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Development of Natural Convection Heat Transfer Correlation for Liquid Metal with Overlying Boiling Coolant

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Abstract

Experimental study was performed to investigate the natural convection heat transfer characteristics and the crust formation of the molten metal pool concurrent with forced convective boiling of the overlying coolant. Tests were performed under the condition of the bottom surface heating in the test section and the forced convection of the coolant being injected onto the molten metal pool. The constant temperature and constant heater input power conditions were adopted for the bottom heating. Test results showed that the temperature distribution and crust layer thickness in the metal layer are appreciably affected by the heated bottom surface temperature of the test section, but not much by the coolant injection rate. The relationship between the Nu number and Ra number in the molten metal pool region is determined and compared with the correlations in the literature, and the experiment without coolant boiling. A new correlation on the relationship between the Nu number and Ra number in the molten metal pool with crust formation is developed from the experimental data.

I. INTRODUCTION

Molten debris coolability after a reactor severe accident involving core meltdown and vessel failure is currently one of the main research items. During a hypothetical severe accident in nuclear power plants, a significant amount of core material can melt and possibly form stratified fluid layers [1]. When two nearly immiscible liquids are brought into intimate contact, the temperature of one of the liquids may be well above the normal boiling point of the second liquid. These layers may be composed of high temperature molten debris pool and water coolant in the lower plenum of the reactor vessel [2] or in the reactor cavity [3]. The debris pool is heated internally at decay power levels, and natural convection is the main heat transfer mechanism from the debris pool to the surroundings in the molten phase. Also, molten debris pool may be stratified into a metal layer and an oxide layer on account of their density difference [4,5]. As shown in Figure 1, a molten metal layer is located in the upper region and may be cooled by the overlying coolant, which may undergo boiling. As a result, a crust, which is a solidified layer of the molten pool, may form at the top [6,7]. Heat transfer is accomplished by a conjugate mechanism of natural convection of the molten debris pool, conduction through the solidified layer and convective boiling heat transfer to the coolant. These complex heat transfer mechanisms between the molten debris pool and coolant layers are very important in the coolability evaluation of the molten debris pool. If a debris pool layer is cooled at the upper region of the molten debris pool by boiling coolant which is injected onto the molten debris pool, it is considered that the natural convection heat transfer in the molten debris pool is enhanced because the boiling heat transfer in coolant layer is very rapid.

A number of experimental and theoretical investigations were carried out to understand the solidification and the change of heat transfer rate of the debris pool, which greatly affects the accident progression. But until recently no data have been reported for heat transfer from an internally heated molten debris pool to an overlying pool of boiling coolant. In particular, the results for natural convection which is induced in the molten pool with local solidification by boiling coolant are not existent. Therefore study on the heat transfer phenomena of the molten metal pool with solidification by the boiling coolant is necessary.

Experimental study was performed to investigate the crust formation and heat transfer characteristics of the molten metal pool with overlying coolant with boiling. The uniform temperature and heat flux are applied over the lower horizontal surface of the test section. The upper region of the molten metal pool is cooled by boiling coolant.

Tests were performed under the condition of the bottom surface heating in the test section and the forced convection of the coolant being injected onto the molten metal pool. The simulant molten pool material is tin (Sn) with the melting temperature of 232°C. Demineralized water is used as the working coolant. The constant temperature and constant heater input power conditions are adopted for the bottom heating. The test parameters includes the heated bottom surface temperature of the molten metal pool, the input power to the heated bottom surface of the test section, and the coolant injection rate.

In this study, the relationship between the Nusselt number and Rayleigh number in the molten metal pool region has been modeled or correlated and compared with the crust formation experiment with subcooled coolant, and against other correlations.

II. EXPERIMENTAL APPARATUS AND TEST PROCEDURE

To investigate heat transfer characteristics of the molten metal pool being solidified by the boiling coolant, the experimental apparatus was constructed as described below. The inner dimension of the rectangular test section was 25cm in length, 35cm in height, and 25cm in depth. Figure 2 shows the schematic diagram of the test apparatus. The test section is made of 10mm thick STS304 stainless steel. The heights of the molten metal and the coolant layer are 20cm and 15cm, respectively. A 20kW heater is installed in the bottom horizontal plate of the test section. The viewports are installed using a quartz glass at the front and at the back of the test section. Four sides of the test section are insulated with a 4cm thick Fiberfrax material to minimize heat loss. A digital pump is installed to deliver uniform mass flow of the coolant onto the molten metal pool. The melting pot is equipped with an 8 kW heater to melt the metal. The temperature distribution inside the test section is measured using 85 thermocouples, which are placed in five vertical arrays of thermocouple bundles located at the one-fourth, one-half and three-fourth positions of the length and width of the test section. The thermocouple is of T-type(copper-constantan) and the thermocouple bundle is made of STS304 stainless steel. Seventeen thermocouples are aligned along the vertical direction in a bundle. Fifteen of the seventeen thermocouples are immersed into the metal layer and two thermocouples are located in the coolant layer.

In case of the constant temperature boundary condition of the bottom heating surface, the test parameters are the bottom surface temperature ranging from 253°C to 266°C, the injection coolant mass flow rate in the range of 0.5 liter/min to 2.5 liter/min. In case of the constant heater input power condition of the bottom heating surface, the test parameters are the input power to the bottom heating surface ranging from 6 to 14kW and the injection coolant mass flow rate is set at 1.0 liter/min and 2.0 liter/min in this case.

Test procedure is as follows. First, the metal is molten in the melting pot and injected into the test section. The metal is maintained as liquid in the test section whose bottom surface is electrically heated. To avoid any potential steam explosion when the coolant is injected onto the metal pool, the coolant is heated near to the boiling point. Next, the coolant is injected onto the molten metal in the test section at the preset mass flow rate. Then, the upper region of the molten metal layer starts to solidify and the solidified layer thickens with the lapse of time. The boiling coolant is transported to the quench tank from the test section. The vapor is condensed in the quench tank and transported to the coolant supply tank. The coolant is recirculated in a closed loop until a steady-state condition is achieved. A steady state condition is assumed when the crust thickness of the metal layer stabilizes with time. After the steady state is accomplished, the PC data acquisition system records the temperature data of the metal and coolant layers.

III. RESULTS AND DISCUSSION

The measurement parameters of this experiment are the temperature distributions in the metal layer and the coolant layer, and the crust thickness in the metal layer. The solidified crust thickness during the experiments is determined by interpolating the melting temperature (232°C) for pure tin from thermocouple readings. The values are obtained after a steady state has been accomplished.

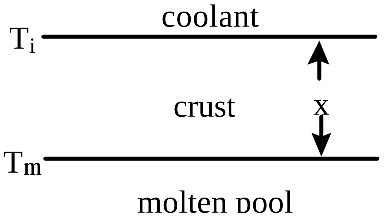
In this experiment, rapid heat transfer takes place from the molten metal layer to the coolant layer because the molten metal layer cooling is accomplished by the boiling heat transfer of the coolant layer. Thus it is difficult to maintain the steady state. Especially, it is difficult to keep the bottom heating surface temperature of the test section constant. In actuality, the quasi-steady state apparently produces fluctuations in temperature in the metal layer and the coolant. The solidification of the molten metal pool is initiated after the coolant injection onto the molten metal pool in the test section, but the solidified crust layer maintains a uniform thickness after some period of time has elapsed. The experimental data in this study are obtained from the averaged values for the duration of measurement after the quasi-steady state has been reached.

III-1. Constant Temperature Boundary Condition Case

Figure 3 shows the temperature profiles of 255°C, 260°C, and 262°C with the water coolant injection rate of 2.5 liter/min. In the metal layer, the region where the temperature is higher than 232°C is in the liquid state and the other region is in the solid state. The portion below the horizontal dotted line is the metal layer, and above is the coolant layer. The vertical dotted line is the melting temperature of tin. The temperature varies linearly in the solidified region, and is almost uniform in the molten pool and in the coolant. This is because the heat transfer is accomplished by pure conduction in the crust region and developed by natural convection flow in the liquid state region. Figure 4 displays the temperature profiles as a function of the water coolant injection rate of 1.0, 1.5 and 2.0 liter/min for a bottom heating temperature of 266°C. As can be seen from Figures 3 and 4, the crust layer thickness may be greatly varied by the heated bottom surface temperature of the test section, but is not much affected by the coolant injection rate because of the developed natural convection flow.

Table I presents the experimental results for crust thickness, heat flux, Nu number and Ra number in the metal layer, for the case of the constant temperature boundary condition and using the water coolant. The values were obtained after a steady state had been accomplished.

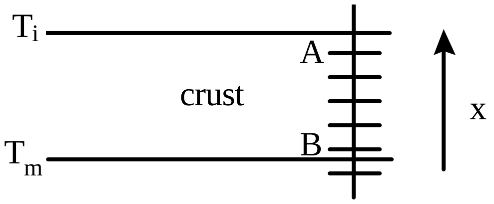
The heat flux can be derived from the temperature difference between the top surface and the bottom surface of the crust layer using the heat conduction equation.



$$q'' = k\frac{T_m - T_i}{x} \tag{1}$$

where q'' : heat flux through crust, (W/m^2)
k : thermal conductivity of crust, (W/m-K)
T_i : interface temperature of crust and coolant, (K)
T_m : melting temperature, (K)
x : crust thickness, (m)

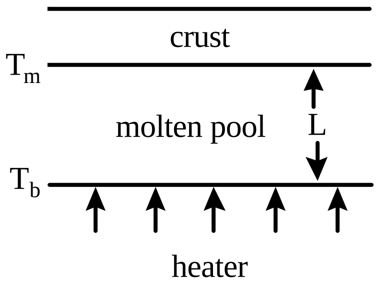
In this experimental tests, the actual heat flux is calculated from the temperature measurements by the thermocouples located right underneath the metal layer and coolant interface and just above the melting point, and the distance between the two points in-between.



$$q'' = k\frac{T_B - T_A}{x_A - x_B} \tag{2}$$

This is necessary because the interfacial temperature T_i and the melting location of the metal layer normally are placed between the two thermocouple locations.

The heat transfer coefficient of the molten metal pool is derived from this heat flux as follows.



$$h = \frac{q''}{T_b - T_m} \tag{3}$$

This calculation is based on the assumption that there is no heat loss to the environment. Natural convection heat transfer in the molten pool is generated by the buoyancy force arising from the density difference. The Nu number is obtained by using the heat transfer coefficient and the height of the liquid metal state region. The Ra number is defined by the temperature difference between the bottom and top surfaces in the liquid metal state region and the height of the liquid metal state region. The Nu number and the Ra number are defined as follows.

$$Nu = \frac{hL}{k} \tag{4}$$

$$Ra = \frac{g b \Delta T L^3}{a n} \tag{5}$$

where h : heat transfer coefficient in the molten pool, (W/m^2-K)
L : height of molten pool layer, (m)
ΔT : temperature difference (T_b - T_m), (K)
g : gravitational acceleration, (m/s^2)
α : thermal diffusivity, (m^2/s)
β : thermal expansion coefficient, (1/K)
ν : kinematic viscosity, (m^2/s)

In this calculation, all the physical properties of the tin are considered to be constant in the molten metal pool region. In this experiments, the range of the Ra number is between 1.6×10^6 and 3.6×10^7, and the Nu number is between 7.1 and 24.8. In general, Nu number increases with an increase in Ra number. With a growth in the crust thickness, Ra number and Nu number decrease in the molten metal pool region because its height decreases.

III-2. Constant Heat Input Power Condition Case

In this case, the input power to the test section bottom heater is the test parameter and it is controlled by the power controller. The input power is varied from 6kW to 14kW. Figure 5 displays temperature distribution of the test section as a function of the input power to the bottom surface at a coolant injection rate of 1.0 liter/min. As can be seen from Figure 5, the results illustrate that the crust layer thickness and temperature distribution may be greatly varied by the heated bottom surface temperature of the test section. The crust thickness varies from 10.67cm in case of 6kW to 3.13cm in case of 14kW. Figure 6 shows temperature distribution of the test section as a function of the input power to the bottom surface at a coolant injection rate of 2.0 liter/min. The temperature distributions are similar with the case of the coolant injection rate of 1.0 liter/min. The heat flux boundary condition case is show that the crust thickness and temperature of the metal layer are dominantly affected by the bottom heater input power and the crust thickness and temperature distribution are barely affected by the coolant injection rate. This is due to the fact that the natural convection flow in molten metal pool is well developed. The crust thickness varies from 10.91cm in case of 6kW to 2.90cm in case of 14kW.

Table II shows the heat transfer rate of the molten metal pool region for the case of the constant heat input power test. As shown in the Table, the range of the Ra number in the tests is from 2.6×10^{6} to 4.3×10^{7} and the Nu number is from 13.3 to 30.1. With a growth in the crust thickness, the Ra number and the Nu number decrease in the molten metal pool region because its height decreases.

III-3. Development of the New Correlation

The relationship between the Nu number and Ra number in the molten metal pool region is determined and compared with the correlations in the literature. Available correlations include the Globe and Dropkin correlation for mercury [8], and the Park correlation for Wood's metal [9]. These correlations were obtained by using the low Prandtl number material as the working fluid. The Globe and Dropkin correlation was developed for the pure mercury in an enclosure without solidification and coolant cooling. The Park correlation was developed for Wood's metal with solidification by subcooled coolant cooling mechanism. These correlations are follows.

$$\text{Globe and Dropkin} \quad : \quad Nu = 0.051\,Ra^{0.333} \quad (1.51\text{x}10^{5} < \text{Ra} < 6.76\text{x}10^{8}) \qquad (6)$$

$$\text{Park et al.} \quad : \quad Nu = 0.092\,Ra^{0.302} \quad (2.0\text{x}10^{4} < \text{Ra} < 5.0\text{x}10^{7}) \qquad (7)$$

In this experiment, the heat transfer is accompanied by conjugate heat transfer mechanisms, which are the natural convection heat transfer in the molten metal pool, the conduction heat transfer in the solidified crust layer and the boiling heat transfer in the coolant layer. Especially, the molten metal layer is cooled by the rapid boiling heat transfer of the coolant. A new correlation on the relationship between the Nu number and Ra number in the molten metal pool with crust formation is developed from the experimental data of the water coolant test case. The new correlation is the following :

$$Nu = 0.0552 Ra^{0.347} \qquad (8)$$

Figure 7 shows the experimental data for water coolant case and its fitting result. The Nu number value of this correlation is approximately 31% higher than Globe and Dropkin's and 11% higher than Park's at the Ra number of 1×10^6. If the Ra number is 5×10^6, the Nu number is approximately 34% higher than Globe and Dropkin's and 20% higher than Park's. If the Ra number is 5×10^6, the Nu number is approximately 35% higher than Globe and Dropkin's and 24% higher than Park's. And, the Nu number value of this correlation is approximately 37% higher than Globe and Dropkin's and 30% higher than Park's at the Ra number of 1×10^6. Generally, the present correlation is higher than the other correlations. In this analysis, the difference of the Nu number between this correlation and the other correlations increases as the Ra number increases. In this study, the experimental tests are performed in the Ra number range from 1×10^6 to 4×10^7. Therefore the new correlation is available in that range. The comparison of this correlation with literature correlations is shown in Figure 8.

IV. CONCLUSION

The experimental study was performed to investigate the natural convection heat transfer characteristics and the crust formation of the molten metal pool concurrent with forced convective boiling of the overlying coolant. In the test, the temperature distribution and crust layer thickness in the metal layer are appreciably affected by the heated bottom surface temperature of the test section, but not much by the coolant injection rate.

The relationship between the Nu number and Ra number in the molten metal pool region is determined and compared against the correlations of the previous investigations, and the experiment without coolant boiling. The present experimental results with coolant boiling on the heat transfer on the molten metal pool are apparently higher than those of the literature correlations for the experiment without coolant boiling. In this experiment, the molten metal layer is cooled by the rapid boiling heat transfer of the coolant. So, rapid heat transfer arises from the molten metal layer to the coolant layer. Through this study, it is considered that the external cooling mechanism affects the natural convection heat transfer of the fluid.

A new correlation on the relationship between the Nu number and Ra number in the molten metal pool with crust formation is developed from the experimental data. The new correlation presents the natural convection heat transfer in low Prandtl number (~0.02) materials which are heated from below and being solidified by external coolant.

However, the result of this study may not directly be applicable to the reactor accident condition because this study is performed in the lower Rayleigh number region than for the actual molten debris. The present tests are performed in the 10^6~10^8 range of Rayleigh number. During a severe accident, the molten debris may reach the 10^{15}~10^{16} range of Rayleigh number for the oxide pool and the 10^9~10^{10} range for the metallic layer [10]. Further study is needed to investigate the effect of the boiling coolant in the high temperature and high Rayleigh number region. Also the study needs to be extended to investigate the molten pool heat transfer with the film boiling region of coolant.

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Table I. Heat Transfer Rates of the Molten-Metal Pool (Constant Temperature)

Bottom Temp. (oC)	Crust Thickness (cm)	Heat Flux ($\times 10^4$ W/m^2)	Ra Number ($\times 10^6$)	Nu Number
253	11.1~12.8	5.97~6.21	1.62~3.50	7.1~8.0
255	10.0~10.9	7.47~7.89	3.54~5.01	10.2~11.2
258	7.6~7.8	9.39~9.60	10.1~11.1	14.5~15.0
262	5.3~6.0	14.4~14.5	20.6~27.8	20.5~23.8
266	3.7~4.3	16.9~18.4	22.4~35.5	20.2~24.8

Table II. Heat Transfer Rates of the Molten-Metal Pool (Constant Power)

Heater Power (kW)	Crust Thickness (cm)	Heat Flux ($\times 10^4$ W/m^2)	Ra Number ($\times 10^6$)	Nu Number
6	10.7~10.9	6.64~6.91	2.45~2.62	13.3~14.3
8	7.2~8.6	9.38~9.52	8.28~11.7	14.4~15.9
10	5.6~5.8	11.6~12.3	19.0~21.1	16.9~18.8
12	5.1~5.2	12.5~13.9	21.9~26.4	18.1~19.9
14	2.9~3.1	21.5~22.9	42.4~43.0	29.4~30.1

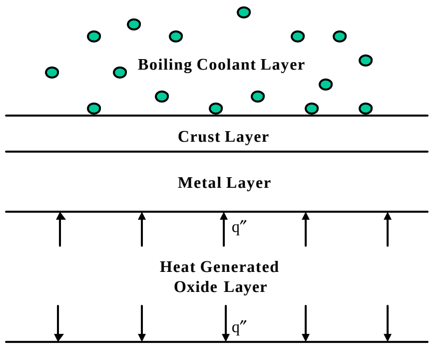

Figure 1. Sketch of the Molten Debris and Coolant Layers

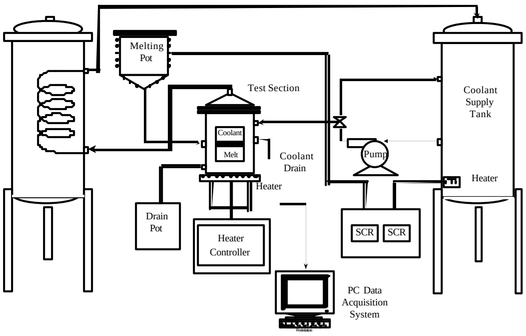

Figure 2. Schematic Diagram of the Test Facility

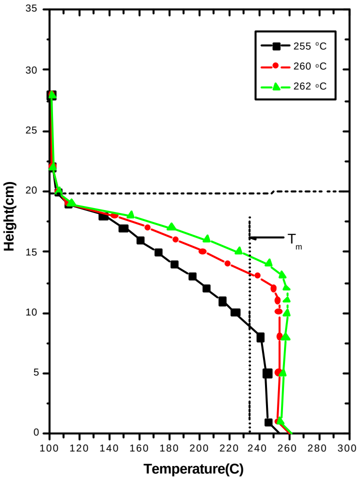

Figure 3. Temperature Distribution in Metal and Coolant Layers (Coolant Rate : 2.5 liter/min)

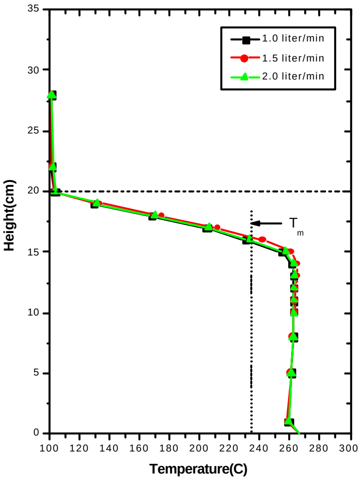

Figure 4. Temperature Distribution in Metal and Coolant Layers (Bottom Temperature : 266°C)

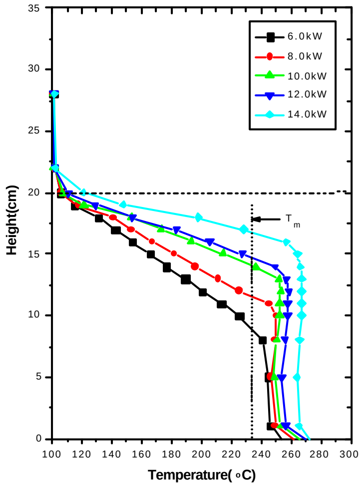

Figure 5. Temperature Distribution in Metal and Coolant Layers (Coolant Rate : 1.0 liter/min)

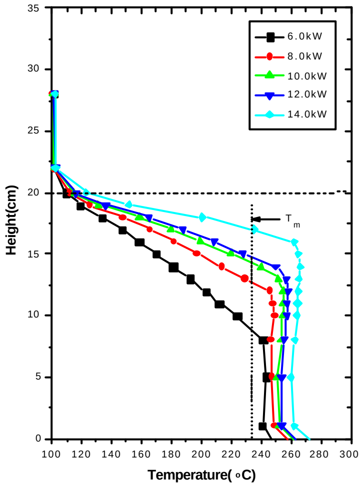

Figure 6. Temperature Distribution in Metal and Coolant Layers (Coolant Rate : 2.0 liter/min)

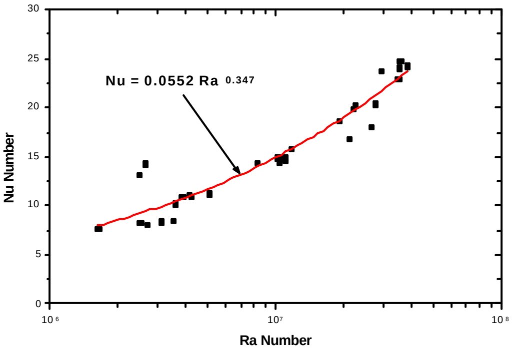

Figure 7. Experimental Data and Its Fitting Result

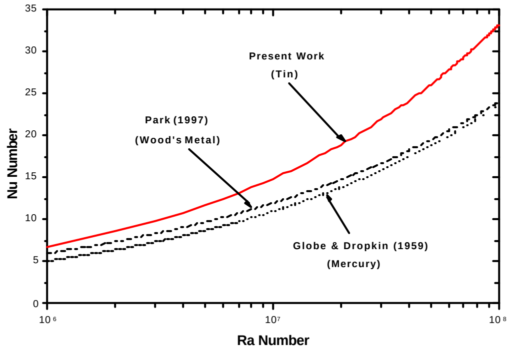

Figure 8. Comparison of the New Correlation with Literature Correlations