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Study on Effective Particle Diameters and Coolability of Particulate Beds Packed with Irregular Multi-size Particles

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Abstract

One of the key questions in severe accident research is the coolability of the debris bed, i.e., whether decay heat can be completely removed by the coolant flow into the debris bed. Extensive experimental and analytical work has been done to substantiate the coolability research. Most of the available experimental data is related to the beds packed with single size (mostly spherical) particles, and less data is available for multi-size/irregular-shape particles. There are several analytical models available, which rely on the mean particle diameter and porosity of the bed in their predictions. Two different types of particles were used to investigate coolability of particulate beds at VTT, Finland. The first type is irregular-shape Aluminum Oxide gravel particles whose sizes vary from 0.25 mm to 10 mm, which were employed in the STYX experiment programme (2001-2008). The second type is spherical beads of Zirconium silicate whose sizes vary between 0.8 mm to 1 mm, which were used in the COOLOCE tests (Takasuo et al., 2012) to study the effect of multi-dimensional flooding on coolability.

In the present work, the two types of particles are used in the POMECO-FL and POMECO-HT test facility to obtain their effective particle diameters and dryout heat flux of the beds, respectively. The main idea is to check how the heaters' orientations (vertical in COOLOCE *vs.* horizontal in POMECO-HT) and diameters (6 mm in COOLOCE *vs.* 3 mm in POMECO-HT) affect the coolability (dryout heat flux) of the test beds.

The tests carried out on the POMECO-FL facility using a bed packed with aluminum oxide gravel particles show the effective particle diameter of the gravel particles is 0.65 mm, by which the frictional pressure gradient can be predicted by the Ergun equation. After the water superficial velocity is higher than 0.0025 m/s, the pressure gradient is underestimated. The effective particle diameter of the zirconium particles is found as 0.8 mm.
The dryout heat flux is measured on the POMECO-HT facility using particulate beds packed with the same particles as in POMECO-FL. The dryout heat flux of the bed with aluminum oxide gravels under top flooding is found to be close to the prediction of the Lipinski model. The dryout heat flux increases by 51% when applying a 12-mm size downcomer. The dryout heat flux of the bed with zirconium particles test lies between the values predicted by the Reed model and Lipinski model. The use of the 12-mm size downcomer increases dryout heat flux by 16%.

Key words

Debris bed coolability, Effective particle diameter, Particulate bed, Dryout heat flux

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Contents

1. Introduction

One of the key questions in severe accident research is the coolability of the particulate bed, i.e., whether decay heat can be completely removed by the coolant ingress into the debris bed. Extensive experimental and analytical work has been done to substantiate the coolability research. Most of the available experimental data is related to the beds packed with single size (mostly spherical) particles, and less data is available for multi-size/irregular-shape particles. There are several analytical models available, which rely on the mean particle diameter and porosity of the bed in their predictions.

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2. Effective particle diameter

2.1 POMECO-FL test facility

The experiment is carried out on the POMECO-FL test facility, as illustrated in Fig. 2, which is basically an adiabatic water/air single and two-phase flow loop for porous media. Major components of the test facility are made of transparent Plexiglas to facilitate visual observation. The test section accommodating the particulate bed is made of a Plexiglas pipe with the inside diameter of 90 mm and the height of 635 mm. Four annular chambers for pressure tapping are designed to surround the pipe at different levels, with radial holes (0.5 mm in diameter) uniformly distributed as opening from the bed to the annular chambers. The chambers not only provide an average pressure reading over the entire circumference of each tapping point, but also prevent gas and particles from entering the impulse lines of pressure transducers. At both the inlet and the outlet of the test section, two pieces of stainless steel wire mesh are applied between the flanges to support the bed from below and prevent the particles from leaving the bed. Air is supplied from the bottom and flows up through the packed bed, but water can be supplied from either the bottom or the top for a bottom-fed (co-current flow) or a top-flooding (counter-current flow) bed.

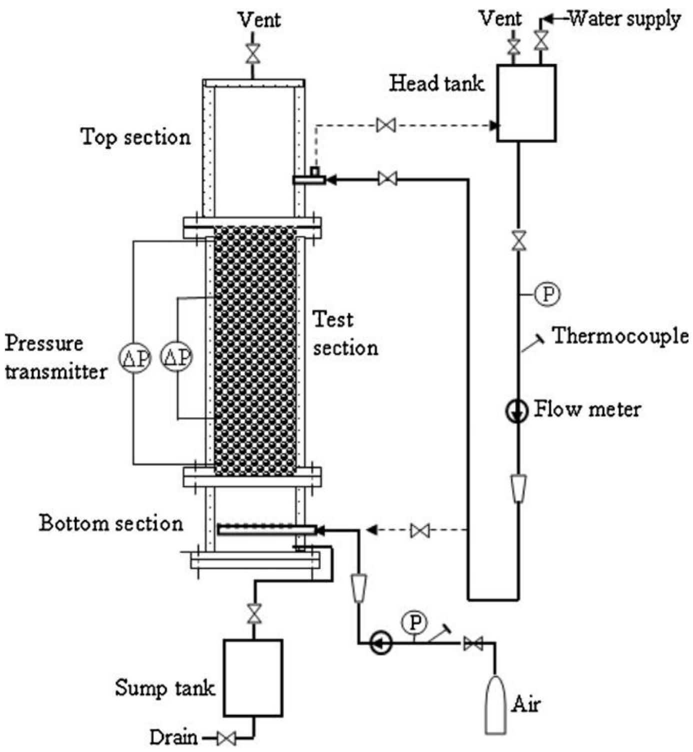


Fig. 1. Schematic of POMECO-FL facility

Two Rosement-3051 differential pressure transmitters with high accuracy are mounted on the test section to measure entire and half pressures drops, respectively, of single- or two-phase flow through the bed. Valve manifolds are used with the differential pressure transmitters to perform the block, equalizing and vent requirements of the transmitters. The flowrates of gas and water flows are measured by seven OMEGA flow meters with different measuring ranges. The pressure and temperature are monitored by using OMEGA pressure transducers and K-type thermocouples. The flow meters and pressure transducers were calibrated prior to experiment. A Data Acquisition System (DAS) is realized via National Instruments data acquisition products and a computer program written in LabView. The program collects the data from thermocouples, pressure transducers, flow meters (via manual input), and employs the indicators to show the numerical data and its graphical representation such as charts.

2.2 Qualification of the facility

After the well-mixed particles are uniformly loaded into the test section, the fluid (air or water for single phase flow) is made to flow through the packed bed at low velocity until there is no change in bed height and in flow resistance, to make sure that the fluid floods the bed and has access to all the pores. For the pressure drop measurement, the impulse lines of the differential pressure transmitters are filled with single phase fluid by proper operation of the valve manifolds, so that the effect of gravity on pressure drop reading can be excluded. Prior to start measurements, the facility is running for no less than half an hour to establish steady state conditions throughout the system. After the steady-state data are recorded by the data acquisition system, changing the operational parameters (e.g., the flowrates), the procedure is repeated.

In addition to the calibration of instrumentation, the test facility and its measurement system were also qualified by measurements of single-phase flow through three beds packed with single-size glass spheres of diameter 3mm. The porosity of the bed is 0.366. Water was employed as working fluid. The measured pressure gradients were then compared with those predicted by the Ergun equation, whose predictions are generally accepted for packed beds of spheres with satisfactory accuracy (Nemec and Levec, 2005). Fig. 2 shows the comparisons between the measured values of the experiment and the predicted values of the Ergun equation, where triangle symbols represent experimental data and the solid curves the predicted ones. The correct operation of the facility and accuracy of the instrumentation can be justified on the basis that measured and calculated results agree excellently in case of a well-known problem.

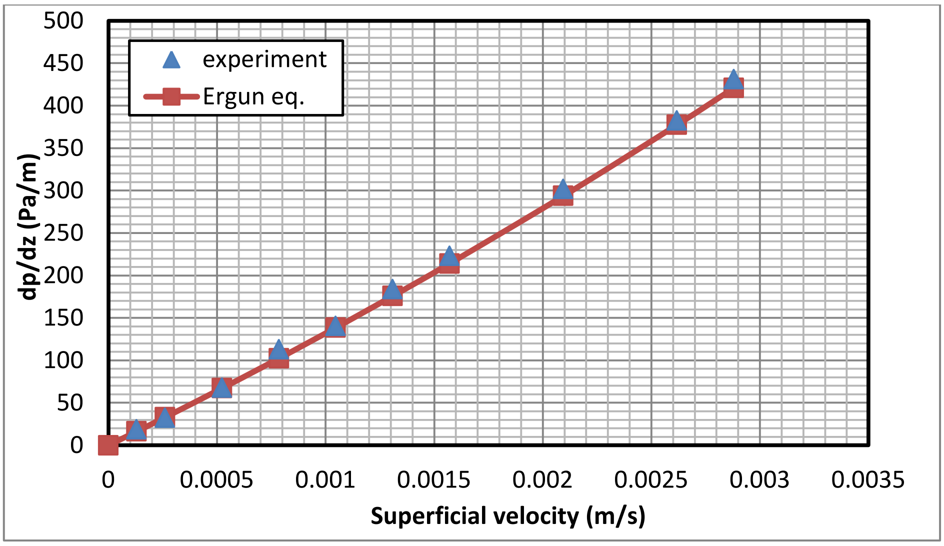


Fig. 2. Frictional pressure gradient of water flow in the bed packed with 3 mm single size spheres

2.3 Test particulate beds

In the present single phase study, the experiment is carried out on POMECO-FL facility using Bed-1 and Bed-2. The pictures of particles used in Bed-1 and Bed-2 are shown in fig. 3. The mass distribution of Alumina gravels was determined by sieving the particles using different size sieves and it is compared (fig. 4) with the distribution used in STYX experiments. The provided density of the particles is 3930 kg/m^3, but in order to maintain the accuracy in the calculations, the density has been recalculated using one of the fundamental methods. The volume measurement beaker is used and the volume of the known mass of the particles is measured by pouring the particles in a beaker containing known volume of water. Taking multiple readings the average density is calculated. Similar process is applied for Bed-2 particles and the density has been deduced. The details of the particulate beds are provided in table 1. Water is employed as a working fluid. The experiment procedure is followed similar to that explained earlier.

Table 1 Details of the beds.

Bed	Particle type	Density (kg/m^3)	Bed porosity	Particle diameter (mm)
Bed-1	Alumina gravels	3900	0.408	0.25-10
Bed-2	Zirconium silicate spheres	4230	0.399	0.8-1

a)

b)

Fig. 3. Particles used in experiments (a. used in Bed-1and, b. used in Bed-2)

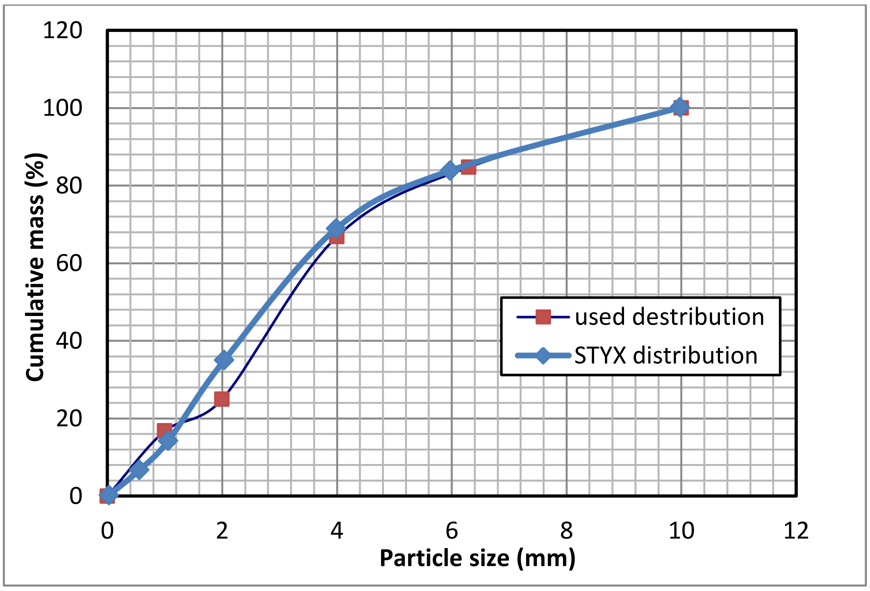


Fig. 4 Alumina gravels particle distribution (compared with Lindholm et al., 2006)

The effective particle diameter of the particles is calculated using frictional pressure gradients obtained from experiment and the Ergun equation.

$$-\frac{dp}{dz} = \frac{\mu}{K} J + \frac{\rho}{\eta} J^2 = 150 \frac{(1-\varepsilon)^2 \mu}{d^2 \varepsilon^3} J + 1.75 \frac{(1-\varepsilon)\rho}{d\varepsilon^3} J^2 \qquad \text{Eq. (1)}$$

Where, *dp/dz* is the pressure gradient along the height of the bed. The parameters K and η are called permeability and passability, respectively. Moreover, in the expression of Eq.(1), 150 and 1.75 are called the Ergun constants, and d is the diameter of particles, ε is the bed porosity , μ is the dynamic viscosity of fluid, ρ is the density and J is the superficial velocity of fluid. The porosity of the Bed-1 is measured as 0.408. The shape factor is taken as 1. Substituting values in Eq. (1), the effective particle diameter (d) is calculated and it is found as 0.65 mm. Similarly, the porosity and the effective particle diameter for the Bed-2 are found as 0.399 and 0.799 ≈ 0.8 mm respectively.

The measured pressured gradients are then compared with those calculated by Ergun equation. Figure 5 shows the comparison between experimental data and the predicted values using Ergun equation for Bed-1. It illustrates that the experimental frictional pressure gradient values are closer to predicted values till 0.0025 m/s water velocity and, thereafter it is slightly underestimated by the Ergun equation.

Figure 6 shows the variation of the experimental frictional pressure gradient with respect to superficial velocity. The values are closely matching with the Ergun equation. Though it is specified that the particles' size varies between 0.8 to 1 mm, the effective particle diameter is found as 0.8 mm, which shows that the porosity and the characteristics of the Bed-2 is equivalent to that of the bed filled with 0.8 mm uniform size particles.

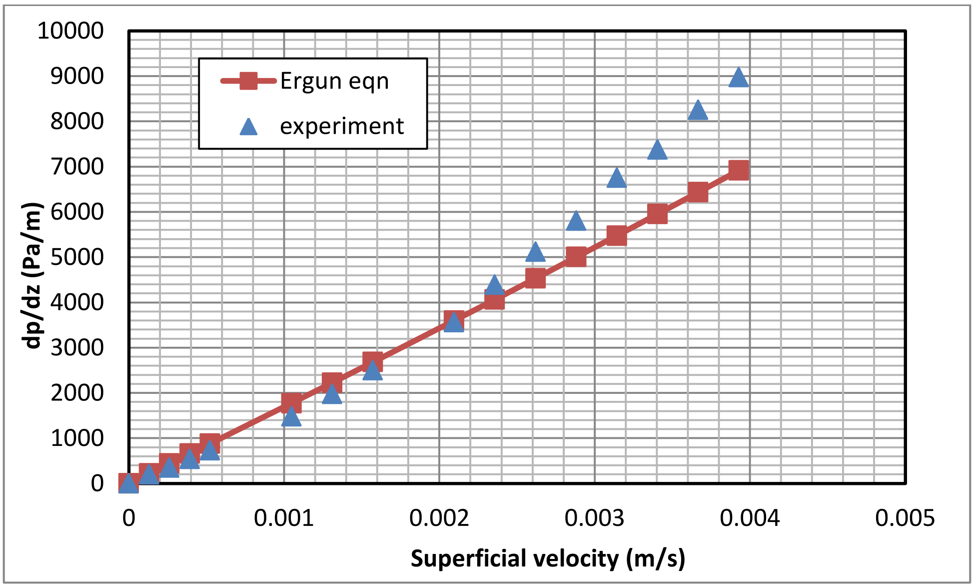


Fig. 5. Frictional pressure gradients of water flow in the Bed-1.

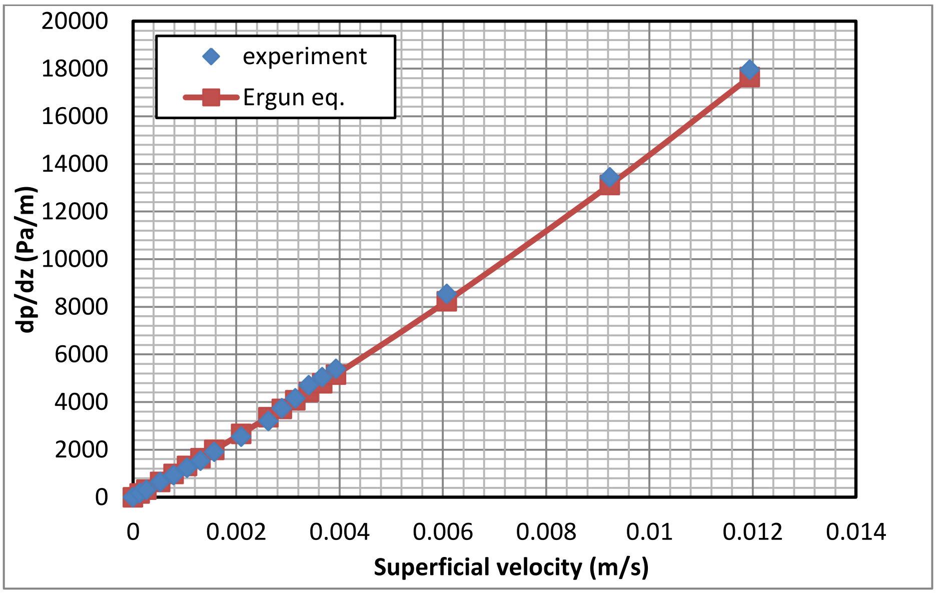
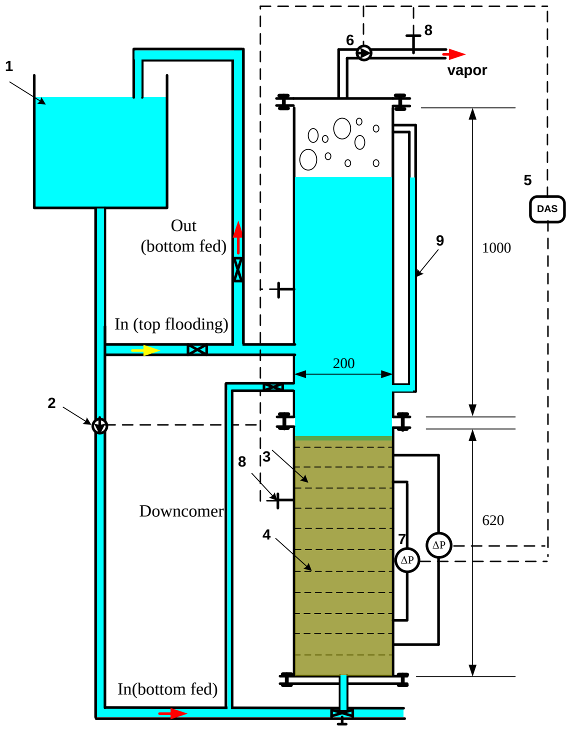


Fig. 6. Frictional pressure gradients of water flow in the Bed-2.

3. Dryout heat flux

3.1 POMECO-HT test facility

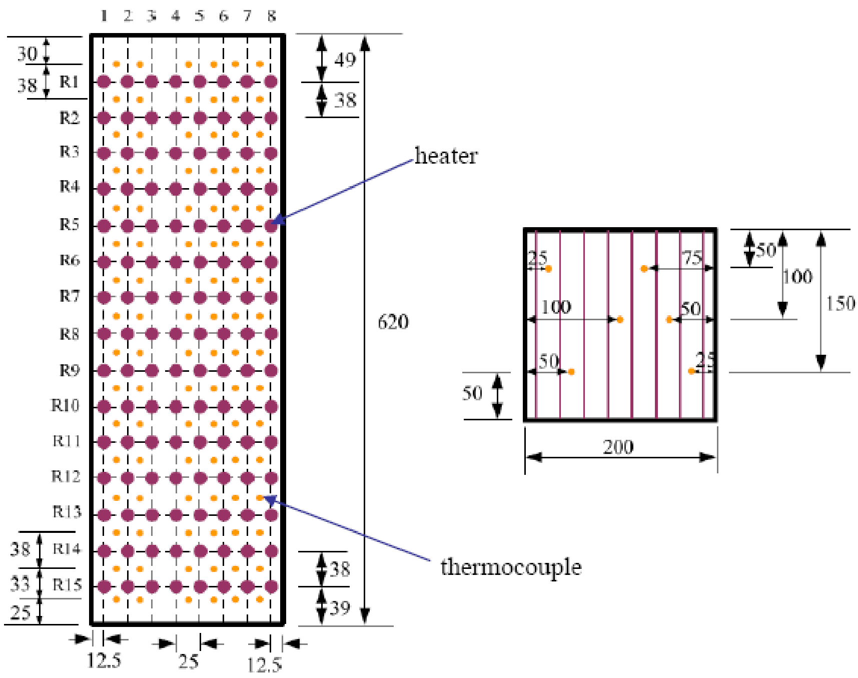
The POMECO-HT facility features a high heat flux up to 2.1 MW/m^2, which enables a sufficient internal power for particulate beds of various characteristics to reach dryout condition for both top-flooding and bottom-fed cases.



1-water tank, 2-water flowmeter, 3-particle bed, 4-heaters, 5-data acquisition system, 6-steam flowmeter, 7-pressure transducer, 8-thermocouples, 9-water level gauge

Fig. 7 Schematic Diagram of POMECO-HT Facility

The schematic of the POMECO-HT facility is shown in Fig. 7, which consists of test section, water supply system, electrical heaters and their power supply system, instrumentation (thermocouples, flowmeters and pressure transducers) and data acquisition system (DAS). The test section for accommodating the particulate bed and heaters is a stainless steel vessel whose cross-sectional area is 200 mm×200 mm rectangular with the height of 620 mm. Over the test section is sitting a stainless steel water tank (200 mm×200 mm) which is 1000 mm tall and connected to the test section through flanges. A level meter is installed on the water tank to monitor the water level during the experiments. The test section and the water tank are well insulated. A total number of 120 electrical resistance heaters are uniformly distributed in the particulate bed with 15 vertical layers and each layer has 8 pcs heaters, as shown in Fig. 7. The average distance between the two adjacent heaters is about 38 mm in vertical direction and 25 mm in horizontal direction. The power rating of each heater is 700 W, so the maximum power capacity of facility is 84 kW. The particulate bed is also provided with 96 thermocouples installed at 16 vertical levels, each having 6 thermocouples at different locations of the cross-section. Basically, the thermocouple layer is 19 mm away from the heater layer. Moreover, 6 thermocouples are specially installed which are very close to the heaters in 6 different layers for monitoring the temperature of heaters. These thermocouples have the same direction with the heaters and are only 2 mm away from the heaters, and the measured location is near the center of the heaters. The diameter of each thermocouple is 1.5 mm with various lengths inserted in the bed, as shown in Fig.8b. While each heater has the diameter of 3 mm and the total length of 235 mm, with the heated part of 195 mm. So the heaters and thermocouples occupy about 0.7% in volume of the test section.



(a) side view (b) top view

Fig. 8 Distribution of Heaters and Thermocouples

For the present experiments, the received particles' amount is 10 liters, which is not enough to fill the total volume (24.4 liters) of the bed. Therefore, 0.01 m^3 of the total test section is utilized for the experiments. The numbers of heaters utilized are 48 and the maximum power capacity of the bed is 33.6 kW.

3.2 Qualification of the POMECO-HT facility

Once the calibration of instrumentation is done, the test facility along with its measurement system is qualified by conducting a single-phase flow measurements through a bed packed with single-size of 1.5 mm diameter stainless steel spheres. Water is employed as a working fluid. The measured pressure gradients are compared with those predicted by the Ergun equation. Fig. 9 shows the comparisons between the measured data and the predicted values of the Ergun equation. The triangular symbols represent experimental data whereas the solid curves are predicted ones. A comparison shows a good agreement which ensured a quality of experimentation and instrumentation.

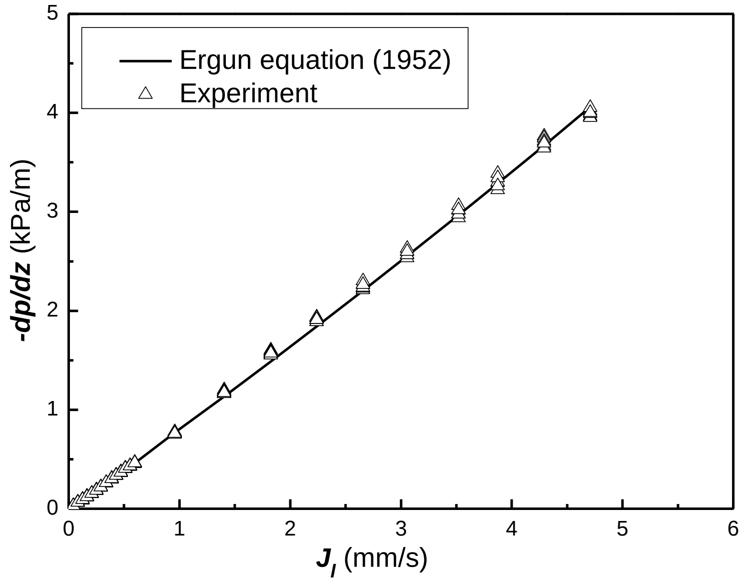


Fig. 9 Pressure gradients of water flow in the bed packed with 1.5 mm stainless steel spheres

3.3 Test particulate beds

In the POMECO-HT experiments, Bed-1 and Bed-2 are regarded (similar to POMECO-FL test beds) to Alumina gravels and Zirconium Silicate beads particles respectively. Initially, the test with Bed-1 is carried out to calculate the dryout heat flux in the bed. The bed is filled with 10 liters of Alumina gravel particles. The porosity of the bed is calculated as 0.35, from the filled volume, density of material and the weight of the bed. The top flooding test is initiated with supplying the hot water to the bed, followed by slowly heating the bed to bring the water to the completely saturated condition and also the uniform temperature across the bed. Thereafter, the power is increased in small steps and the time between each power step increment is at least 15 minutes. Near the expected dryout, the power increment step is further reduced and the time span is increased. The dryout is recognized by the sudden rise in the temperature anywhere in the bed, detected by the thermocouples. The dryout for the Bed-1 is found at 3.59 kW power, which gives the dryout heat flux of 89.9 kW/m^2, under top flooding conditions. The location of dryout inception is found at 96 mm from the bottom which is in the lower half of the bed. Figure 10 shows the comparison of the dryout heat flux with different models. It illustrates that the dryout heat flux calculated from the experiment is slightly higher than those values predicted by the models. Among the comparison, the Lipinski model predicted dryout heat flux closer to the experimental value.

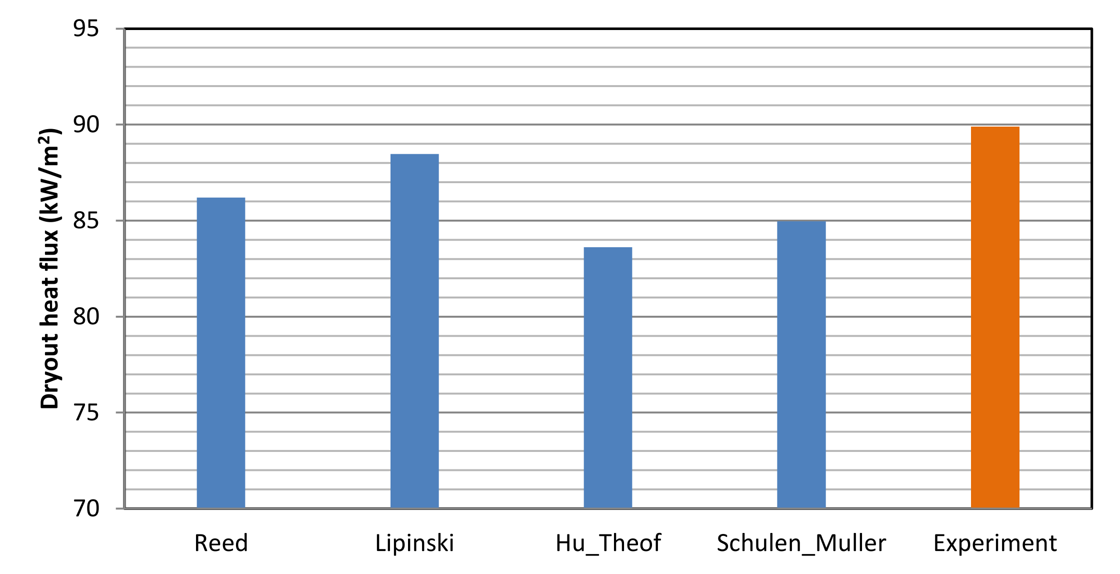


Fig. 10 Comparison of the dryout heat flux in Bed-1 with various models under top flooding conditions

In order to test the effect of downcomer on the dryout heat flux of Bed-1, 12 mm downcomer is installed in the test. The dryout heat flux is found at 135.75 kW/m^2. Figure 11 compares the dryout heat flux between top flooding and with the downcomer and it shows the 51% increment in the dryout heat flux using 12 mm downcomer.

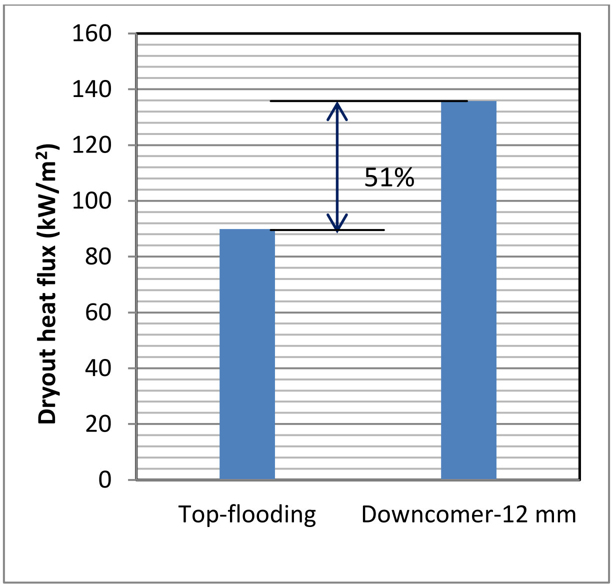


Fig. 11 Effect of downcomer on dryout heat flux in Bed-1

Secondly, the Bed-2 (Zirconium Silicate beads) is prepared for the next test on POMECO-HT facility. Similar to Bed-1, the volume of Bed-2 is 10 liters. The porosity of the bed is calculated as 0.371. The top flooding test is performed using the similar process as described for Bed-1. The dryout heat flux is found as 161.82 kW/m^2. Figure 12 shows the comparison of dryout heat flux obtained from the experiment with various models, which illustrates that the value is closer to the predictions by Lipinski model and Reed's model.

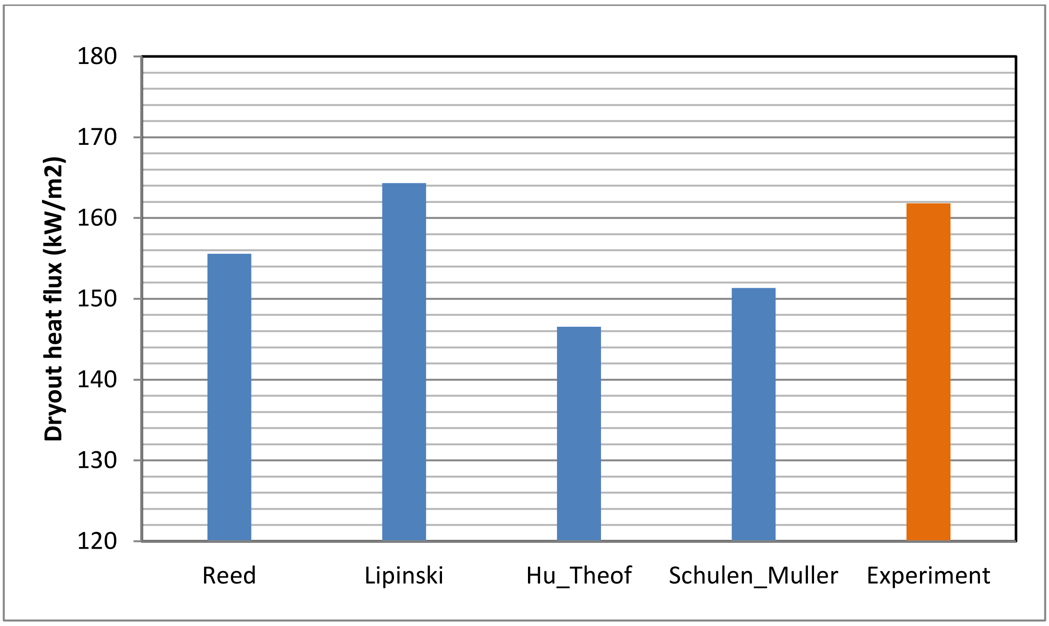


Fig. 12 Comparison of the dryout heat flux in Bed-2 with various models under top flooding conditions

The effect of downcomer is also studied for Bed-2 using 12 mm size downcomer. The dryout heat flux obtained in this case is 188.39 kW/m^2. It is 16% higher than that of top flooding case, as shown in fig. 13.

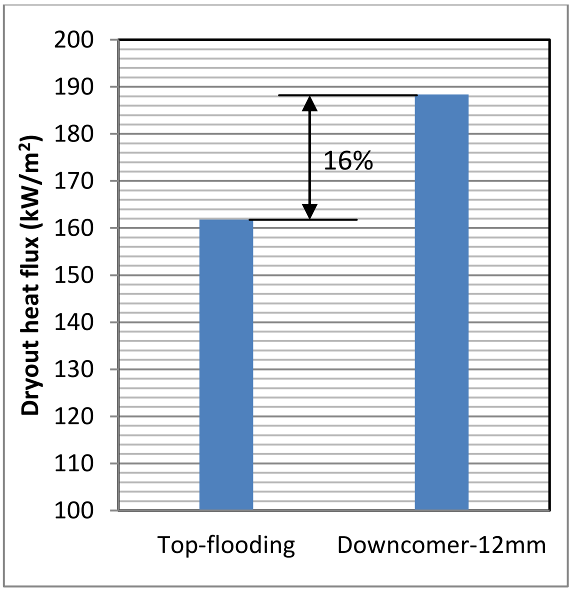


Fig. 13 Effect of downcomer on dryout heat flux in Bed-2

4. Concluding remarks

The tests carried out on the POMECO-FL facility using a bed packed with aluminum oxide gravel particles show the effective particle diameter of the gravel particles is 0.65 mm, by which the frictional pressure gradient can be predicted by the Ergun equation. After the water superficial velocity is higher than 0.0025 m/s, the pressure gradient is underestimated. The effective particle diameter of the zirconium particles is found as 0.8 mm.

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