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Coolant Material Effect on the Heat Transfer Rates of the Molten Metal Pool with Solidification

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Abstract

Experimental studies on heat transfer and solidification of the molten metal pool with overlying coolant with boiling were performed. The simulant molten pool material is tin (Sn) with the melting temperature of 232℃. Demineralized water and R113 are used as the working coolant. This work examines the crust formation and the heat transfer characteristics of the molten metal pool immersed in the boiling coolant. The Nusselt number and the Rayleigh number in the molten metal pool region of this study are compared between the water coolant case and the R113 coolant case. The experimental results for the water coolant are higher than those for R113. Also, the empirical relationship of the Nusselt number and the Rayleigh number is compared with the literature correlations measured from mercury. The present experimental results are higher than the literature correlations. It is believed that this discrepancy is caused by the effect of the heat loss to the environment on the natural convection heat transfer in the molten pool.

I. INTRODUCTION

An interesting heat transfer problem arises between two stratified liquid layers with solidification taking place in a lower layer. If the solidification temperature of the lower layer material is higher than the boiling temperature of the upper layer material, the heat transfer is effected by a conjugate mechanism of natural convection of the molten metal pool, conduction through the crust layer and convective boiling of the coolant. The heat transfer and solidification processes in the molten metal pool are of fundamental importance in the severe accident analysis.[1] 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 course of accident progression. But there exists scarcity of database on the natural convection heat transfer with low Prandtl number materials and high Rayleigh number region. In particular, the results for natural convection which is induced in the molten pool with local solidification by boiling coolant are not existent.

The purpose of this study is to examine the external cooling condition effect on the natural convection heat transfer in the molten pool. 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 conducted under the condition of the bottom surface heating in the test section and the forced convection of the coolant, which was injected onto the molten metal pool. The test parameters spanned the bottom heating power of the molten metal pool and the coolant material.

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 described below was constructed. The inner dimension of the rectangular test section was 25cm in length, 35cm in height, and 25cm in depth. Figure 1 shows the schematic diagram of the test section for R113. The test facility for water was reported in Reference 2. 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 electric power input to this heater is monitored using a wattmeter. The input power is controlled to maintain uniform value within ± 0.1kW by utilizing heater controller. 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 translating tube, which is connected from the melting pot to the test section, is wrapped so as to prevent solidification of the molten metal using a heating tape. The temperature distribution inside the test section is measured using 85 thermocouples of 0.5mm diameter, 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. Figure 2 shows the thermocouple locations in the test section. The data acquisition system(DAS) consist of an IBM PC using the Visual Designer, which displayed and stored all of the thermocouple readings.

The simulant molten pool material is tin (Sn) with the melting temperature of 232°C. Tin has no toxicity and has a low the corrosion effect on other materials. The solidification shrinkage of tin is estimated to be 2.7%.[3] Table I presents the physical properties for tin. Demineralized water and R113 are used as the working coolant. The boiling temperature of R113 is 47.5°C and its latent heat of vaporization is only 7% of that of water. The properties for water and R113 are presented in Table II. For water coolant, the input power to the bottom heating surface is varied from 6 to 12kW. The injection coolant mass flow rate is set at 1.0 liter/min and 2.0 liter/min in this case. For R113 coolant, the input power is varied from 8 to 11kW and the coolant flow rate is set at 3.0 liter/min. The tests were performed at atmospheric pressure.

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, the coolant is heated up to nearly the boiling temperature of coolant. 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 metal and coolant layers.

III. RESULTS AND DISCUSSION

The results obtained for temperature distribution in metal layer and coolant layer are shown in *Figures 3* and *4*. *Figure 3* shows temperature distribution of the test section as a function of the heater input power at a water injection flow rate of 1.0 liter/min. For the case of water coolant, virtually no distinction can be made between the coolant flow rate of 1.0 liter/min and 2.0 liter/min. Previous tests, which adopted the constant temperature boundary condition, also showed similar results.[2] The portion below the horizontal dotted line is the metal layer, and the upper portion is the coolant layer. The vertical dotted line is the melting temperature of tin. The temperature varies linearly in the solidified region, and is practically uniform in the molten pool and in the coolant. Figure 4 displays the temperature profile in the metal and coolant layers for R113 with the coolant injection rate of 3.0 liter/min. The temperatures in coolant region reveal the data at 55 ~ 57°C because the test section was pressurized to 1.3 ~ 1.4 bar due to vaporization of R113 at a rate exceeding condensation in the quench tank.

Table III presents the 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.

The Nusselt and Rayleigh numbers in the molten metal pool region were derived from the experimental data as explained in Reference 3. 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 in this work, but the cooling mechanism was subcooled coolant natural convection using a heat exchanger at the top of the test section.[4] Figure 5 compares the present experimental results with the experiment without coolant boiling and other correlations in the molten metal pool region. Available correlations are the Globe and Dropkin correlation[5], and the Rossby correlation[6] for mercury, which were obtained from an enclosure without phase changes.

Globe and Dropkin : $Nu = 0.051\,Ra^{0.333}$ $(1.51\text{x}10^5 < \text{Ra} < 6.76\text{x}10^8)$ (1)

Rossby : $Nu = 0.147\,Ra^{0.247}$ $(2.40\text{x}10^4 < \text{Ra} < 5.50\text{x}10^5)$ (2)

The present experimental results for heat transfer from the molten metal pool are apparently higher than those without coolant boiling and other correlations. Also, test results of water coolant for heat transfer are shown to be higher than those for R113 coolant case. This difference results from the higher nucleate boiling heat transfer rate of water than of R113. It is presumed that the external cooling mechanism affects the natural convection heat transfer in the molten pool.

IV. CONCLUSION

An experimental study was performed to investigate the characteristics of heat transfer and crust formation of the molten metal pool natural convection concurrent with forced convective boiling of the overlying coolant. In this experiment, the heat transfer is effected with accompanying solidification in the molten metal pool by coolant with boiling. The present experimental results for the heat transfer on the molten metal pool are apparently higher than those without coolant boiling and other correlations. This is probably because this experiment was performed in concurrence of solidification in the molten metal pool and the rapid boiling of the coolant. The comparison experimental tests were performed without coolant boiling, and the literature correlations were developed for the mercury without external cooling.

The current test results for water coolant show higher heat transfer than for R113 coolant. This is caused by higher nucleate boiling heat transfer rate of water than that of R113. It is presumed that the external cooling mechanism affects the natural convection heat transfer in the molten pool.

REFERENCES

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Table I. Physical Properties of Tin

	Solid (200°C)	Liquid (232°C)
Density (kg/m3)	6300	7000
Specific Heat (J/kg K)	260	250
Thermal Conductivity (W/m K)	60	30
Thermal Expansion (/K)	2.42x10-5	1x10-4
Viscosity (kg/m s)		1.85x10-3
Prandtl Number		0.015
Melting Temp.	232 °C	
Latent heat of Fusion	60900 J/kg	
Solidification Shrinkage	2.7 %	

Table II. Physical Properties of Coolant

	Water (90°C)	R113 (43°C)
Density (kg/m3)	995	1521
Specific Heat (J/kg K)	4174	425
Thermal Conductivity (W/m K)	0.623	0.086
Thermal Expansion (/K)	2.92x10-4	
Viscosity (kg/m s)	7.65x10-4	5.30x10-4
Prandtl Number	5.12	2.62
Boiling Temp. (°C)	100	47.5
Latent heat of Vaporization (J/kg)	2.27x10+6	1.48x10+5

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

Water					R113		
Input Power (kW)	Crust Thickness (cm)		Heat Flux (W/m^2)		Input Power (kW)	Crust Thickness (cm)	Heat Flux (W/m^2)
	1 liter/min	2 liter/min	1 liter/min	2 liter/min		3 liter/min	3 liter/min
6	10.67	10.91	6.91E+4	6.64E+4	8	11.36	8.87E+4
8	8.55	7.16	9.38E+4	9.52E+4	9	10.16	9.52E+4
10	5.81	5.61	1.23E+5	1.16E+5	10	8.49	1.13E+5
12	5.21	5.14	1.39E+5	1.25E+5	11	7.04	1.31E+5

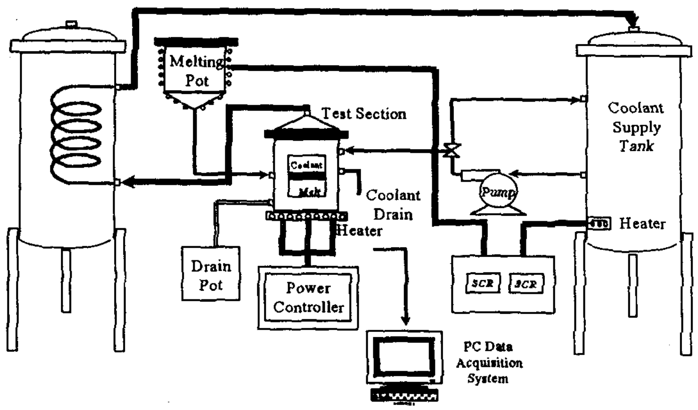

Fig. 1 Schematic Diagram of the Experimental Setup

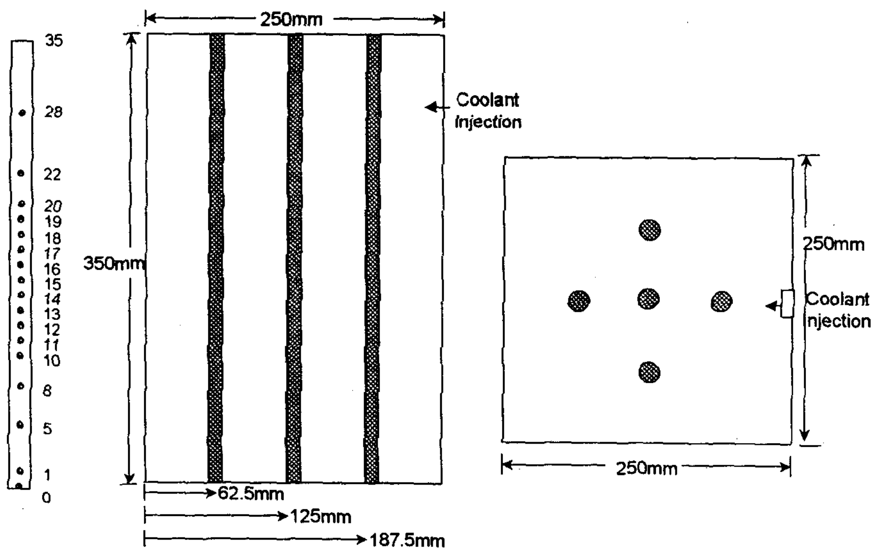

Fig. 2 Thermocouple locations in the Test Section

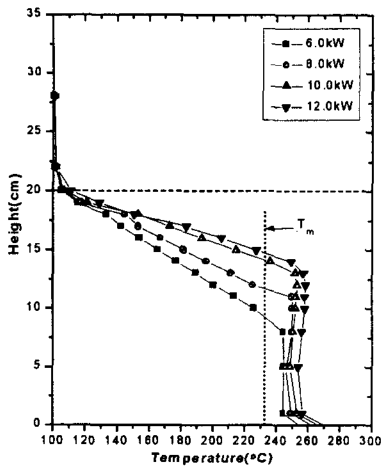

Fig. 3 Temperature Distribution for Water Coolant
(Coolant Injection Rate = 1.0 liter/min)

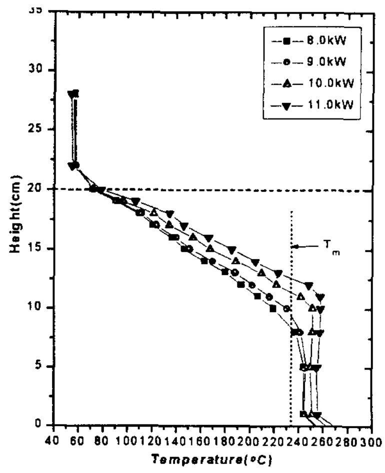

Fig. 4 Temperature Distribution for R113 Coolant
(Coolant Injection Rate = 3.0 liter/min)

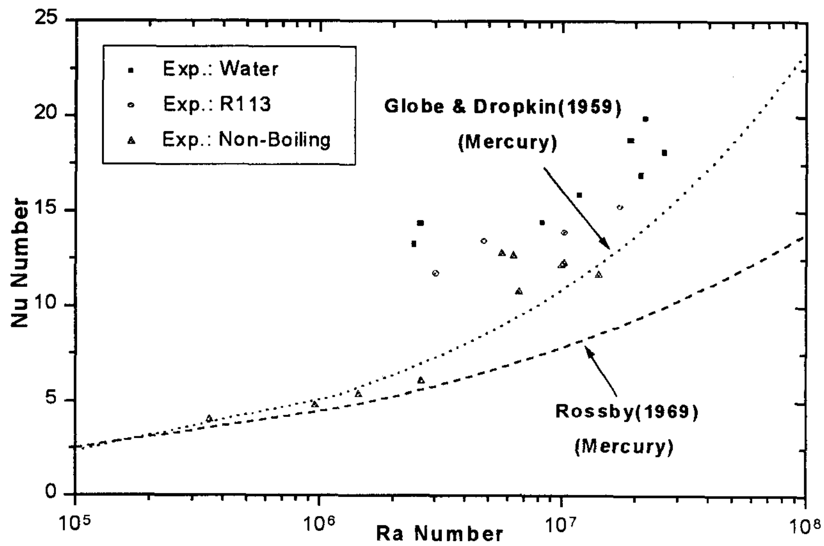

Fig. 5 Comparison of the Present Results with Literature Correlations