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# Natural Convection Heat Transfer Characteristics of the Molten Metal Pool with Solidification by Boiling Coolant

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## Abstract

*This paper presents results of experimental studies on the heat transfer and solidification of the molten metal pool with overlying coolant with boiling. The metal pool is heated from the bottom surface and coolant is injected onto the molten metal pool. As a result, the crust, which is a solidified layer, may form at the top of the molten metal pool. Heat transfer is accomplished by a conjugate mechanism, which consists of the natural convection of the molten metal pool, the conduction in the crust layer and the convective boiling heat transfer in the coolant. This work examines the crust formation and the heat transfer rate on the molten metal pool with boiling coolant. The simulant molten pool material is tin (Sn) with the melting temperature of 232℃. Demineralized water is used as the working coolant. The crust layer thickness was ostensibly varied by the heated bottom surface temperature of the test section, but not much affected by the coolant injection rate. The correlation between the Nusselt number and the Rayleigh number in the molten metal pool region of this study is compared against the crust formation experiment without coolant boiling and the literature correlations. The present experimental results are higher than those from the experiment without coolant boiling, but show general agreement with the Eckert correlation, with some deviations in the high and low ends of the Rayleigh number. This discrepancy is currently attributed to concurrent rapid boiling of the coolant on top of the metal layer.*

## I. INTRODUCTION

During a hypothetical severe accident in nuclear power plants, it is possible to form stratified fluid layers. These layers may be composed of high temperature molten debris pool and water coolant in the lower plenum of the reactor vessel or in the reactor cavity.[1-5] Also, molten debris pool may be stratified into a metal layer and an oxide layer on account of their density difference.[2-6] Molten metal layer is located in the upper region and cooled by overlying coolant which may undergo boiling. As a result, the crust, which is a solidified layer of the molten pool, may form at the top. Heat transfer is accomplished by a conjugate mechanism consisting of the natural convection of the molten metal pool, the conduction through the crust layer and the convective boiling heat transfer to the coolant.

The heat transfer and solidification processes in the molten metal pool are of fundamental importance in the severe accident progression. A number of experimental and theoretical investigations were performed to understand the solidification and the change of heat transfer rate of the debris pool which greatly affects the accident progression.

An experimental study on the crust formation and heat transfer characteristics of the molten metal pool with overlying coolant with boiling was performed to determine the heat transfer rate of the molten metal pool. Tests were performed under the condition of the bottom surface heating in the test section and the forced convection of the coolant, which is injected onto the molten metal pool. The test parameters spanned the heated bottom surface temperature of the molten metal pool, the coolant injection rate and the coolant injection temperature.

## II. EXPERIMENTAL SETUP

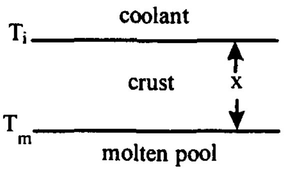
Figure 1 shows the schematic diagram of the test section. The inner dimension of the rectangular test section is 25cm in length, 35cm in height, and 25cm in depth. The test section is made of 10mm thick STS304 stainless steel. The heights of the molten metal and the coolant layer are 20cm and 15cm, respectively. 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 the back of the test section. Four sides of the test section are insulated with a 4cm thick Fiberfrax material to reduce heat loss. A digital pump is installed to deliver a uniform mass flow of the coolant onto the molten metal pool. The temperature distribution inside the test section is measured using 51 thermocouples, which are placed in three arrays of thermocouple bundles located at the one-fourth, one-half and three-fourth positions of the length of the test section. The simulant molten pool material is tin (Sn) with the melting temperature of 232°C, and demineralized water is used as the working coolant. 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 0.5kg/min to 2.5kg/min, and the injection coolant temperature ranging from 82°C to 95°C.

In this experiment, the molten metal is injected to the test section, and the bottom surface temperature is set at a prescribed value. Next, the coolant is injected onto the molten metal in the test section at the preset mass flow rate. The coolant is recirculated in a closed loop until the steady state condition is achieved.

## III. RESULTS AND DISCUSSION

Figure 2 shows temperature distribution of the test section as a function of the coolant injection rate at a bottom heating temperature of 255°C. The portion below the horizontal dotted line is the metal layer, and the 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. The crust thickness and temperature distribution are barely affected by the coolant injection rate. Figure 3 displays the temperature profile in the metal and coolant layers for the bottom heating surface temperatures of 253°C, 255°C, 258°C, 262°C and 266°C with the coolant injection rate of 1.5kg/min. The results illustrate that crust thickness and temperature of the metal layer are affected by the bottom surface temperature. As can be seen from Figures 2 and 3, the crust layer thickness may be greatly varied by the heated bottom surface temperature of the test section, but not much affected by the coolant injection rate.

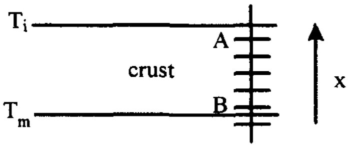
Table 1 presents the natural convection heat transfer rates and crust thickness in the molten metal layer. The crust thickness is determined by the linear interpolation method from the thermocouple reading data and the melting temperature (232°C) for tin. The heat flux can be derived from the temperature 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
k : thermal conductivity of crust
$T_i$ : interface temperature of crust and coolant
$T_m$ : melting temperature
x : crust thickness

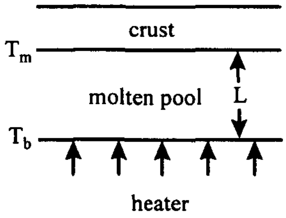
In this study, the actual heat flux was calculated from the temperature measurements by the thermocouples located right underneath the metal layer and coolant interface and just above the melting point, and the distance between the two points in-between.



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

This was necessary because the interfacial temperature $T_i$ and the melting location of the metal layer normally fell 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 and the Ra number are defined as follows.

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

$$Ra = \frac{g\beta \Delta T L^3}{\alpha \nu} \tag{5}$$

where h : heat transfer coefficient in the molten pool
L : height of molten pool layer
$\Delta$T : temperature difference ($T_b$ - $T_m$)
g : gravitational acceleration
$\alpha$ : thermal diffusivity
$\beta$ : thermal expansion coefficient
$\nu$ : kinematic viscosity

The relationship between the Nusselt number and the Rayleigh number in the molten metal pool region was determined and compared against the experiment without coolant boiling and the literature correlations. The experiment without coolant boiling was performed using the low temperature melting alloy which has a composition by weight percentage of Bi(49.92%), Pb(26.93%), Sn(13.28%) and Cd(9.85%) with the melting temperature of 70°C. The bottom heating method was the same as this work but the cooling mechanism was subcooled coolant natural convection using the heat exchanger at the top of the test section.[7] Figure 4 shows a comparison of the present experimental results with the experiment without coolant boiling and other correlations in the molten metal pool region. Many experimental studies were performed on the Rayleigh-Bernard problem which deals with the natural convection heat transfer. Their results are generally presented in the following fit correlation.

$$Nu = a\,Ra^{b} \tag{6}$$

Available correlations are the Eckert correlation[8] for tin, the Globe and Dropkin correlation[9] for mercury, and the Chu and Goldstein correlation[10] for water, all of which were developed in an enclosure without phase changes. The Globe and Dropkin correlation and the Chu and Goldstein correlation are developed empirically. The Eckert correlation is a theoretical relation for natural convection of low Prandtl number materials for vertical plates. The equation is generally presented in the following correlation.

$$Nu = 0.68[\mathrm{Pr}/(0.952+\mathrm{Pr})]^{0.25}\,Ra^{0.25} \tag{7}$$

Empirical correlation :

Globe and Dropkin : $$Nu = 0.051\,Ra^{0.333} \tag{8}$$

Chu and Goldstein : $$Nu = 0.183Ra^{0.278} \tag{9}$$

Theoretical correlation :

Eckert : $$Nu = 0.24\,Ra^{0.25} \tag{10}$$

Equation (10) is developed from equation (7) by substituting for Pr the value of 0.015 for Tin.

The present experimental results for the heat transfer from the molten metal pool are apparently higher than those without coolant boiling, but show better agreement with the Eckert correlation than with the other correlations. However, the experimental results of the heat transfer are lower than the Eckert correlation in the low Rayleigh number region and higher in the high Rayleigh number region.

## IV. CONCLUSION

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

In this experiment, the heat transfer is achieved with accompanying solidification in the molten metal pool by coolant with boiling. The present experimental results of the heat transfer on the molten metal pool are apparently higher than those without coolant boiling, but show general agreement with the Eckert correlation. However, the present experimental results of the heat transfer show deviations in the low and high Rayleigh number regions. This is probably because this experiment was performed in concurrence of solidification in the molten metal pool and the rapid boiling of the coolant. On the other hand, the comparison experimental tests were performed without coolant boiling and the correlation was developed for the pure molten metal without coolant phase change. Note however that the test results may not directly be applied to the actual reactor accident condition because this study was performed in the lower Ra number region than for the actual molten debris. During a severe accident, the molten debris reaches the $10^{15}\sim10^{16}$ range of Ra number for the oxide pool and the $10^{9}\sim10^{10}$ range for the metallic layer.[11] Further study is planned to investigate the effect of the boiling coolant in the high temperature and high Rayleigh number region.

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Table 1. Heat Transfer Rate and Crust Thickness of the Molten Metal Pool

| Bottom Surface Temperature (°C) | Coolant Injection Rate (kg/min) | Heat Flux (W/m$^2$) | Crust Thickness (cm) |
|---|---|---|---|
| 253 | 0.5 | 5.97E+4 | 12.79 |
| 253 | 1.0 | 6.02E+4 | 11.83 |
| 253 | 1.5 | 6.05E+4 | 11.70 |
| 253 | 2.0 | 6.14E+4 | 11.38 |
| 253 | 2.5 | 6.21E+4 | 11.09 |
| 255 | 0.5 | 7.74E+4 | 10.46 |
| 255 | 1.0 | 7.68E+4 | 10.68 |
| 255 | 1.5 | 7.89E+4 | 10.02 |
| 255 | 2.0 | 7.78E+4 | 10.48 |
| 255 | 2.5 | 7.47E+4 | 10.93 |
| 258 | 0.5 | 9.58E+4 | 7.83 |
| 258 | 1.0 | 9.60E+4 | 7.56 |
| 258 | 1.5 | 9.50E+4 | 7.66 |
| 258 | 2.0 | 9.57E+4 | 7.58 |
| 258 | 2.5 | 9.39E+4 | 7.76 |
| 262 | 1.0 | 1.45E+5 | 5.27 |
| 262 | 1.5 | 1.45E+5 | 5.38 |
| 262 | 2.5 | 1.44E+5 | 5.95 |
| 266 | 1.0 | 1.69E+5 | 4.07 |
| 266 | 1.5 | 1.84E+5 | 3.67 |
| 266 | 2.0 | 1.74E+5 | 3.96 |
| 266 | 2.5 | 1.80E+5 | 4.26 |

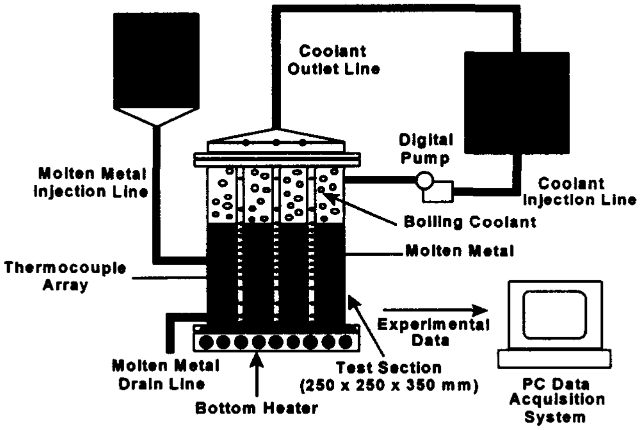

Fig. 1 Schematic Diagram of the Experimental Setup

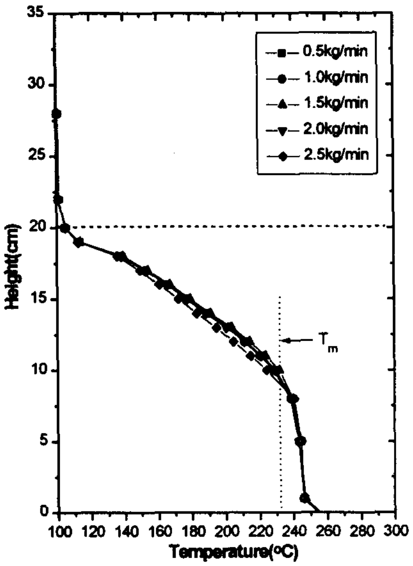

Fig. 2 Temperature Distribution in Metal Layer and Coolant (Bottom Temperature:255 °C)

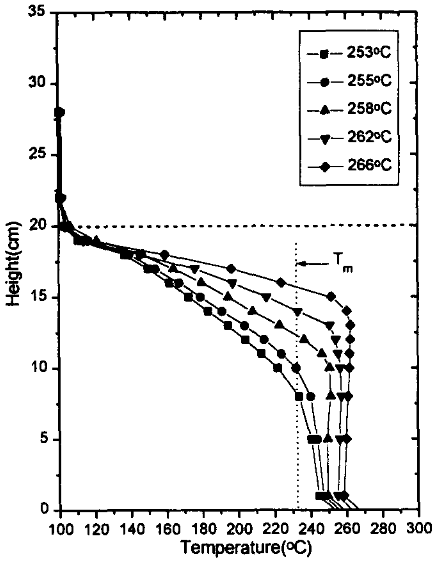

Fig.3 Temperature Distribution in Metal Layer and Coolant(Coolant Injection Rate:1.5kg/min)

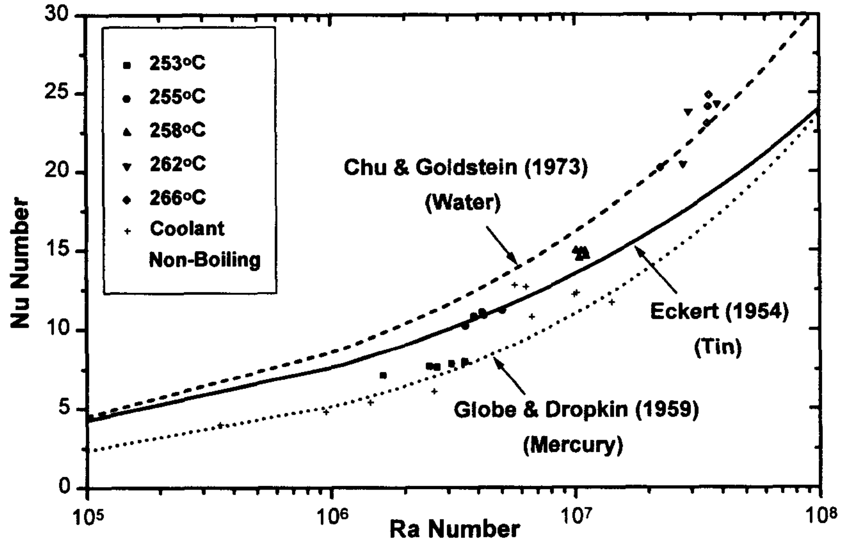

Fig. 4 Comparison of the Experimental Results with Literature Correlations