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Effect of water entrainment on the coolability of a debris bed surrounded by a by-pass: Integral reflood experiments and modelling

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ABSTRACT

To assess the severe accident management strategy, the question of debris coolability has to be resolved. In this framework, large scale debris bed reflood tests have been performed in the PEARL facility. The debris bed, 500 mm in height and 450 mm in diameter, was made of 4 mm stainless steel balls surrounded by a 45 mm-thick bypass filled with 8 mm quartz balls. Bottom-reflood tests have been successfully conducted under pressure (1–2–3–5 bar) with different water injection velocities (2–5–10 m/h) and initial temperatures (150–400–700 °C). For each tests, the bed has been cooled down and the quench front progression was mainly axial from the bottom to the top and homogeneous in most of the experimental bed. The experimental results show that the reflood time tends to a lower limit when the water injection velocity or the pressure is increased. To interpret this result, an analytical model has been developed. It shows that, for high injection velocities (>5 m/h) or low pressure (<2 bar), water can flow faster in the bypass: this phenomenon limits the reflood efficiency as some of the injected water is not used for bed cooling. Calculations have been made with the severe accident code ICARE-CATHARE V2 as a complement to the interpretation of experimental data. The calculated steam and water velocity fields confirm the experimental observations and the analytical model interpretation, showing the entrainment of water in the bypass under some conditions.

1. Introduction

In the event of a severe accident in a PWR, a debris bed may be formed due to the core heat-up and the collapse of fuel rod assemblies. To stop the progression of the accident and to prevent core melting and vessel failure, the main management procedure consists in injecting water into the reactor core by means of various safety injection devices. Nevertheless, the success of a core reflood is not guaranteed depending on the particle size, the bed porosity and the operating conditions (water injection velocity, system pressure) (Nayak et al., 2006).

Numerous experimental studies were conducted in small scale facilities to study debris bed coolability. First experiments in the 1970s and 1980s were devoted to the determination of the dry-out heat flux (DHF), i.e. the maximum volumetric power that can be removed by water (Hardee and Nilson, 1977; Dhir and Catton, 1977; Lipinski, 1984). The effects of bed height, pressure, particle size and bed porosity were investigated mainly with one-dimensional debris beds. Hu and Theofanous (1984) studied the DHF considering non-spherical particles. Later, dry-out experiments were conducted on two-dimensional beds providing more data and showing that the DHF could be increased in such situation (Decossin, 1999; Atkhen and Berthoud, 2003).

Reflood experiment data are more scarce and mainly concern top flooding (Cho et al., 1984; Ginsberg et al., 1982; Tutu et al., 1984a; Tung and Dhir, 1988). They all lead to models based on the counter current flow limitation (CCFL) and on correlations for the friction laws (Tung and Dhir, 1988; Schulenberg and Müller, 1987 and more recently by Burger et al. (2006) and Fichot et al. (2006a)).

Bottom flooding was studied by Hall and Hall (1981),Tutu et al. (1984b) and Tung and Dhir (1986) for one-dimensional beds at a small scale (around 50 kg). Depending on the water injection velocity, several categories of bottom flooding could be distinguished. For low velocities, the steam flow rate is almost constant. For higher velocities and as long as the bed remains fixed, there is an initial steam peak followed by a decreasing flow rate with a possible plateau phase. For very high velocities, the bed is fluidizied and the heat removal rates may increase up to 8–10 times those

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given by CCFL. Nevertheless, due the small height of the bed, transient effects at the beginning and at the end of reflood are too much emphasized in such experiment. Result experimental results obtained in the DEBRIS facility (USTUTT) were presented in Leininger et al. (2014),Starflinger et al. (2015).

The role of interfacial drag on debris coolability has been highlighted in case of CCFL, mainly considering 1D bed configuration. But little attention was paid to water entrainment by steam in case of co-current flow, in particular for 2D bed configurations. The PRELUDE reflood tests (Repetto et al., 2013) performed on small scale bed surrounded by a bypass revealed that the reflooding time decreases, as the water injection velocity increased but it was shown that it tends towards a lower limit which depends on the geometrical characteristics of the bed and the bypass.

The effect of system pressure on coolability has not been addressed in existing experimental database. Regarding the safety issues, it is known that high pressure influences indirectly the reflood mass flow rate (because the flow rate of the pumps or the accumulators depends on the primary pressure). But in the experiments presented in this paper, the mass flow rate can be prescribed, independently of the pressure. It is also known that pressure has a significant effect on the DHF (Hering and Homann, 2004).

To gain a deeper insight into reflooding phenomenology at large scale with a volumetric heat source and at pressure up to 10 bar, the PEARL facility has been built at IRSN Cadarache. In the present work, the results of seven PEARL tests are presented. These tests have been carried out in a two-dimensional bed at various water injection velocities (2–5–10 m/h) and initial temperatures (150–400–700 °C), under pressure (1–2–3–5 bar). The debris bed was made of 4 mm stainless steel balls surrounded by a bypass filled with 8 mm quartz balls.

A specific instrumentation has been developed to measure the debris bed temperature, pressure drop inside the bed and the steam flow rate during the reflooding (Chikhi et al., 2015). It allows measuring the progression of water within the bed and the timing of quenching. It also provides the 'conversion ratio' which is the steam flow rate produced divided by the water injection flow rate. There are two specific features of the PEARL facility. First, the large bed scale with the presence of a lateral by-pass allows to simulate the presence of less-damaged zones at the periphery of the bed. This by-pass induces flow patterns which differ significantly from previously observed patterns in 1D experiment. Second, reflood under pressure up to 10 bar can be carried out in the PEARL facility. The effect of pressure can also be investigated for the first time.

To interpret the experimental results, an analytical model has been developed to study, from a qualitative point of view, the exit steam path of steam. This model is presented and compared with the experimental results from PEARL tests.

Finally, calculations with the severe accident code ICARE-CATHARE V2 are made in order to provide complementary information about the flows of water and steam within the debris bed. The velocity fields are examined in the quench front region and the boundary between the heated bed and the bypass. It appears that the pressure difference between the main bed and the bypass leads to a diversion (or cross-flow) of both steam and water towards the bypass. This partly explains why the flow of water in the bypass is larger than expected from a simple mass balance. In addition, the large steam flow rate in the bypass produces a large pressure gradient in the axial direction which may explain that the velocity of water in the bypass is higher than the quench front velocity. Therefore, the results of the calculations confirm the experimental observations and justify the interpretation made with the analytical model. This will be discussed further in the paper.

2. Experimental set-up

2.1. The PEARL facility

The PEARL facility (Fig. 1) has been designed to perform quenching (or dry out) tests with a large scale debris bed, 50 cm in height and 50 cm in diameter, under pressure (up to 10 bar). It consists of a pressure vessel, a pressurized water tank and a steam generator as major components. The debris bed is held in place by a quartz cylinder. It is heated by an induction coil linked to a high frequency generator. The quartz tube is housed in a pressure vessel and connected to the water injection line (bottom or top) and to a steam exit line. The test section consists of a quartz tube (Fig. 2). It has a total height of 2660 m and an inner diameter of 540 mm. The debris bed, 500 mm in height and 450 mm in diameter, is composed of 4 mm stainless steel balls surrounded by a 45 mm-thick bypass filled with 8 mm quartz balls. The porosity of the debris bed was measured as 0.42 and the porosity of the bypass was estimated as 0.48. The debris bed represents the collapsed fuel rods and the bypass represents a less damaged zone of the core (almost intact fuel assemblies for example), surrounding the debris bed. In principle, the bypass should be heated with the same massic power as the central debris bed, in order to be perfectly representative. But it was not possible to achieve that kind of heating with induction. Therefore, the by-pass is not heated. As it was observed in the experiments, this does not affect the temperature profile in the central bed because the bypass plays the role of an insulation and contributes to get a very flat temperature profile in the central bed. A quartz ball bed, 100 mm in height, supports the experimental debris bed so that it is well positioned according to the induction coil position. To track the quench front progression during reflood, thermocouples have been inserted into the bed and the bypass (see Fig. 2 for their location). The water injection flowrate is controlled by an electropneumatic valve and measured by a Coriolis flowmeter. The steam flowrate and temperature are measured in the exit steam line downstream the test section. The description of PEARL facility instrumentation is summarized in the Table 1 providing range and accuracy. Differential pressure sensors are also inserted in the bed but their results will not be discussed in this paper.

2.2. Debris bed heating

The bed is heated by a single induction coil connected to a high frequency generator (100–400 kHz). In case of perfect electrical contact between balls, the power deposit would be concentrated on the external area of the stainless steel ball bed. To avoid this and to obtain an homogeneous heating, particles have been oxidized so that a thin oxide layer (about few micrometers) surrounds each ball. As the oxide layer has a very high electric resistivity, balls are insulated from each other and the induced current remains contained in each ball, preventing large current loop.

To check the power deposit, a heating test has been performed increasing the bed temperature from 15 °C to 25 °C. At such temperature, the heat losses can be neglected with respect to the volumetric power and the energy balance in each point of the bed can be written as:

$$P(\mathrm{W/kg}) = C_p \frac{\partial T}{\partial t}. \tag{1}$$

The measurements from the 42 bed thermocouples are presented in Fig. 3. The average value is equal to 149 W/kg (with 150 W/kg as a setpoint) with a standard deviation equal to 9 W/kg, i.e. 6% of the average value. Thus, the power distribution can be considered as homogeneous in all the bed.