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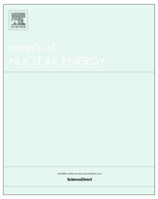

Scaling analysis of the spreading and deposition behaviors of molten-core-simulated metals

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ABSTRACT

On March 11, 2011, huge earthquake and tsunami attacked Fukushima Daiichi Nuclear Power Plant. After the accident, research on plant decommissioning has become actively worldwide. Several research institutes have performed experiments to investigate methods of identifying the location and spreading/deposition behaviors of molten core debris in the bottom of Primary Containment Vessel (PCV) using Severe Accident (SA) analysis codes. Nevertheless, knowledge of spreading and deposition behaviors of corium is not sufficient, especially phenomena involving collision against the floor surface. In this study, experimental investigations on molten metal spreading and depositing behaviors on the steel plate were carried out. Zinc and copper were utilized for the molten metal samples and spreading behaviors were carefully observed using high speed video camera. Immediately after the collision between falling molten metal and steel surface, initial pause on spreading was observed. New scaling relation based on Dinh et al. (2000) was developed by focusing on the initial spreading pause of the molten metal droplet. Proposed correlation is capable to predicting the spread and deposition of falling molten metal at average error of 18.1%.

1. Introduction

The Pacific coast of Tohoku Earthquake occurred and attacked northwest Japan on 2011. This earthquake caused large tsunami and unprecedented accident in Fukushima Daiichi Nuclear Power Plant (1F). In 1F Accident, it is expected that molten core has leaked out to Primary Containment Vessel (PCV) pedestal floor from Reactor Pressure Vessel (RPV) (TEPCO, 2012). In the present circumstances, it is still impossible to visually observe the condition of the PCV pedestal floor. Hence, it is necessary to estimate the condition of accumulated molten core debris to execute the decommissioning of the reactors.

In the Severe Accident (SA) events at the Light Water Reactor (LWR), there are complicated thermal hydraulic phenomena in the RPV and the PCV. Over the past several decades, research on SA had been performed by research organization in U.S., Europe and Japan. Researches on SA analysis code have been carried out to estimate the accident sequence, and position and characteristic of molten core (generally called “corium”). However, subsequent stage phenomena of the SA which corresponds to the corium relocation behaviors in the RPV or the PCV include large uncertainty because subsequent stage phenomena are greatly affected by the pre-stage phenomena in the SA events. Atomic Energy Society of Japan (AESJ) has conducted the assessment of knowledge level of the SA event with Phenomenological Identification and Ranking Table (PIRT) method (AESJ, 2013; Aoki et al., 2013). According to the research report published by AESJ, knowledge of subsequent stage phenomena of the SA, which correspond to the corium relocation or source term estimation, is clearly in an insufficient level compared to the pre-stage phenomena which represent accident initiation events such as the reactor superheat due to the coolant loss.

Several past experiments investigated how corium-simulated metals spread on the floor. Table 1 shows major previous experiments focusing on corium spreading phenomena. BNL (Greene et al., 1988) was conducted at the Brookhaven National Laboratory. In this experiment, spreading behaviors of the molten fuel debris in the PCV pedestal floor of the boiling-water reactor (BWR) were studied. Visual observation using molten lead as the simulant molten material was carried out in the spreading experiments on the floor surface. SPREAD (Suzuki, 1993) is the molten metal spreading

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Abbreviations: EPR, European Pressurized Reactor; LWR, Light Water Reactor; PCV, Primary Containment Vessel; RPV, Reactor Pressure Vessel; SA, Severe Accident.

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Nomenclature

A_0	total volume spreading diameter at δ_{stop} [m^2]
A_{sp}	melt spreading area [m^2]
Bi	Biot Number [–]
C	experimental coefficient [–]
C_{p_m}	melt heat capacity at constant pressure [J/kg·K]
C_{p_p}	plate heat capacity at constant pressure [J/kg·K]
C_T	empirical coefficient of Hoffman-Voinov-Tanner law [–]
Ca	Capillary Number [–]
D	channel width of one dimensional experimental apparatus [m]
D_0	nozzle diameter/ melt jet diameter [m]
D_{max}	maximum spreading diameter [m]
D_{sp}	melt spreading diameter [m]
G	volumetric flow rate [m^3/s]
g	gravitational acceleration [m/s^2]
H	falling height [m]
ΔH_m	melt latent heat [kj/kg]
k_m	melt heat conductivity [W/m·K]
k_p	plate heat conductivity [W/m·K]
L	deposition thickness [–]
L^*	dimensionless deposition thickness [–]
l_{sp}	spreading radius except nozzle radius [m]
M	melt mass [kg]
Pe	Peclet Number [–]
q_{up}	upper heat flux [W/m^2]
q_{down}	downward heat flux [W/m^2]
q_v	melt internal heat generation [W/m^3]
Re	Reynolds Number [–]
Ste	Stephen Number [–]
T	time [–]
T^*	dimensionless time [–]
T_m	melt temperature [°C]
T_p	plate surface temperature [°C]
Δt_{sold}	solidification time [s]
Δt_{stop}	elapsed time before stopping spreading [s]
$\Delta T_{S.H.}$	melt initial superheat [°C]
U_{inert}	spreading speed [m/s]
U_{sp}	spreading speed [m/s]
V_{total}	melt volume [m^3]
V_{drop}	melt droplet volume [m^3]
We	Weber Number [–]
Z_0	spreading length of one dimensional experimental apparatus [m]
Z_{sold}	spreading length with solidification of one dimensional experimental apparatus [m]

Greek Symbols

δ_{cap}	minimum spreading thickness [m]
δ_{sp}	melt deposition thickness [m]
δ_{stop}	melt thickness at the maximum spreading [m]
θ_a	advancing contact angle [°]
θ_D	dynamic contact angle [°]
θ_e	equivalent contact angle [°]
μ	viscosity [Pa·s]
ρ_m	melt density [kg/m^3]
ρ_p	plate density [kg/m^3]
σ	surface tension [N/m]
σ_{sv}	surface tension of the solid/vapor [N/m]
σ_{sl}	surface tension of the solid/liquid [N/m]
ν	velocity of the contact line of the solid/liquid [m/s]
ξ_{max}	the ratio of spreading diameter [–]
τ_{conv}	spreading time [s]
τ_{sold}	elapsed time before solidifying melt front edge [s]
τ_{sp}	spreading time [s]
τ_{stop}	elapsed time before spreading to δ_{stop} [s]

experiment conducted in Hitachi, Ltd. This is the first experiment using the molten material at elevated temperature. Molten stainless steel was introduced to a floor surface with thermite reaction using oxidized iron and aluminum. CORINE (Veteau, 1994) was conducted in the CEA/DRN/DTP to verify the validity of the analysis code which calculates the corium spreading behaviors. In this experiment, low temperature fluids were used. Cerrobend, Cerrotru, Hitec and the mixture of glycol and water were selected as the experimental materials. KATS (Fieg, 1988) is the experimental series conducted at Karlsruhe Institute of Technology (KIT) of Germany for the research on the spreading behaviors of the molten materials at the elevated temperature. VULCANO (Cognet and Bouchter, 1994; Journeau et al., 2003, 2006) is the experimental project conducted at the CEA of France. The objective of this experiment was to acquire the knowledge of the Corium spreading behaviors on the dry floor surface for designing of the core catcher structure of the European Pressurized Reactor (EPR). COMAS (Steinwarz et al., 2001) was conducted in Siempelkamp of Germany. This experiment was aimed at acquiring the technical knowledge for the development of the core catcher structure of the EPR. S3E (Sehgal et al., 1997) was carried out at Royal Institute of Technology (RIT) of Sweden. The objective of this experiment was to discover the effect of physical-properties values on the Corium spreading behaviors in the various spreading regimes. PULiMS (Konovalenko et al., 2012) is the experiment conducted at RIT of Sweden. The objective of this experiment was to obtain the data-

Table 1
Previous experiments of corium spreading (Sehgal, 2012; Dinh et al., 2000).

Name	Country	Sample metal	Melt volume (liters)	Injection type	Floor condition
BNL	USA	Lead	~1	Jet	dry, wet
SPREAD	Japan	SUS	1–15	Bottom	dry
CORINE	France	Low Melting Point Alloy	~50	Bottom	dry, wet
KATS	Germany	Steel, Ceramics	~60	Bottom	dry, wet
VULCANO	France	Corium	3–10	Bottom	Dry
COMAS	Germany	Corium	20–300	Bottom	Dry
S3E	Sweden	Wood Metal $NaNO_3$-KNO_3	5–20	Bottom	dry, wet
PULiMS	Sweden	Bi_2O_3-WO_3 ZrO_2-WO_3	3–10	Jet	wet