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Development of an ex-vessel corium debris bed with two-phase natural convection in a flooded cavity

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HIGHLIGHTS

- For ex-vessel severe accidents in LWRs with wet-cavity strategy, development of debris bed with two-phase natural convection flow due to thermal characteristics of prototypic corium particles was investigated experimentally by using simulant particles and local air bubble control system.
- Based on the experimental results of this study, an analytical model was established to describe the spreading of the debris bed in terms of two-phase flow and the debris injection parameters.
- This model was then used to analyze the formation of debris beds at the reactor scale, and a sensitivity analysis was carried out based on key accident parameters.

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ABSTRACT

During severe accidents of light water reactors (LWRs), the coolability of relocated corium from the reactor vessel is a significant safety issue and a threat to the integrity of containment. With a flooded cavity, a porous debris bed is expected to develop on the bottom of the pool due to breakup and fragmentation of the melt jet. As part of the coolability assessment under accident conditions, the geometrical configuration of the debris bed is important. The Debris Bed Research Apparatus for Validation of the Bubble-Induced Natural Convection Effect Issue (DAVINCI) experimental apparatus facility was constructed to investigate the formation of debris beds under the influence of a two-phase flow induced by steam generation due to the decay heat of the debris bed. Using this system, five kilograms of stainless steel simulant debris were injected from the top of the water level, while air bubbles simulating the vapor flow were injected from the bottom of the particle catcher plate. The airflow rate was determined based on the quantity of settled debris, which will form a heat source due to the decay of corium. The radial distribution of the settled debris was examined using a 'gap–tooth' approach. Based on the experimental results of this study, an analytical model was established to describe the spreading of the debris bed in terms of two-phase flow and the debris injection parameters. This model was then used to analyze the formation of debris beds at the reactor scale. A sensitivity analysis was carried out based on key accident parameters, including the quantity of corium melt, cavity flooding level, volumetric decay heat rate, and the size of the melt jet.

1. Introduction

Severe accidents of light water reactors (LWRs) are situations that progress beyond design-based accidents (DBAs), and involve significant melting of the core fuel. The hot molten core fuel that results from inadequate cooling during the accident can threaten the integrity of the boundaries of defense-in-depth barriers for preventing the release of radioactive materials. The coolability of ex-vessel corium directly affects the integrity of the containment building, which is the final barrier against release of radioactive material, and determines the likelihood of termination or mitigation of accidents.

In a wet cavity that is flooded with water, discharged corium can be adequately cooled by low-temperature coolant water. The fuel–coolant interaction (FCI) allows the corium to break up into small debris particles, which increase the specific surface area for cooling. Furthermore, in comparison with the corium cake in a dry-cavity strategy, the porous characteristics of the resulting debris

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Nomenclatures

A, B, C, m, n, p	constants
A_e	area of the vessel failure (m^2)
A_H	area of the upper surface of the melt in the reactor vessel (m^2)
C_B	energy conversion coefficient
C_D	drag coefficient [$C_D = (8E_o)/(3E_o + 12)$] (Kolev, 2011)
D_{bc}	diameter of the bubble mixing column (m)
D_{pc}	diameter of the particle-mixing column (m)
D_{ji}	diameter of the melt jet at the water surface (m)
D_{hole}	diameter of the vessel failure hole (m)
d_v	diameter of a sphere with an equivalent volume [$d_v = \left(6 \cdot \mathrm{Vol}_p/\pi\right)^{1/3}$] (m)
$E_{P,B}$	change in potential energy of the vapor bubble swam (J)
$E_{K,L}$	kinetic energy of the coolant liquid (J)
g	acceleration due to gravity (m/s^2)
H_f	cavity flooding height (m)
H_s	particle sedimentation height (m)
H_{melt}	level of the melt from the vessel failure point in reactor vessel (m)
h_{ff}	free-fall height of the melt (m)
h_{lg}	latent heat of vaporization (J/kg)
L	arbitrary characteristic length of the debris bed (m)
L_b	the jet breakup length (m)
L_{ref}	reference characteristic length (m)
m_l	mass of coolant (kg)
$\dot{m}$	particle release rate (kg/s)
ΔP	pressure difference between the inside and outside of the reactor vessel (Pa)
q_d'''	volumetric decay heat rate (W/m^3)
R_c	radius of the conical debris bed (m)
$R_{75\%}$	radius of the equivalent circle containing 75% of the total bed volume (m)
$R_{75\%\_final}$	$R_{75\%}$ at the end of melt release (m)
u_b	the velocity of rising bubbles [$u_b = u_{ter,s} + u_l$] (m/s)
u_l	the velocity of the liquid [$u_l = u_b - u_{ter}$ or $u_l = B \cdot \dot{Q}_g^{0.244}$] (m/s) (Castello-Branco and Schwerdtfeger, 1994)
u_p	the velocity of falling particles (m/s)
u_{single}	terminal velocity of a single bubble [$u_{single} = \left((4g\Delta\rho d_v)/(3\rho_l C_D)\right)^{1/2}$] (m/s)
$u_{ter,s}$	terminal velocity of the bubble swarm [$u_{ter,s} = u_{single}(1-\alpha)$] (m/s) (Wallis, 1969)
$\dot{V}_g$	total bubble generation rate (m^3/s)
V_s	volume of a single bubble (m^3)
V_l	volume of liquid (m^3)
v_e	exit velocity of the melt (m/s)

Greek letters

α	void fraction in the bubble mixing column
β	constant
ε	porosity
ρ_g	density of the vapor (kg/m^3)
ρ_j	density of the melt jet (kg/m^3)
ρ_l	density of the coolant (kg/m^3)
ρ_p	density of the solid particles (kg/m^3)
θ_s	side slope angle of the debris bed (°)
Φ_L	energy flux of the coolant flow (W/m^2)
Φ_P	energy flux of the particle swarm (W/m^2)
τ	time duration of melt release (s)
τ_u	unit time, 1 s
Ω_{LP}	energy flux ratio, Φ_L/Φ_P

bed at the bottom of the water pool in the reactor cavity are advantageous for effective long-term cooling. The effectiveness of these inherent benefits is dependent on the particular conditions and circumstances of the accident. To carry out an accurate coolability assessment and to devise an effective accident management plan, it is necessary to understand the nature of the debris bed under accident conditions, and the sequence of events, which includes melt jet break-up, particle sedimentation, and debris bed formation. Given the history-dependent characteristics of the corium debris bed (Fig. 1), we must consider each constitutive process and the associated mechanism during the development of a corium debris bed.

Previous studies into ex-vessel severe accidents have focused mainly on the FCI (Sairanen et al., 2007; Magallon, 2006; Park et al., 2013) and the molten corium–concrete interaction (MCCI) (Farmer et al., 2007) to investigate the threat to structural integrity. However, relatively little attention has been paid to the development of the debris bed. Previous investigations into debris beds have described the particle size distribution of the fragmented melt (Magallon, 2006; Park et al., 2013; Moriyama et al., 2005) as well as the geometry of the resultant particle bed (Magallon, 2006; Karbojian et al., 2009), and there has been progresses in understanding the thermo-hydraulic phenomena inside a porous particle bed (Li and Ma, 2011; Hofmann, 1984). However, without knowledge of the particle settling and sedimentation accumulation processes, conservative assumptions on bed configuration must be made as part of coolability assessments of given accident conditions, which may limit the accuracy of the assessment of the feasibility of a given strategy (Ma and Dinh, 2010; Yakush et al., 2012).

Some recent studies have focused on the thermal characteristics of corium particles from the viewpoint of coolability. The thermally generated steam bubbles primarily affect the sedimentation process of debris particles, resulting in a flatter debris bed compared with the heaped debris bed with steep sides that forms without steam bubbles, as well as leveling of the existing debris bed (termed 'self-leveling'). Fig. 2 shows a schematic diagram of debris sedimentation and bed formation affected by steam bubble generation and two-phase natural convection. The self-leveling concept due to escaping gas bubbles was first described several decades ago, as part of an investigation of core disruption accidents (CDAs) in fast reactor applications (Alvarez and Amblard, 1982). More recently, parametric studies have been carried out to investigate self-leveling using simulant particles of various materials and sizes (Zhang et al., 2010; Cheng et al., 2013; Konovalenko et al., 2012). There has been relatively little investigation of the sedimentation process, however; for accurate coolability assessments of a debris bed, the configuration of the debris bed is important, especially the external shape and internal structure, which are commonly used as boundary conditions for simulations. Moreover, there is a lack of detailed information on the characteristics of the debris bed, including its porosity and structure. Yakush et al. (2008, 2009) simulation studies that showed that two-phase natural convection induced by a swarm of steam bubbles affects particle settling trajectories, the final location of particles, bed shape, and resulting coolability. It is reasonable to assume that two-phase natural convection was significant in the debris beds investigated in previous FCI experiments with a high initial melt temperature; however, it appears that the duration of melt release in previous FCI studies was too short to create a fully developed flow and observe the effects on the resultant debris bed. Therefore, it can be argued that there have been insufficient validation experiments of the simulation results of Yakush et al. (2008, 2009), and that there has been a lack of physical modeling of the thermal characteristics of particles during sedimentation processes.