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Experimental study on molten metal spreading and deposition behaviors on wet surface

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ABSTRACT

In this paper, experimental investigation of the molten metal jet's colliding and spreading behaviors on the flat steel surface covered with water layer was carried out. High-frequency induction heating system was utilized to produce the molten metal sample and it was released to the wet surface from a fixed elevation. As the molten metal collides against the surface, it rapidly goes through solidification while spreading on the wet surface. High-speed thermo-camera was utilized to measure the molten metal's surface temperature during the spreading transient. Once the molten metal completely solidifies, molten metal's spread area and thickness were measured. From the obtained database, a dimensional analysis was conducted to investigate the key parameters responsible for the molten metal spreading on the wet surface. Based on the key non-dimensional parameters identified in the current analysis, the new empirical correlation was proposed. Its predictive capability was found to be 18.9% in mean absolute relative deviation.

1. Introduction

The spreading behavior of the molten core (“corium”) has been studied for past several decades to investigate the effective long-term cooling of the debris for the nuclear reactor safety applications (Dinh et al., 2000; Burger et al., 2010; Sehgal, 2012). Following the Fukushima-Daiichi nuclear accident, a predictive capability of the molten core spreading and deposition behaviors have been given increased attention in severe accident analysis (Miwa et al., 2017). It is crucial in severe accident (SA) analysis to have reliable predictive capability of the molten metal condition since it provides the boundary conditions for the molten core concrete interaction (MCCI). Analysis of the MCCI is perhaps the most vital part of the SA analysis to ensure that corium is contained within the reactor building. In the past, numbers of experiments were carried out to investigate the spreading behavior of molten metal using actual UO_2, Zirconium materials, or pure metal. However, most of the spreading experiments conducted in the past were performed on dry concrete surface or ceramic type materials via bottom-injection. In addition, the effect of the receiving surface condition on molten metal spreading has not been addressed thoroughly by the past experiments. Particularly, experiments to investigate the collisional impact between molten metal and subcooled liquid layer haven't been addressed thoroughly in the literature. Hence, aim of this study is to experimentally investigate the molten metal spreading and deposition behaviors on floor surface covered with liquid layer. Experimental works carried out in the current study will be explained followed by a comprehensive literature review.

2. Literature review

Many of the past molten metal spreading experiments were performed primarily for the severe accident analysis for the nuclear thermal-hydraulic applications, as well as for the core catcher design (Alsmeyer et al., 2000; Journeau et al., 2006; Sehgal, 2012; Kobayashi et al., 2014). However, for most of those reported experiments, molten metal was smoothly injected to the spreading surface from the side or bottom without involving the collision between falling molten metal jet and receiving surface.

One of the few existing experiments on molten metal spreading analysis was carried out by Greene et al. (1988), which was targeted for the debris spreading analysis under severe accident conditions. Their experimental objective was to assess the influence of metal spreading behavior due to the metal mass, superheat, and water depth. Spreading experiments were performed using molten lead of 4, 6, 8, and 10 kg. Melt superheat was adjusted to 10, 50, 100, 150, and 200 °C, and water pool depths of 5, 10, 20, 40, and 60 mm were utilized as the initial experimental conditions. It was found that the melt superheat and water depth were the two most influential parameters to determine the

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Nomenclature

A_{sp}	Spreading Area [m^2]
A_{sp}*	Non-dimensional Spreading Area [-]
c_p	Specific Heat [kJ/kg/°C]
d	Outlet Nozzle Diameter [mm]
h_{fg}	Latent Heat of Vaporization [kJ/kg]
h_{fs}	Latent Heat of Solidification [kJ/kg]
H	Pool Water Depth [mm]
L	Fall Height [m]
$m_{rel,abs}$	Mean Absolute Relative Deviation [-]
M	Melt Mass [kg]
N_{sp}	Non-dimensional Spreading Parameter [-]
N_{sp}*	Modified Non-dimensional Spreading Parameter [-]
t	Thickness [m]
t*	Non-dimensional Thickness [m]
T	Temperature [°C]
T_0	Initial Temperature [°C]

Greek symbols

ρ	Density [kg/m^3]

melt thickness. Additionally, it was reported that the melt mass was not sensitive to the spreading behavior. Based on the collected database, five different spreading regimes were identified and non-dimensional correlation to predict the spreading area was proposed.

For the interaction between the molten metal and water pool, Mishima et al. (1999) conducted the visualization study using Wood's metal. The molten metal was dropped into the water pool and high-frame-rate neutron radiography was utilized to observe the interaction behavior between the molten metal and liquid pool. The atomization of molten metal was observed when its initial melt temperature was over 500 °C, but when the liquid pool temperature was higher than 20 °C, atomization was not observed. Solidified molten metal particles were collected after the experiment to investigate the break-up behavior of the molten metal jet.

Saito et al. (1999) also utilized high-frame-rate neutron radiography to visualize the interaction between the molten metal particle and heavy water filled in a rectangular tank. The molten metal particle diameter of 6, 9, and 12 mm at 600–1000 °C was utilized for the experiment. From the direct contact interaction of molten metal particle and heavy water pool, steam generation behavior was observed. It was reported by authors that the amount of steam generated from the interaction was proportional to the molten metal particle size and temperature.

Abe et al. (2004) conducted the experiment to observe the fragmentation behavior of the molten metal jet within the water pool. A high-speed camera was utilized to observe the break-up transient, and particle image velocimetry (PIV) system was utilized to obtain the local flow characteristics. It was found that the solidified fragments tended to be in different shape for static free fall method and jet ejection method. It was also suggested that the two key instability mechanisms, namely Rayleigh-Taylor and Kelvin-Helmholtz, were the major factors to determine the sizes and shape of melt fragments.

Grishchenko et al. (2013) conducted experiments to investigate the steam explosion phenomena due to molten metal. In their experiment, 80 kg of oxidic molten metal was dropped into the deep-water pool. Steam explosion phenomenon was observed in their experiments, and the formation of the 8 cm thick premixing layer was confirmed. Melt spreading was observed in a quasi-periodic manner and following characteristics were identified by the authors: (1) initial melt spreading and formation of a solid debris “dam” around the periphery, (2) gradual accumulation of the oncoming melt, (3) “dam overflow” and re-spreading of the melt, and (4) continuation of the melt spreading.

Bang et al. (2014) proposed the molten metal jet break-up model based on their experimental database. Kelvin-Helmholtz instability concept was adopted to explain the unstable surface created by the relative velocity between melt jet and surrounding vapor film as well as the water pool. Proposed model showed good agreement with the experimental database on the melt particle size prediction.

As can be seen from above, majority of the previous experiments were mainly focused on molten metal to water interaction involving steam explosion and jet fragmentation, and analysis on melt's spreading behavior hasn't been investigated well enough. Hence, as a continuation of the previous experiment conducted by the authors on dry-surface (Matsumoto et al., 2017), the experimental investigation on molten metal spreading behavior on the wet surface was conducted in this study.

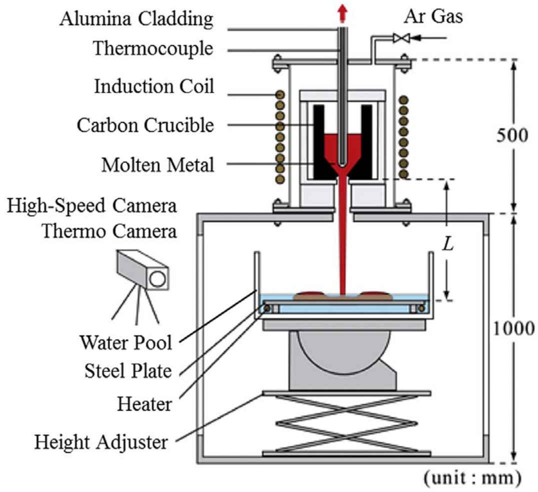

Fig. 1. Schematic of the test section for molten metal spread experiment with receiving water pool.

3. Experimental work

Fig. 1 depicts the schematic of the test section utilized in the current experiment located at the Laboratory of Nuclear System Safety Engineering at Hokkaido University. The overall height of the test section is 1.5 m. Its pictorial image is shown in Fig. 2. High-frequency induction heating system with the maximum power output of 30 kW was utilized to create the molten metal using pure copper (Cu). Metal samples were initially placed inside the graphite crucible which is capable of handling metal mass up to 0.5 kg. At the bottom of the crucible, a nozzle with inner diameter d was placed and the molten metal flows out from the opening in a form of jet. At the initial state of the experiment, the nozzle is completely plugged by an alumina cladding equipped with a thermocouple to contain the melt sample and to monitor the temperature. The crucible was placed inside the cylindrical chamber and Argon gas was constantly injected to prevent the oxidation. Underneath the heating system, water pool tank equipped with steel plate with temperature control device was placed. The tank is placed on top of the height adjuster so that molten metal jet length (L) can be changed for the test condition. High-speed thermo-camera was utilized to observe the spreading transient of the molten metal.

Table 1 summarizes the current experimental condition. The initial melt temperature was maintained at 1100 °C for all the test conditions, where its melting point is reported as 1085 °C (JSME Handbook, 2009). Pool water depth was adjusted from 1 to 100 mm, and outlet nozzle diameter d was set to 3.0, 5.8, and 8.0 mm, respectively. For each