Annals of Nuclear Energy 92 (2016) 251–261

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

An experimental study of the coolability of debris beds with geometry variations

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A R T I C L E   I N F O

Article history:
Received 29 October 2015
Received in revised form 19 January 2016
Accepted 23 January 2016
Available online 15 February 2016

Keywords:
Severe accident
Corium
Debris bed
Coolability
Dryout heat flux
Experimental facility

A B S T R A C T

The coolability of porous debris beds consisting of a simulant of solidified corium was investigated in an experimental study. The focus was on the effects of the geometrical shape of the debris bed and multi-dimensional flooding on the dryout heat flux. Dryout heat flux (DHF) was measured for six variations of the debris bed geometry, one of which was a classical, top-flooded cylinder and five that had more complex geometries. The complex geometries included conical and heap-shaped beds which can be considered prototypic to reactor scenarios. It was found that the multi-dimensional flooding related to heap-like geometries increases the DHF compared to top flooding by 47–73%. It was emphasized that the debris bed height has to be taken into account when assessing the coolability of realistic geometries: the heap-like geometry increases the dryout heat flux by facilitating multi-dimensional infiltration of water into the bed, but it also decreases the dryout power by having a greater height. The measured DHF increase represents a limit for the debris bed height, because if the increase in bed height is greater than the DHF increase, the direct benefit from the multi-dimensional flooding is lost. In addition, post-dryout conditions and their significance in the overall coolability of multi-dimensionally flooded beds were discussed.

1. Introduction

One of the most important questions in the management of a severe nuclear reactor accident is how to cool and stabilize the molten corium. In a postulated severe accident at a Nordic-type BWR, the corium is expected to discharge from the reactor pressure vessel into a deep water pool in the cavity below the RPV, which is called the lower drywell. The lower drywell is flooded by operator action prior to the RPV rupture. Then, the corium is discharged into the water pool where it is fragmented and solidified. Ultimately, after the initial quenching in the pool, a porous (ex-vessel) debris bed is formed on the floor of the containment. The debris bed continues to produce decay heat in the water pool, the power of which is great enough to result in re-melting of the debris and a potential threat to the containment structures, unless it is effectively transferred from the debris. Sufficiently large heat removal rate is achieved by boiling the water in the pool. Then, the key question becomes how to ensure that an adequate amount of water may infiltrate into the debris bed to replace the evaporated coolant.

Numerous studies on debris coolability are found in the scientific literature, ranging from the fundamental studies in the early 80s (e.g. Trenberth and Stevens, 1980; Barleon and Werle, 1981; Lipinski, 1982; Hofmann, 1984) to more recent and still on-going research efforts that account for more complex conditions (e.g. Konovalikhin, 2001; Atkhen and Berthoud, 2006; Rashid et al., 2008; Repetto et al., 2011; Li et al., 2012). In addition to experimental work, the development and validation of different types of models to predict dryout has been a topic of significant interest (e.g. Bürger et al., 2006; Kudinov et al., 2014). Most of the debris coolability experiments have been performed in pipe-like set-ups in which the bed is flooded either through its top or bottom surface. These types of set-ups, designed for effectively one-dimensional flows, offer a very limited possibility to examine the effect of multi-dimensional flooding. Moreover, the realistic debris bed geometry is not considered at all in classical analyses. If the debris bed has a heap-like shape, i.e. it resembles a cone, complex multi-dimensional flow of coolant into the debris bed is possible. The geometry of the debris bed may determine whether the debris bed is coolable or not through the flooding mode.

The heap-shaped geometry can be considered as realistic based on fuel-coolant interaction experiments, in which such shapes have been formed as a result of the settling of melt particles (Spencer et al., 1994; Karbojian et al., 2009). This is a plausible assumption also because the pouring of granular material on a

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http://dx.doi.org/10.1016/j.anucene.2016.01.030
0306-4549/

Nomenclature

Latin letters

A	area (m^2)
P	power (W)
q	heat flux (W/m^2)
Q	power density (W/m^3)
r	radius (m)
z	height (m)

Abbreviations

CHF	maximum coolable heat flux
DHF	dryout heat flux
TC	thermocouple

planar surface forms a conical heap. However, experimental data on the coolability of heap-shaped debris beds was practically non-existent prior to the test programme which is summarized in this paper. In this test programme, six variations of the debris bed geometry were chosen for experimental measurements of dryout power. One of the geometries was a classical top-flooded bed consisting of a cylinder with impermeable sidewall and bottom. The dryout heat fluxes measured in the different geometry variations were compared to the dryout heat flux of the top-flooded bed. The objective was to reveal which types of geometries are favourable for achieving coolable conditions, and which are less so. One of the main goals was also to provide a basis for the validation of simulation codes that are used to assess severe accident scenarios on a realistic scale.

The coolability increase related to the bottom flooding and multi-dimensional configurations has been emphasised in many experimental studies (e.g. Hofmann, 1984; Atkhen and Berthoud, 2006; Takasuo et al., 2011; Rashid et al., 2012), as well as in summary-type publications on the topic (Bürger et al., 2010; Sehgal, 2012, p. 344). For pure bottom flooding, the DHF increase may be up to 100% compared to top flooding. The increased coolability is a result of the change in the two-phase flow pattern compared to one-dimensional flooding: in multi-dimensional flooding, co-current flow of steam and water may be formed in the debris bed – pool system, while in top flooding, the flow is purely counter-current. The co-current flow has more cooling potential since, in this mode, the upwards flow of steam does not prevent the water from accessing the bed when the counter-current flow limitation at a critical steam generation rate is met. Instead, dryout is seen only when the steam generation is great enough to fully replace water in a bed cross-section.

In this study, the dimensions of the debris bed are taken into account, instead of dealing only with the flooding mode differences. If the debris bed has a heap-like geometry, it is greater in height than a flat-shaped and top-flooded bed which is distributed against the walls of the debris spreading area. This allows the presence of great local steam fluxes in the top parts of the bed, which makes this location especially vulnerable to dryout. For a bed with lower height and the same volumetric power generation, the maximum steam flux at the top is always smaller. If realistic geometries are to be considered, it is not sufficient to consider only the flooding mode (top flooding vs. multi-dimensional). Here, the geometry of the bed, specifically the bed height, is taken into account in evaluating the overall coolability.

2. Experimental set-up

2.1. Geometry variations

In this work, the flooding modes are divided to top flooding, lateral flooding and multi-dimensional flooding. Principal sketches of the debris bed geometries and flooding modes addressed in the experiments are illustrated in Fig. 1. For instance, in the case of a conical bed in Fig. 1(a), the flooding mode is multi-dimensional because water can infiltrate into the porous bed through the full surface of the cone. The cylindrical bed with closed walls in Fig. 1(b) is top-flooded because only the top surface is permeable to fluid flow. Lateral flooding applies to the geometry that has an impermeable top but open sidewall in Fig. 1(d).

Heap-shaped beds shown in Fig. 1 (a) and (f) can be formed in the corium discharge and settling if the particles are not effectively spread by the flows in the water pool. The cylinder with open sidewall in Fig. 1(c) is also a type of approximation of the heap-shaped bed, since the vertical surface of the geometry is permeable to fluid flow, in addition to the top. It is also possible that the debris settles partially against the wall while the top part of the bed has a conical shape, which is represented by the bed in Fig. 1(e). The cylinder with lateral flooding and an impermeable top in Fig. 1(d) represents a case in which a layer of solid but non-fragmented corium has been formed on an otherwise heap-like bed.

It is important to note that the debris bed properties depend on the melt discharge process, the properties of which (e.g. melt jet diameter) depend on the in-vessel progression of the accident and the RPV failure mechanism. The chain of events leading to the formation of the porous bed is highly complex, and it would be practically impossible to take all possible debris distributions into account in experimental studies, or even in numerical simulations. In addition, the melt discharge from the RPV, the droplet solidification and the particle settling are stochastic processes which always include some randomness. It is possible that the real, irregular debris bed is not axially symmetric and/or has a non-homogenous internal structure. Here, the possible non-symmetry is not taken into account to keep the number of tests reasonable. Also, the effects of internal non-homogeneity, for instance, regions of higher porosity in the bed, have not been addressed.

2.2. Test facility

The experiments were conducted using the COOLOCE test facility, which has a modifiable test section for experimenting with different test bed geometries. The test bed is housed in a stainless steel pressure vessel which has an outer diameter of 613 mm and a volume of 270 dm^3. The pressure vessel contains the pool in which the test bed is immersed during experiments. The internal heating is achieved by vertically oriented electrical cartridge heaters, inserted into the bed through tapered holes in the bottom of the pressure vessel. The temperature sensors used for dryout detection are installed into the porous bed between the heaters, and they are connected through the bottom similarly to the heaters. In addition to the pressure vessel containing the test bed, the facility consists of feed water, steam removal and data acquisition systems.

Photographs of the test beds are shown in Fig. 2. The volumes and diameters of the test beds are indicated in the figure. The height of all test beds is 270 mm with the exception of the truncated cone, the height of which is 160 mm. The slope angle of