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Experimental results on the coolability of a debris bed with down comer configurations

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ABSTRACT

In case of a severe accident, a debris bed is formed from a mixture of molten core and the residual water in the lower plenum of the reactor pressure vessel. The presence of decay heat in a debris bed poses a critical threat to the reactor pressure vessel. To avoid any damage to the reactor pressure vessel, the removal of decay heat from the debris bed is of great importance. In order to investigate experimentally the long-term coolability of debris beds, the non-nuclear test facility "DEBRIS" has been established at IKE. Experimental investigations of coolability limits for such a debris bed, based on two different bed configurations and at various thermo-hydraulic conditions, are carried out at IKE. This paper presents the experimental results for multidimensional cooling effects on boiling and dryout tests with different bed configurations and different system pressures.

Two different down comer configurations (cylindrical and perforated cylindrical tubes with inner diameters of 10 mm each) are used to investigate the multidimensional cooling effects. The down comer is concentrically installed inside the debris bed which is contained in a cylindrical crucible with an inner diameter of 125 mm. Different bed configurations, e.g. polydispersed particle bed with spherical particles 2, 3 and 6 mm in diameters and irregular particles of equivalent diameters 2–10 mm, have been used with a bed height of 640 mm. A layer of ceramic balls of diameter 4 mm with 40% porosity is used to make up a water pool at the bottom of the bed. The bottom inflow via the down comer tube as well as the lateral inflow of water through the perforated down comer tube into the bed improves the coolability of the debris bed, and therefore an increase of the dryout heat flux can be observed. Experimental results also show that the system pressure has no significant effect on the characteristics of pressure gradients inside the bed, whereas with increasing system pressure the coolability limits are increased.

1. Introduction

During a severe accident in a light water reactor, the core can melt and be relocated to the lower plenum of the reactor pressure vessel (RPV). There it can form a particle debris bed due to the possible presence of water. The insufficient heat removal of decay heat in the debris bed may lead to the failure of the RPV. Therefore, addressing the issue of coolability the behaviour of heat generating particle debris bed is of prime importance in the framework of severe accident management strategies, particularly in the case of above mentioned late phase accident scenario.

Due to the large surface area of porous media, the coolability of a particle beds is normally not limited by the heat transfer from the particle to the coolant, viz. the boiling critical heat flux. A feature of boiling beds with volumetric heat sources is a rise of the vapour velocity with increasing bed height. At a certain vapour velocity the uprising vapour will block the penetrating water from an overlaying water pool. Not enough water can then enter the porous bed, and it will dry out. The installation of a down comer in the centre of the bed will offer a low resistance flow path for water. In addition to the water supply from the top, the water flowing through the down comer will establish an upward flow from the bottom of bed (bottom-flooding) which will enhance the coolability of the heated bed respectively will increase the dryout heat flux (DHF). In bottom-flooding experiments at POMECO test facility (Nayak et al., 2005) an increase in DHF has also been observed by applying a down comer. Many experiments have been carried out on counter-current flooding limitation (CCFL) and led to the dryout model which is first presented by Lipinski (1982). In a modified experiment performed by Hofmann (1984), in which water was supplied by a lateral water column to the bottom of the bed, a drastically increased coolability was observed. This increase could not be explained by models without interfacial drag (Reed, 1982; Hu and Theophanous, 1991). Better agreement was achieved with models including the interfacial drag (Lipinski, 1984; Tung and Dhir, 1988; Schulenberg and Müller, 1987).

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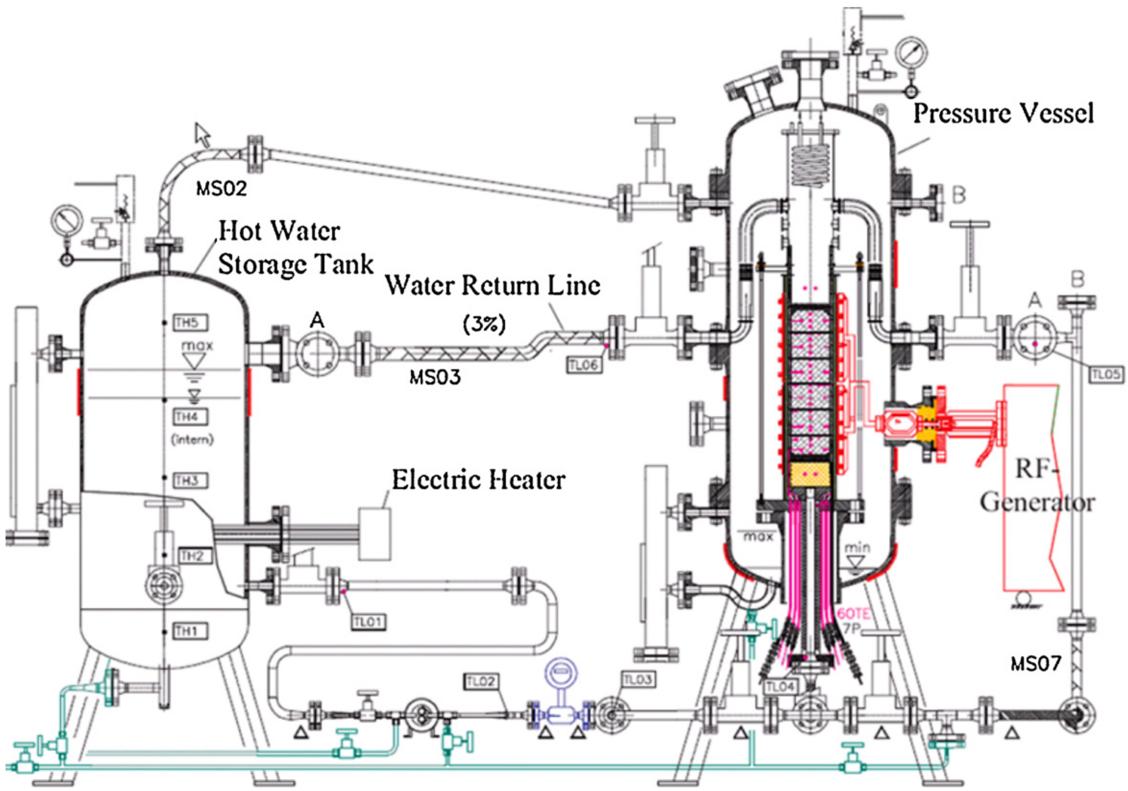

Fig. 1. Test facility "DEBRIS".

In order to gain a deeper insight into boiling phenomena of a debris bed with volumetric heat sources, a non-nuclear single effect experiment (test facility DEBRIS, Fig. 1) was built up at IKE which focuses on the general understanding of two-phase flows in porous media. The major tasks of the experimental investigations are the determination of local pressure drops for steady state boiling to check friction laws, the determination of dryout heat fluxes under various conditions (e.g. bed content, system pressure, flow condition), and the analysis of quenching processes of dry hot debris beds. All experimental data are used for validation of numerical models in IKE's computer code WABE-2D which serves for the German system code ATHLET-CD (Analysis of Thermal-Hydraulics of Leaks and Transients – Core Degradation) (Trambauer et al., 2003). A large number of experiments have been carried out at IKE on particle beds composed of single-sized spheres and polydispersed spheres (Groll et al., 2008) as well as for irregularly shaped particles (Rashid et al., 2008). In this paper experimental results, obtained from investigations of coolability limits of polydispersed particle bed with the use of a central tubular down comer, are presented.

2. Debris test facility

The experimental set-up consists of a pressure vessel designed for pressures up to 40 bar in which the crucible filled with particles is mounted. The pressure vessel is connected to a storage tank filled with demineralised water and a pumping system, which allows performing boiling experiments with feeding water to the crucible at the bottom (bottom-flooding) or at the top (top-flooding). Fig. 1 shows the complete set-up including piping and heat removal system. The debris bed is volumetrically heated via an oil-cooled 2-winding induction coil by an RF-generator. The RF generator operates at a frequency of 200 kHz and has a nominal output power of 140 kW.

The test section consists of a crucible made from material PTFE (Teflon) (Fig. 2). It has a total height of 870 mm and an inner diameter of 125 mm. A down comer is also installed at the centre of the test section. The tubular down comer made of PTFE has an inner diameter of 10 mm and an outer diameter of 18.5 mm. The test section is equipped with 60 shielded thermocouples (OD 1 mm, Type N), of which 51 are located in the debris bed on 25 levels at different radii of the bed's cross section. The thermocouples measure the temperature in the voids between the particles, which are filled by liquid, vapour or a mixture of both. For pressure measurements, 8 differential pressure transducers are used (100 mbar, class 0.1).

The pressure taps dp1–dp8 are uniformly distributed in 100 mm intervals along the bed height (pressure transducer dp8 records the pressure difference between levels PL0 and PL7). The exact position of the thermocouples and pressure taps can be seen in Fig. 2. Due to the installation of a down comer in the centre of the bed the thermocouples shown in the centre of the test section are bent a little bit laterally.

Two different bed configurations, polydispersed particle bed and irregular particle bed, are used for the current set of experiments. The polydispersed particle bed is composed of a mixture of pre-oxidised stainless steel balls of 3 diameters 2 mm, 3 mm and 6 mm mixed in a ratio of 20%, 30% and 50% by weight respectively. The irregular particle bed consists of a mixture of irregular aluminium oxide particles (68.5%wt) with equivalent diameters 2–10 mm and stainless steel balls of 3 mm and 6 mm diameters (31.5%wt). The measured porosities of polydispersed particle bed and irregular particle bed are 0.37 and 0.38 respectively. The bed height is 640 mm for both bed configurations with an additional water pool of 310 mm above the bed.

At constant system pressure the bed is heated up to steady-state boiling condition at saturation temperature. Then, the heating power is increased in small steps until the dryout is reached. An appreciable fast increase in bed temperature above the saturation