Description of the MONET test facility to study quenching of porous bed – Cylindrical particle bed

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1. Introduction

Severe accidents (SA) in Light Water Reactors (LWRs) consist of a sequence of thermal-hydraulic events which leads to situations that progress beyond design-based accidents (DBAs), and involve significant core degradation (severe accidents) which threatens the integrity of the containment. In the wet cavity strategy, it is estimated that when the corium melt with a moderate release rate falls in the deep water pool, the corium jet will break up into small debris particles and create porous debris beds on the bottom of the water pool in the reactor cavity [1-2].

In contrast to the long-term coolability analysis, the quenching of porous debris bed will be characterized by the localized thermal non-equilibrium between the solid particles and fluid (water and vapor). The complex flow patterns and heat transfer mechanisms during quenching process makes it difficult for experimental measurement and modeling. Tutu et al. [3] studied the quenching of porous debris bed by the saturated water injected from the bottom with constant flow rates. Author reported that the quench front of a homogeneous bed during bottom flooding usually proceeds with a uniform one dimensional rate. One of the most important conclusion from the DEFOR-E experiment (Karbojian et al. [4]), suggests development of dry zone in a debris bed which is hardly accessible by coolant. Similar observations were reported by Chikhi et al. [5] in PEARL tests. Earlier in COOLACE tests [6] conducted at VTT, Finland, demonstrated effect of multidimensional particle bed on the long term coolability of particle bed. While the one-dimensional bed configurations were intensively studied since 1980s [7-8], lately problem extends to multi-dimensional configuration in which the lateral water inflow becomes possible. Under this circumstance, the predicting amount of water inflow rate is further complex as the pressure loss at each stream line should be accurately predicted. Rahman [9-10] presented the dryout heat flux under bottom water in flow condition. However a previous attempt [11] on predicting dryout power for multi-dimensional particle bed supports reported that the Rahman model [9, 10] tended to over-estimate dryout power. In view of this, efforts have been made earlier [12-15] for the development of two-phase flow model for predicting dry-out heat flux in particle packed bed.

To enhance the understanding of multidimensional particle bed coolability, here the objective is to understand the mechanism of heat transfer inside the cylindrical heated debris bed with varied particle sizes (Ø 3 - 10 mm alumina) during quenching by cooling water supplied from the bottom of the bed. This paper reports the description of the test facility MCCI-mitigatiON through passive cooling Effect Test (MONET) apparatus established to investigate the quenching behavior of the cylindrical debris bed by means of experiments.

2. Monet test facility

Fig. 1 shows photographic and schematic view of the MONET test facility, which was designed to simulate the particulate debris bed quenching performance. The MONET test facility consists of three major components; testing tank, particle (debris) bed bottom support (DBS) and cylindrical particle (Debris) bed (CDB). Additionally a separate storage water tank was fabricated to heat the water to saturated level. A radiation furnace was used to heat the particle bed to superheated temperature. The testing tank of dimensions 800 x 1000 x 1000 mm is made of SS 304 material. Two sides of the testing tank have a solid SS 304 wall which comprises of various ports for thermocouple connections along the vertical direction. While, the other two sides are made from the polycarbonate window of 10 mm thickness to allow visualization. The bottom of the tank has provision for water input and drainage.

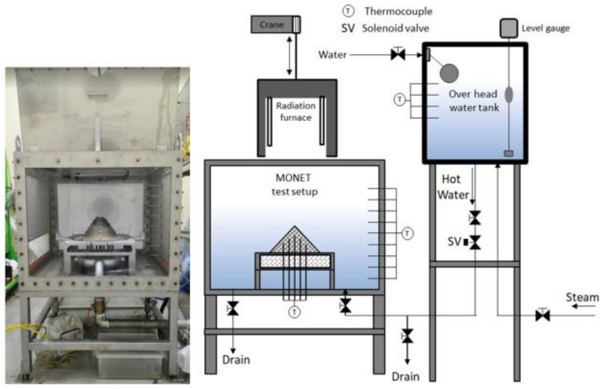


Fig. 1: Monet test setup

The Particle bed (debris) bottom support (DBS) is made from SS 304 and high temperature cement to withstand high temperatures during tests as depicted in Fig. 2). The DBS frame is of 520 x 520 x 100 mm in dimensions and supported by 150 mm high SS 304 legs. Bed (DBS) has 17 openings allowing a passage for TC's to particle bed from bottom of the testing tank. The particle bed is heated to required test temperature using a radiation furnace (15.6 kW) which is maneuvered by an overhead crane.

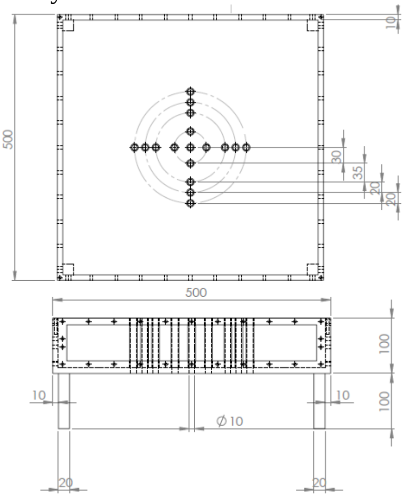


Fig. 2: Particle bed (debris) bottom support (DBS)

Cylindrical particle (Debris) Bed (CDB) has a height of 145 mm and 290 mm and made of SS 304 as shown in Fig. 3. The outer frame will be enclosed by 2 mm thick SS mesh from all sides using M5 bolt. The particle bed consist of 20 shielded thermocouples (OD 1/8 inch, Type K), of which 16 are located in 4 concentric circles (4 TC's in each circle, C1; *r* = 30 mm, C2; *r* = 65 mm, C3; *r* = 85 mm, & C4; *r* = 105 mm from center line of the particle bed) and one at center (CM; *r* = 0) as shown in Fig. 4. The thermocouples measure the temperature in the voids between the particles, which are filled by liquid, vapor or a mixture of both. The test beds were filled with spherical beads (SS 304 or Alumina), used as the debris simulant material as depicted in Fig. 5 (a-b). The size of the beads was measured by vernier calipers for a sample of 100 particles for each type.

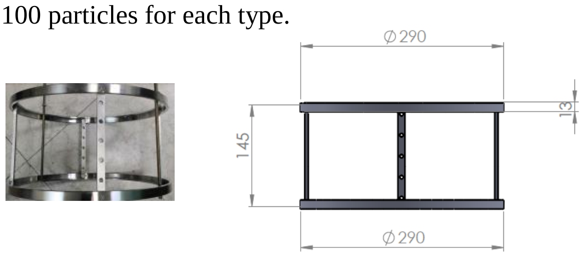
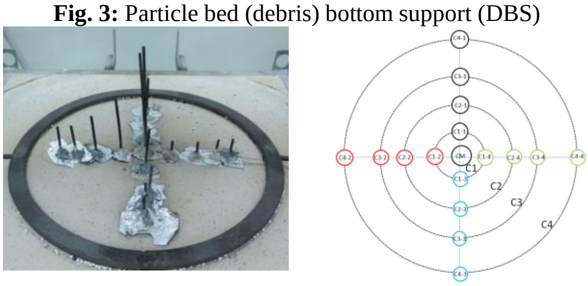
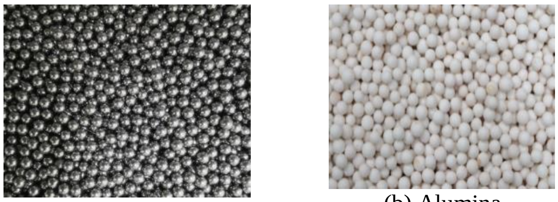


Fig. 3: Particle bed (debris) bottom support (DBS)



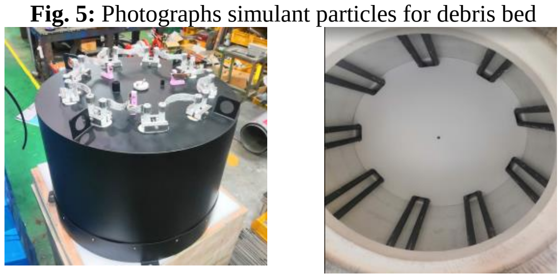
(a) Photographic view of TC's in the bed (b) total TC's spread

Fig. 4: Thermocouples location (r,z) inside the cylindrical debris bed (CDB)



(a) SS 304 (b) Alumina

Fig. 5: Photographs simulant particles for debris bed



(a) Outer furnace housing (b) Inside heating element

Fig. 6: Radiation furnace (15 kW) employed for heating the debris particle bed

A custom made radiation furnace is employed for heating the debris particle bed as shown in Fig. 6 (a-b). The furnace has a power rating of 15.6 kW which can raise the temperature of 900^{o}C in 20 mins. The furnace is guided over the conical particle bed using an electric crane and placed over the top of the DBS supporting frame. The furnace outer surface is insulated with glass wool and ceramic housing, which are then enclosed by a steel cover.

Table 1: Test Matrix for MONET experiments

Test Case	Particle (Dia.; Type)	Debris bed weight	Porosity	Initial bed temp. range	Water temp.
Identification tests					
MONET-CL-1	3 mm; SS 304	46.16 kg	0.423	700^{o}C-400^{o}C	92^{o}C-95^{o}C
MONET-CL-2	3 mm; Al2O3	23.16 kg	0.421	700^{o}C-400^{o}C	92^{o}C-95^{o}C
MONET-CL-3	5 mm; SS 304	43.44 kg	0.457	700^{o}C-400^{o}C	92^{o}C-95^{o}C
MONET-CL-4	5 mm; Al2O3	22.32 kg	0.442	700^{o}C-400^{o}C	96^{o}C-98^{o}C

The saturated water for the experiments was produced in a separate storage water tank of dimensions 1500 x 600 x 800 mm as shown in Fig. 7. The tank is connected a 90 kW steam generator to heat the water to saturation level. Temperature was measured at 9 different locations (1/8 inch, K type) and their average was considered for experiments. The heated tank is connected to the testing tank by 2 inch SS pipe which is insulated with fiber glass wool to reduce temperature drop during flooding. A solenoid valve is provided in the input water line to control the water flooding.

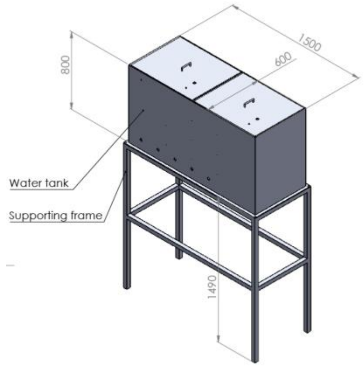


Fig. 7: Schematic of over head tank for water heating

3. Tests procedure

Preparation for the tests began with the installation of the DBS module at the bottom of the testing tank water pool. After assembling the test pool, the cylindrical particle (Debris) bed (CDB) was arranged at the position where the centerlines of radiation furnace and CDB can be vertically aligned. Then, the CDB was filled step wise with spherical beads to the predetermined level. On each step, the weight of the spherical beads was measured to evaluate the total weight of the conical debris bed in order to determine the bed porosity.

Once the debris bed is ready, the visualization window was closed using M8 bolts. A general O-ring is used for sealing against water leakages. The radiation furnace is maneuvered using the crane at center of DBS above cylindrical particle (Debris) bed (CDB). The test runs are started with heating the debris bed using the radiation furnace. As the radiation furnace and the particle bed (debris) bottom support (DBS) is not completely sealed, after a certain period of time the rise in the temperature of the particle bed becomes almost stagnant. Thus the heat-up sequence consists of stepwise increases of heating power until temperature rise of the particle bed at each location becomes less than ~ 0.5oC/min. The water in the storage tank was heated using the steam from the steam generator (Make: Pyeong HWA; Model: HA-90) till the saturated conditions are reached. Due to the condensation of steam, the water level in the storage tank rises and it was monitored continuously using level gauge (Make: Omega; Model: LVR500-Series). Saturated temperature conditions of the tank was maintained using the immersion heater (Make: Omega; Model: ARTM-1500TH/240V). Each experimental scenario was observed visually and recorded using two digital video cameras (Make: Sony, Model: ILCE-7M3, 120 fps and Make: View Works, Model: VC-12MX-C180, 345 fps). The heat up sequence approximately takes 6 hrs. to reach the specified bed temperature for each test case. When the required temperature conditions in the bed and the water is reached, the test facility is ready for quenching tests. The radiation furnace was switched off and removed from top of the DBS and placed in the side of the testing tank on a furnace mounting which seals the bottom of the furnace from steam generated during quenching. A data acquisition system (DAQ) (Make: Keysight; Model: 973DAQ) is employed to monitor and record the temperature transients of different location in particle bed, testing tank and inside the water storage tank during the heating up sequence and quenching process.

To initiate the quenching tests, the solenoid valve was opened and saturated water was allowed to flow into the testing tank. At the same time, both the high-speed camera started recording the flooding and quenching process. When the water level reaches the top of the testing tank, the solenoid valve was closed. The major physical variables for current tests are as follows:

• Temperature of the particle bed (thermocouples at different elevations and radial positions: center, mid radius and periphery),
• Quench front propagation inside the particle bed,
• Visualization of quenching process of debris bed.

The experimental parameters studied in present tests are reported in Table 1. Initially preliminary (Identification) flooding tests were carried out on both types of particles at atmospheric pressure. A number of experimental parameters were established in these pre-tests runs which include the particle bed heat up rate at different elevations and radial positions, temperature uniformity at same elevations and radial positions, total particle bed heating up sequence time period, water flooding mass flow rate, variation in particle packing (porosity) due to self levelling after quenching experiments and, total particle mass to be filled in particle bed for each particle type and size. The pre-test also demonstrated the feasibility of flooding experiments up to 700◦C, with variation of mass flow rate due to gravimetric injection. Once all the required experimental parameters were attained from the pre-test runs, the actual quenching experiments were initiated with MONET - CB test cases. Here, the studies were made with two different particles types (Ø 3 mm; SS 304 and alumina) and bed type (closed and open bottom wall).

4. Considerations of the test arrangement

The test facility aims at representing a porous medium, which is at super-heated transient state as in the case during initial cooling of porous core debris bed. In the present experimental set-up, the heating solution deviates from the one expected in a real situation.

The main difference is in the heating of particle bed accomplished with radiation heater from outside. Different possibilities for the heating arrangement were considered during the design of the test facility. These included using the cartridge heater from inside as in the case of COOLOCE tests [11] or electrical wire heaters threaded into the spherical particles and coiled to form the particle bed [16]. However, taking into account the volume occupied by the heaters and thermocouples inside the bed, the present MONET configuration (heating from outside) was considered the most feasible approach.

The main technical benefits of the test set-up are the possibility to change the test bed dimensions and the relatively simple design, making the usually tedious work required for test bed alterations easier. In addition, local repairs to temperature measurements and bed are possible.

Compared to the COOLOCE experiments [11], here the presence of polycarbonate window make it possible to visually observe the steam generation and quenching process. This will also allow to correctly correlating the quench front movement from visual observation with the tests data from the TC's. The porosity of the test beds is estimated by weighing the particles when building the test beds. The porosities of the different test beds and experiments are listed in Table 1. The volumes of the TC's, which are approximately 2% of the total volume, are subtracted from the total volume in the porosity estimates. The small porosity might be due to the stretching of the wire net, which would increase the amount of particles that can be fitted into the test bed. The wire net is a flexible structure, which means that the dimensions of the test beds supported by the net are more uncertain than those of the flooded cylinder constrained by a solid wall.

5. Conclusions

A new test facility MONET (MCCI-mitigatiON through passive cooling Effect Test) has been designed for investigations of quenching behavior in porous particle beds of different geometries. The issue is of importance in the severe accident management of nuclear power reactors since debris beds may be formed of solidified corium. The main objective of the experiments to be performed with the new experimental set-up is to compare the quenching in a cylindrical particle bed with varied bed porosity. This is done in order to increase knowledge on the coolability of particle beds that have complex geometries and to produce data for code validation purpose.

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