therefore identical to the experiments mentioned above, water will also be used in our test. Because of the average temperature range adopted for the test (25-85℃), the range of Pr number is small (3.13-7.05).

There are two main experiments in HELM. The experiment I is mainly to test and validate the correlation at higher Rayleigh number (10^8<Ra<10^{12}) or sum up a more appropriate correlation. Experiment I study the Rayleigh-Bénard convection in metal layer, which is used to calculate the heat flux in the upper surface of the metal layer. The experiment II is mainly to predict the heat flow distribution using experiment I result and C-C correlation in metal layer. It simulates the heat transfer in the metal layer: axial heat transfer from the oxidic pool to the metal layer, radiative heat transfer from the metal layer to the upper space in the RPV and radial heat transfer from the metal layer to the carbon steel RPV wall. 39 runs were carried out with the HELM facility in experiment I, with an electric heating power of 1 / 2 / 5 / 10 / 15 / 20 / 25 kW but the same experimental condition at different stages. 47 runs in experiment II were carried out by the HELM facility, with a power of 15 / 20 / 25 / 30 / 35 kW and different cooling flows but the same experimental condition at different stages. The schematic diagram of the HELM experiment system is shown in Figure 1. The apparatus includes the test section and the auxiliary system. The latter consists of a recirculation cooling water system, a measuring instrument and data acquisition system, a control console, and an electricity supply.

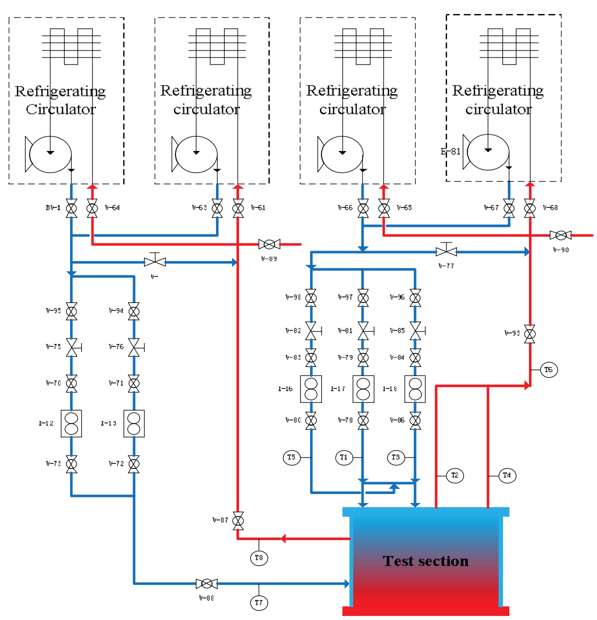

Figure 1. Schematic Diagram of HELM Experiment System

3. EXPERIMENT APPARATUS

The experiment facility, called HELM, is shown in Figure 2. The apparatus includes the test section and the auxiliary system. The latter consists of recirculation cooling water system, measuring instrument and data acquisition system, control console, and electricity supply.

Figure 2. Experiment Facility

3.1. Test Section

The test section simulating boundary conditions of metal layer is the major component of the system, which is illustrated in Figure 3. The metallic layer is heated from below and cooled from above and the sides. 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 following paragraph describes the function and the structure of each part of the test section.

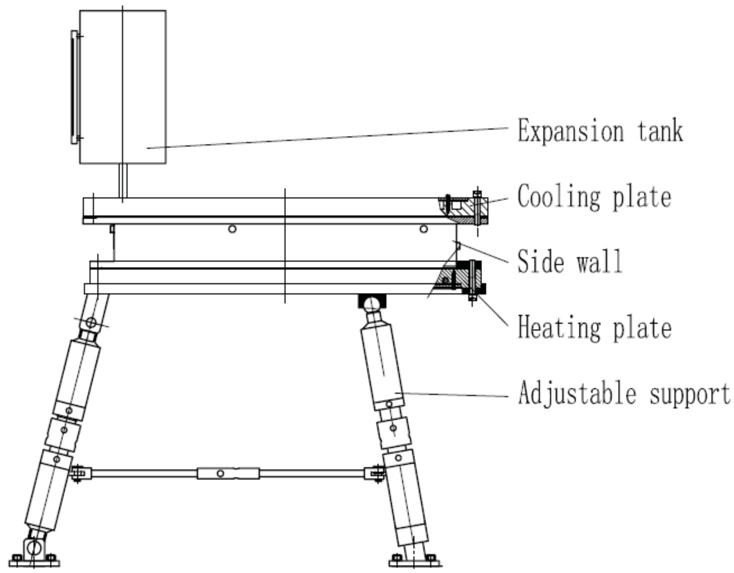

Figure 3. Schematic of the Configuration of Test Section

The copper heating plate simulates heat transfer from the oxidic layer to metallic layer. There are the heaters and several platinum resistors (RTD) embedded in the plate. The RTDs are used to measure temperature on the upper surface of the plate and monitor temperature uniformity. Top copper cooling plate, connected with recirculation cooling water system, simulates the heat transfer from the metal layer to air. The steel sidewall simulating the adiabatic wall boundary condition is made of stainless steel without cooling channels in experiment I. There are three cylindrical barrels with different heights (150 / 400 / 1000 mm) in HELM. In experiment II, the copper sidewall (corresponding heights: 200 / 300 / 400 mm) have cooling channels on the outer surface. The cooling channels are connected with the recirculation cooling water system and are independent from the cooling plate. In this way, the cooling wall boundary condition is simulated. The expansion tank contains water and provides room for expansion when water inside the cylindrical barrel is heated, to ensure that the test section is always filled with water. The adjustable support can provide enough space for the heater extensions and adjust the angle of test section in order to discharge gases when water is heated.

3.2. Auxiliary System

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. Near the water inlet and outlet of the test section, several Pt1000 RTDs are inserted in the tubes to measure the local water temperature. A mass flow meter is installed on each branch to measure their flow rates. 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. The Data Acquisition System (DAS) has 60 digital input channels. The silicon controlled rectifier is used to control the power of heaters. Harmonic detector, which can measure accurately with harmonic wave, is used to measure the voltage, current and power.

4. EXPERIMENT RESULTS AND ANALYSIS

4.1. Experiment I Results and Analysis

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. Each run consisted of the stabilizing process and the stabilized process, both of which lasted about 30 minutes.

There are 39 runs preformed in the present experiment. The overall heat transfer phenomenon is characterized by Nu. In the research of this field, results are mainly fitted to the following form:

$$Nu = C \times Ra^{m} \tag{2}$$

Where C is constant number, the values of m vary greatly in different research results. Because of the complexity of the turbulent convection, which is still to be learnt, there are not enough experimental data to remodel the details so far. Many kinds of work fluids had also been adapted to study in wide range of Ra, such as water, mercury, silicone oil, helium etc.

The following examples are the experiment results of water. The value of m=0.31 had been obtained by Silveston (1958) [9] for $3\times10^{5}< Ra <6\times10^{7}$. Globe & Dropkin (1959) [1] used several work fluids such as water, silicone oil and mercury to study natural convection, where m=1/3, $1.51\times10^{5}\leq Ra\leq6.76\times10^{8}$. Rossby (1969) [10] reported the value of m=0.30 for water in Ra>34000. Chu & Goldstein (1973) [4] reported m=0.278 for $2.76\times10^{5}<Ra< 1.05\times10^{8}$. The different value of m=0.28 in the study of Chilla et al (1993) [11] was slightly different with m=0.292 given by Coini et al (1997) [6]. The value of m changes from 0.22 to 0.33 according to the results of water. Figure 4 shows the present experiment data including Nu and Ra. It should be noted that the Nu Ra of the vertical axis is to reduce any possible maximum error in ΔT, because ΔT has only effect on the horizontal axis. In the logarithmic graph, log (Nu Ra) 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.

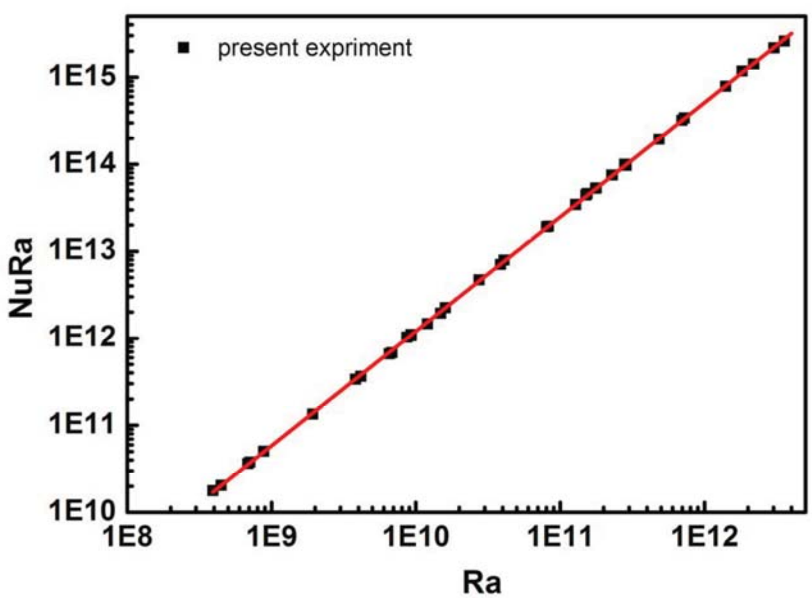

Figure 4. Present Experiment Data in Experiment I

The experiment data in this paper are consistent with other studies using water as working medium (Figure 5). The maximum deviations of data points by Coini and MELAD with the fit are 9.28% and 18.61% in the range of present experiment. In the present experiment, the result is enveloped by other experimental results with water, which confirms the reliability of the experimental data and the data processing method used in these experiments.

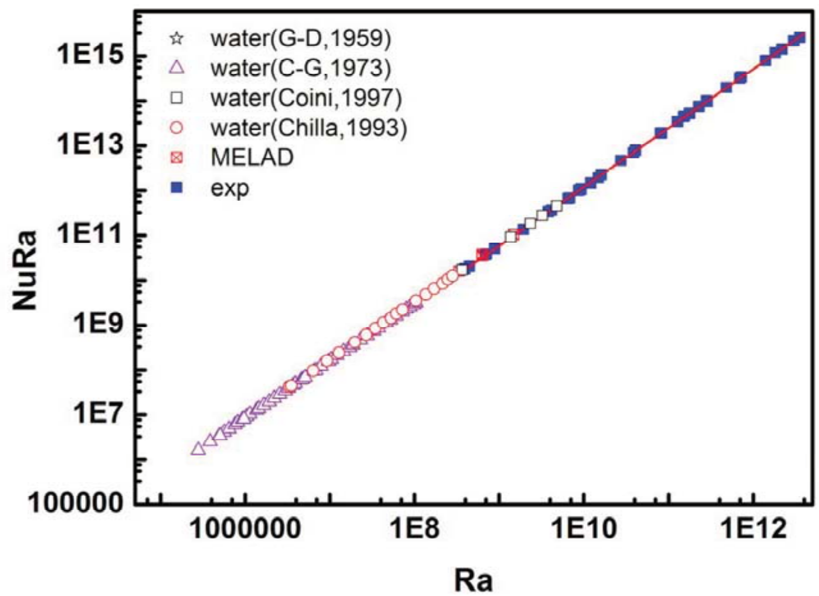

Figure 5. Comparison of the Present Experiment Data and Other Experiment Data Using Water as Fluid

Since the experiment results with water are consistent, the data of high Ra range are still need to be compared. Chavanne et al (1997) [12] reported the value of m=0.389 for gas and liquid helium, and the Ra up to 10^{11}. Ashkenazi & Steinberg (1999) [13] reported m=0.3 for $Ra<5\times10^{14}$ in which SF_6 were adopted. Niemela et al (2000) [14] studied cryogenic helium gas, and got the value of m=0.309 in large range $10^6<Ra<10^{17}$. By comparison of these data in high Ra range, a good agreement is reached as shown in Figure 6.

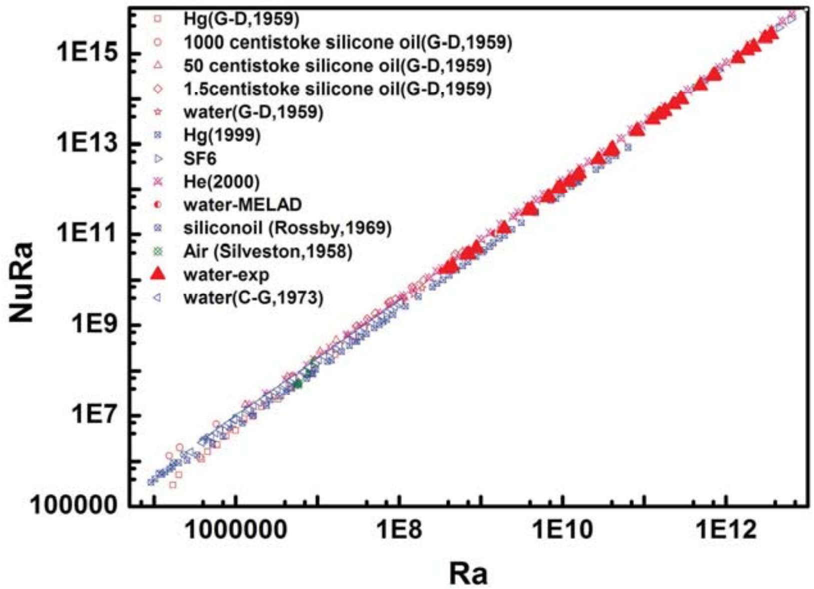

Figure 6. Comparison of the Present Experiment Data and Other Experiment Data Using Different Fluids

4.2. Experiment II Results and Analysis

In this work, it is combined with the result of the experiment I and the C-C correlation to predict the distribution of heat flow on the upward and the sideward. The result of experiment I represents the heat transfer of boundary at corresponding Ra number in upward heat transfer. The heat transfer of turbulent at such high Ra depends on the behavior of the independent thermal boundaries. The temperature of bulk beside the thermal boundaries is consisting by turbulent mixing. Consequently, it can be used to solving the upward distribution in coupling heat transfer when Ra is in the range $3.93\times10^8<Ra<3.57\times10^{12}$. The "bulk" temperature is introduced. The driving force of the top, the bottom or side heat transfer is resulted respectively from the differences between the "bulk" temperature and the temperature of every side wall. The themophysical parameters are calculated at the "film" temperature, which is the average value of the "bulk" temperature and the corresponding boundary temperatures on every side. Using the energy balance, the following equations are obtained:

$$
\begin{aligned}
Q_{up} &= Q_o + Q_w \\
q_{up} &= 0.211\left(\frac{g\beta}{\alpha\nu}\right)_{f,i}^{0.315} k_{f,i}\left(T_i - T_b\right)^{1.315} L^{-0.055} \\
q_o &= 0.211\left(\frac{g\beta}{\alpha\nu}\right)_{f,o}^{0.315} k_{f,o}\left(T_b - T_o\right)^{1.315} L^{-0.055} \\
q_w &= h_{f,w}\left(T_b - T_w\right)
\end{aligned} \tag{3}
$$

Where Q is the heat transfer, the subscripts i, o, w, b and up represent the heating plate, top cooling plate, side cooling wall, the bulk, and the heat from oxide pool to the metal layer respectively. The subscripts (f,i), (f,o) and (f,w) represent the average value of the "bulk" temperature and the temperatures on the heating plate, the average value of the "bulk" temperature and the temperatures on top cooling plate, and the average value of the "bulk" temperature and the temperatures on side cooling wall. $h_{f,w}$ is heat transfer coefficient calculated by the C-C correlation. The C-C correlation is

$$Nu = 0.825 + \frac{0.387 Ra^{1/6}}{\left[1 + \left(\frac{0.492}{Pr}\right)^{9/16}\right]^{8/27}}, Ra < 10^{13} \tag{4}$$

In the equations 3, q_{up}, T_o, and T_w are known, and q_o, q_w, T_b, and T_i can be computed. The experiment II was designed to study the distribution of heat flow on the upward and sideward. The experiment data are also compared with the predicted results. The comparison of the results of heat flux on the upward and sideward is shown in Figure 7. The comparison of predicted temperature differences between the top and bottom boundary layers is shown in Figure 8. The experiment data has a good agreement with the predict values, 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. The result comparison of the driving force of heat transfer is similar with MELAD experiment. 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.

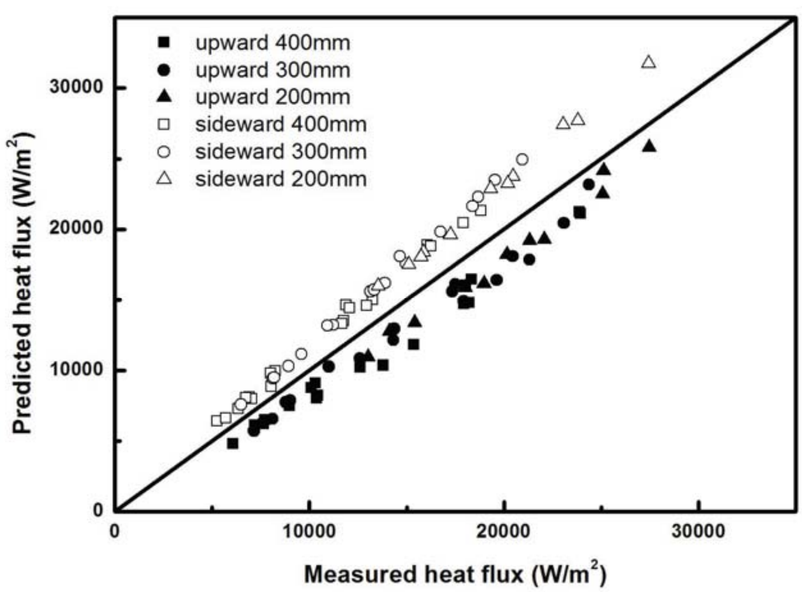

Figure 7. Comparison of Predicted Heat Fluxes on the Upward and Sideward

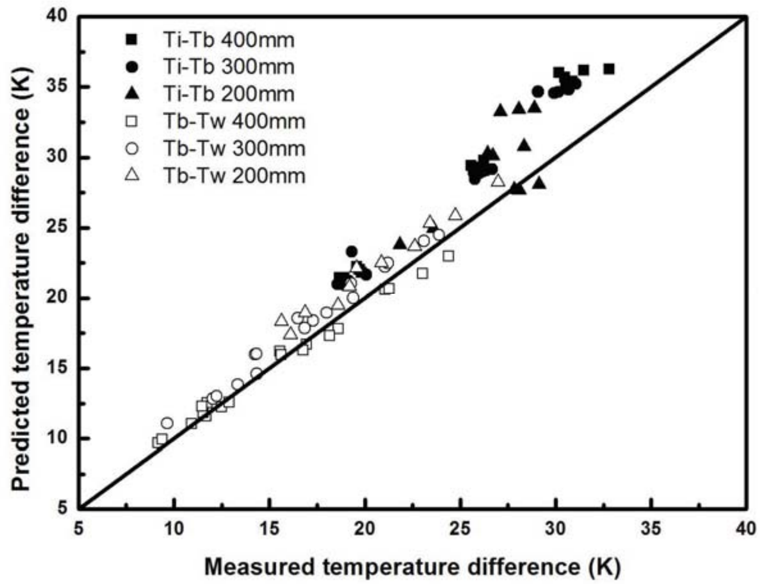

Figure 8. Comparison of Predicted Temperature Differences Across the Top and Bottom Boundary Layers

5. CONCLUSIONS

In summary, the facility reached high Ra number at 10^{12} in the high power reactor working condition, at the same time, the test facility simulates the whole cooling side wall, which is closer to the real condition.

In experiment I, metallic layer heated from below and cooled from above has been simulated. The result is documented by the agreement with other experiment results. Meanwhile, experiment I provides the test data at high Ra number for engineering application.

It was combined with the result of experiment I and the C-C correlation to calculate the heat transfer characteristic of metal layer in core-melt debris, and the analysis is supported by experiment II. The predicted values of the sidewall heat flow from oxide pool to the metal layer are higher than experiment results. With these results, the coupling of the experiment I fitting formula and the C-C correlation can accurately and safely predict the heat flow distribution of metal layer in high Ra number conditions.

ACKNOWLEDGMENTS

This work is supported by the National Science and Technology Major Project of the Ministry of Science and Technology of China----Large-scale advanced pressurized water reactor and high temperature gas cooled reactor nuclear power plant (2010ZX06002-004).

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