RESEARCH REPORT

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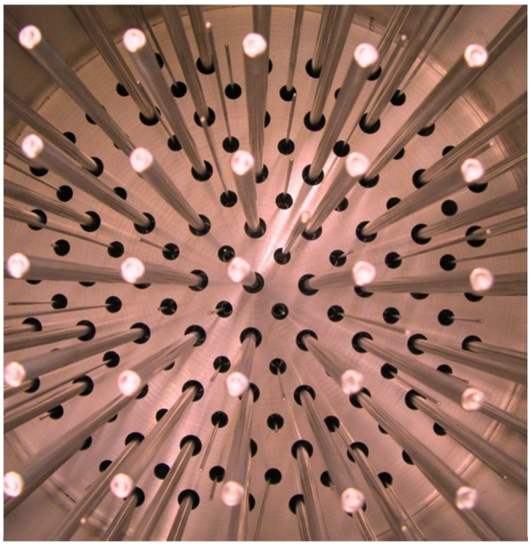

The COOLOCE particle bed coolability experiments with a cylindrical geometry: Test series 3 – 5

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Summary

The COOLOCE experiments aim at investigating the coolability of particle beds of different geometries. A particle bed may be formed of core debris as a result of a core melt accident in a nuclear power reactor. The main objective of the experiments is to compare the dryout power of conical (heap-like) and cylindrical particle bed geometries. Following the first experiments using a conical test bed (COOLOCE-1 – 2), a cylindrical test bed that is flooded through the top surface has been installed into the test facility for the test series 3 – 5. Dryout power has been measured for the pressure range of 1-7 bar. The measured dryout power varies between 17 kW and 34 kW.

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1 Introduction

A porous particle bed – or debris bed - that consists of solidified corium may be formed as a result of a core melt accident in a nuclear power reactor. Depending on the design of the reactor, such a debris bed may be formed in the containment, e.g. in the flooded lower drywell of the Finnish BWR's after the failure of the reactor pressure vessel, or inside the pressure vessel. In order to ensure the coolability of the core debris and to prevent dryout and possible re-melting of the material, decay heat has to be removed from the material.

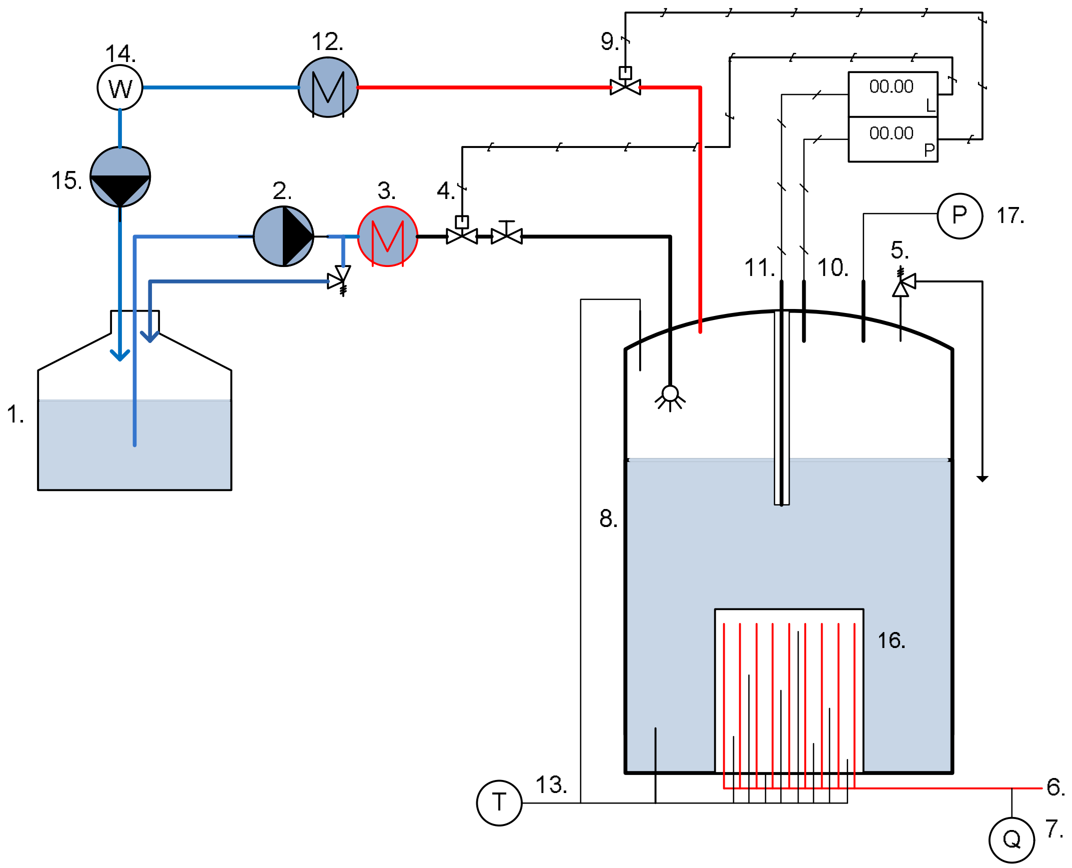
The COOLOCE test facility is used to investigate the coolability of porous particle beds of different geometries, focusing on ex-vessel cases. The main objective of the experimental programme is to compare the dryout power of a conical (heap-like) particle bed configuration to that of a cylindrical (evenly-distributed) configuration. In addition to providing new data of the effect of particle bed geometry on coolability, the experimental results are used for code validation and development.

The present report describes the experiments with a cylindrical bed. The first set of experiments (COOLOCE-1 – 2) with a conical particle bed has been performed and reported earlier [1], [2]. After the conical bed experiments, a cylindrical test bed was installed into the test facility, including the design of the new heater and sensor configurations.

A new bottom plate for the pressure vessel tailored for the cylindrical bed experiments was designed. This was done in order to make it easier to change between the two geometries without the need to remove and re-install the numerous heaters and thermocouples in the test set-up. Also, the electrical heaters were changed to a model that has a more corrosion and heat resistant outer sheath than the previous heaters. A built-in thermocouple is included in three of the heaters to monitor the heater sheath temperature. The aim of the improvements was to avoid the overheating problems encountered in some of the heaters of the conical set-up [2]. Description of the previous analytical work and background information of the studies can be found in [3], [4] and [5].

2 The test facility

The main components of the COOLOCE test facility are the pressure vessel which houses the test particle bed, the feed water and steam removal systems and instrumentation. The custom-made pressure vessel has a volume of 270 dm³ and design pressure of 7 bar (overpressure). The schematic of the arrangement is presented in Fig. 1. A photograph of the experimental set-up is shown in Fig. 2. The total volume of the cylindrical particle bed is 20.4 l. The bed is 310 mm in diameter and 270 mm in height. The dimensions of the conical and cylindrical beds are illustrated in Fig. 3.



1) Feed water tank
2) Feed water pump
3) Feed water pre-heater
4) Feed water control valve
5) Safety valve
6) Resistance heaters of the test bed
7) Power input and measurement
8) Pressure vessel
9) Steam line control valve (pressure control)
10) Pressure measurement (control)
11) Water level measurement (feed water control)
12) Condenser
13) Temperature measurements
14) Bench scale for condensate mass measurement
15) Water circulation pump
16) Test bed (cylindrical)
17) Pressure measurement

Fig. 1. Schematic flow chart of the COOLOCE test facility.

Fig. 2. COOLOCE experimental set-up:1) feed water pre-heater, 2) feed water control valve, 3) connection box for the heaters, 4) pressure vessel, 5) steam line condenser and scale, 6) sightglass with video monitoring, 7) water level and pressure gauges.

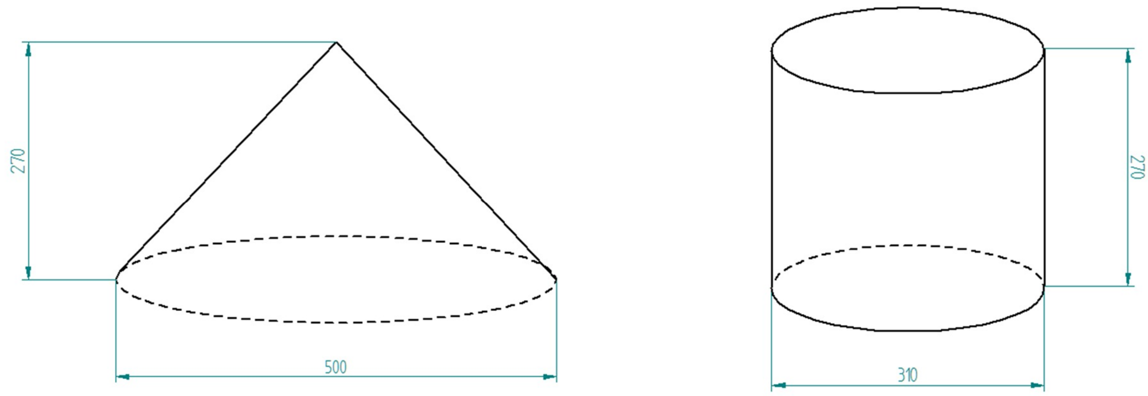
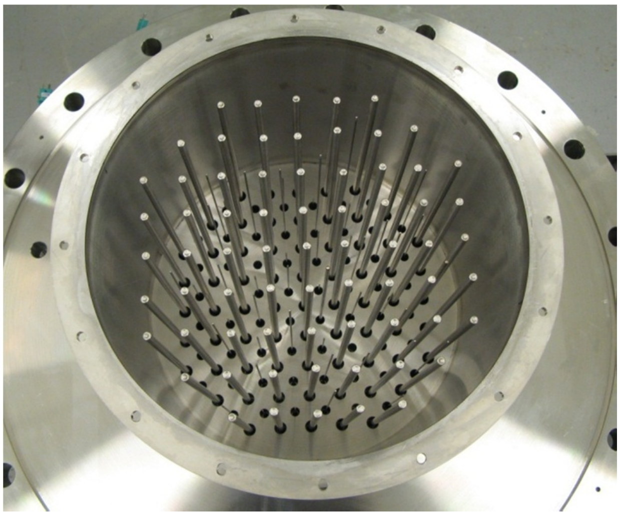


Fig. 3. Dimensions of the conical and cylindrical test beds of the COOLOCE experiments in mm.

The test particle bed consists of ceramic beads that are being held in shape by an inner cylinder and a dense wire net on top of the test bed. This facilitates top flooding while no lateral flooding is allowed through the sides of the cylinder. The particle bed is heated by ∅ 6.3 mm vertically installed cartridge heaters. There is a 40 mm layer of unheated particles above the heaters. In the cylindrical test bed, all the heaters have a heated length of approximately 230 mm.

The configuration aims at achieving a uniform temperature distribution within the test bed. In the previous conical bed experiments (COOLOCE-1 – 2), the heaters had outer sheaths made of heat-resistant steel. For the cylindrical bed experiments, new heaters with Incoloy outer sheaths were acquired.

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 electrical connections for the heaters and the thermocouples are lead through (with connectors) through the bottom plate of the pressure vessel. The heater and temperature sensor configuration prior to the installation of the particle material and the complete particle bed filled with the ceramic beads are shown in Fig. 4.


a)

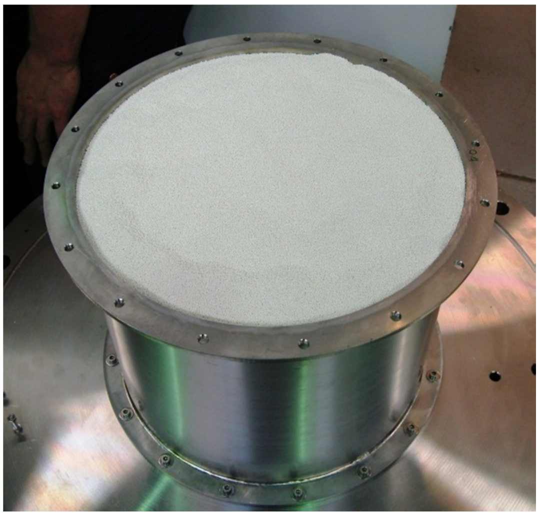

b)

Fig. 4. a) The heater and thermocouple arrangement and b) the test bed filled with particles for the cylindrical debris bed experiments. The diameter of the cylinder is 310 mm and the height is 270 mm.

2.1 The test procedure

The test procedure consists of a heat-up sequence and the main test sequence. Generally, these are similar for the cylindrical and conical bed experiments. Prior to the experiments, the test pressure vessel is filled with pre-heated distilled water to a level of approximately 300 mm above the test bed surface. During the heat-up sequence the facility is heated up to the saturation temperature and steady-state boiling is reached. The power level of the heat-up sequence depends on e.g. the test pressure and the expected dryout power.

In the test sequence, a stepwise power increase is conducted until a dryout is indicated by one or more thermocouples within the test bed. Dryout is seen as a stable increase of the sensor temperature from the saturation temperature. A holding time of 20 to 30 minutes is applied for each power step. This is necessary because the boil-off of liquid inside the particle bed after the critical power level has been reached takes some time (the time depends on the excess power). The size of the power increments is 1 kW - 2 kW. During the test sequence, the water level and pressure in the test vessel are controlled by the feed water and steam line control valves according to given set points.

The heating power is manually controlled by adjusting the output voltage of a purpose-tailored power transformer. The heaters are arranged in three groups according to the electrical phase. The heater locations are presented in Appendix A. Three of the heaters in the cylindrical test bed are equipped with temperature sensors which help to detect possible overheating. They also complement the temperature measurements of the test bed in addition to the thermocouples in the porous material between the heaters. The thermocouple map is presented in Appendix B. The thermocouples numbered 100-45 and 400-8 have multiple measuring points. The other thermocouples have a single measuring point at the upper end. Total number of sensors is 70, excluding the heater measuring points.

The heat-up sequence typically lasts from 1 to 2 hours during which the temperature is gradually increased up to the saturation temperature at the pressure of the experiment to be conducted. The temperatures near the bottom plate of the pressure vessel tend to increase more slowly than in the other parts of the test bed. The bottom plate temperature remains slightly below the saturation temperature in steady-state conditions due to heat losses.

Several dryout points at different pressures may be run during one day of experiments because the test bed pressure may be easily controlled and the test facility temperatures adjust quickly to the changes in pressure. If necessary, it is possible to quench a dryout by pressurization of the test vessel.

The test matrix for the cylindrical bed experiments is presented in Table 1. The experiments denoted R were conducted in order to verify the repeatability of the experiments and investigate the possible differences between similar test runs. The saturation temperature and evaporation energy for each test are also given. Heat of evaporation describes the amount of heat consumed by boiling which decreases as a function of pressure. However, within the pressure range of the experiments, coolability is expected to increase with increasing pressure because the density of steam increases. This means that, in a higher pressure, a higher mass flux of steam can escape the particle bed in the same volume as in a lower pressure. This effect is more significant than the decrease of evaporation energy.

Table 1. Test matrix for the cylindrical bed experiments.

COOLOCE Experiment	Pressure [bar]	Saturation temperature [°C]	Heat of evaporation [kJ/kg]
3	1.1	102	2250
3R	1.1	102	2250
4a	1.6	113	2221
4b	1.9	119	2206
4bR	2.0	120	2202
5a	3.0	134	2163
5b	4.0	144	2133
5c	5.0	152	2108
5d	7.0	165	2066

2.2 Estimation of dryout power by steam flow

Heat losses through the thermally insulated walls, uninsulated bottom plate and connections of the test vessel cause the power consumed by boiling to be smaller than the control power. Also, since the capacity of the feed water pre-heater is not high enough to increase the feed water temperature to boiling point, maintaining the saturation temperature at the test vessel pressure has to be done by the heaters. The pre-heater increases the feed water temperature to 60-90°C, depending on the experiment.

The heat losses and the feed water heat-up within the test vessel reduce the heat flow directed to evaporation in the control volume formed by the test vessel. Because of this, the boiling rate is verified by measurements of the condensing steam mass flow rate. The measurement is done by directing the condensate flow to a bench scale with online measurement of mass. The condensate container is emptied sequentially after the mass flow reading has been obtained. The water is then re-circulated back into the feed water tank.

The power calculated from the condensate mass, i.e. the condensate mass flow rate q_m (kg/s) multiplied by the latent heat of evaporation h_{fg}, (kJ/kg) during the power step that leads to dryout gives an estimate of the actual dryout power:

$$P_{calc} = q_m \cdot h_{fg} \tag{1}$$

The difference between the *control power* (electrical output power of the transformer) and *calculated power* (Eq. 1.) represent the heat losses of the facility. In the present analysis, we examine the average values of the liquid mass change rate for calculating the average mass flow rate. The calculation assumes that the water which is collected to the scale per unit of time is equal to the mass flux evaporated by the heated test bed.

The calculation does not account for possible condensation in the pressure vessel. Condensation may occur on the walls of the vessel steam volume or as direct contact condensation in the water volume, depending on the input of the cooler feed water. Feed water is pumped into the test vessel through an inlet located above the water surface. The feed water flow rate varies during the test run (according to the value set for the water level) and it is possible that direct contact condensation occurs in connection with peaks in the feed water mass flow rate. As a result, the mass flow that reaches the condenser is reduced. On the other hand, in connection with the condensation, latent heat is released and also the water level may be increased which reduces the feed water mass flow. This, in turn, counters the effect of condensation.

The aforementioned uncertainties are difficult to estimate. However, we take the calculated power to be a reasonably accurate representation of the dryout power. The power based on the condensate mass is also more conservative since it is smaller than the control power.

3 Experimental results

In the cylindrical particle bed test series COOLOCE-3 – 5, nine test sequences for which dryout was measured were performed. The pressure range was 1 – 7 bar, with the upper limit close to the design pressure of the test vessel. The experiments provide a comprehensive set of comparison data to the conical bed experiments. Comparison between the different geometries will be provided in a later report.

3.1 COOLOCE-3 and -3R

The first experiment with the cylindrical debris bed COOLOCE-3 was conducted at nominally atmospheric pressure (1.1 bar with fully open steam line valve). Dryout was observed at the control power of 19.0 kW. The dryout power was determined by three "approaches" as seen in the power and temperature history of the experiment in Fig. 5.

During the first approach, the heaters 111-00 and 211-90 started to show increased temperatures at the power of about 17.3 kW. During the second approach, dryout was indicated by temperature sensors near the centre of the test bed at the heights of 17 cm, 15 cm and 12 cm (sensors 117-45, 115-45 and 112-45 of the multi-point thermocouple near the centre of the test bed) at the power of about 19 kW. Nearly simultaneously with the increase of temperature of the aforementioned sensors, the central heater 111-00 started to show an increased temperature. The multi-point sensor and the heater sensor are located next to each other as shown in Appendix B. The power was switched off when the temperature of the sensor reached 400°C in order to avoid damage to the heaters. At his time the reading of sensor 117-45 had increased to 340 °C. No lateral spreading of the dry zone was seen.

The third approach was conducted with 1 kW power steps until the sensor 117-45 started to show increase from the saturation temperature at the power 19.0 kW, verifying the dryout power for the experiment.

The pressure and water level in the test vessel as well as the feed water temperature during the test are shown in Fig. 6. At the power level leading to dryout, the average mass flow rate based on the water collected on the scale was 0.0077 kg/s. The power corresponding to this steam production rate is 17.3 kW.

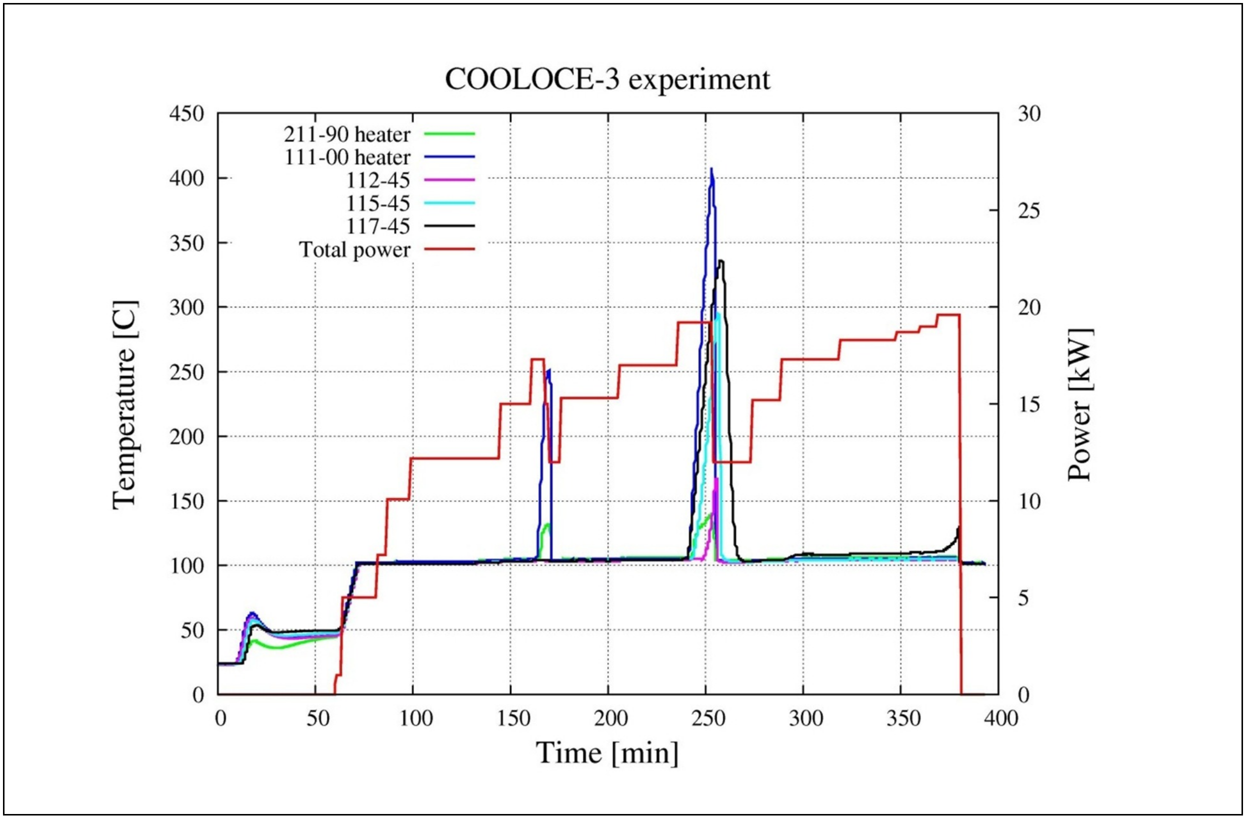


Fig. 5. Control power and temperature log in the COOLOCE-3 experiment at the pressure of 1.1 bar (control valve fully open).The control power has been recorded manually due to a malfunction in the output of the power analyzer.

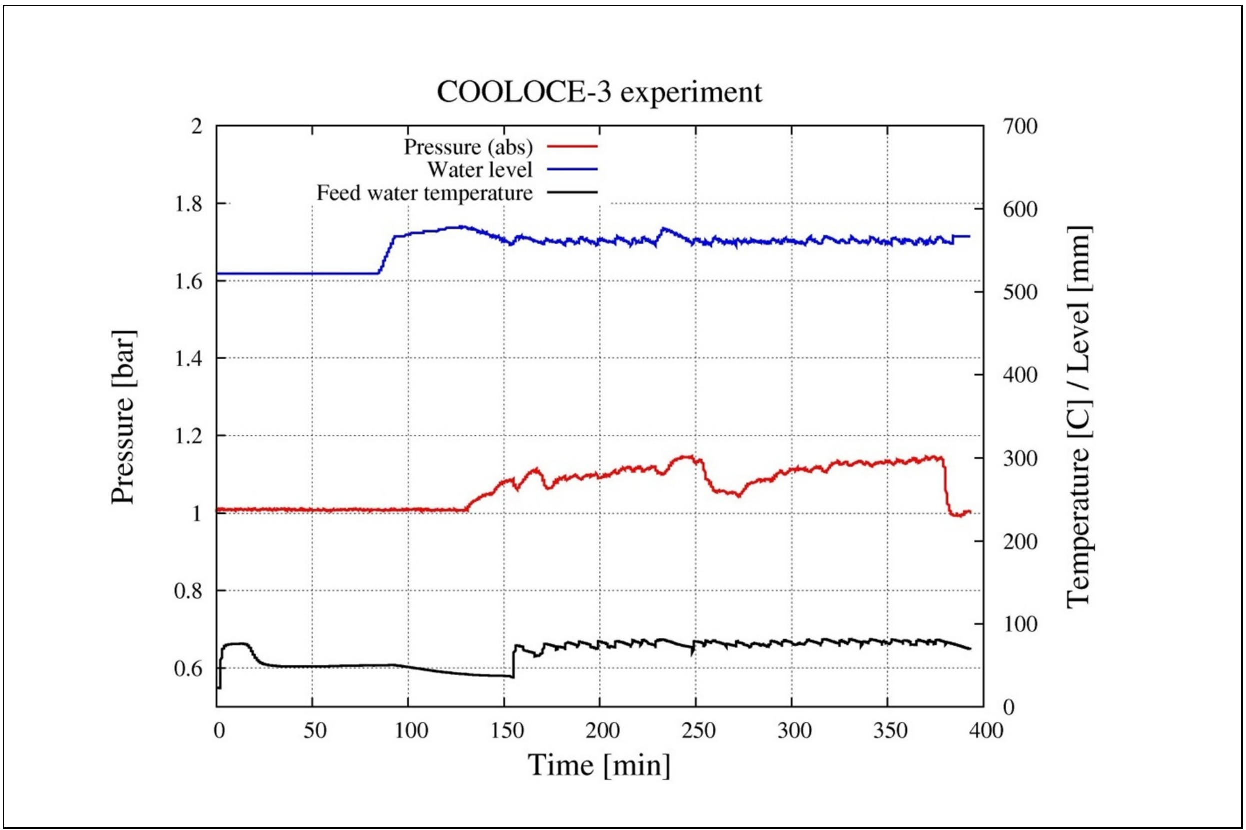


Fig. 6. Pressure and water level in the test vessel and the feed water temperature during the COOLOCE-3 experiment.

The experiment at atmospheric pressure was re-run in order to verify the repeatability of the test. The COOLOCE-3R experiment, similarly to the previous one, was run after a heat-up sequence from a “cold state”. Dryout was observed at the input power of 20.4 kW at the heights of 12 cm, 15 cm and 11 cm by the sensors numbers 112-45, 115-45 (the multi-point sensor) and 111-225 which is located on the opposite side of the central heater as the multi-point sensor.

Contrary to the previous experiment, the central heater started to show increased temperature about 30 minutes before the detection of dryout by the test bed sensors at the power level of 19.3 kW. At his power level, the heater temperature appeared to stabilize at around 270°C and started to increase again only after the next power increment at the same time when the test bed temperature started to increase. This suggests that a stable dry zone might have been formed around the central heater without spreading to the sensors between the heaters. This may be interpreted that the first dry zone was achieved at the same power level (~19 kW) in both COOLOCE-3 and -3R experiment but in a slightly different location. However, since we systematically use the increase of temperature of the sensors in the porous material between the heaters as the criterion of dryout, the increase of heater temperatures alone is not considered a dryout for the particle bed.

The power and temperature history during the experiment are presented in Fig. 7. The pressure and water level in the test vessel as well as the feed water temperature during the test are shown in Fig. 8. At the input dryout power level of 20.4 kW the corresponding condensate mass flow rate was approximately 0.0084 kg/s which means a power of 18.8 kW.

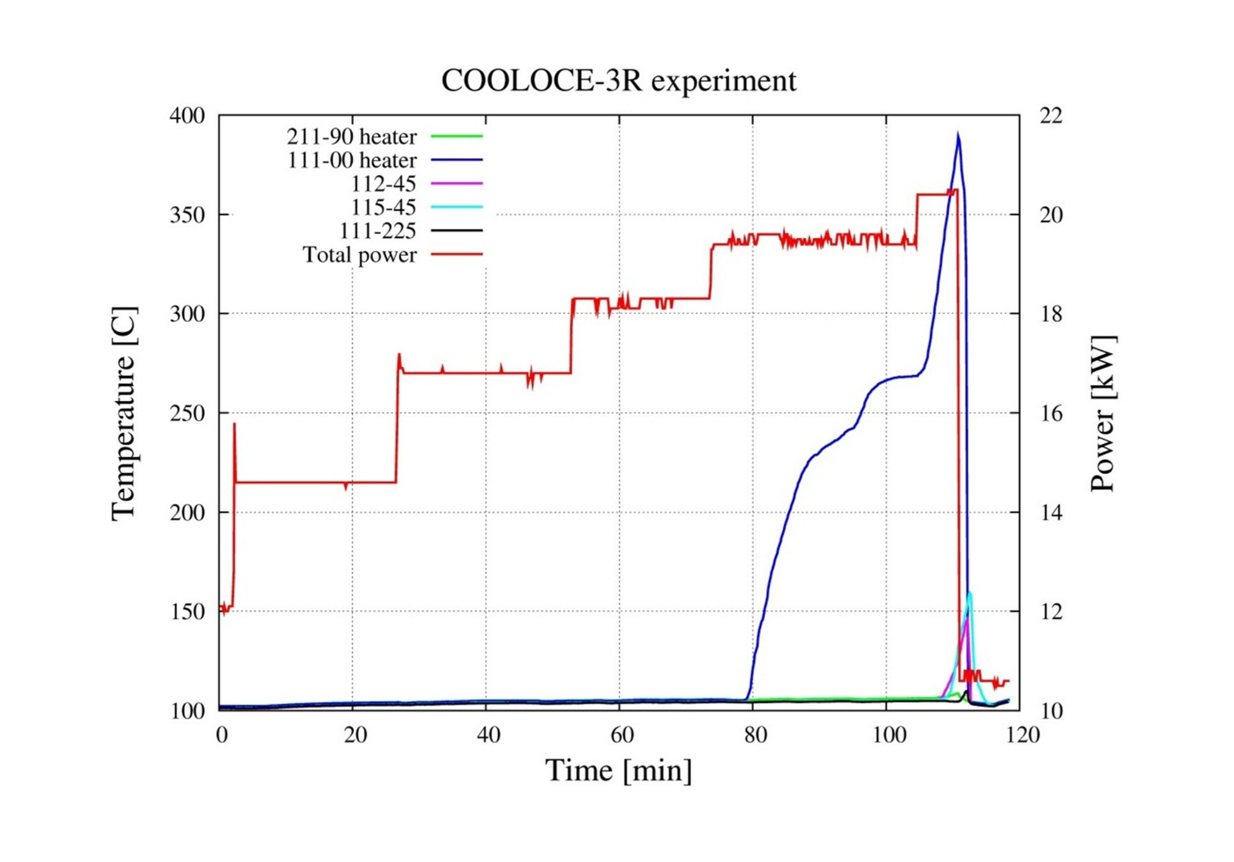


Fig. 7. Control power and temperature log in the COOLOCE-3R experiment at the pressure of 1.1 bar (control valve fully open).

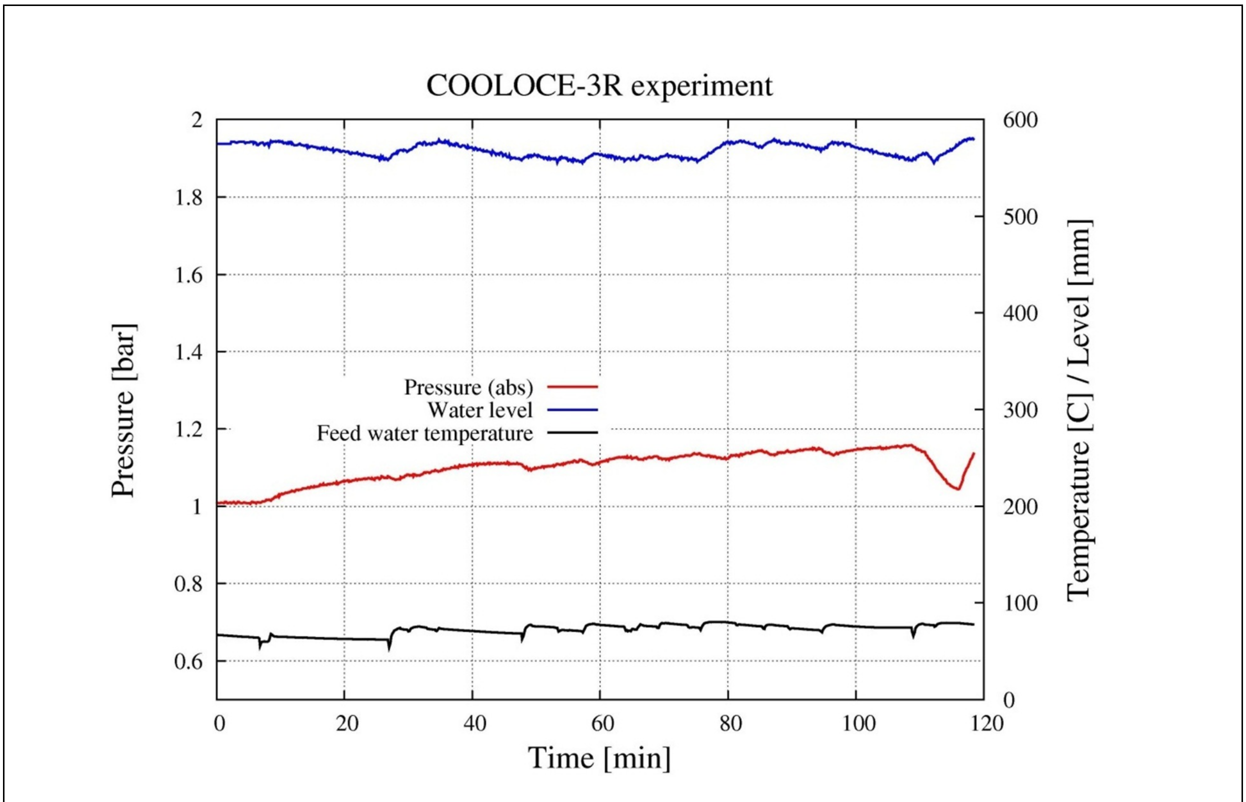


Fig. 8. Water level and pressure in the test vessel and the feed water temperature in the COOLOCE-3R experiment.

3.2 COOLOCE-4a, -4b and -4bR

The COOLOCE-4 run consisted of the pressure levels of 1.6 bar and 1.9 bar which are the comparison pressure levels for the conical bed experiments conducted thus far. We denote the 1.6 bar run COOLOCE-4a and the 1.9 bar run COOLOCE-4b. The 1.6 bar run was repeated in the COOLOCE-4bR experiment to further verify the repeatability of the experiments.

At the pressure of 1.6 bar, dryout was observed at the control power of 23.4 kW near the centre of the cone, indicated by the temperature sensors at 120 mm, 150 mm and 110 mm from the bottom. These are the same sensors as in the COOLOCE-3R experiment which was run before the present experiment after a pressure increase of 0.5 bar. The temperature of the central heater started to increase some time before the detection of dryout by the test bed sensors. As can be seen in the power and temperature log in Fig. 9, two approaches with slightly different control power levels were needed for reaching dryout because in the first attempt at the power of 23.9 kW the heater started to overheat but no transition of dryout to the test bed sensors was seen.

The temperature of the sensors indicating dryout and the power history of the COOLOCE-4a experiment are shown in Fig. 9. The water level and pressure and the feed water temperature are shown in Fig. 10. At the dryout power level, the condensate mass flow was approximately 0.0093 kg/s which corresponds to a power of 20.6 kW.

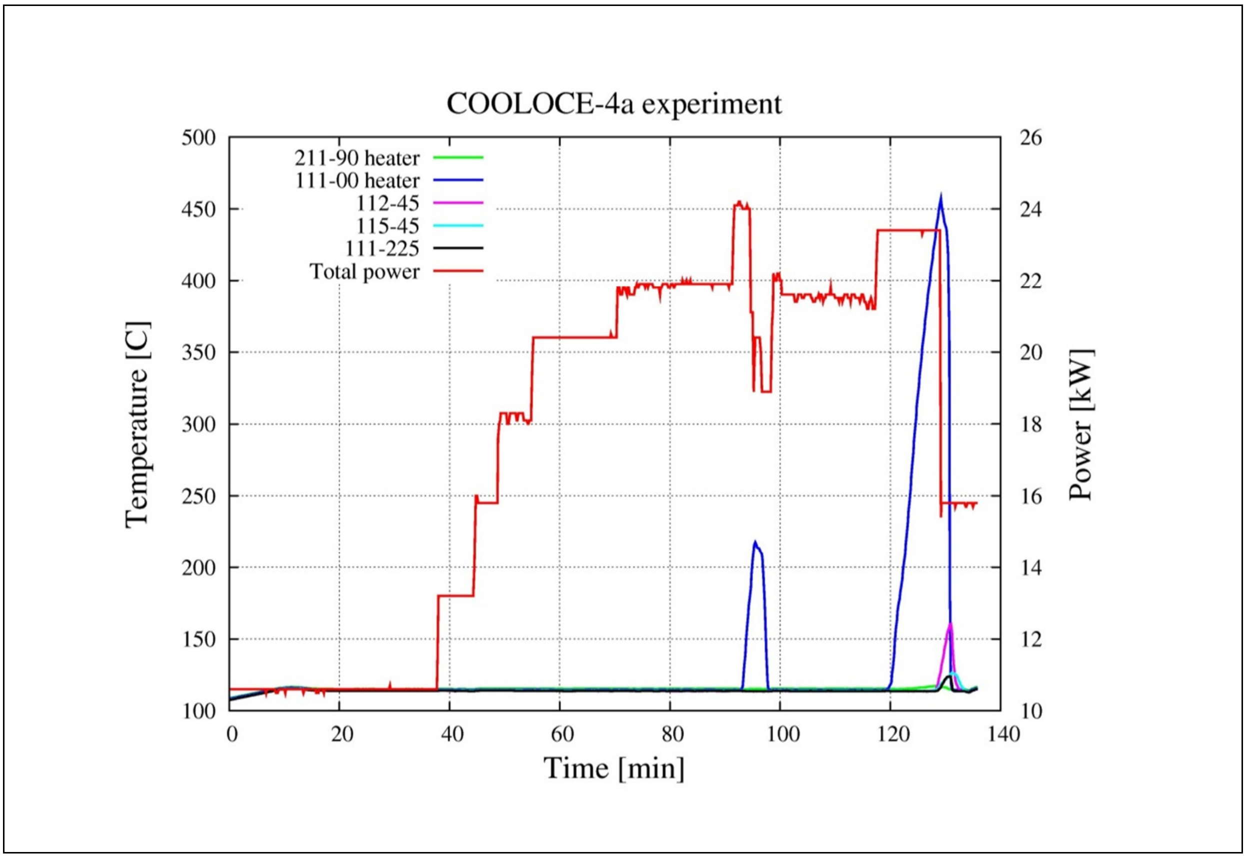


Fig. 9. Control power and temperature log in the COOLOCE-4a experiment at the pressure of 1.6 bar.

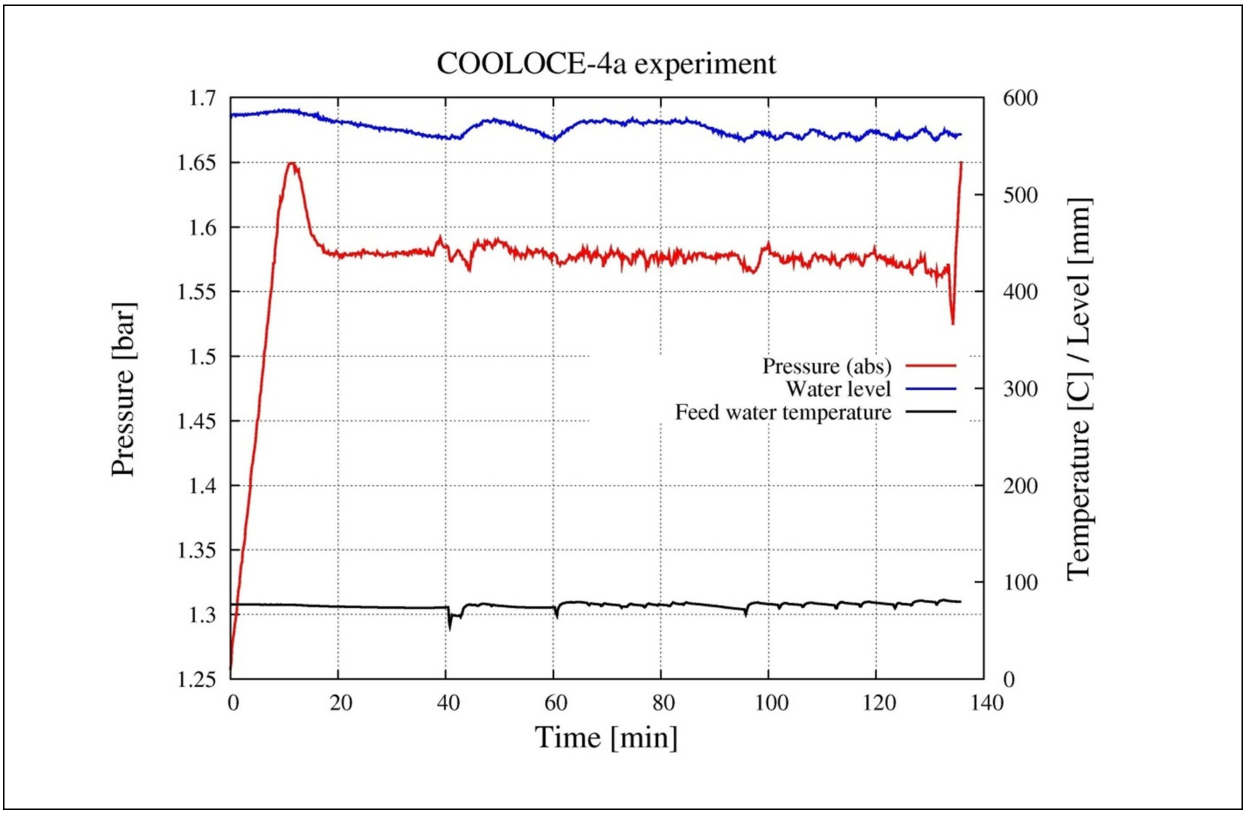


Fig. 10. Water level and pressure in the test vessel and the feed water temperature in the COOLOCE-4a experiment.

In the 1.9 bar experiment, dryout was seen at the control power of 26.1 kW, indicated by the sensors near the centre of the test bed at 120 mm, 150 mm and 110 mm from the test bed bottom, i.e. the same sensors as in the two previous experiments, COOLOCE-3R and COOLOCE-4a. The temperature behaviour followed closely the experiment at 1.6 bar: first a sharp increase in the temperature of the central heater was seen which was followed by a temperature increase in the sensors on both sides of the central heater approximately 7 minutes later. The power was cut off after the heater temperature exceeded 450°C in order to avoid damaging the heaters. At this time, the hottest sensors of the bed had reached 160 °C.

The temperature of the sensors indicating dryout and the power history of the COOLOCE-4b experiment are shown in Fig. 11. The water level and pressure and the feed water temperature are shown in Fig. 12. According to the condensate mass flow of about 0.010 kg/s, the heat flow of boiling was 22.9 kW.

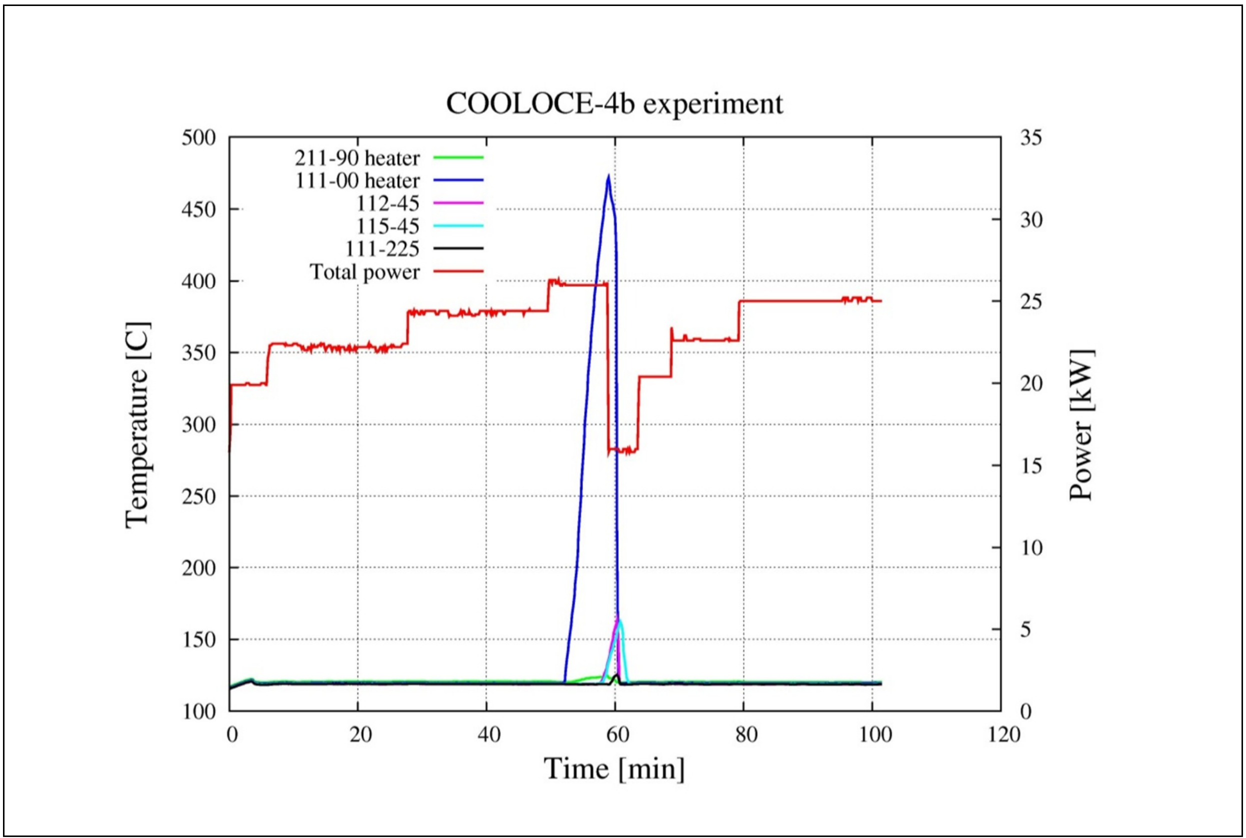


Fig. 11. Control power and temperature log in the COOLOCE-4b experiment at the pressure of 1.9 bar.

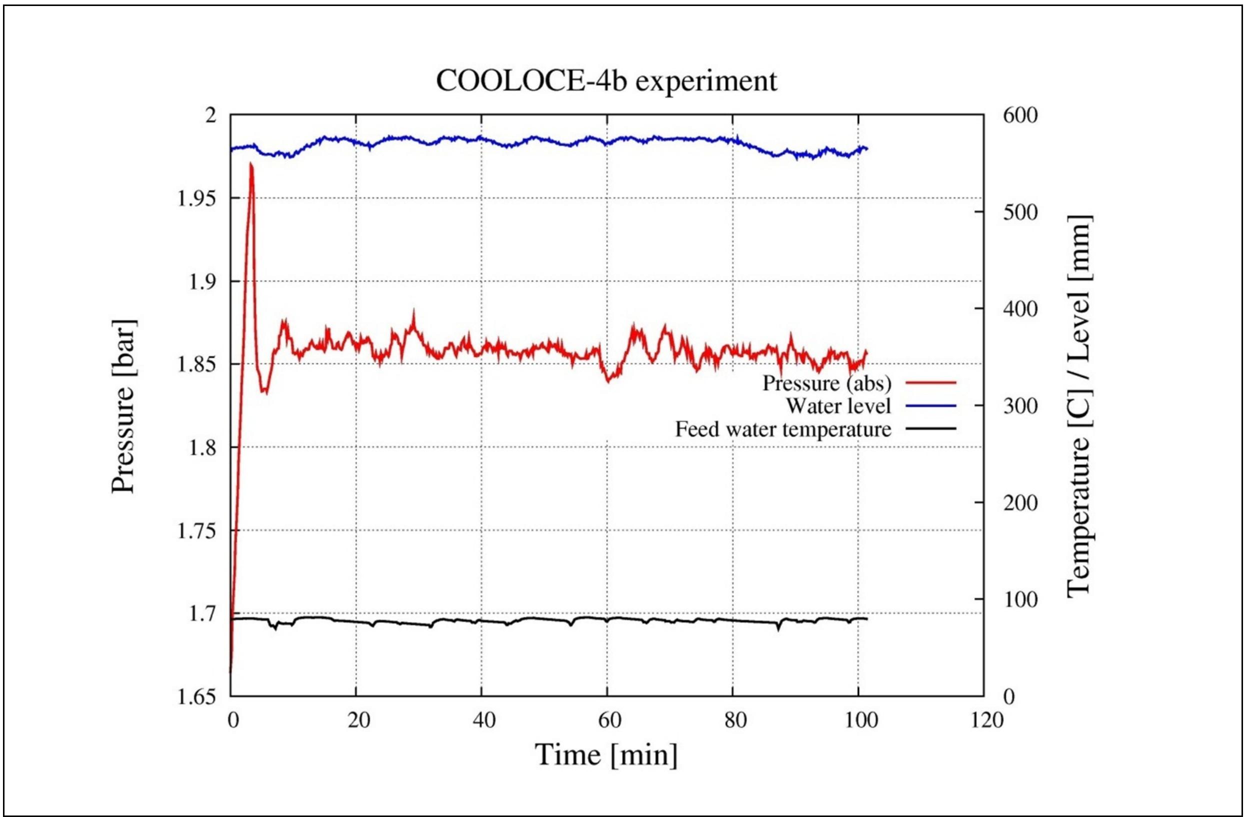


Fig. 12. Water level and pressure in the test vessel and the feed water temperature in the COOLOCE-4b experiment.

In the repeatability experiment COOLOCE-4bR, dryout was seen at the control power of 26.2 kW, detected by the multi-point sensor near the centre of the test bed at the heights of 110 mm and 120 mm from the test bed bottom. The test was run after a start from a cold state and a heat-up sequence.

The temperature of the sensors indicating dryout and the power history of the COOLOCE-4bR experiment are shown in Fig. 13. The water level and pressure and the feed water temperature are shown in Fig. 14. As can be seen in Fig. 13, the temperature behaviour was very similar to the 4b experiment but with no final lateral spreading of dryout to the sensor 111-225 on the opposite side of the central heater. Also, the dryout power of COOLOCE-4b and -4bR are very close to each other (26.1 kW and 26.2 kW). At the dryout power level of COOLOCE-4bR, the average mass flow rate of condensate was about 0.011 kg/s which corresponds to a heat flow of 23.2 kW.

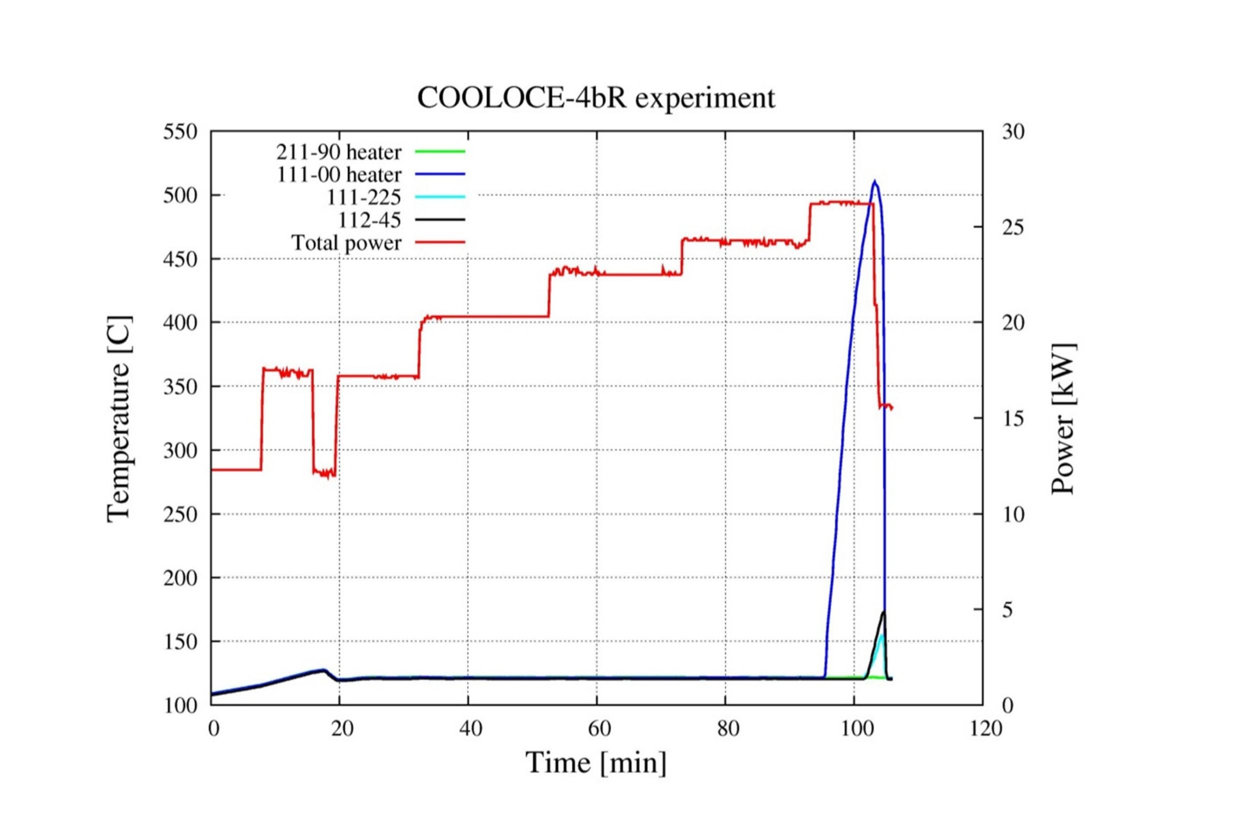


Fig. 13. Control power and temperature log in the COOLOCE-4bR experiment at the pressure of 2.0 bar.

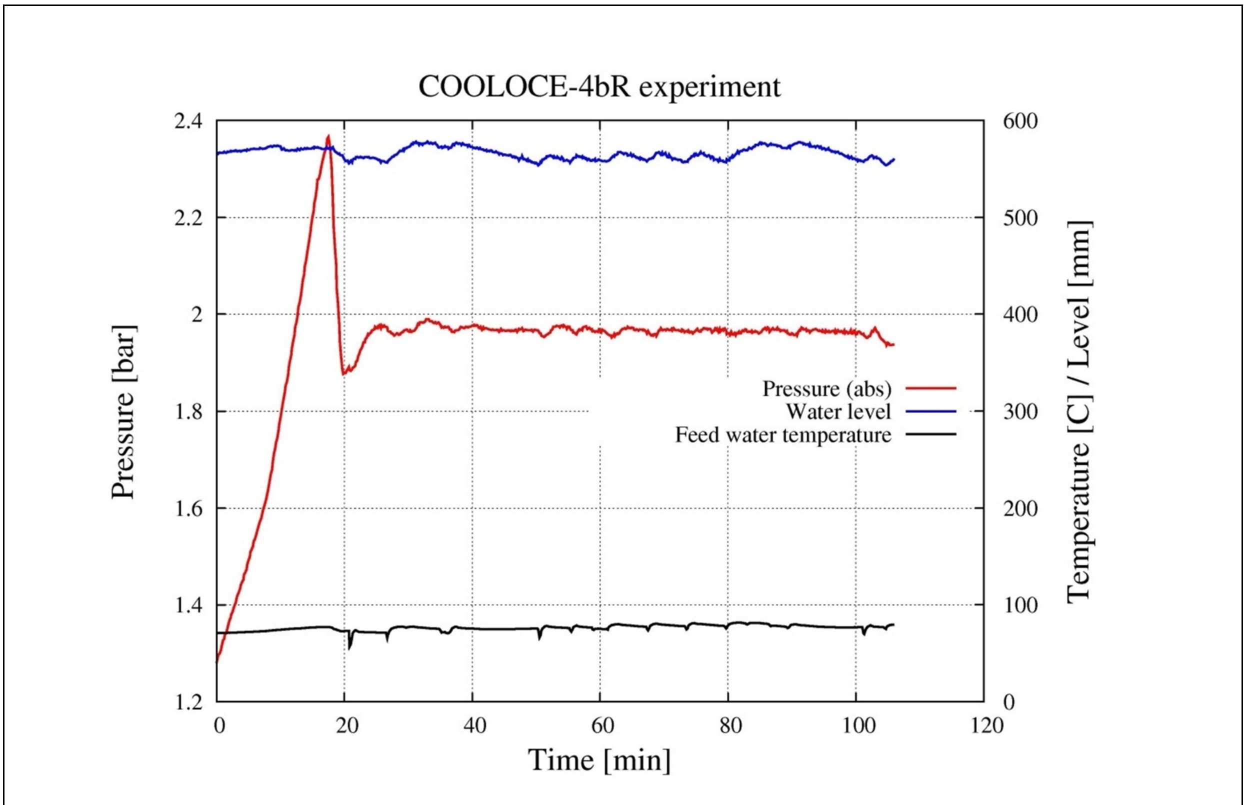


Fig. 14. Water level and pressure in the test vessel and the feed water temperature in the COOLOCE-4bR experiment.

3.3 COOLOCE-5a – 5d

The COOLOCE-5 test series consisted of the experiments at the higher pressures of 3-7 bar. The 3.0 bar experiment (5a) consisted of two parts. First, an alternative way of approaching dryout was tested: the power was kept constant at around 30 kW while the pressure was gradually decreased from 5 bar to 2.5 bar until dryout was seen as a result of decreasing steam density and increasing void (steam volume) within the test bed. Immediately after this, the power was decreased to quench the dryout and a new dryout was search was conducted using the usual power increments at 3 bar pressure.

During the pressure transient, dryout was seen at 30 kW power and 2.5 bar pressure indicated by the sensors 111-225 and 211-288 at the height of 110 mm. The built-in sensors of the heaters are also at the height of 110 mm from the bottom. Contrary to the previous experiments, dryout did not spread in vertical direction. However, it should be noticed that there are no sensors directly above the sensors that indicated dryout and the exact size of the dried-out zone is not known.

In the power step experiment that followed, dryout was seen at the control power of 31.9 kW and 3.0 bar pressure at the sensor located 110 mm from the test bed bottom (111-225). The dryout did not spread from this sensor until the central heater had reached 600°C at which point the power was switched off. Because the scale had to be emptied during the power step that led to dryout no reliable measurement of the condensate mass flow was obtained for the experiment. Based on interpolation of the power data calculated for the eight other experiments, the heat flow directed to boiling at this pressure and control power level is 26.6 kW.

The temperature of the sensors indicating dryout and the power history of the COOLOCE-5a experiment are shown in Fig. 15. The water level and pressure and the feed water temperature are shown in Fig. 16. The first of the dryouts in the figures is the pressure decrease transient.

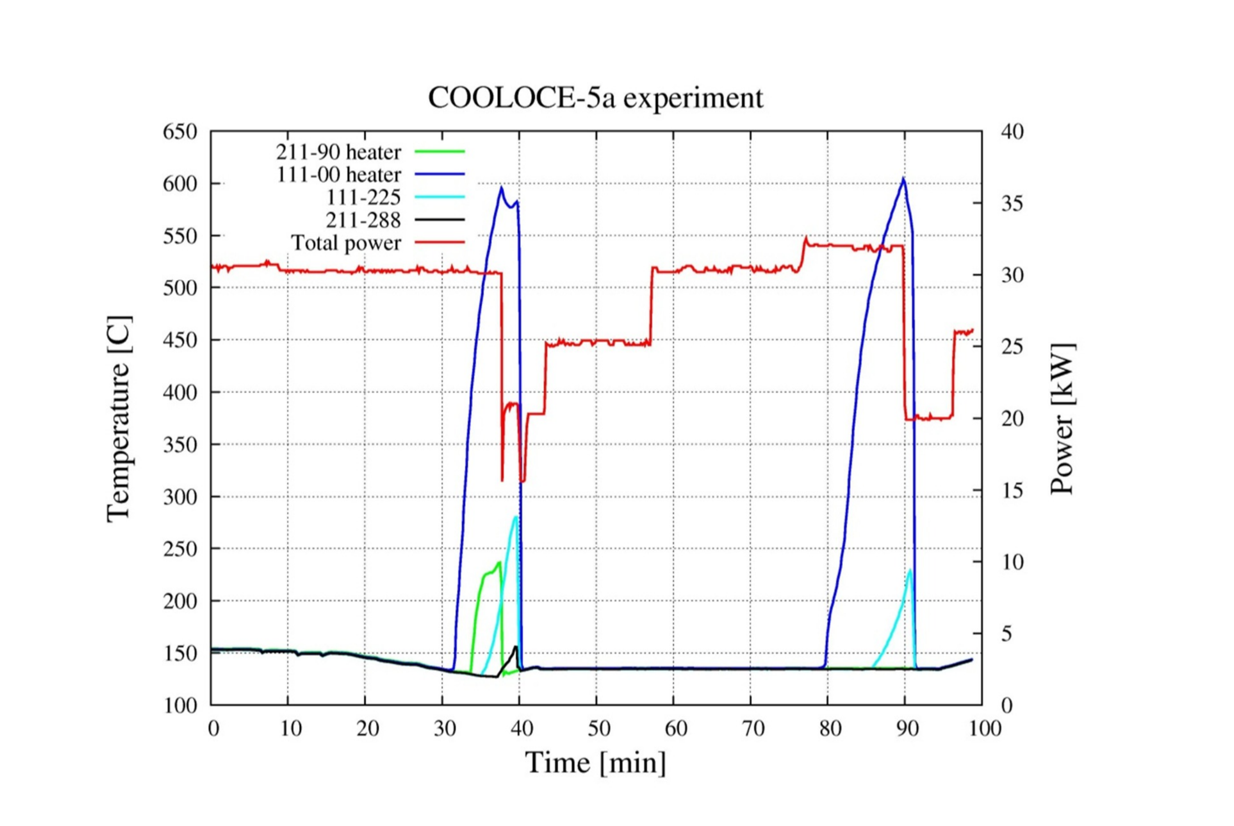


Fig. 15. Control power and temperature log in the COOLOCE-5a experiment at the pressure of 3.0 bar.

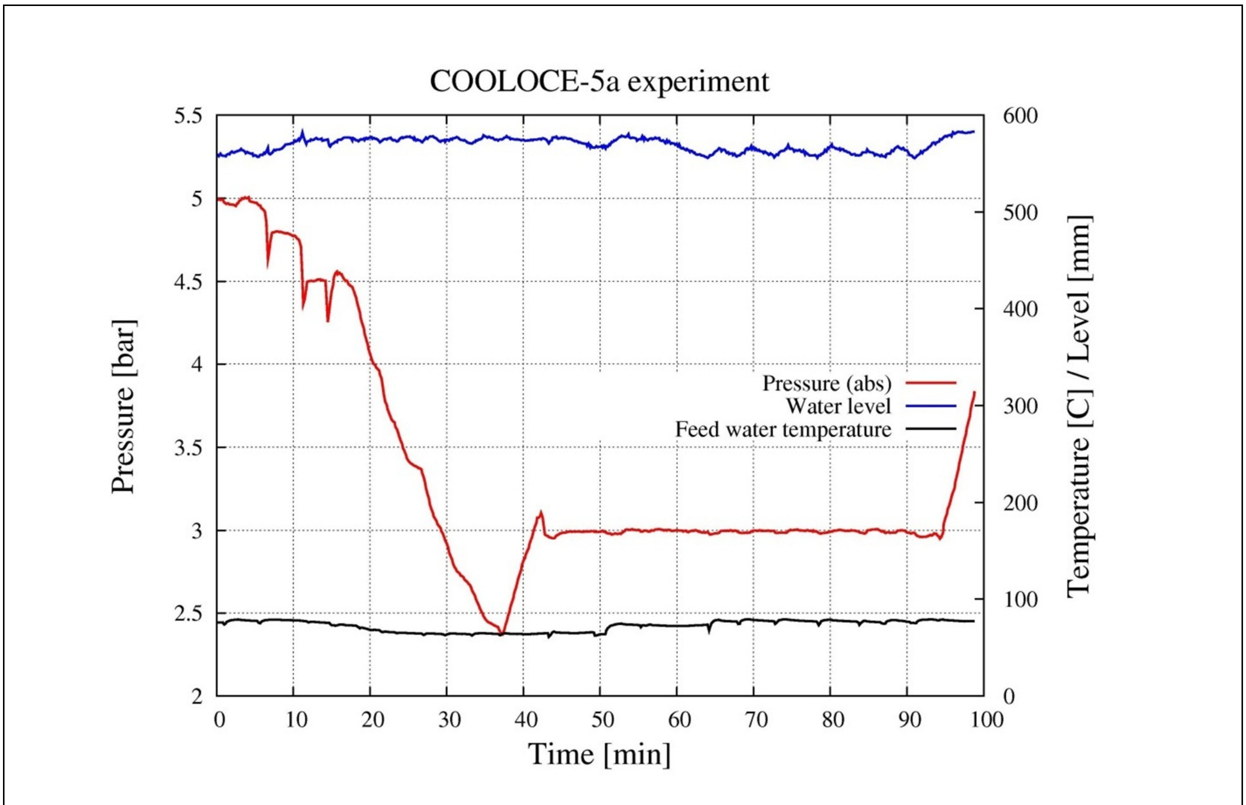


Fig. 16. Water level and pressure in the test vessel and the feed water temperature in the COOLOCE-5a experiment.

In the 4.0 bar experiment (5b), dryout was first seen at the control power of 34.6 kW at two different sensors at the height of 110 mm from the test bed bottom (111-225 and 211-288). The dryout spread to the second "ring" of sensors away from the center of the cylinder. This kind of spreading was earlier seen only in the pressure transient experiment in which the sensor 211-288 showed a moderate increase from saturation temperature just before the power was turned off.

The temperature of the sensors indicating dryout and the power history of the COOLOCE-5b experiment are shown in Fig. 17. The water level and pressure in the test vessel and the feed water temperature are shown in Fig. 18. The average mass flow rate during the power step that led to dryout was 0.014 kg/s which corresponds to a heat flow of 29.3 kW.

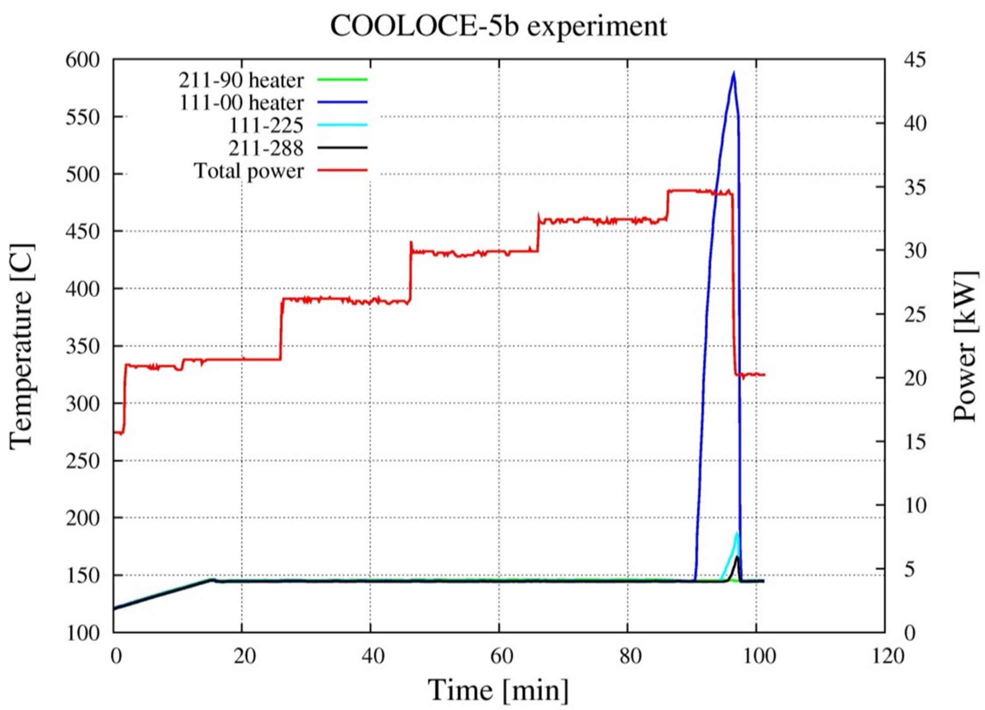


Fig. 17. Control power and temperature log in the COOLOCE-5b experiment at the pressure of 4.0 bar.

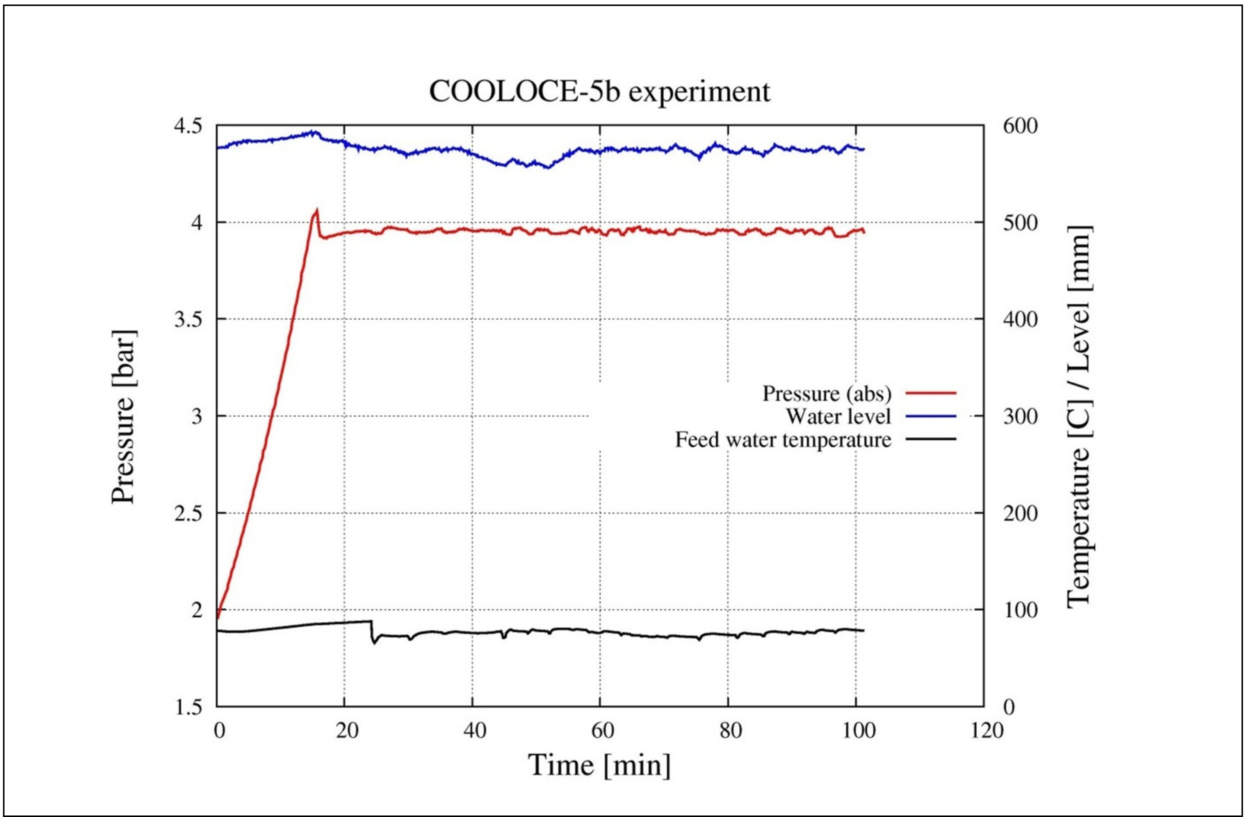


Fig. 18. Water level and pressure in the test vessel and the feed water temperature in the COOLOCE-5b experiment.

At 5 bar ambient pressure (5c), the dryout control power was 37.2 kW. The sensor indicating dryout was 111-225, 110 mm from the test bed bottom. No spreading of dryout to other sensors was seen until the temperature of the central heater had exceeded 600°C at which time the power was switched off.

The temperature of the sensors indicating dryout and the power history of the COOLOCE-5c experiment are shown in Fig. 19. The water level and pressure and the feed water temperature are shown in Fig. 20. The condensate mass flow at the power step leading to dryout was 0.015 kg/s corresponding to a power of 31.0 kW.

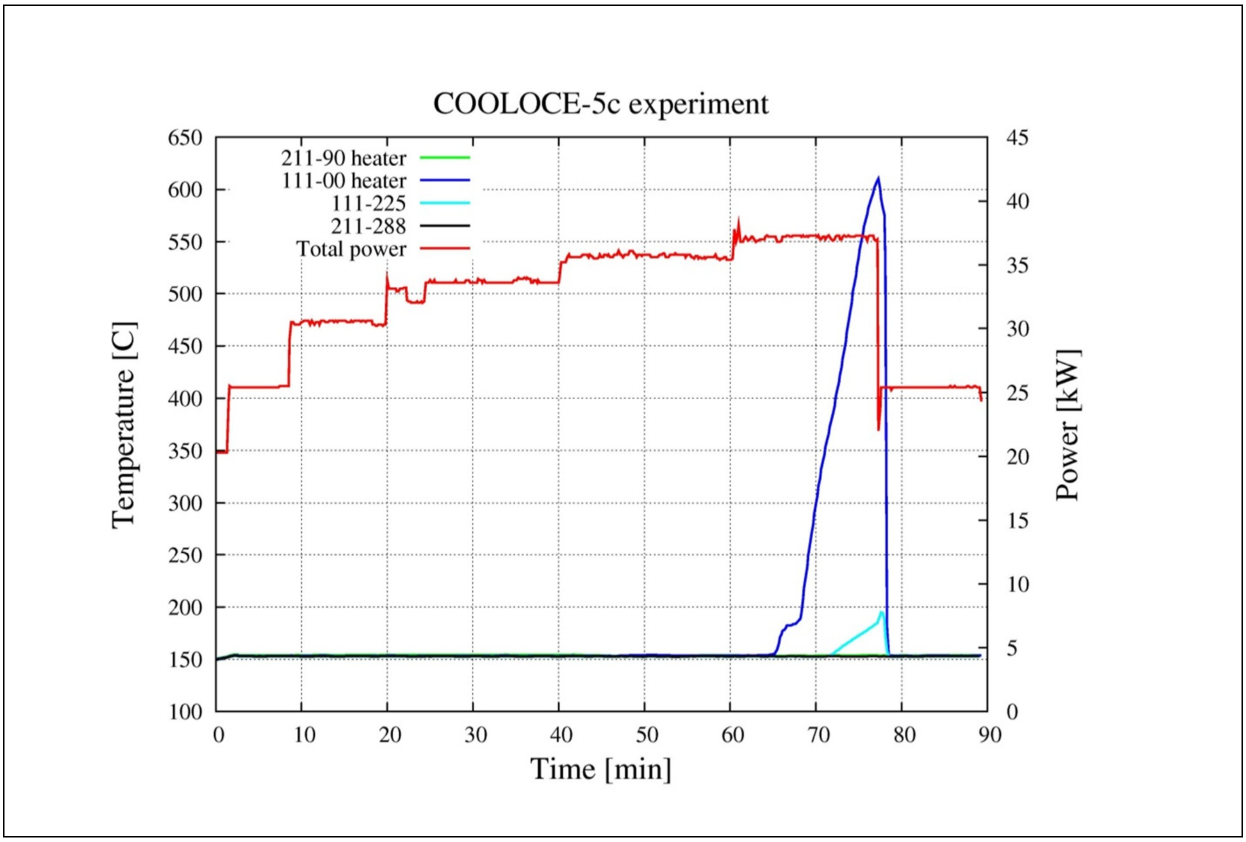


Fig. 19. Control power and temperature log in the COOLOCE-5c experiment at the pressure of 5.0 bar.

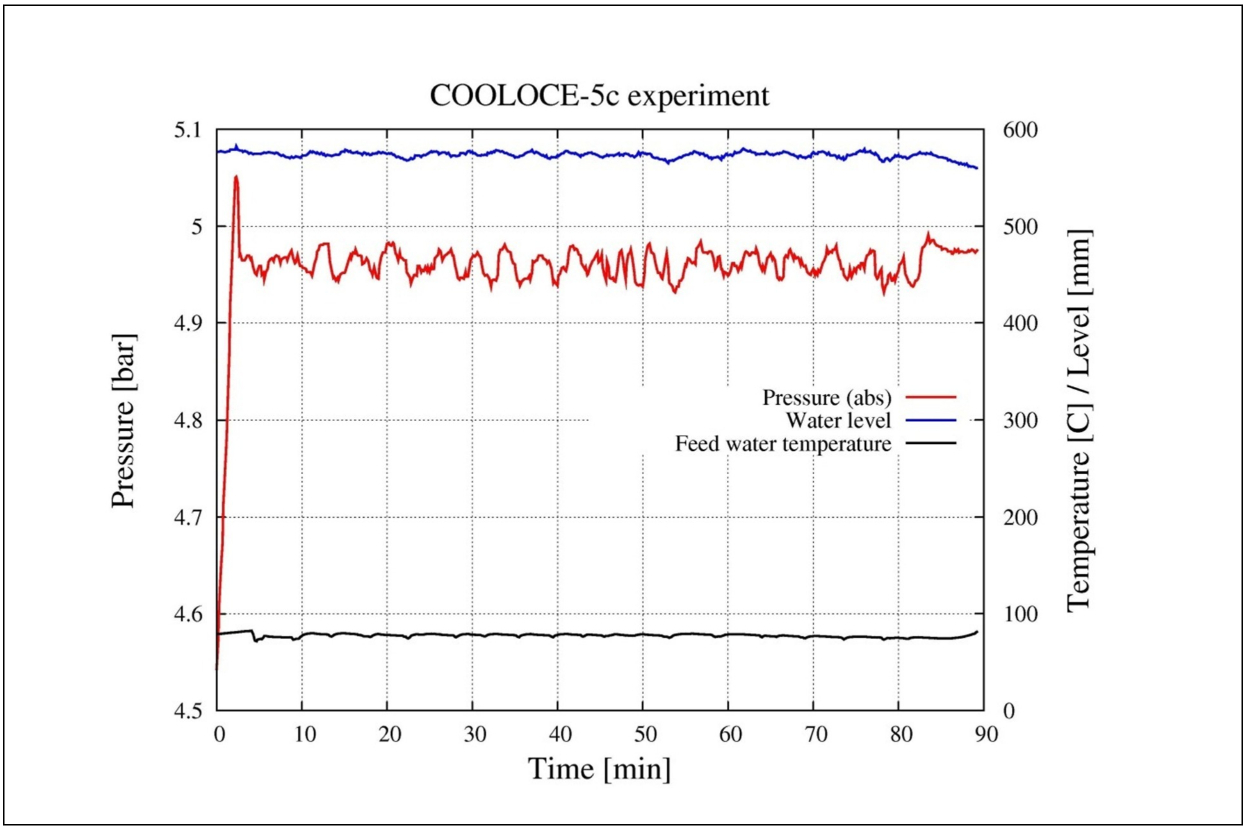


Fig. 20. Water level and pressure in the test vessel and the feed water temperature in the COOLOCE-5c experiment.

At the highest of the tested pressure levels, 7 bar, the measured dryout power was 42.3 kW. Again, dryout was indicated by one sensor (111-225) at 110 mm from the test bed bottom and next to the central heater. The power was switched off when the temperature of the central heater had reached 550°C. The temperature of the sensors indicating dryout and the power history of the COOLOCE-5d experiment are shown in Fig. 21. The water level and pressure and the feed water temperature are shown in Fig. 22. The condensate mass measurement showed the mass flow rate to be 0.016 kg/s which yields a heat flow of 33.9 kW.

It is noteworthy that for the pressure of 5 bar, the experiment had to be repeated in order to be able to achieve reliable results for the dryout power. The first attempt to increase pressure to 5 bar war conducted directly after the COOLOCE-4b experiment but it was seen that only the heaters 111-00 and 211-90 started to show increased temperatures. No increase in the sensors within the porous material was seen until the heaters had reached temperatures which might compromise the heater integrity. The power level of this heater dryout was 37.3 kW.

No attempt to increase the pressure to 7 bar was made after this because dryout can be more difficult to detect in greater pressures because of increased steam density and smaller void fraction. In addition, the saturation temperature increases along with pressure which leaves considerably less margin (and time) for the formation of dryout within the bed before considerable overheating of the heaters at higher pressures.

In the next test sequence on the following day, after the start-up from a cold state, dryout in the test bed was achieved for the 5 bar pressure at the power of 37.0 kW as described above. This might suggest that dryout was formed at practically the same power level but in a slightly different location on separate test days. After this experiment, a reliable result was obtained even for the pressure of 7 bar.

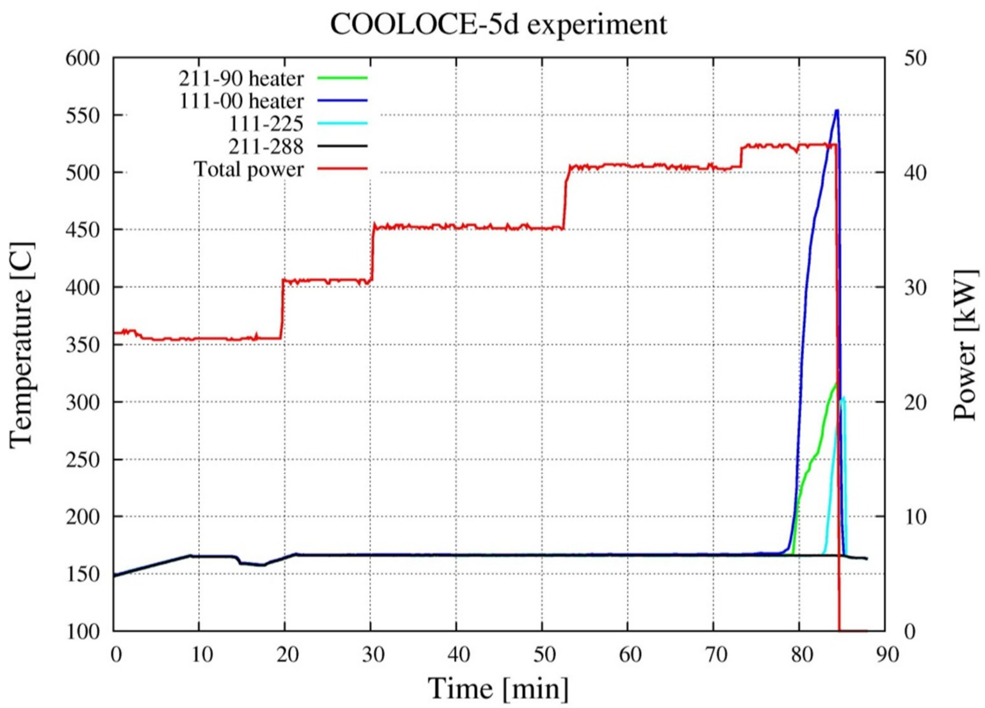


Fig. 21. Control power and temperature log in the COOLOCE-5d experiment at the pressure of 7.0 bar.

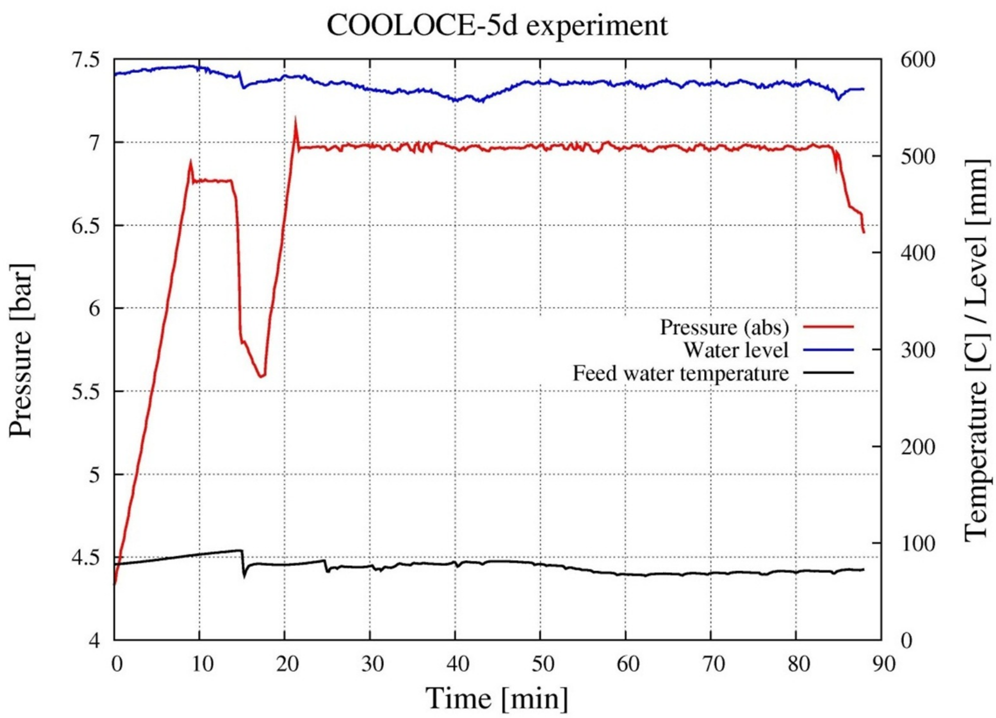


Fig. 22. Water level and pressure in the test vessel and the feed water temperature in the COOLOCE-5d experiment.

4 Discussion and summary

The experiments conducted within the COOLOCE test programme until the publication of this report have been summarized in Table 2. The COOLOCE-0 test was a preliminary experiment conducted in order to verify that heaters and instrumentation were working as required. The maximum control power applied in the preliminary experiment was 20 kW (for which no dryout was seen). The COOLOCE-1 – 2 test series were performed with the conical particle bed and the COOLOCE-3 – 5 series with the cylindrical bed.

Table 2. Summary of the COOLOCE experiments in chronological order. Dryout power density and heat flux are given for the control power. Heat flux is given only for the cylindrical bed because a directly comparable heat flux does not exist for the conical bed.

Experiment	**Date**	**Pressure [bar]**	**Dryout results**			
			Control power (kW)	Calculated power (kW)	Power density (kW/m³)	Heat flux (kW/m²)
Conical test bed						
COOLOCE-0 (preliminary test)	Aug 31, 2010	2.0	-	-	-	-
COOLOCE-1	Oct 21, 2010	1.9	46.2	40.7	2326	-
COOLOCE-2	Nov 4, 2010	1.6	43.8	38.3	2206	-
Cylindrical test bed						
COOLOCE-3	May 19, 2011	1.1	19.0	17.3	932	252
COOLOCE-3R	Jun 17, 2011	1.1	20.4	18.8	1001	270
COOLOCE-4	Jun 17, 2011	1.6 1.9	23.4 26.1	20.6 22.9	1148 1281	310 346
COOLOCE-4bR	Jun 20, 2011	1.95	26.2	23.2	1286	347
COOLOCE-5	June 20, 2011	3.0 4.0 4.95 6.95	31.9 34.6 37.2 42.3	26.6* 29.3 31.0 33.9	1565 1698 1825 2076	423 458 493 560

**Estimate based on the heat losses of the other experiments*

In all the experiments, dryout was seen in the central region of the test bed, both in vertical and horizontal direction. The sensors indicating dryout are highlighted in the map of Appendix B. Theoretically, dryout would be formed near the bottom of the test bed and favour lateral spreading in a cylindrical configuration with uniform heat generation and top flooding. In the experimental set-up, the heat losses through the bottom plate of the test vessel, the fact that the exact dryout power is impossible to reach experimentally and the local heat generation affect the dryout location. In this light, dryout in the central parts of the test bed is acceptable. However, it would be of interest to gain more information of the possible effect of the vertical heating configuration (downcomer effect by vertical channels of increased porosity) on the dryout power and location. All measured dryouts were accompanied with a clear temperature increase. The maximum temperatures of the test bed sensors were approximately 50°C above the saturation temperature. The maximum temperature of the heater sensors was 350-600°C.

Overheating and damage to some of the central heaters was encountered during the conical bed experiments. The removal of the particle material after the experiments revealed that the outer sheath was damaged in the upper parts of the heaters, giving a clear indication of the location of dryout.

No such problems were encountered with the cylindrical bed which suggests that the new heaters may have performed better than the previous ones. Also, the built-in thermocouples help in avoiding damaging the heaters by accident. In a few of the cylindrical bed experiments, only the increase in heater temperatures revealed local dryout after which the test sequence was terminated. In experiments without the heater temperature measurement (such as the conical bed experiment), this type of temperature excursion would have been (and may have been) undetected. On the other hand, the power levels needed for dryout in the cylindrical bed experiments were lower compared to the conical bed experiments which may reduce the loading of the heaters.

5 Conclusions

Debris bed coolability experiments have been performed with a cylindrical test bed installed into the COOLOCE test facility. The experiments aim at providing data of the effect of particle bed geometry on dryout power by comparisons of cylindrical and conical test beds. The pressure range of the cylindrical bed experiments varied from 1 bar to 7 bar and the measured dryout power varied between 17 kW and 34 kW. Dryout power was evaluated based on the mass flow rate of the condensing steam which gives an estimate of the heat flow directed to boiling. This is lower than the control power by a few kilowatts because of heat losses from the facility.

References

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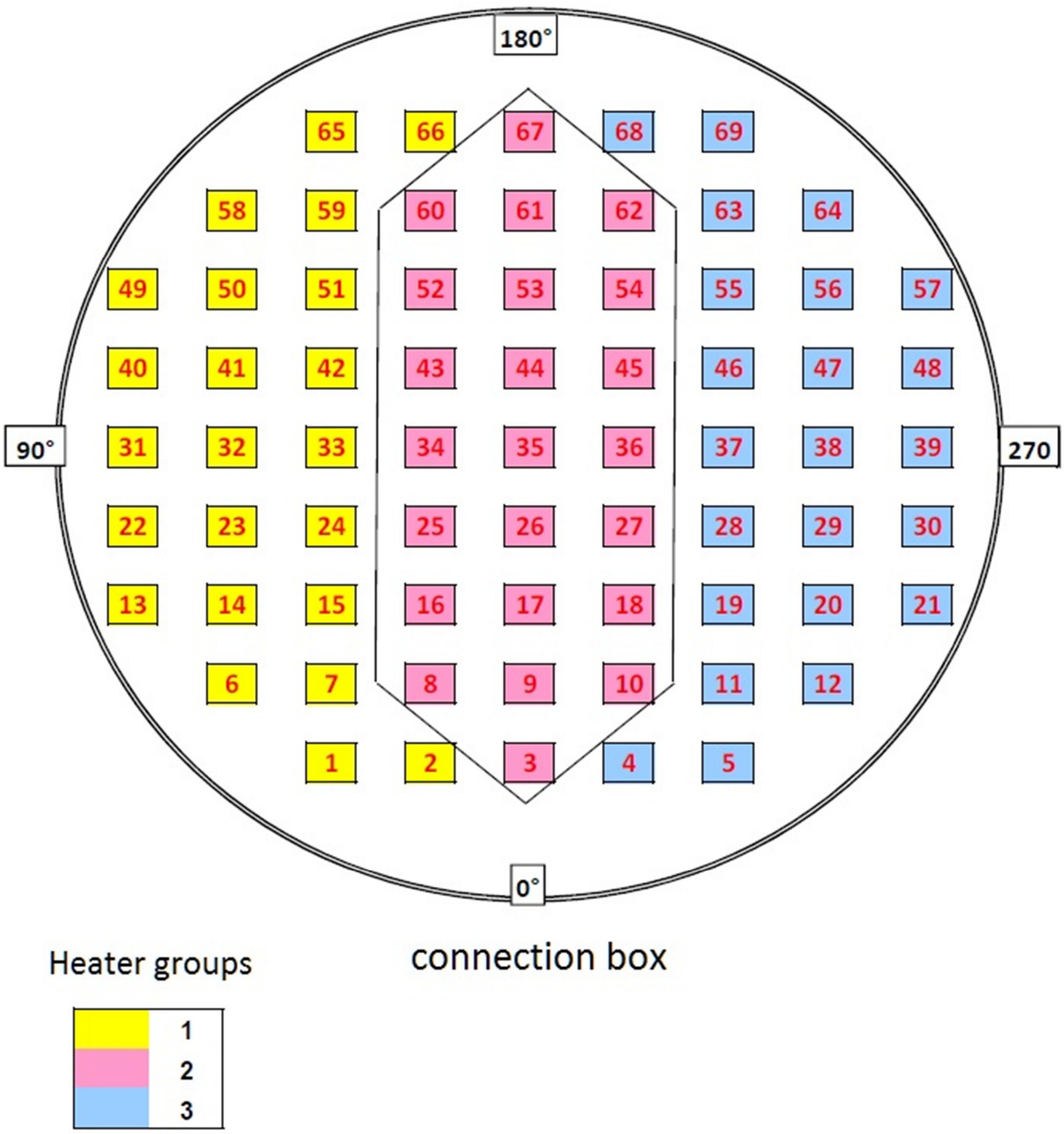
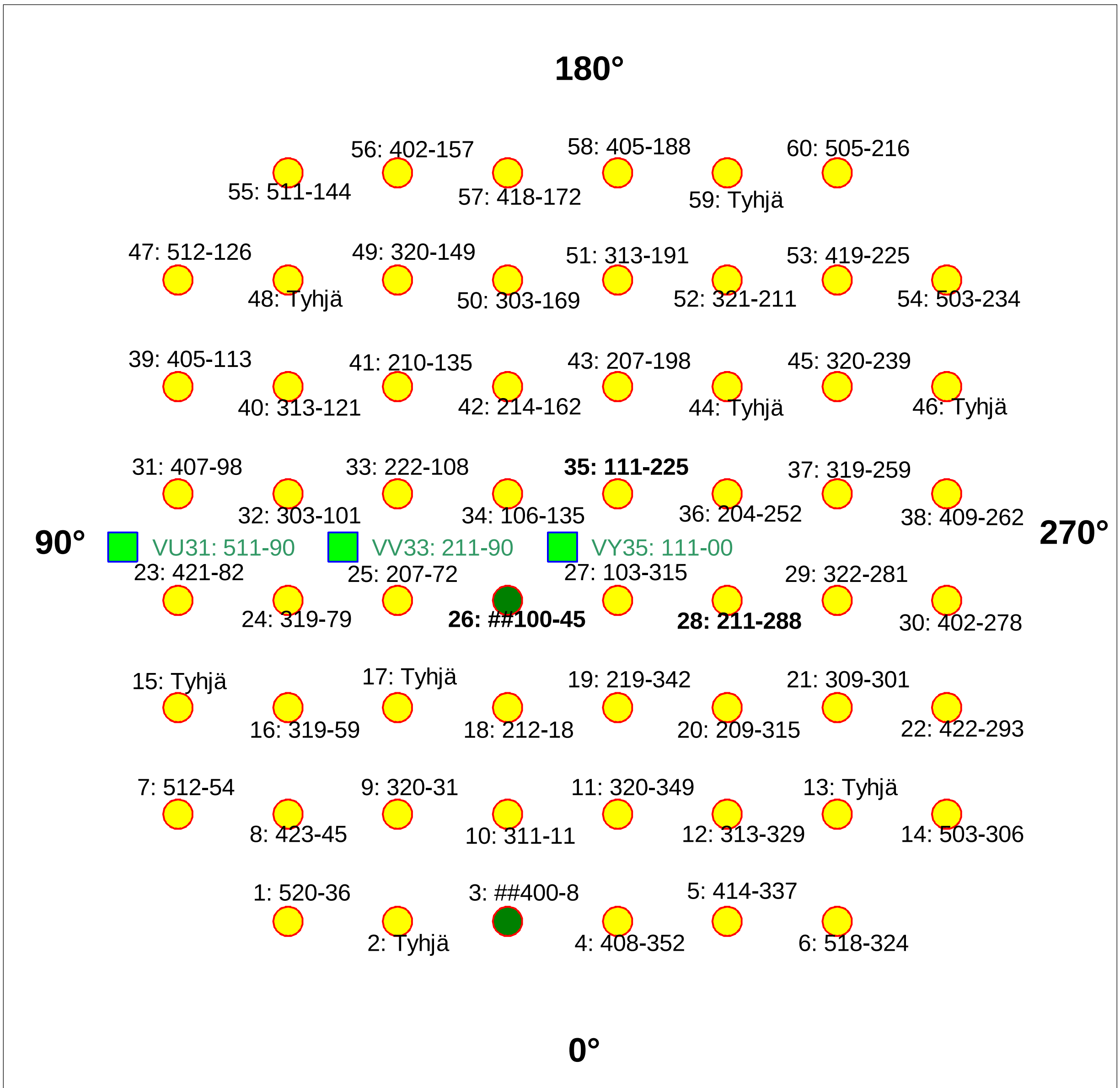
5. Lindholm, I., Holmström. S., Miettinen, J., Lestinen, V., Hyvärinen, J., Pankakoski, P., Sjövall, H. 2006. Dryout Heat Flux Experiments with Deep Heterogenous Particle Bed. Nuclear Engineering and Design 236 (2006), p. 2060-2074.

APPENDIX A. Heater arrangement of the COOLOCE cylinder (top view of the pressure vessel bottom plate)



APPENDIX B. Thermocouple arrangement of the COOLOCE cylinder (top view of the pressure vessel bottom plate)



Multi-point sensor 26: ##100-45	Multi-point sensor 3: ##400-8	Heaters with internal sensors	Example of how to read the map: **117-45**
100-45 102-45 105-45 107-45 110-45 **112-45** **115-45** **117-45** 120-45 122-45 (Sensors that indicated dryout are in **bold)**	400-8 402-8 405-8 407-8 410-8 412-8 415-8 417-8 420-8 422-8	VU31: 511-90 VV33: 211-90 VY35: 111-00	1 – number of the ring to which the thermocouple belongs to (1 indicates the central sensors, 7 the outermost) 17 – height of the thermocouple from the bottom in cm 45 – angle between the thermocouple location and 0°