

QUENCHING EXPERIMENTS: COOLABILITY OF DEBRIS BED

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Abstract

In case of a severe accident, continuous unavailability of cooling water to the core will result in over heating and subsequent melt down of the fuel elements which would eventually result in the loss of fuel integrity. Under such conditions a porous structure made of heat generating particles of different sizes and shapes may be formed. The presence of decay heat in such 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. The debris bed needs to be quenched by the water either flooding from top or flooding from the bottom before the continuous cooling is established. In order to investigate the quenching behaviour of debris bed by means of experiment, the non-nuclear test facility “DEBRIS” has been established at IKE. Experimental investigations of quenching behaviour for a preheated debris bed, at various initial bed temperatures, are carried out at IKE. In the new quenching tests, the cooling down behaviour of superheated polydispersed particles bed from stainless steel spheres at different thermo-hydraulic conditions has been investigated. Then, IKE’s MEWA-2D code has been applied to the DEBRIS quenching experiments in order to promote better understanding of the experimental results as well as to verify its applicability on the quenching process.

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 particles 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 particles bed is of prime importance in the framework of severe accident management strategies, particularly in the case of above mentioned late phase scenario of accident.

Earlier test series at DEBRIS test facility have been focused on addressing the issue of long term coolability of hot debris beds [1]. Schäfer et al. investigated the quench behaviour of monodispersed particles bed for both top- and bottom- flooding conditions [2]. POMEKO experiments are performed at KTH Stockholm with sand particles to study the quenching of non-uniform, irregularly shaped particles of small size under top- and bottom- flooding conditions [3]. Experiments of Tung and Dhir discussed the quenching behaviour of relatively large size spherical particles. They also studied bottom quenching of a hot particulate bed with either constant liquid flow rate or constant driving head [4, 5]. Tutu et al. experimentally investigated debris quenching under forced water flow from the bottom with spherical particles at Brookhaven National Laboratory [6]. In their experiments one-dimensional quenching process is observed for small liquid flow rates and low initial temperatures. But at high flow rates and high

initial temperature of the particles, more complex and multi-dimensional quenching process is observed.

The investigation of quenching of an initially hot dry polydispersed particles bed under top- and bottom- flooding is discussed in this paper. The bottom flooding is provided via a lateral water column. Differing from classical experiments of Tutu et al. (fixed water flow rate at bottom) [6], here water flow is determined by feed back with internal processes in the bed, i.e. the pressure build up due to friction with the water flow, evaporation, limited release of steam etc.. Experiments were performed for different initial bed temperatures varying from 300 to 700 °C. The purpose of this experiment is to provide better understanding and support of the modelling of the quenching process. In this contribution, results of top- and bottom- flooding experiments are presented at first. Then results of DEBRIS bottom- flooding experiments are analysed with the MEWA-2D code[7, 8]. Based on the experimental results and analysis finally a conclusion is drawn .

2. DEBRIS TEST FACILITY

The experimental set-up (Fig. 1) 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 water and a pumping system, which allows performing experiments with feeding water to the crucible at the bottom (bottom-flooding) or at the top (top-flooding). An additional water tank is connected to the bottom of the main test section to perform bottom-flooding quenching experiments under gravity driven flows. Figure 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 main test section consists of a ceramic crucible (Fig. 2). It has a total height of 870 mm and an inner diameter of 150 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.

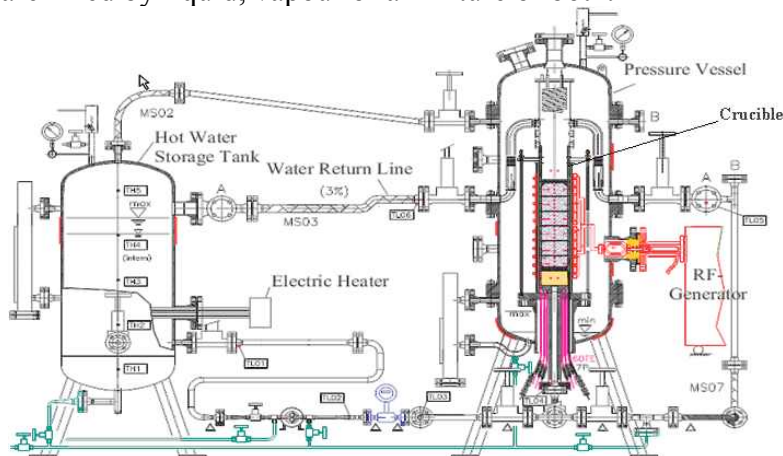


Figure 1: Test facility "DEBRIS"

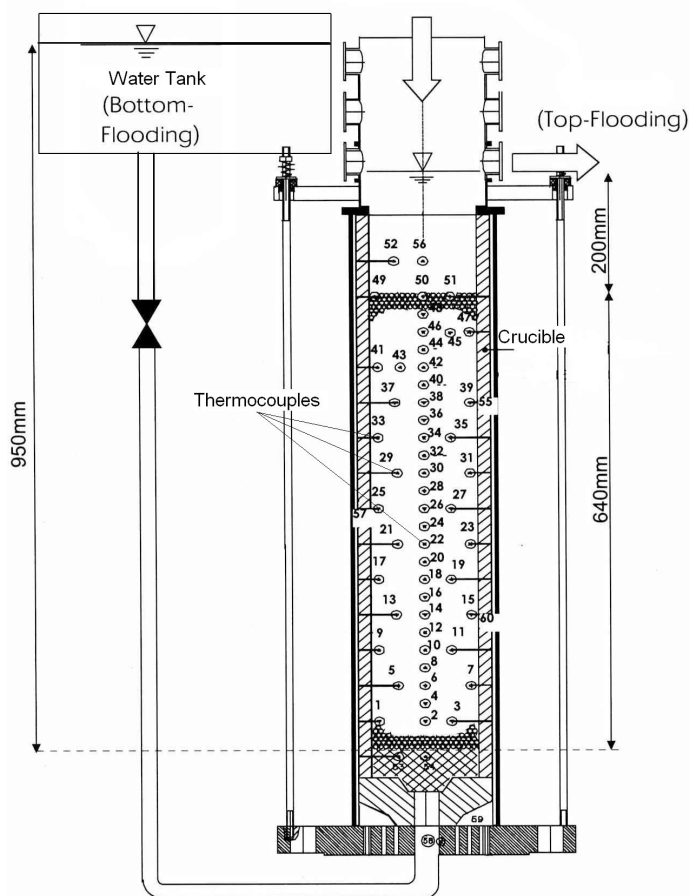


Figure 2: Quenching test section with instrumentation

Polydispersed particles bed is mounted inside the main test section. The polydispersed particles bed is composed of a mixture of pre-oxidized stainless steel balls of three different diameters 2, 3 and 6 mm mixed in a ratio of 20, 30 and 50 % by weight respectively. The measured porosity of polydispersed particles bed is 0.37. The bed height is 640 mm. For bottom– flooding experiments a water tank at a height of 950 mm is connected to the bottom of the bed. So far only bottom– flooding experiments under gravity driven flows are carried out. At ambient pressure the bed is heated up to specified temperatures (300-800 °C). After switching off the heating, the bed is flooded with cold water either from top or from bottom.

3. EXPERIMENTAL RESULTS

3.1 Top-Quenching

In first test series the quenching behaviour of superheated polydispersed particles bed under ambient pressure is investigated for top– flooding conditions. The bed is inductively heated to specified temperatures ranging from 300 °C up to 600 °C. Some in-homogeneities in the initial temperature profiles are observed. For example, in the top– flooding experiment series TF350

(Fig. 3), the maximum temperature is 451 °C (T40, see Fig. 2) in the center of the bed and the minimum temperature is around 200 °C (T7, see Fig. 2) near the wall of the crucible. Such inhomogeneities may be attributed to the heat losses and the smaller inductive heat generation near the crucible wall. After switching off the heating power, the bed is flooded with cold water from top. After some time a water pool of height 200 mm is formed above the bed. The height of the water pool is maintained by a continuous supply of water to the water pool, the excess water is taken out of the system via an overflow line at a height of 200 mm (Fig. 2).

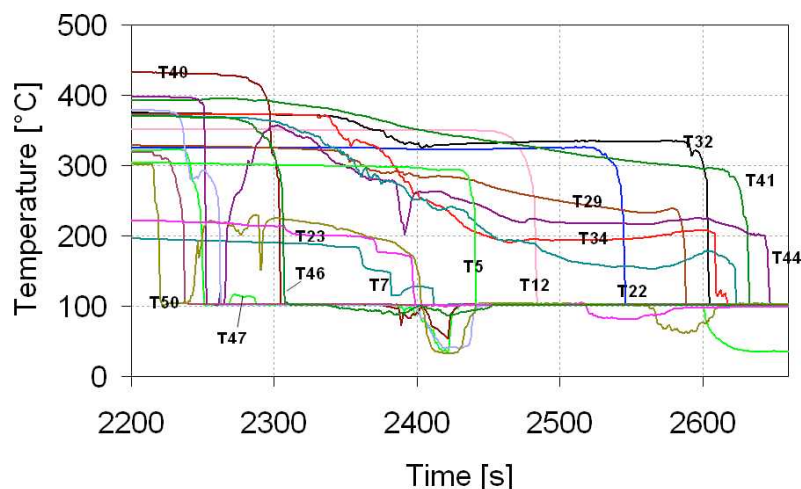


Figure 3: Temperature measurements (top - flooding, TF350)

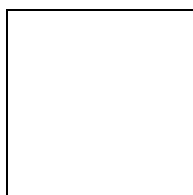


Figure 4: Quenching front progression (top - flooding, TF350)

At the very beginning of top-flooding, the quench front moves uniformly over the whole cross section of the bed. The top-flooding quenching process is quite complex and more of three dimensional in nature. As evident from experiments, after a short time water starts to penetrate into the bed preferably near wall regions where quench front moves faster than in the rest of the bed (Fig. 4). This can be explained by the lower bed temperature and higher porosity (wall effect) near the crucible wall. Once the water reaches the bottom of the bed, the quench front starts to move upwards and the temperature measurements indicate more of a one-dimensional progression of the quench front (Fig. 5). A sharp decrease in temperature is observed when the quench front reaches a thermocouple. Some thermocouple measurements show transient temperature behaviour, e.g. T44, T50 (Fig. 3). The amount of water available at quench front dictates such transient behaviours. If there is sufficient amount of water available in certain parts of the bed, the thermocouples indicate a sharp decrease in temperature of the bed but if the amount of water is insufficient at the quench front, the temperatures will remain on a superheated temperature level. Similarly thermocouple T22 and T23, placed at the same axial position, show different quench behaviour. Although the T23 shows a steep decrease in

temperature T22 remains at about 322 °C for about 148 s until it is also quenched to saturation temperature.

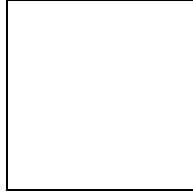


Figure 5: Temperature profile (top - flooding, TF350, $T_{\max} = 451$ °C)

3.2 Bottom-Quenching

Bottom- flooding experiments are carried out for polydispersed bed configuration in a temperature range from 350 °C to 700 °C. The elevated water storage tank is interconnected to the bottom of the bed. After the valve connected between the water tank and the test section is opened the water, driven by gravity, is fed into the bottom of the bed with an initial hydrostatic head of 950 mm.

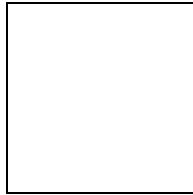


Figure 6: Quench front progression (bottom - flooding, BF400)

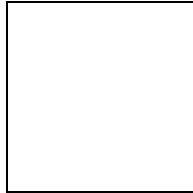


Figure 7: Quench front progression (bottom - flooding, BF600)

The quench front progression observed in the case of bottom– flooding experiments is relatively simple and one-dimensional compared to the top– flooding case. The bottom- flooding experiments show a well defined unidirectional (upward directed) quench front progression. Figures 6 and 7 show the quench front propagation for two different initial bed temperatures BF400 with $T_{\max} = 454$ °C and BF600 with $T_{\max} = 721$ °C. At beginning the quench front progression is relatively fast and slows down with time due to the rising water level inside the crucible which equates more and more the hydrostatic head of the water storage tank (Fig. 8). In previous studies at IKE, quenching experiments were carried out for monodispersed particles bed. In this case, for the maximum initial temperatures up to 430 °C a violent quenching process was observed. In most of the quenching experiments strong “eruptions” were observed which led to an ejection of the bed contents out of the crucible [2]. In present test series with polydispersed particles bed no such strong eruptions are observed.

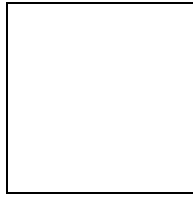


Figure 8: Temperature profile quenching bottom – flooding (BF600, $T_{\max} = 721\text{ }^{\circ}\text{C}$)

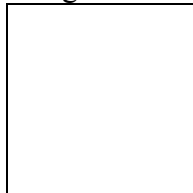


Figure 9: Quench front progression (Bottom - flooding) in the center of the bed for different initial bed temperatures

Figure 9 shows the quench front progression in the center of the bed for different initial bed temperatures. Higher initial bed temperatures lead to higher quench times. Even though the initial bed temperature does not have a qualitative effect on the quench front progression but a slight jump in overall quench time has been observed between the data sets BF500 and BF600 (Fig. 9). At higher initial bed temperatures, it is difficult to explain an increase in quench time only based on the higher thermal energy stored in the bed. The only driving force for water in this case is the hydrostatic head which decreases with the increase of water level inside the bed. In parallel, the increasing amount of vapours generated inside the bed the interactions of water and vapour would also increase which may introduce counter pressure inside the bed and. This counter pressure may resist the inflow of water resulting in higher quenching times.

4. MEWA-2D Analysis

The calculations have been performed for axisymmetric geometry. As in the experiments, a radial temperature profile has been chosen with lower bed temperature at the outer boundary. The driving head from the lateral water column is considered in the calculation by imposing the pressure corresponding to the system pressure plus hydrostatic head of water column at the bottom of the bed. This pressure is considered constant assuming no driving head loss due to pipe friction.

Calculations have been performed for two sets of experiments BF400 and BF600. Results of the MEWA calculation for BF400 with $T_{\max} = 454\text{ }^{\circ}\text{C}$ are shown in Fig. 10. In this figure, the status of cooling and water filling inside the bed at 75 s after start of water inflow is shown. It can be seen that the quenching front progression is not homogeneous; water penetrates preferably at the outer region of the bed (also observed in the experiments). This can be explained by the lower bed temperature there. A thin quenching front, due to slow progression of water (average water inflow of 2 mm/s) and rapid quenching, results from the calculation.

Comparison between experimental and MEWA-2D simulation results for the quench front progression with two different initial temperatures (BF400 and BF600) are given in Fig. 11. The quench front progression predicted by MEWA-2D agrees well with the experimental results in the center of the bed for both experiments. Different explanations could be envisaged for the

slower quench front progression obtained at the higher bed temperature: reduction of water by evaporation, pressure build-up by evaporation acting against driving pressure or increased friction due to flow pattern changes. A detailed inspection of the results indicated that the counter pressure of steam is responsible. This counter pressure is only to a smaller part due to the increased evaporation, but mainly results from the increased steam temperature yielding a larger volume of steam which cannot be released at a sufficient rate. Thus, the resulting counter pressure reduces the average water inflow at bottom from 2 mm/s for test series BF400 to 1.2 mm/s for test series BF600.

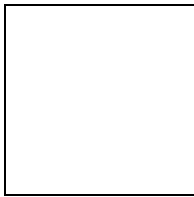


Figure 10: Distribution of temperature and saturation (water contained inside the pore) as well as steam and liquid velocities from MEWA-2D simulations for BF400, bottom-flooding

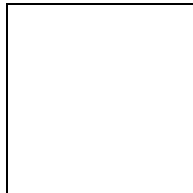


Figure 11: Comparison of measured and calculated quench front progression for bottom-flooding at initial bed temperatures BF400 and BF600

5. Conclusion

At the beginning of the top-flooding quenching experiments a complex multi-dimensional, downward directed quench front progression takes place. In the later phase of the experiments an upward directed, one-dimensional, quench front progression has been observed. Whereas, for bottom-flooding experiments a quasi one-dimensional quench front progression has been observed. For higher initial bed temperatures, higher quenching times have been found. The quench front progression predicted by MEWA-2D agrees well with experimental results measured in the center of the bed. The slower progression of quenching at higher initial bed temperatures is due to the counter pressure of steam reducing the water from the lateral column. From analysis it was found that water moves in the debris bed in a slowly propagating front due to high friction, and the quenching is rapid enough to occur in a thin front. This thin quenching front may also be valid for reactor conditions. Then, a detailed modelling of heat transfer regimes may be less important since quenching occurs anyway in a small front and rather an appropriate description for the friction may be essential.

6. ACKNOWLEDGEMENTS

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7. References

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