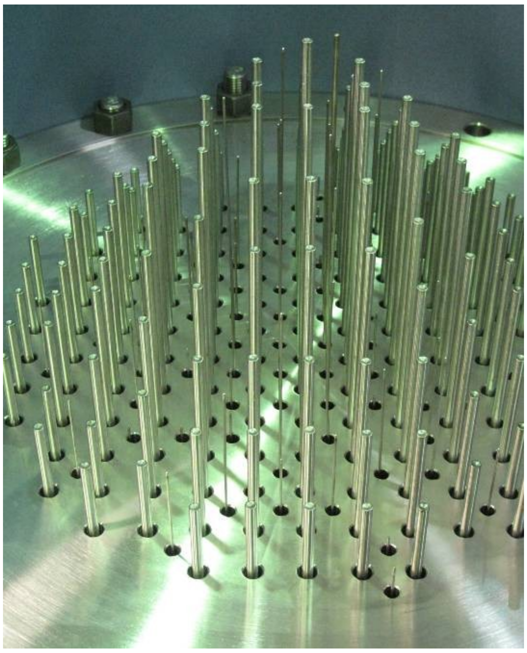
RESEARCH REPORT

VTT-R-08956-10



Description of the COOLOCE test facility – Conical particle bed

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Summary

A new test facility has been designed and constructed for investigating the coolability of porous core debris beds in different geometries. Particle bed coolability is an important issue in the severe accident management of e.g. the Nordic boiling water reactors. During a core melt accident, particle bed that generates decay heat is expected to be formed in the flooded lower drywell of the containment.

In the new COOLOCE (Coolability of Cone) test facility, the effect of the particle bed geometry is taken into account: dryout heating power measured in a conical (heap-like) geometry is compared to that of a cylindrical geometry. The main questions investigated are the effects of multi-dimensional flows allowed by the conical geometry, and the increased particle bed height in the centre of the conical bed as compared to the cylindrical particle bed.

The new test facility consists of the test particle bed housed in a pressure vessel, the particle bed resistance heating system, the feed water and steam removal systems and the process controls and measurements. The description of the test facility with the conical particle bed configuration and the results of the first experiment aiming for dryout are presented.

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Contents

1 Introduction

At the Finnish BWRs in Olkiluoto the flooding of the lower drywell of the containment is a key part of the severe accident management strategy. In the course of a severe accident, the corium is discharged from the ruptured pressure vessel into a deep water pool in the lower drywell. The corium is fragmented and it forms a porous particle bed from which decay heat must be removed in order to prevent re-melting of the material.

The coolability limits (dryout power) of particle beds have been investigated in the various STYX experiments during 2001-2008 (see e.g. Lindholm et al. 2006 and Takasuo et al. 2009) that were conducted within the frame of the SAFIR2010 research programme and its predecessors. The STYX test rig consisted of a cylindrical particle bed. The first STYX tests (series 1-9) investigated particle beds with top flooding, with or without particle size stratification. In this configuration, the water infiltrates the particle bed only through the top surface of the bed.

Lateral bottom flooding was taken into account in the test series 10-13 in which downcomers were installed on the sides of the test rig to feed cooling water to the bottom section of the test bed, in addition to the top flooding. These experiments revealed a modestly increased coolability for a homogenously distributed particle bed compared to the case with no downcomers. For a stratified bed with a layer of very fine particle on top of the bed, no consistent increase in dryout power was seen with the applied downcomer size (Takasuo et al. 2009).

The dryout power measured in the experiments can be converted to dryout heat flux or volumetric heat flux using which the coolability of particle beds of different size may be compared to each other. The dryout heat flux is defined as the surface heat flux that leads to local dryout in the particle bed interior. The volumetric dryout heat flux is the power generation per unit volume corresponding to this.

The COOLOCE (Coolability of Cone) test design described in this report was initiated using a completely new approach in which the experimental particle bed is conical (heap-like). The dryout power obtained for the conical set-up can be compared to a corresponding cylindrical set-up. The same test vessel can be used for both geometries.

Experiments such as DEFOR at KTH in Sweden (Karbojian et al. 2009) that study the formation of the particle bed suggest that heap-like particle beds with significant inhomogeneities could be possible in reactor scenarios instead of the evenly distributed, cylindrical bed with top flooding. The complex multi-dimensional flows allowed by the heap-like geometry may yield significantly increased coolability compared to particle beds with top flooding only (see e.g. Schmidt, 2004). On the other hand, the heap-like configuration is higher than a cylindrical configuration of the same volume. This means that heat load in the centre of the heap-like particle bed is also greater than in a cylindrical bed. The effect of bed height in this sense is one of the main questions studied in the COOLOCE experiments. Other important goals are to provide data to complement the code validation database for severe accident analysis and increase knowledge of two-phase flows in porous media.

2 The COOLOCE test facility

The conical particle bed of the COOLOCE test facility is installed inside a custom-made pressure vessel that has a design pressure of 7 bar. The particle bed consists of ceramic spheres that are being held in conical shape by a dense wire net. The particle bed is heated by resistance heating system that uses ∅ 6.3 mm vertically installed heaters of different lengths whose arrangement shown in Appendix 1. The configuration aims at achieving a uniform temperature distribution within the test bed. The maximum heating power of the power source is 63 kW but the nominal maximum power is limited to 55 kW due to heater specifications. Overviews of the main components of the COOLOCE facility are presented in Fig. 1 and Fig. 2.

Fig. 1. COOLOCE test facility details, 1) feed water pre-heater (3kW), 2) feed water control valve, 3) input power connection box, 4) pressure vessel, 5) condenser, 6) video monitoring and recording, 7) water level control and pressure gauges.

To measure the particle bed temperature and detect dryout, K type thermocouples are installed in a distributed configuration striving for maximal coverage of the particle bed volume between the heaters. The heaters and the thermocouples are connected through the pressure vessel bottom that contains a total of 215 tapered holes for the different connections. The detailed maps of the heaters and thermocouples are presented in Appendices 1 and 2.

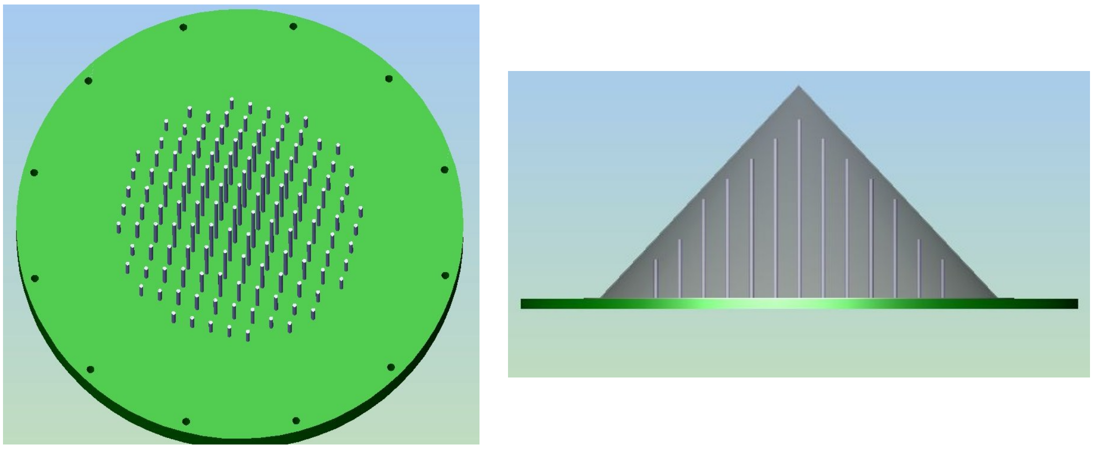
In the beginning of the experiments the vessel is filled with demineralised water, pressurized and heated up to the saturation temperature. After this first steady-state has been established, a stepwise power increase is conducted until local dry-out is observed. The start-up power may vary according to the expected dryout power. A nominal waiting time of 20 to 30 minutes is applied between the power increments in order to see whether the particle bed stabilizes to a coolable state or local dryout is reached. Dryout is detected as an offset (software alarm offset e.g. 5°C) from the saturation temperature.

Fig. 2. The COOLOCE test facility with the condenser in front.

2.1 The heating arrangement

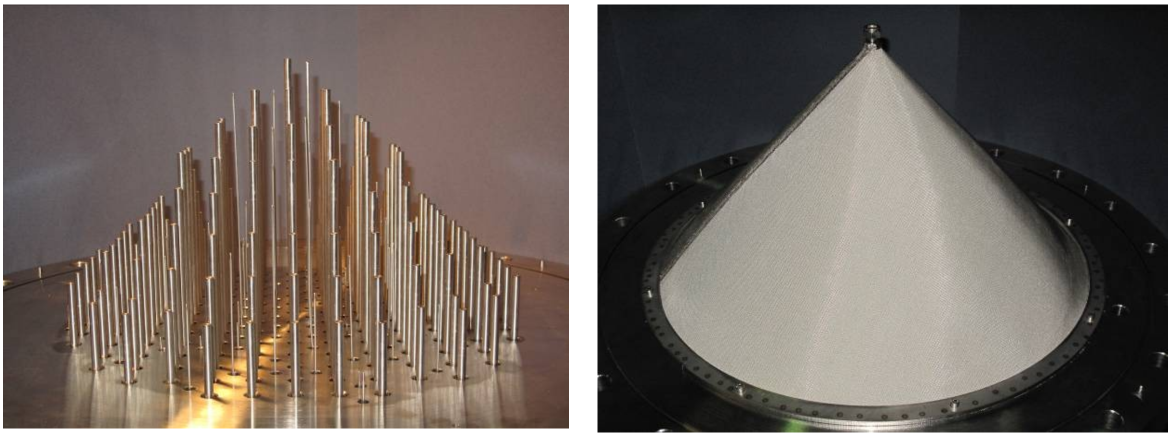
The radius of the conical particle bed is 250 mm and the height is 267 mm. The volume of the cone is 0.0175 m^3 (17.5 l). Conceptual sketches of the cone with the heaters are given in Fig. 3(a) and Fig. 3(b). The final arrangement of the heating and temperature measurements is seen in Fig. 4(a) and the particle bed filled with particles and being held in place by a wire net in Fig. 4(b). The net is made of 0.25 mm thick stainless steel wire. The mesh size of the net is 0.63 mm.

A total of 137 cartridge heaters of different lengths are installed inside the particle bed in such a way that volumetrically a nearly-uniform power distribution can be obtained during the test runs (see Appendix 1). The specifications of the heaters are given in Table 1. The nominal maximum surface power of the heaters is 25 W/cm^2. The heaters occupy about 2% of the cone volume and their total nominal maximum power is 55 kW. The height of the longest heater in the centre is 225 mm from the test bed bottom. Each of the heaters has an approximately 5 mm tip with no heating in the topmost part, and a non-heated part of 80 mm in the bottom for the connections through the pressure vessel bottom.



(a) (b)

Fig. 3. Views of the conical particle bed with the heaters.



(a) (b)

Fig. 4. (a) The heating and temperature measurement configuration and (b) the particle bed composed of ceramic particles held in place by a wire net.

The heaters are divided in three different groups according to electrical phase. The power is regulated by setting the power level manually. The input power can be followed from a power meter (D96FM-4) with calibrated measuring transformers. The control variable is the input voltage (0 - 230 V) from a purpose tailored power transformer with the maximum output of 63 kW. The manual setting of input-power level has an accuracy of around 0.2 kW.

Thermocouples are placed in the center points of the "square mesh" formed by the heaters. The thermocouples are seen as the thin rods between the heaters in Fig. 4(a) and their positions are indicated in Fig. 5. The set-up has a total of 69 thermocouples which are used to determine dryout time and location: an increase from the saturated conditions during the test at a fixed power level indicates dryout. The thermocouple density is highest in the upper central part of the conical configuration in the region in which dryout is expected to occur. The detailed mapping of the thermocouples is found in Appendix 2.

Table 1. Heaters (∅6.3 mm) in the conical configuration. Total length, heated length, maximum power and the number of heaters are given.

Total length [mm]	Heated length [mm]	Power [W]	Amount
305	220	950	1
280	195	850	8
255	170	740	12
230	145	620	16
205	120	515	8
180	95	400	24
155	70	290	28
130	45	175	40

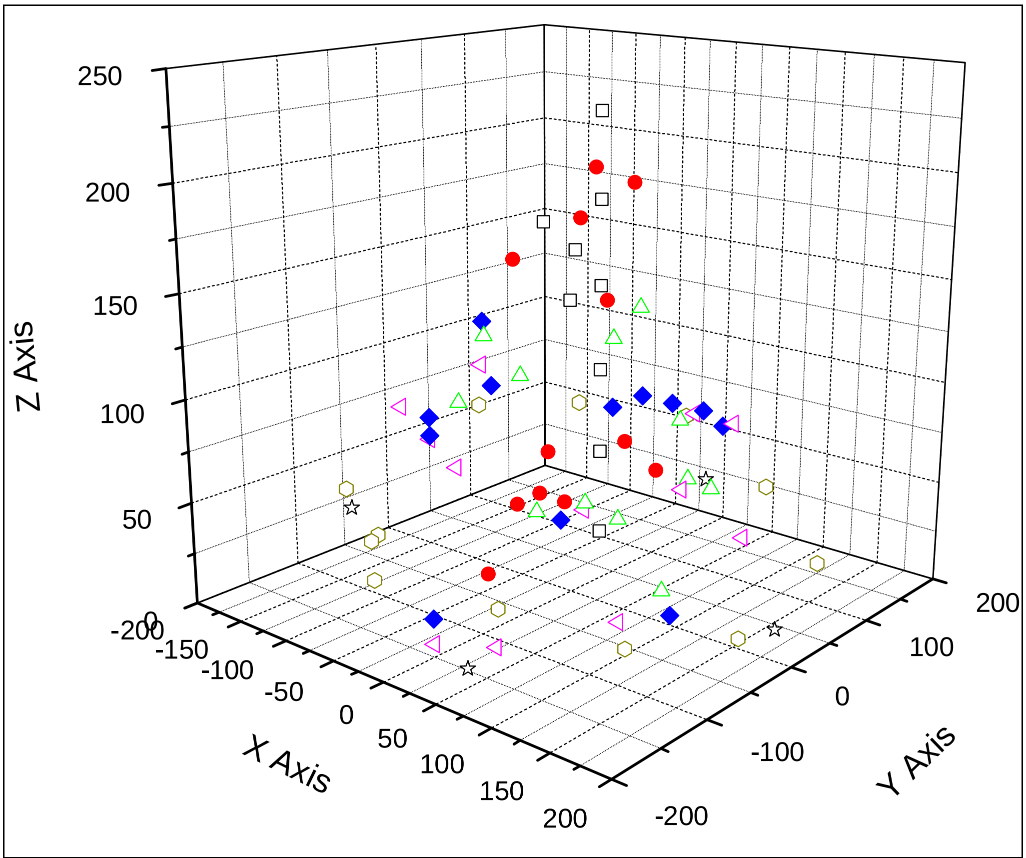


Fig. 5. Temperature measurement locations (see Appendix 2).

2.2 The particle material

The test particle bed is composed of zirconia/silica beads, a blend of ceramic materials (Alpine Power Bead SZS, $ZrO_2 \geq 65\%$, $SiO_2 \leq 35\%$) that have a diameter of 0.8 mm – 1.0 mm. The density of the material is 4000 kg/m^3. The thermal conductivity of the material is of the order of 2.0 W/mK. The advantages of ceramic beads are their corrosion resistance and hardness, as well as the cost-effectiveness. A sample of the material is shown in Fig. 6.

Fig. 6. The particle material is composed of ceramic beads (∅ 0.8-1.0 mm).

The effectiveness of the heat transfer from the heaters to the porous material plays an important role in the experimental set-up. The better the heat transfer from the heaters, the more representative the configuration is considering a uniformly heated particle bed. Insufficient heat transfer from the heater surfaces may cause the heaters to overheat and fail.

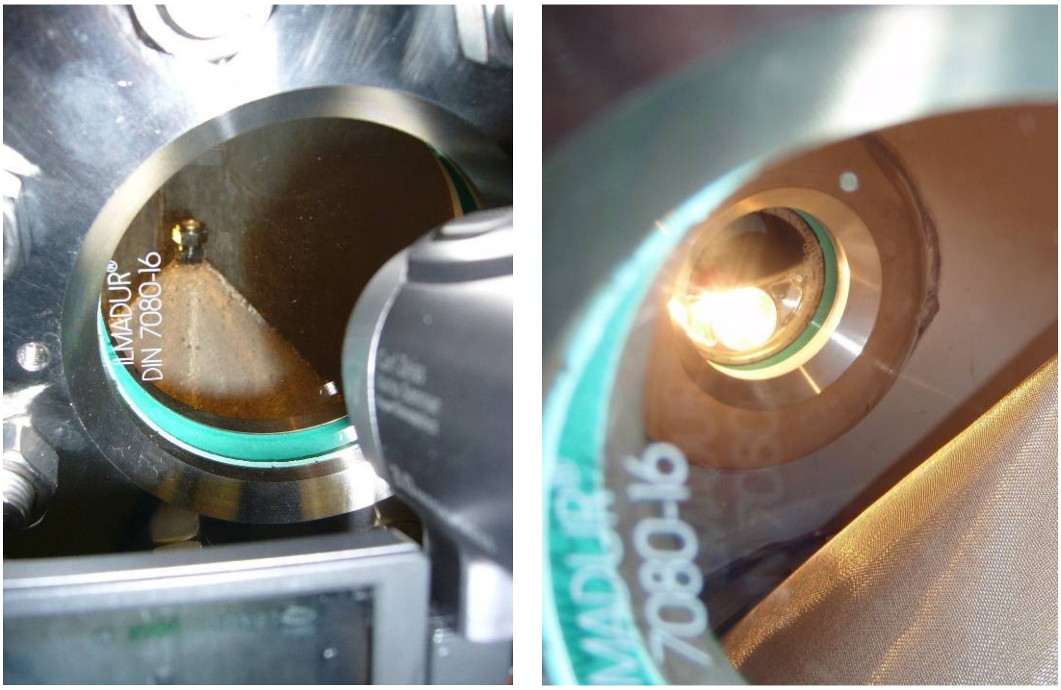
In general, the effective thermal conductivity of porous media depends on e.g. the solid thermal conductivity, emissivity, porosity and particle size. Heat transfer in a porous bed filled with gas can be seen consisting of the following mechanisms: 1) heat conduction through the gas phase and radiation between the solid surfaces, 2) heat transfer through a path consisting of solid phase and gas film near the contact surfaces of particles and 3) solid conduction directly through the particle contact surfaces (Imura and Takegoshi, 1974).

The test particle bed can be seen as a system consisting of two solids with different material properties – the heaters and the ceramic particles – and the two fluid phases. The possible heat transfer mechanisms in this type of system are rather complex. However, during the experiments, prior to dryout it is expected that boiling is the most significant heat transfer mechanism. Considering only solid conduction, it would be of advantage to use a highly conductive material such as aluminum in the experiments. However, because the role of solid conduction is expected to be limited and metallic materials, in addition to being heavy, may be corrodible, the use of metal particles could be impractical.

The conical net is filled with beads so that porosity is reduced as close as possible to the maximum packing density of randomly packed spheres which is 36.6% (Song et al. 2008). Porosity was of the same order in the STYX test bed which consisted of irregular particles of varying sizes (taken to be 37% in the analysis of the experiments). In the experimental configuration it is important that conservative choices are used for both porosity and particle diameter because dryout has to be achieved with the available power and without destroying the heaters due to overheating. Scoping calculations addressing the selections of particle size and porosity within the available power range have been performed during the design phase.

2.3 The pressure vessel

The COOLOCE particle bed is housed in a pressure vessel (steel 1.4404) with a volume of 270 dm^3 and an outer diameter of 613 mm. The wall thickness is 5 mm. The vessel is equipped with three Lumistar DN80 sightglasses, one on the upper head with integrated lighting and two in the walls at 135° division (one of these has a light). Video cameras can be mounted to the sightglasses to monitor the particle bed. The camera set-up in the start-up experiment is presented in Fig. 7(a) and the window on the other side of the cone in Fig. 7(b).



(a) (b)

Fig. 7. (a) A view of the conical particle bed inside the pressure vessel with the video camera in front of the sightglass and (b) the light on the opposite sightglass.

The vessel rests on four legs about 500 mm from the ground. The vessel can be opened from the bottom end, i.e. the cylindrical part of the vessel is removable from the bottom plate that contains the lead-throughs for the heating and measurement systems. The technical drawing of the pressure vessel and the bottom plate with the connections are presented in Fig. 8 and Fig. 9. The vessel outer surface is insulated with mineral wool.

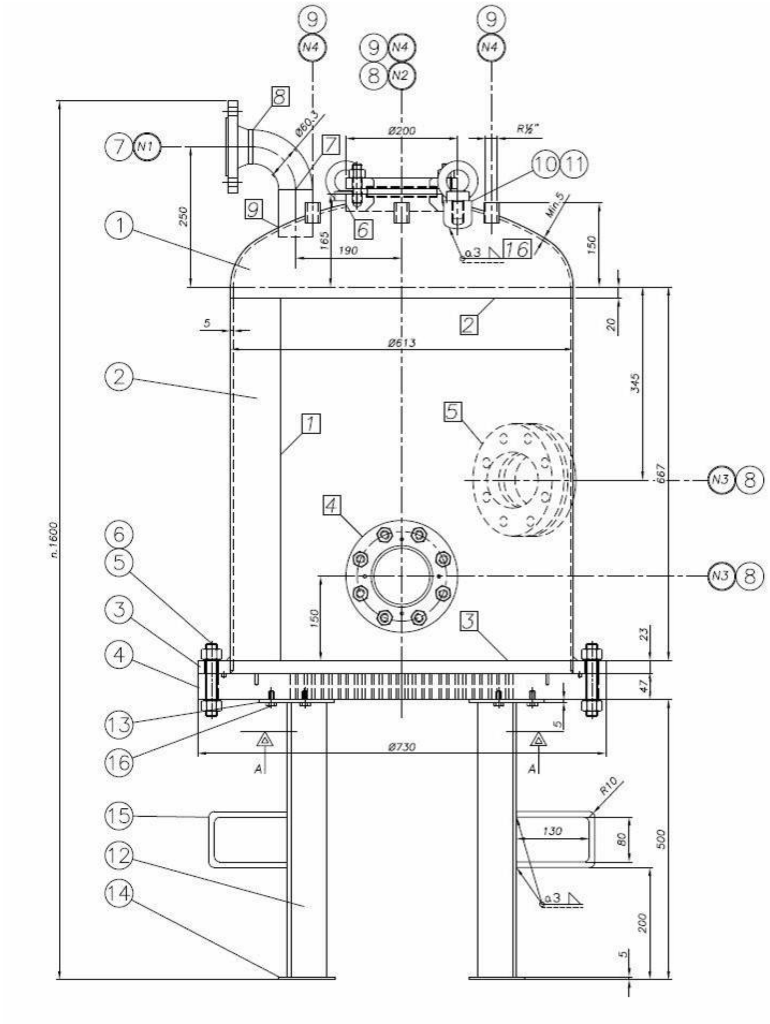


Fig. 8. Pressure vessel technical drawing.

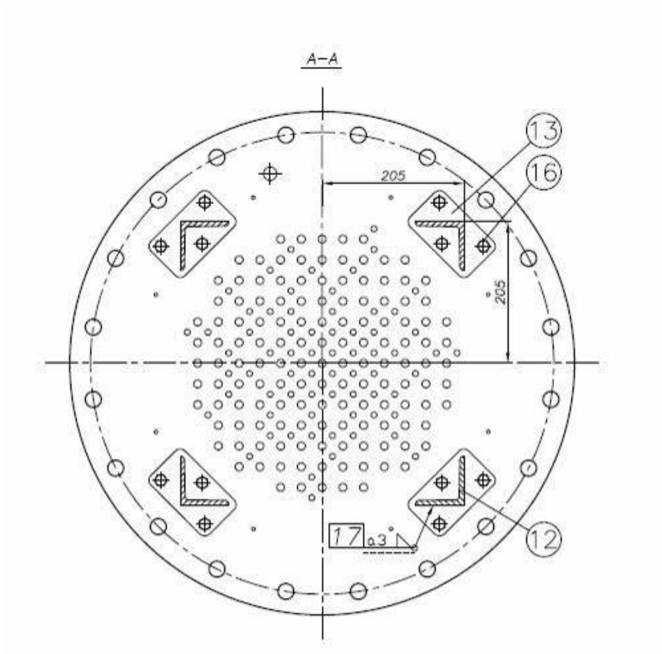


Fig. 9. Bottom plate of the pressure vessel with the lead-through for the heaters and thermocouples.

2.4 The feed water and steam removal systems

The demineralised feed water is fed from a feed water tank through a pre-heater (maximum power 3 kW) which is capable of increasing the water temperature up to 70°C-80°C depending on the required feed water mass flow. The feed water temperature is measured as a surface measurement at the inlet. Since the pre-heater is not capable of increasing the water temperature to the saturation temperature, the slightly colder feed water is mixed with the saturated water within the pressure vessel. This means that the final increase of the feed water temperature is done with the help of the particle bed heaters.

The feed water is fed through a control valve into the steam volume. The vessel pressure is regulated and excess steam is led out of the vessel through the control valve. The nominal capacity of the condenser is 0.039 kg/s at 0.6 MPa. The condensed steam mass flow rate is measured on-line by a bench scale that has a capacity of 150 kg and accuracy of 50 g. The heat losses of the system (and the power that is actually consumed by boiling) can be estimated by comparing the power calculated from condensate mass flow to the control power.

3 The COOLOCE-1 test results

The first experiment aiming for dryout was performed at nominal 1 bar overpressure (2 bar absolute). The test power was raised by 2 kW steps with a holding time of 20 to 30 minutes from a nominal 10 kW to the observed dry-out which occurred at 46 kW. A heating sequence during which steady-state saturated conditions were obtained preceded the test sequence.

The condensate mass was measured throughout the test run and the heating power was calculated based on the measured mass flow. The calculated power and the control power are compared in Fig. 10. The results indicate that heat losses of the test rig are the order of a few kW. The mass flow log from the experiment is shown in Fig. 11. The capacity of the container into which the condensate water is collected is about 20 kg. The container had to be emptied when this was reached which is seen in Fig. 11.

The first dryout was encountered at 47 kW control power. This was seen after a higher power step of 5 kW. The dryout was extinguished by a power drop after which the final power step from 42 kW to 47 kW was repeated with the small nominal 2 kW increases. After 5 smaller steps dryout was reached again at 46 kW. The temperature readings and the control power during the test are shown in Fig. 12. The first dryout was indicated at the height of 170 mm from the bottom of the particle bed near the central heater. The second dryout (46 kW) was also seen at 170 mm level indicated by the multi-point sensor that is located next to the sensor of the earlier dryout (see the thermocouple map of Appendix 2). The dryout did not spread to other sensors during the short period from dryout to power shutdown. A more detailed illustration of the temperature increases during the dryout phase is presented in Fig. 13.

The test pressure was nominally intended to be constant at two bar absolute but the test rig stabilized at around 1.92 with a slight decrease during the test to a value of 1.87. The water level above the test bed was kept at about 550 mm from test bed bottom. The pressure, feed water temperature, vessel water temperature and the water level histories are presented in Fig. 14.

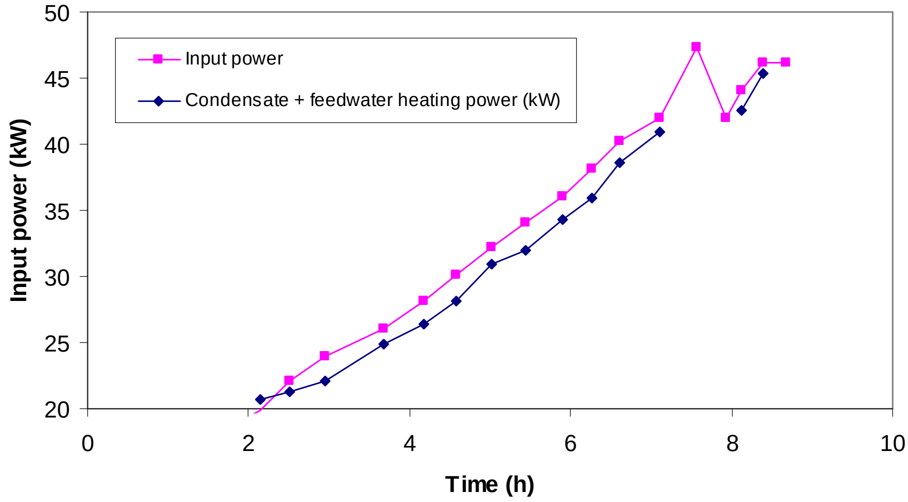


Fig. 10. Condensate mass flow converted to power in comparison to input power. Note that the condensate values are based on 10 minutes averages.

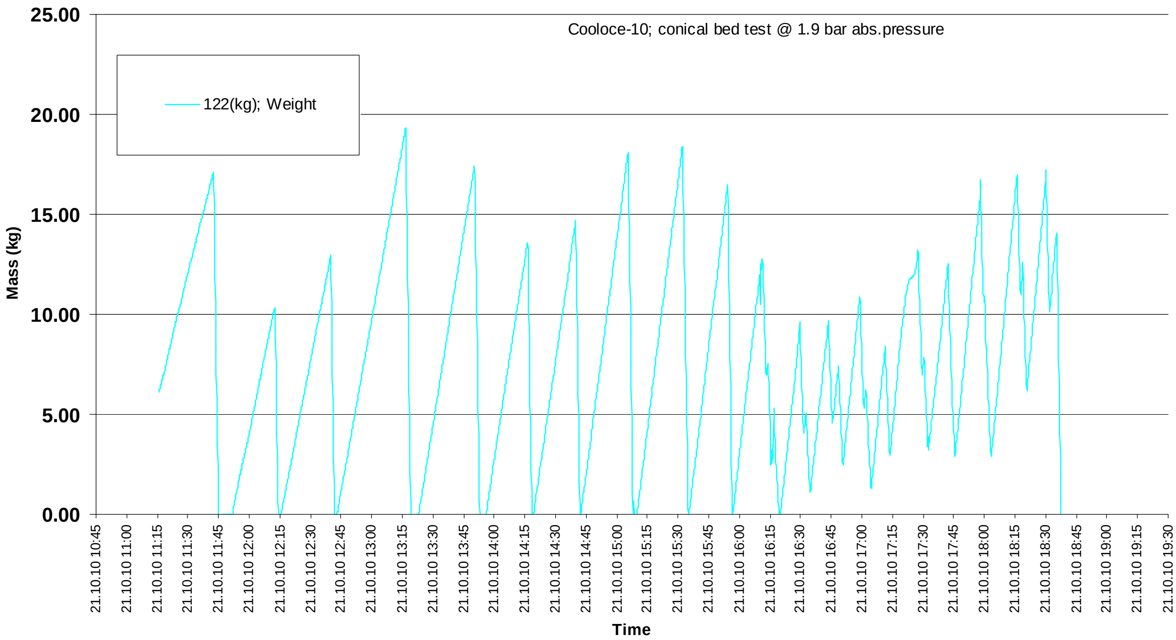


Fig. 11. Condensate mass flow log from the 1 bar overpressure test.

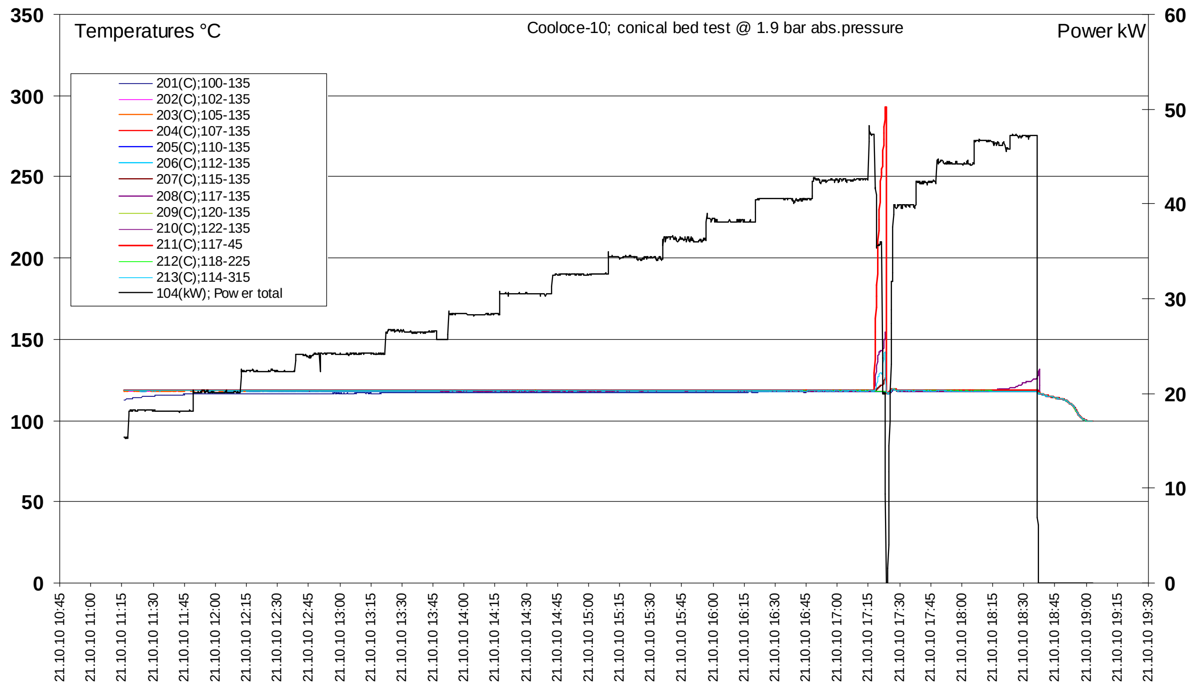


Fig. 12. Power and temperature log from the 1 bar overpressure test. Two instances of dryout are seen at 47 kW and 46 kW, respectively. The dryout is initiated near the top of the bed at 170 mm level (sensors 117-45 and 117-135).

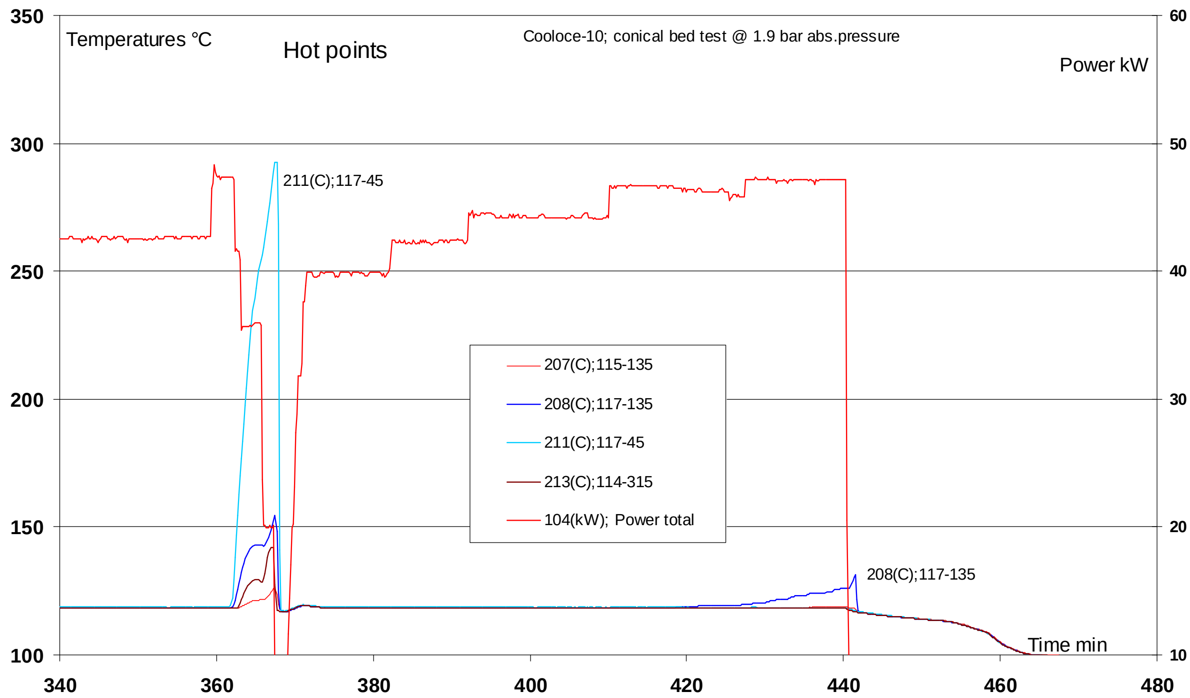


Fig. 13. Power and temperature log detail in the 2 bar abs test.

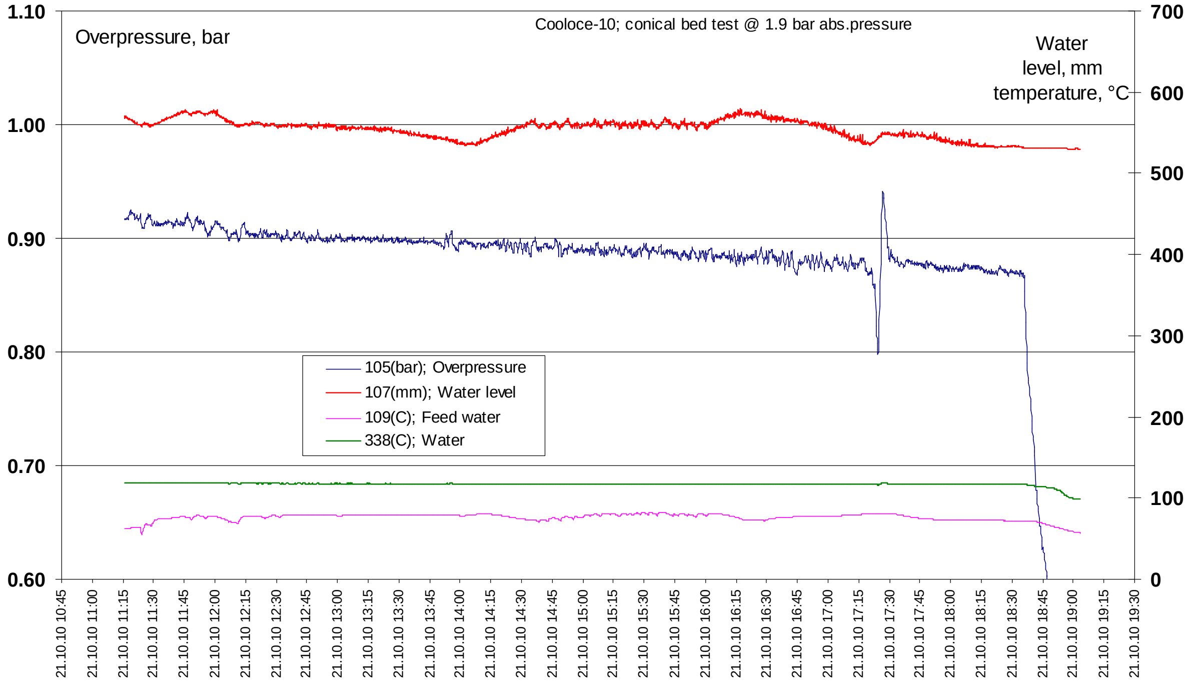


Fig. 14. Water level, pressure, feed water temperature (inlet) and temperature in the pressure vessel measured during the 2 bar abs. test.

The power input showed a slight deviation in phase 2 (central heaters in the map of Appendix 1) after the first dryout. It is suspected that one heater in the vicinity of the dry-out might have been damaged. However, the following power raise sequence resulted in a repeated dryout at approximately the same power.

Considering the maximum possible power capability of the test facility, the acquired dryout power is high. However, since the tests are targeted to acquire information on the effect of the test bed geometry the higher pressures are of less interest than in the previous STYX experiments.

4 Considerations of the test arrangement

The test facility aims at representing a porous medium which includes uniform internal heat generation as is the case with porous core debris heated by decay heat. 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 power generation accomplished with electrical heaters. Next, considerations on the technical issues and representativeness of the experimental facility and a brief comparison to simulation results are presented.

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. Also, local repairs to temperature measurements and heaters are possible. The facility contains a large number of separate, electrically insulated heaters which means that a damaged heater does not compromise the test safety, and does not necessary mean that the test has to be interrupted in case of suspected overheat.

According to the first dryout experiment, the present input power control shows a more stable power characteristic than its predecessor, the one used in the STYX experiments. The new measurement of condensing water mass flow enables control calculations of the power fed to the test bed, and it can be used to estimate the heat losses of the facility. Another advantage is that the test pressure showed only minor fluctuations during the test.

Compared to the STYX experiments, the presence of sightglasses is a completely new concept for the observation of the test bed boiling. The viewing glasses make it possible to visually observe the steam generation and, potentially, they can be used for the implementation of a more sophisticated instrumentation utilizing e.g. high-speed video cameras.

Because of the heat transfer characteristics and the large volume of water present in the test vessel, relatively long heating sequence is needed prior to the experiments in order to achieve a uniform temperature distribution within the test bed. However, once saturated conditions are reached, visual observations indicate rapid alteration of the boiling intensity at power raise.

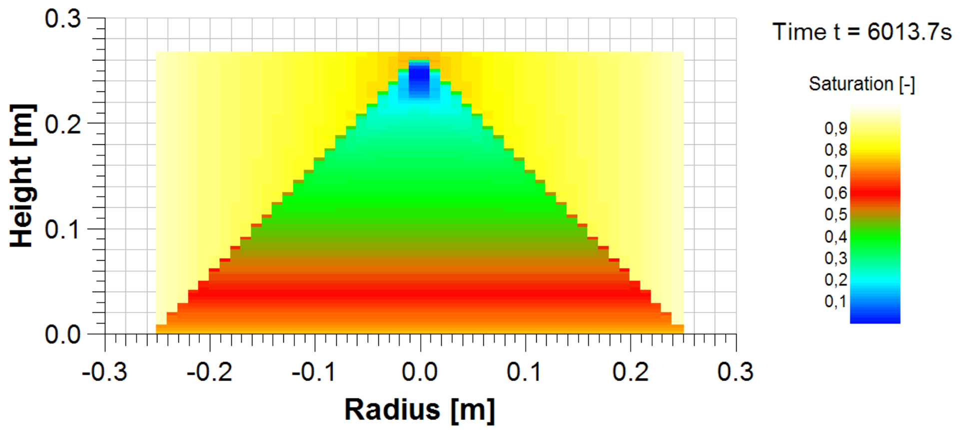
Concerning the representativeness of the experimental set-up, it should be kept in mind that the COOLOCE facility does not have direct heating of the solid. The vertical arrangement of the heaters may produce three-dimensional downcomer effects in the particle bed because porosity is expected to be locally increased near the relatively thick (compared to the particle size) heaters. Because of this, the conical particle bed results should not be directly comparable to previous results from e.g. the STYX experiments. In order to find out the effect of the conical geometry, experiments using different particle bed geometries have to be run with the same vertical heating arrangement. However, the comparison of cylindrical particle bed experiments using the COOLOCE and STYX heating arrangements will give more information on the possible effect of the heating configuration.

Different possibilities for the heating arrangement were considered during the design of the test facility. These included electrical wire heaters threaded into the spherical particles and coiled to form the particle bed, a concept close to the one used by Hu and Theofanous (1991). However, taking into account the power limitations, the size of the designed particle bed and other practicalities, the present COOLOCE configuration was considered to be the most feasible approach.

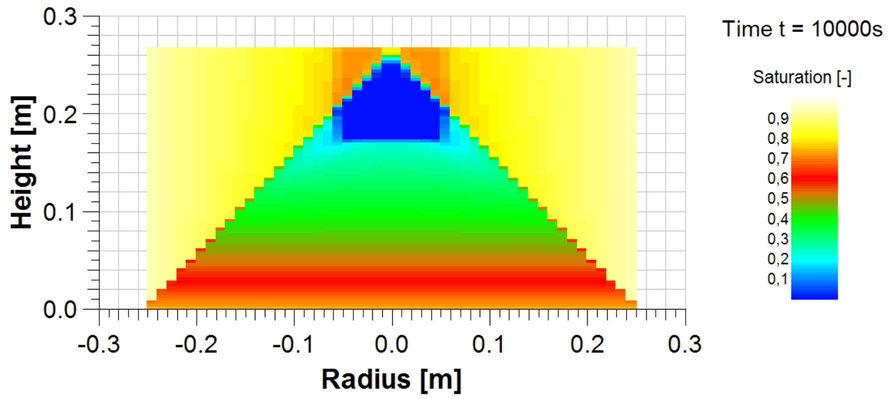
4.1 Comparison to simulation results

It was seen that the dryout in the experiment presented in the previous chapter was initiated in the location close to the one predicted by MEWA-2D calculations, in the upper central region of the cone. In the calculations, dryout starts in the point of the cone and the dry region spreads downwards when the power is increased beyond the exact dryout power. The dryout height observed in the experiment is somewhat lower than the calculated one. This is partially explained by the fact that the heaters do not reach the test bed surface in the experiments. Also, the locations of the temperature sensors in the tests limit the accuracy of the dryout location determination.

Simulation results are illustrated in Fig. 15. The figures represent saturation (liquid fraction in the pores) at two different power levels, 30 kW and 40 kW. Both of these power values are high enough to achieve dryout (i.e. saturation reaches zero in some part of the modelled geometry). The maximum coolable power in the simulation is 27.5 kW and the minimum dryout power is 30.0 kW.



(a)



(b)

Fig. 15. Post-dryout saturation (liquid volume fraction in the pores) at two different power levels: (a) 30 kW which is the minimum power leading to dryout and (b) 40 kW. The figures are taken from one long simulation with stepwise power raise.

In the simulation, heating power is assumed to be uniformly distributed into the solid material, and the effect of the heating arrangement is not accounted for. This might be the reason for the deviation between the calculated (30.0 kW) and the experimental (46 kW) dryout power. The possible downcomer effect caused by the vertical heaters (and thermocouples) could increase the coolability of the experimental particle bed. A more detailed post-test analysis will be conducted when more experimental data is available.

5 Conclusions

A new test facility COOLOCE (Coolability of Cone) has been designed for investigations of dryout heat flux 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 dryout heat flux in a conical (heap-like) and a cylindrical (evenly distributed) particle bed. 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 purposes.

The first successful test run has been performed with the conical configuration and dryout has been reached at an input power of approximately 46 kW. The experiment shows that the test facility can be operated at nearly maximum power output (80% of nominal). The dryout location is as expected in the higher region of the heated volume of the conical test bed. The calculated power retrieved from the condensate water mass measurement validates the input power and added confidence in the dryout power determination has been gained. New experience has also been gained in the operation and performance of the test facility and the conical test bed. The test programme will continue with a test at atmospheric pressure.

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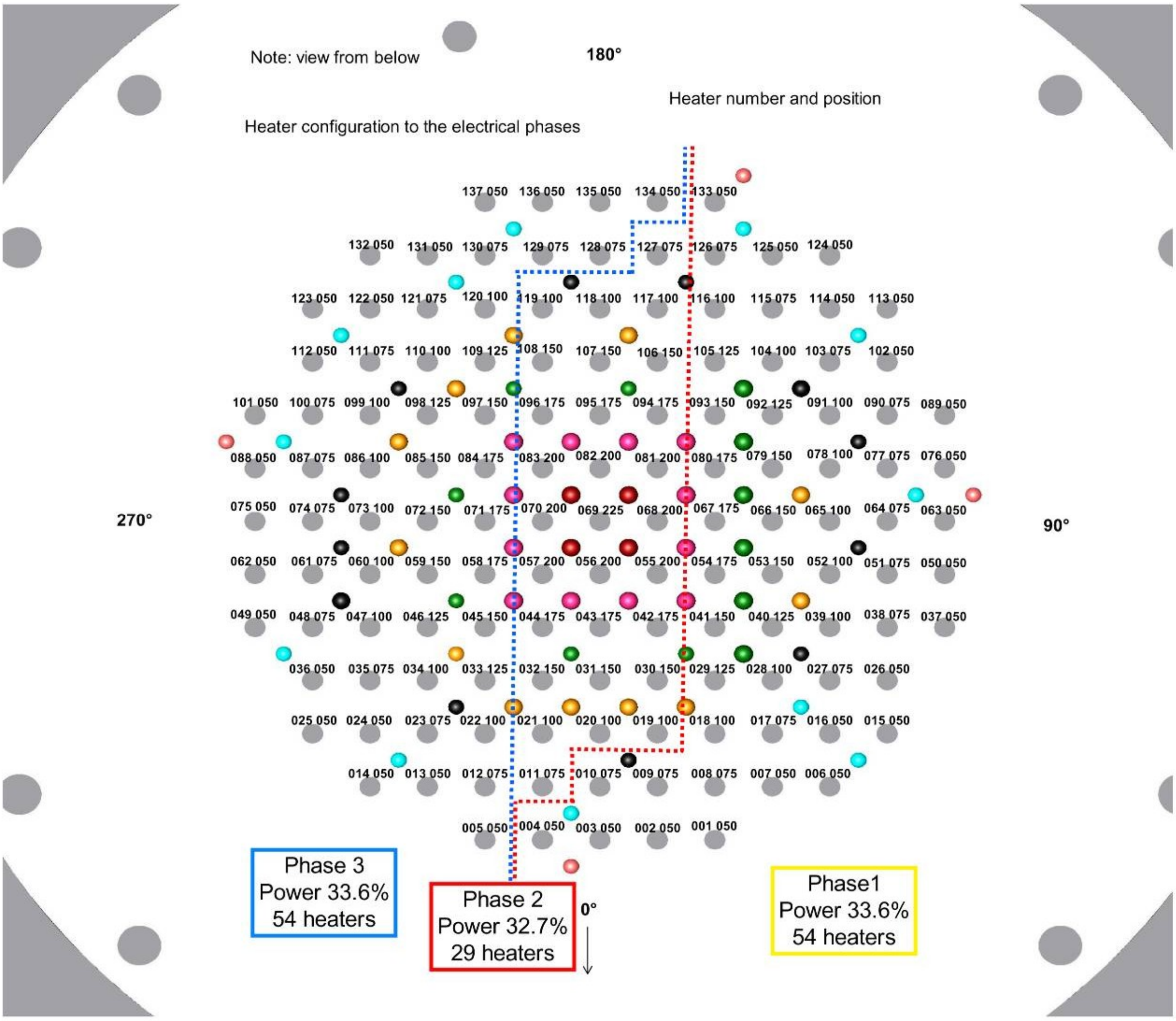
APPENDIX 1. Heater arrangement



APPENDIX 2. Thermocouple arrangement (top view)