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Evaluation of an effective diameter to study quenching and dry-out of complex debris bed ☆

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ABSTRACT

Many of the current research works performed in the SARNET-2 WP5 deal with the study of the coolability of debris beds in case of severe nuclear power plant accidents. One of the difficulties for modeling and transposition of experimental results to the real scale and geometry of a debris bed in a reactor is the difficulty to perform experiments with debris beds that are representative for reactor situations. Therefore, many experimental programs have been performed using beds made of multi-diameter spheres or non-spherical particles to study the physical phenomena involved in debris bed coolability and to evaluate an effective diameter. This paper first establishes the ranges of porosity and particle size distribution that might be expected for in-core debris beds and ex-vessel debris beds. Then, the results of pressure drop and dry-out heat flux (DHF) measurements obtained in various experimental setups, POMECO, DEBRIS, COOLOCE/STYX and CALIDE/PRELUDE, are presented. The issues of particle size distribution and non-sphericity are also investigated. It is shown that the experimental data obtained in "simple" debris beds are relevant to describe the behavior of more complex beds. Indeed, for several configurations, it is possible to define an "effective" diameter suitable for evaluating (with the porosity) some model parameters as well as correlations for the pressure drop across the bed, the steam flow rate during quenching and the DHF.

1. Introduction

It is acknowledged that in the late stages of a severe accident in a nuclear reactor core, accumulations of fuel and structure materials, commonly called debris beds, may be formed. Such debris beds may be formed in the core after collapse of the fuel rods or in the lower plenum of the reactor pressure vessel after melt–water interaction. Both configurations have been observed in the TMI-2 reactor (Broughton et al., 1989). Similarly, a debris bed may form in the reactor pit when it is filled with water, after failure of the vessel and melt-water interaction.

The NEA/SARNET2 Workshop on "In-vessel coolability" (Amri and Clement, 2009) and the SARNET-SARP group (Schwinges et al., 2010) considered the question of debris coolability to be a high priority issue. Many of the current research works performed in the SARNET-2 WP5 deal with the study of the coolability of such debris beds. One of the difficulties for modeling is the transposition of experimental results to the real scale and geometry of a debris bed in a reactor. First, processes of debris formation are very complex and make it very difficult to manufacture similar debris for an experiment. Secondly, even if it would be possible to manufacture realistic debris, the bed itself results from a stochastic collapse of particles of various sizes, and there are infinite possible debris bed configurations, that could result from a sample initial damaged geometry. Therefore, any modeling must use some assumptions and extrapolations in order to use experimental data obtained with a set of particular debris beds in models that can be applied to any debris bed.

The question arises whether the complex debris bed can be characterized by only few parameters that are used in the constitutive laws. Especially, is it possible to describe a complex debris bed with only one diameter, i.e. an effective diameter?

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Two approaches have been used up to now. The first step consists in measuring some characteristics of the debris bed such as the pressure drop across the bed or the Dry-out Heat Flux (DHF) Lindholm et al., 2006; Takasuo et al., 2011; Rashid et al., 2008; Rashid et al., 2011, 2012. In this first approach, a model (as Lipinski (1982) for the DHF model) involving an equivalent diameter is needed. The equivalent diameter that gives the best agreement between the model and the experiment is considered as the effective diameter (Kulkarni et al., 2010). In the second approach, the results (the DHF or the quenching velocity for example) obtained in realistic configurations are compared with results obtained in monodisperse beds of various sizes. The diameter of the monodisperse bed that is the most suitable to represent the realistic bed is considered as the effective diameter.

This paper first establishes the ranges of porosity and particle size distribution that might be expected for in-core debris beds and ex-vessel debris beds. Then, the results obtained in various experimental setups, POMECO, DEBRIS, COOLOCE/STYX and CALIDE/PRELUDE, are presented and analyzed. The issues of particle size distribution and non-sphericity are also investigated. Finally, the knowledge gained from the experimental works and the common findings are drawn.

2. Typical particle distribution and porosity ranges for realistic debris beds

2.1. In core debris bed

Debris could form in the reactor core of a PWR in case of water injection to slow down a core meltdown accident transient. Several observations indicate that this phenomenon occurred during the TMI-2 accident (Akers et al., 1986; McCardell et al., 1990) and in severe fuel degradation experiments like LOFT (Coryell et al., 1994; Hobbins and McPherson, 1990), PBF (Petti et al., 1989) and PHEBUS.

The examination of the debris bed formed in the TMI-2 core by ten debris grab samples analysis (Akers et al., 1986) have shown that the samples can be divided in three parts. In the first part, the largest amount of material is in the greater than 4 mm fraction. In the second part, 80–86 wt% of the sample material is larger than 1 mm in size with the 1.68–4 mm particle size containing the most material. For the third part, the fraction of the sample material larger than 1 mm is less than 75 wt%. There is a bimodal distribution of particles with the major peak lying at the 1.68–4 mm size fraction and a minor peak at the 0.3–0.71 mm size fraction. For these samples, located in the depth of the debris bed, settling of the fine material and/or washout of the fine material from the upper layers has probably occurred. This analysis has shown us that the particles in the TMI-2 core are mostly millimeter-sized.

Concerning fuel particles, it was observed in the rubble beds formed in the upper part of the bundle in the LOFT LP-FP-2 (Coryell et al., 1994; Hobbins and McPherson, 1990) and in the PBF-SFD (Petti et al., 1989) that their size is set primarily by the crack distribution prior to the transient. Indeed, the pellet cracking occurs right from the beginning of the reactor operation as consequence of differential expansion between the centre of the pellet and the periphery. The final number of radial fragments ranges from 10 (Walton and Husser, 1983) to 16 (Oguma, 1983) leading to a minimum equivalent fuel diameter (d_{Sauter}, see Section 3.1) of 2 mm for fuel pellet of 13.5 mm height and 8.2 mm diameter according to (Coindreau et al., 2013). Under accident conditions, additional fuel cracking could occur with very highly irradiated fuel (Kolstad et al., 2011). This has been attributed to the formation of the High Burn-Up Structure (HBS) in the periphery of PWR fuel UO_2 pellet beyond 40 GW d/t_U. If fine particles from the HBS structure, whose size can reach around 30 μm (Hiernaut et al., 2008) are considered, it can contribute to a significant decrease of the mean diameter of fuel particles. The occurrence of this phenomenon for moderately to highly irradiated fuel is not proven but it is not excluded that fine particles could come from the most irradiated fuel assemblies of the reactor core. Concerning cladding particles, they are millimetre-sized. It can be computed that their equivalent diameter (d_{Sauter}, see Section 3.1) ranges between 1.1 and 1.7 mm for an inner cladding diameter of 8.36 mm and a thickness of 570 μm (Coindreau et al., 2013). It is more difficult to evaluate the size of prior molten material particles.

The porosity of the debris bed formed during the TMI-2 accident can be deduced from measurements of the bulk tap density of the core debris grabbed samples that ranges between 3.5 and 5.5 g cm^{-3} (Akers et al., 1986). This corresponds to a porosity ranging between 0.35 and 0.4 (depending on the assumption about the material composition) for the denser sample to a porosity higher than 0.55 for the less dense material. The 0.37–0.4 range corresponds to the porosity of an unarranged configuration of monosized spheres (Dias et al., 2005). For mixed spherical particles, the porosity can be lower, depending on the size distribution. If fine particles coming from the HBS structure are mixed with coarse particle, it was computed that a minimum theoretical value of 0.35 could be reached for fuel with a burn-up of 60 GW d/t_U (Coindreau et al., 2013). For moderately irradiated fuel, the average porosity of 0.4, usually used in coolability analyses for instance in Bürger et al. (2006), consequently seems to be reasonable.

2.2. Ex-vessel and lower plenum debris bed

If the damaged core cannot be cooled, the molten corium will relocate downwards, and finally fall into the water pool in the lower plenum. The melt fragments in the coolant, and a debris bed is expected to form on the pool bottom. If the debris is not coolable there either, it will re-melt. Ultimately, the vessel will fail under the aggressive attack of the molten corium in the lower plenum, and the melt jet ejected into the cavity under beneath the RPV. In case the cavity is flooded (as a strategy of severe accident management or a result of containment spray), the melt jet will breakup and the debris will settle down on the floor.

In order to obtain the characteristics (porosity, particle morphology and size distribution, etc.) of so-formed debris beds for coolability study, a good number of fuel–coolant interaction (FCI) experiments has been carried out during the past two decades. The debris bed of interest is formed because of the corium fragmentation and settlement in the coolant. Thus, the first question of coolability significance is how the debris bed looks like. Among them are the well-known FCI tests CCM, KROTOS, FARO, TROI and COTELS programs, as well as the DEFOR tests dedicated to debris bed formation.

Corium-Coolant Mixing (CCM) tests were performed in Argonne National Laboratory to investigate the phenomena associated with molten fuel–coolant interaction (Spencer et al., 1994). Molten corium (60% UO_2, 16% ZrO_2, 24% SS at ∼2800 °C) fell through a water pool around one meter in depth. Table 1 shows the initial conditions and some debris characteristics of the series of 6 CCM tests.

The CCM-1 test had mass of 2.15 kg, and the formed debris bed was heap-like with loosely bound and sintered particles. All sizes and shapes of particles were present, with many spheroidal and ellipsoidal fragments. Typical particle diameter is 3 mm, with fragments having diameters of over 10 mm. A large number of the particles were hollow shells. CCM-3 was similar to CCM-1 except for a higher water temperature near saturation and a higher porosity. CCM-4 test was identical to CCM-1 except a larger melt mass and ejection diameter. Similar debris bed was obtained with a higher porosity. Interestingly, it was found that the variation in