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Investigation of the structure of debris beds formed from fuel rods fragmentation

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ABSTRACT

This paper is a study of debris beds that can form in the core of a nuclear power plant under severe accident conditions. Such beds are formed of fragments of pellets and cladding remnants, as observed in the TMI-2 core. Many important issues are related with the morphology of those debris beds: are they coolable in case of water injection and how does molten corium progress through them if they are not coolable? The answers to those questions depend on the structure of the debris bed: porosity, number and arrangement of particles. In order to obtain relevant information, a numerical simulation of the formation of the debris bed is proposed. It relies on a granular approach of the type called "Contact Dynamics" to simulate the collapse of debris and their accumulation. Two different schemes of fuel pellet fragmentation are considered and simulations for different degrees of fragmentation of the pellets are performed. The results show that the number of axial cracks on fuel pellets strongly influences the final porosity of the debris bed. Porosities vary between 31% (less coolable cases) and 45% (similar to TMI-2 observations), with a most probable configuration around 41%. The specific surface of the bed is also evaluated. In the last part, a simple model is used to estimate the impact of the variation in geometry of the numeric debris beds on their flow properties. We show that the permeability and passability can vary respectively with a range of 30% and 15% depending on the number of fragment per pellet. The other benefits of the approach are finally discussed. Among them, the possibility to print 3D samples from the calculated images of debris beds appears as a promising perspective to perform experiments with realistic debris beds.

1. Introduction

What does a debris bed look like, after the collapse of fuel assemblies, in a severe nuclear accident? The concept of debris bed was introduced after the post-accident examination of the Three Mile Island unit 2 (TMI-2) reactor (Akers and McCardell, 1989; McCardell et al., 1990). In the top part of the damaged core a large area was made of small fuel particles and fuel rod segments. Since then, it is usually assumed that similar debris beds would form during water injection, if fuel claddings are highly oxidized, broken or even have melted away and have become unable to withstand the thermal shock. The coolability of a debris bed formed in a degraded core of a pressurized water reactor (PWR) is a crucial issue for nuclear safety. During a severe accident the dry-out and heat-up of the fuel rods together with cladding oxidation progressively lead to embrittlement of the claddings and partial melting of the core. Although reflooding aims at slowing down this degradation, the thermal shock potentially induced by a rapid cooling can compromise the mechanical integrity of unclad fuel rods and embrittled oxidized claddings and trigger their collapse. Even though it was never clearly demonstrated experimentally, it is commonly accepted that 'in-core' debris beds are formed from the resulting relocation of fuel pellets and cladding fragments. Examination of several samples coming from Three Mile Island unit 2 (TMI-2) (Akers and McCardell, 1989; McCardell et al., 1990) and experimental studies with aim to model core degradation like LOFT or PBF (Akers et al., 1994; Petti, 1989) confirm this formation process. But the microstructure of 'in-core' debris beds, which governs the progress of water and steam through them, remains poorly known, even now. Most of the available data about debris beds come from the analysis of the severe accident which occurred in the unit 2 of Three Mile Island in 1979. According to several acquisition/examination campaigns (Akers and McCardell, 1989; McCardell et al., 1990; Akers et al., 1986), it has been shown that the core region of TMI-2 consisted of an upper void region surrounded by damaged fuel assemblies and below which a large region of loose debris laid on a hard crust. Samples extracted from the loose debris region were composed of the remnants of oxidized

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Nomenclature

α	contact number
δt	time interval
η	passability
$\langle\gamma\rangle$	aspect ratio
$\langle d\rangle$	average volume-equivalent diameter
μ	coefficient of friction
ϕ	porosity
ψ	sphericity
$\mathbf{F}$	vector of forces and moments
$\mathbf{f}$	vector of contact forces
$\mathbf{F}_{ext}$	vector of external bulk forces
$\mathbf{H} = \mathbf{G}^T$	matrices containing informations of geometry of contact network
$\mathbf{M}$	diagonal matrix of particle masses and moments of inertia
$\mathbf{U}$	vector of particle velocity components
$\mathbf{u}$	vector of contact velocities
ε	specific surface
d_h	hydraulic diameter
d_{St}	mean Sauter diameter
e_n	coefficients of restitution in the normal direction
e_t	coefficients of restitution in the tangential direction
f_n	normal contact force
f_t	tangential contact force
K	permeability
L	maximum length of particle
l	minimum length of particle
L_x, L_y	sample dimensions
n_a	number of axial elements
N_c	number of contacts
n_f	number of fragments per pellet
N_p	number of particles
n_r	number of radial elements
u_n^+,u_n^-	normal relative velocities at the beginning and the end of each step
$u_t^+u_t^-$	tangential relative velocities at the beginning and the end of each step
u_n	normal relative velocity
u_t	sliding velocity

fuel rods (whole and fragmented fuel pellets) that probably shattered during the cooling. A particle size analysis showed that 90 per cent (in mass) of the debris collected were between 1 and 5 mm (McCardell et al., 1990). Bulk tap density measurements indicated that the porosity ranged between 0.35 and 0.40 for the denser samples and around 0.55 for the less dense samples (Akers and McCardell, 1989; Van Dorsselaere et al., 2006). However, informations about particle size distribution are scarce and porosity measurements depended on uncertainties linked to the bulk tap density method and to material composition assumptions. The very representative LOFT-LP-FP2 experiment (Loss Of Fluid Test) (Coryell et al., 1994), which aimed at reproducing a Loss of Coolant Accident in a PWR, showed a similar final degraded core configuration as TMI-2 one: a metallic hard crust surrounding a ceramic molten pool covered by a large debris bed. The authors showed that the formation of the debris beds resulted from the relocation of fragmented fuel rods exposed to water during the cooling, confirming the assumption of a thermal shock. In that experiment, debris collected had a size around 1–2 mm (Van Dorsselaere et al., 2006). Finally the Severe Fuel Damage (SFD) tests performed in the Power Burst Facility (PBF) between 1982 and 1985 (Petti, 1989) also confirm a layered structure for degraded cores in which the upper part is a loose debris bed constituted of pellet fragments. The analysis of the debris beds obtained showed that the shape of the fragments was mainly determined by the crack pattern developed during the pre-irradiation of the pellets. Given the large number of uncertain parameters that can modify the microstructure of a debris bed, such as the shape of the fragments, their size and the way they relocate, characterizing their coolability is a difficult task. The first experiments deliberately used a simplified approach by dealing with uniform packings of spheres. In several experimental programs in the 1980s, the objective was to determine the maximum power that can be removed by water cooling from a heated debris bed, also called dry-out heat flux (DHF) (Hu and Theofanous, 1991; Hofmann, 1984; Reed, 1985). More recently, experimental studies like DEBRIS (Schaffer et al., 2006), POMECO (Li and Ma, 2011a,b) and STYX (Lindholm, 2006) have linked the determination of DHF with the measurement of pressure drops in the bed and studied beds made of polydisperse spheres or non spherical particles. Indeed, pressure drops measurement can be more easily related to the bed structure, i.e. its porosity and the effective particle diameter. In the last years, PRELUDE (Repetto et al., 2013), DEBRIS (Rashid, 2011), CALIDE (Chikhi et al., 2014; Clavier et al., 2015), and PEARL (Chikhi, 2014) aimed at characterizing the pressure drops and the heat transfer laws when reflooding various debris beds under different temperature and pressure conditions. One of the conclusions about pressure drops was that single phase pressure drop through a debris bed can be predicted using an Ergun law (Ergun, 1952) and introducing a Sauter diameter representing a monodisperse bed of equivalent spheres. Concerning the modeling of heat transfers, it has been shown that a second effective diameter should be introduced. These last findings show that a good prediction of the debris beds microstructure, and in particular of their porosity and specific surface area, is a necessary step to predict correctly their coolability. An advanced knowledge of debris beds microstructure is consequently a crucial issue not only for 'in-core' debris but also for other kind of debris beds that can form later when hot corium interacts with residual water in the lower-plenum (Fichot et al., 2006). In a slightly different context, such debris beds are studied in other kinds of nuclear power plants, such as in sodium-cooled fast reactor for example (Cheng et al., 2014). However due their particular formation process, consisting in corium fragmentation followed by fragments sedimentation, these 'out-core' debris beds present a very different composition (rounded particles, large size distribution) that cannot be compared to 'in-core' debris beds in an straightforward way.

From a granular viewpoint, it is well known that the porosity of a discrete medium strongly depends on the particles properties (size distribution, shape) and on the way it was generated (Aste and Weaire, 2000; Aste, 1996; Bezrukov et al., 2002; Herrmann et al., 2003; Kansal et al., 2002; Vu et al., 2010; Al-Raoush and Alsaleh, 2007; Santiso and Müller, 2002; Farr and Groot, 2009; Hermes and Dijkstra, 2010). Previous works have already allowed to quantify independently the influence of several dispersion factors using classical granular approaches such as Discrete Elements Methods (DEM). For example, the influence of the size distribution on the texture and the mechanical behavior is the subject of many studies in soils mechanics (Mitchell and Soga, 2005) and in industry for obvious reasons (Aste and Weaire, 2000; Akers, 1992; de