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Model for particle behavior in debris bed

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ABSTRACT

In analyzing the safety of core disruptive accidents in Sodium-cooled Fast Reactors (SFRs), it is important to evaluate whether the decay heat of debris bed can be removed. The decay heat removability changes depending on the shape of debris bed, which would be deformed by coolant vapor with time. In the present paper, a new model was developed to analyze debris bed behavior with SIMMER, which is a safety analysis code for SFRs. In the new model, the effects of inter-particle collisions and contacts are modeled as inter-particle interaction. Test simulation results show the roles of physical properties in the new model on the dense particle behavior. Assessment results of proposed model based on model experiments indicate that the new model is capable of describing the transient of the shape of the particle bed in the liquid driven by the gas phase. Considering the fact that the process of leveling behavior in model experiments is common for the debris bed in SFRs, the new model can be employed as an analysis tool for debris bed behavior.

1. Introduction

When Core Disruptive Accidents (CDAs) occur in Sodium Cooled Fast Reactors (SFRs), part of the molten core materials are discharged to the lower plenum. Because Unprotected Loss of Flow (ULOF) is associated with a high frequency of CDAs, it is considered as a representative event in CDAs. In ULOF, the coolant is vaporized only in the core region and exists in the lower plenum. Based on THERMO/FARO (Magallon et al., 1991) experiments, it is considered that the discharged molten core materials are fragmented, and solidified to small particles by Fuel Coolant Interaction (FCI). These particles are called debris. In SFR's conditions, debris are known to be approximately 300 μm in Sauter mean diameter (Fauske and Koyama, 2002). The achievement of In-Vessel Retention (IVR) in CDAs requires that the decay heat of debris is safely removed by the surrounding coolant. For mitigation of severe-accident consequences in SFRs, it is important to achieve IVR against hypothetical CDAs because the additional coolant injection is not considered.

Debris are deposited on the surface of the lower plenum structure in a reactor vessel and form a debris bed. In this situation, the debris bed may assume the shape of a sand pile due to the influence of contact friction (left of Fig. 1). Since a debris volume fraction cannot exceed the closed-packing fraction, porosity exists in the debris bed. Coolant sodium initially exists in the porosity, and also can penetrate the porosity, and may boil due to the decay heat. The decay heat removability may depend on the shape of the debris bed, which would be agitated by sodium boiling and gradually flattened (Kotake et al., 2010; Ottinger et al., 1987) (right of Fig. 1). This phenomenon is called “self-leveling.” Therefore, debris bed behavior must also be evaluated for decay heat removability under SFR conditions.

To analyze the thermal hydraulic behavior of CDAs in SFRs, the SIMMER code (Tobita et al., 2006; Yamano et al., 2009) has been developed based on mechanistic and physical models for multiphase and multi-component flows. The SIMMER code expresses the debris bed as shown in Fig. 2. Since the SIMMER code does not take into account the inter-particle contact friction, the SIMMER code cannot express the shape and behavior of the debris bed. Therefore, the SIMMER code has limitations in the estimation of decay heat removability from the debris bed and the thermal load on structures in the lower plenum in a reactor vessel.

To simulate particle assemblage behavior such as the debris bed, the particle method, which directly simulates each particle motion and interaction, is often used. However, because the computational load of the particle method is too high, the particle method is impractical for a whole reactor analysis. Therefore, a new model needs to be devised to apply to the thermal hydraulic model of the SIMMER code because computational load is also very important for the safety analysis. For this purpose, the modeling of inter-particle collisions and contacts in a dense particle bed should be beneficial. In the present paper, a new model related to debris bed behavior is presented in Section 2. In

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Nomenclature

c	adhesion force
c_p	model parameter of particle pressure
$\boldsymbol{F}_{nis}$	sum of fluid–structure drag, virtual mass and mass transfer terms
$\boldsymbol{g}$	gravity acceleration
$H(x)$	Heaviside unit function
h_1	surface height at the side of a particle bed
h_2	surface height at the center of a particle bed
Δh	$\equiv h_2 - h_1$
K	momentum exchange coefficient
M	model parameter of particle viscosity
p	pressure
p_f	pressure of fluid domain
p_p	particle pressure
Δp	pressure loss with momentum exchange
r_p	particle radius
$\boldsymbol{S}$	shear tensor
t	time
$\boldsymbol{v}$	velocity
v_t	terminal velocity
$\boldsymbol{VM}$	virtual mass
Δx	cell width in horizontal direction

Greek symbols

α	volume fraction
η	friction coefficient in particle phase
$\dot{\gamma}$	shear rate
$\Gamma_{q'q}$	mass-transfer rate from q to q'
ϕ	internal friction angle
$\bar{\rho}$	macroscopic density
σ	normal stress
τ	shear stress
τ_c	yield stress
τ_s	solid-state shear stress
μ	viscosity

Subscripts

ap	assuming packed state
f	fluid component
i, k, j	tensor notation
m	density component
q, q'	indices of velocity fields
qS	stands for a term existing at an interface between velocity field q and structure
qq'	stands for a term existing at an interface between velocity fields q and q'
GL	stands for a term existing at an interface between vapor and averaged liquid velocities
p	particle component
cp	random close packing
x, y, z	horizontal, longitudinal and vertical direction

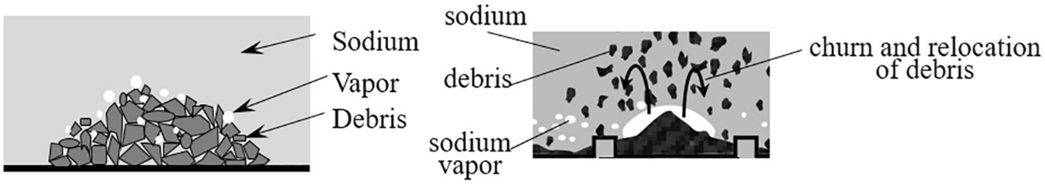

Fig. 1. Images of the static state of debris bed (left) and behavior of debris bed in the lower plenum (right). Fragmented and accumulated debris are churned by sodium vapor during debris bed behavior.

Section 3, test simulations performed to demonstrate the model's capabilities are described. To check the applicability of the model to the debris bed, assessment of proposed model based on model experiments is also described.

2. Model description

2.1. Outline of SIMMER code

The SIMMER code is capable of treating multiphase and multicomponent flows. Because the present paper focuses on particle interaction, material behaviors are considered. Mass and momentum conservation equations in the current SIMMER code are shown in Eqs. (1) and (2).

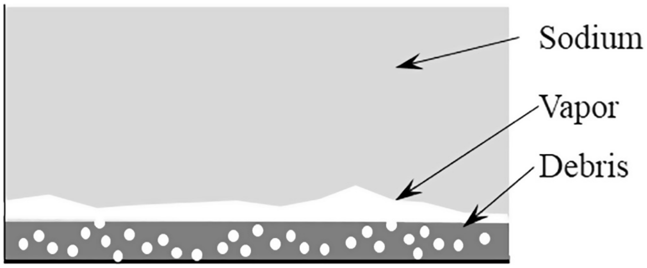

Fig. 2. An image of the debris bed (dark gray) and sodium vapor (white color) distributions expressed by the conventional SIMMER code. The debris are expressed as a fluid.

Mass conservation equation:

$$\frac{\partial \bar{\rho}_q}{\partial t} + \nabla \cdot (\bar{\rho}_q \boldsymbol{v}_q) = -\Gamma_q. \tag{1}$$

Momentum conservation equation:

$$\frac{\partial (\bar{\rho}_q \boldsymbol{v}_q)}{\partial t} + \nabla \cdot (\bar{\rho}_q \boldsymbol{v}_q \boldsymbol{v}_q) + \alpha_q \nabla p - \bar{\rho}_q \boldsymbol{g} + K_{qS} \boldsymbol{v}_q - \sum_{q'} K_{q'q} (\boldsymbol{v}_{q'} - \boldsymbol{v}_q) - \boldsymbol{VM}_q = -\sum_{q'} \Gamma_{qq'} [H(\Gamma_{qq'}) \boldsymbol{v}_q + H(-\Gamma_{qq'}) \boldsymbol{v}_{q'}], \tag{2}$$

where subscript q represents the components of phases. The components include liquid-fuel, liquid-steel, sodium, fuel-particle, steel-particle, control rod particle, fuel chunk and gas. The terms in the left-hand side of Eq. (2) are, respectively, the variation of momentum, momentum convection, pressure force, gravitational force, fluid–structure drag, fluid–fluid drag and virtual mass. In the momentum drag terms, K denotes a momentum exchange function. In the SIMMER code, the momentum exchange function is calculated with the method described by Ishii and Zuber (1979). The term in the right-hand side of Eq. (2) is the momentum exchange by mass transfers. The subscript q' represents all other components that interact with component q. In Eq. (2), the interaction between the same components is not considered.