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D2.3 – Heat exchanger design trial report

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Abstract	The deliverable provides a report on the heat exchanger (PCM module) detailed design trial.	

REVISION HISTORY

Version	Date	Main Authors/Contributors	Description of changes

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[1] Dissemination level security:

PU – Public (e.g. on website, for publication etc.) / **PP** – Restricted to other programme participants (incl. Commission services) /
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Summary

WP2 delivers the pre-design of the heat storage demonstrators that will be designed, manufactured, installed and tested in respectively WP6 (Insheim site) and WP7 (Kizildere 2 site). WP2 includes several Tasks such as the selection of suitable storage materials and alloys (Task 2.1), the design of the thermal energy storage system (Task 2.2), the thermal storage modelling and optimisation (Task 2.3), the manufacture and test of the storage modules at small scale (Task 2.4) and the study of the pre-installation on site (Task 2.5 and 2.6).

In particular, the preliminary design of the PCM module at lab-scale and demonstration scale was done in Task 2.2 and detailed in the deliverable D2.2 using the PCM 2D model developed in Task 2.3.

The deliverable D2.3 provides the heat exchanger (PCM module) detailed design trial. The small-scale PCM storage module will be manufactured and tested on CEA site in Task 2.4 before the installation of the large-scale module at the ZORLU site.

Objectives Met

The main objective is to provide the detailed design of the small-scale PCM module that will be manufactured and tested in task 2.4. The selected PCM is HITEC salt mixture (Melting temperature: 140 – 142°C, see deliverable D2.1). For reasons that are dependant to the CEA centre operation rules, the amount of HITEC is limited to 1000 kg in the small-scale module.

Two detailed studies were undertaken successively for the small-scale PCM module:

– **Detailed design 1**: In this version, there are 55 finned tubes and hydraulic inserts inside the tubes. This solution was abandoned at the end of 2021 because the risk of scaling was too high in the annular flow section.
– **Detailed design 2**: In this version, there are 19 finned tubes without hydraulic inserts inside the tubes, but with aluminium profiles around the tubes. The aluminium profiles have a specific shape that was designed in order to enhance the thermal conductivity in the PCM as uniformly as possible.

The detailed design included:

– The support of the PCM module (skirt)
– The retention tank in case of PCM leak
– The instrumentation definition
– The high pressure piping connecting the module to the testing installation at CEA
– The supports for the piping and valves
– The calculation notes for the module and the piping

The deliverable contributes towards the following work package objective:

Selection of the most appropriate storage media for each of the case study examples; Development and validation of the storage and heat exchanger systems around this, based on the storage requirements specified. Production of large scale demonstrator equipment ready for the case studies. The results of this work package will be utilised by both case studies and will be used up until the end of the project.

CONTENTS

1. INTRODUCTION

The proposed technology is for the Phase Change Materials (PCM) storage module is a shell and tubes heat exchanger with a single pass on the tubes side for ease of cleaning, and with finned tubes on the PCM side in order to enhance its conductivity.

The PCM module will consist of:

– The brine circuit including 2 collectors, 2 distribution plates and the finned tubes.
– The shell filled of Phase Change Material and having at the top a gas sky (header space) to accommodate the volume changes associated with the PCM phase change.

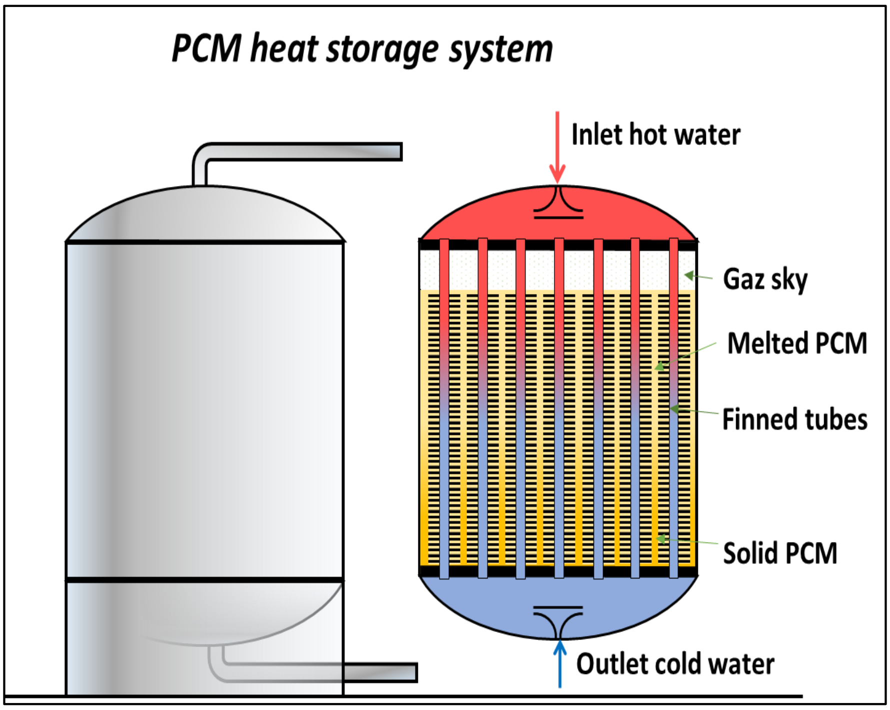


Figure 1: PCM heat storage working principle

Thermally, the PCM storage functions as follows:

– During the charge, the "heat transfer hot fluid" (whose temperature is higher than the PCM melting temperature) enters by the top collector and flows down the module inside the finned tubes, transfers its heat to the PCM, and goes out colder by the bottom collector. During this phase, the solid PCM melts and becomes liquid.
– During the discharge, the "heat transfer cold fluid" enters by the bottom collector and flows up the module inside the finned tubes, recovers the PCM heat, and goes out hotter by the top collector. The temperature of the heat transfer fluid at the output during the discharge is close to the melting temperature of the PCM. During this phase, the PCM changes its state from liquid to solid.

The small-scale PCM module will be similar to the Kızıldere 2 demonstrator, in terms of geometry, range of temperature and pressure, type of finned tubes, PCM, and the flowrate by tube will be conserved. The instrumentation principle will also be similar, but it will be denser than in the demonstrator. The capacity is approximately 100 kWh, 0.5% of the full-scale capacity.

There are two main differences with the demonstrator. The heat transfer fluid is demineralized water with no risks of scaling, and the durations of charge and discharge are shorter, 3 hours for the demonstrator and 1.5 hours for the small-scale module. This is due to the shorter height of the lab-scale module that will be installed indoors.

In this deliverable two detailed studies of the small-scale PCM module will be presented.

2. DETAILED STUDIES OF THE SMALL-SCALE PCM MODULE

Two detailed studies of the small-scale PCM module have been carried out successfully:

- **Detailed design 1**: 55 tubes with hydraulic inserts inside the tubes
- **Detailed design 2**: 19 tubes without hydraulic inserts inside the tubes, but with aluminium profiles around the tubes

The first detailed design was undertaken from November to December 2021 after the final selection of PCM and metallic alloys (see D2.1 for details). At the end of December, it appeared that the scaling risk was too high with hydraulic inserts inside the tubes as the brine is a highly mineralized water with a high risk of deposition as soon as the temperature drops, the minerals being mainly made up of silicate compounds whose solubility decreases with temperature. Therefore, a second design had to be proposed by CEA to avoid these inserts, by increasing the PCM amount around each tube and enhance the heat exchange in the PCM by adding aluminium profiles (FIOCCO) in the PCM zone. This new design allows a decrease of tube numbers, which increases the flowrate by tube, increasing the Reynolds number in each tube and maximises the transition zones between the natural convection and forced convection flow (unsteady and hardly predictable zones) (c.f. deliverable D2.2).

The preliminary second design was achieved in January 2022, and the detailed design was developed from January to the end of February 2022. The majority of the first detailed design was nearly complete end of December 2021 the parts which could be kept include: the shell and domed ends dimensions, the skirt, the retention tank and the instrumentation. For the demonstration scale, the optimal gap between fins is 70 mm (see D2.2) but it has to be lowered to 60 mm in the small-scale module in order to keep the same shell diameter. Therefore, both modules have a slightly different geometry but this is minor and an acceptable compromise.

2.1 Detailed design 1

The detailed study of the small-scale PCM module has started in November 2021. It was led by CEA, supported by a mechanical engineering office. With the HITEC as PCM, the geometry and properties of the module for this study are:

- Triangular step between tubes.
- Pitch between fins : 10 mm (Figure 2).
- Hydraulic inserts: 10 mm.
- Number of tubes: 55 instead of 61 tubes in order to minimize the PCM in the periphery (Figure 3).

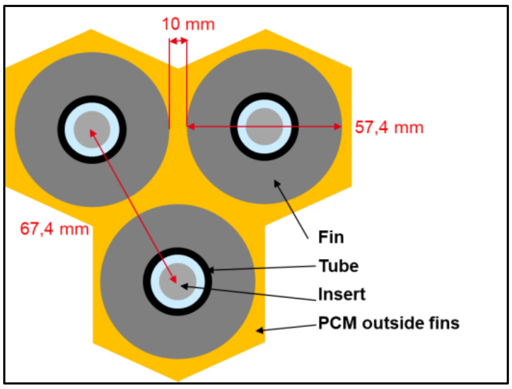


Figure 2. Triangular step between tubes in the module

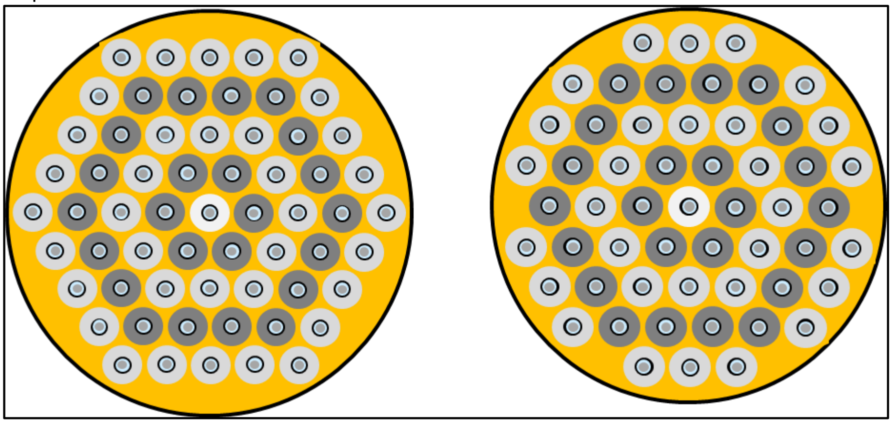


Figure 3. Cross sectional drawings of the PCM module with 61 tubes on the left and 55 tubes on the right

The shell, tubes and hydraulic inserts are made of carbon steel, and the fins are made of aluminium (Figure 4). The shell will be mainly filled with PCM, but a gas sky is kept to accommodate the volume change commensurate to the phase change of the PCM.

The heat exchanger is designed for 14 bar and 196°C and is submitted to pressure equipment regulations. The shell is designed for 0.5 bar and 196°C and is not submitted to pressure equipment regulation.

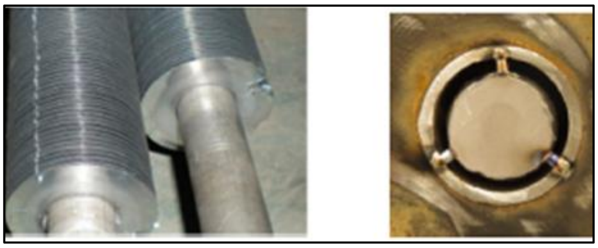


Figure 4. Carbon steel tubes with circular helical aluminium fins and cylindrical insert used as cross-sectional area reducer

Figure 5 shows the 3D and 2D drawings of the PCM module with 55 tubes. The 3D drawing shows the complete module details: the shell, the top and bottom collectors, the connections, the skirt, the retention tray, the ground base and the compensator which absorbs the thermal expansion created by the difference of temperature between the tubes and the shell in the module.

After installation on CEA site, the module will be filled with solid PCM through an inlet at the top of the shell. The PCM will melt thanks to the water circuit. At the end of the tests, the module will be emptied, the liquid PCM will flow through an outlet at the bottom of the shell, this outlet is equipped with an on/off valve, the pipe and the valve will have electric trace heating to melt the PCM in the pipe.

One difficulty of the design was to have removable hydraulic inserts, in order to be able to perform tests with and without inserts at lab-scale. This was achievable by an opening in the upper flange.

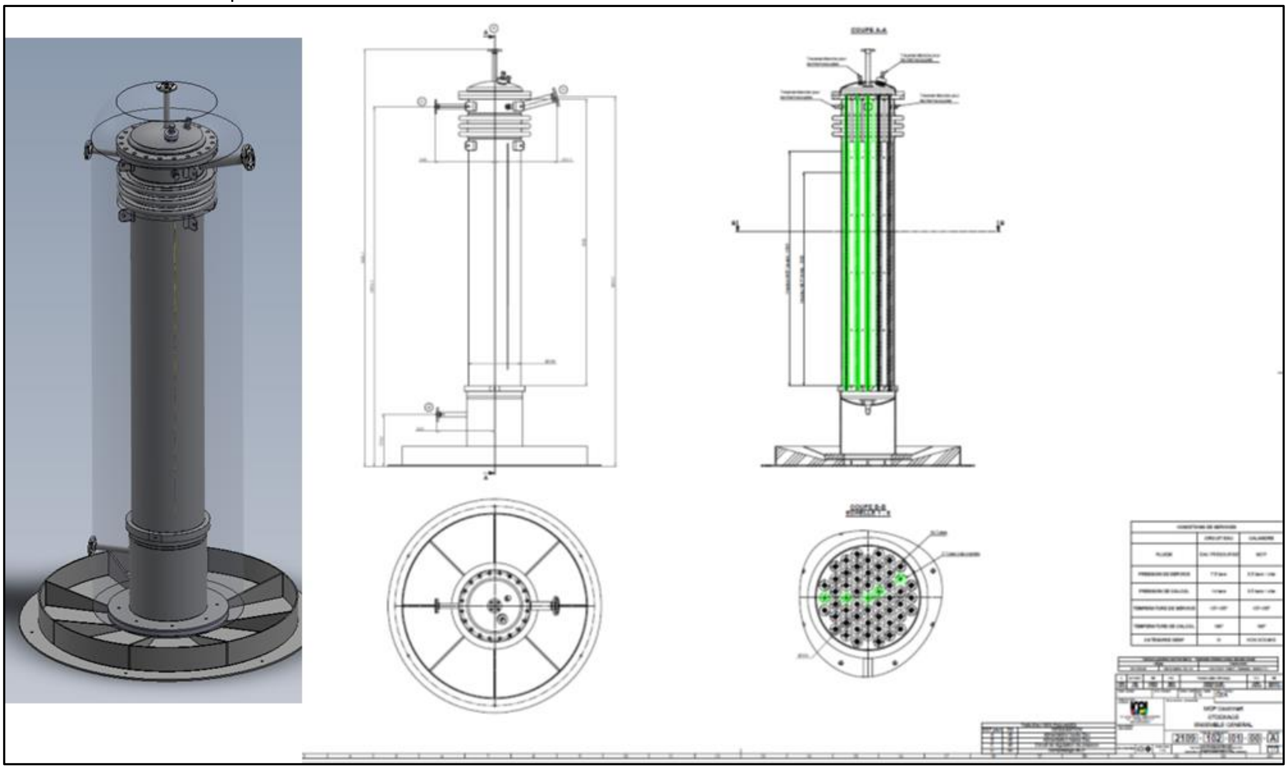


Figure 5. 3D and 2D drawings of the PCM module with 55 tubes

One of the detailed design difficulties is the instrumentation of the module, the major issue being to place the thermocouples and to feed-through all the cable connections.

The instrumentation of the module is shown in Figure 6. Temperature and pressure sensors are installed at the inlet and outlet of the module in order to measure the inlet and outlet HTF conditions, a mass flowmeter is also installed upwards the module on the experimental loop to measure the HTF flowrate. Five finned tubes are instrumented on eight height levels as follows: 1 thermocouple (TC) in the heat transfer fluid (cable of the TC attached to the hydraulic inserts), 1 TC in the PCM between fins and 1 TC in the free PCM. The shell is also instrumented with 2 TC at each level.

The top and bottom collectors are instrumented, to estimate the homogeneity of the temperature of the heat transfer fluid in these regions.

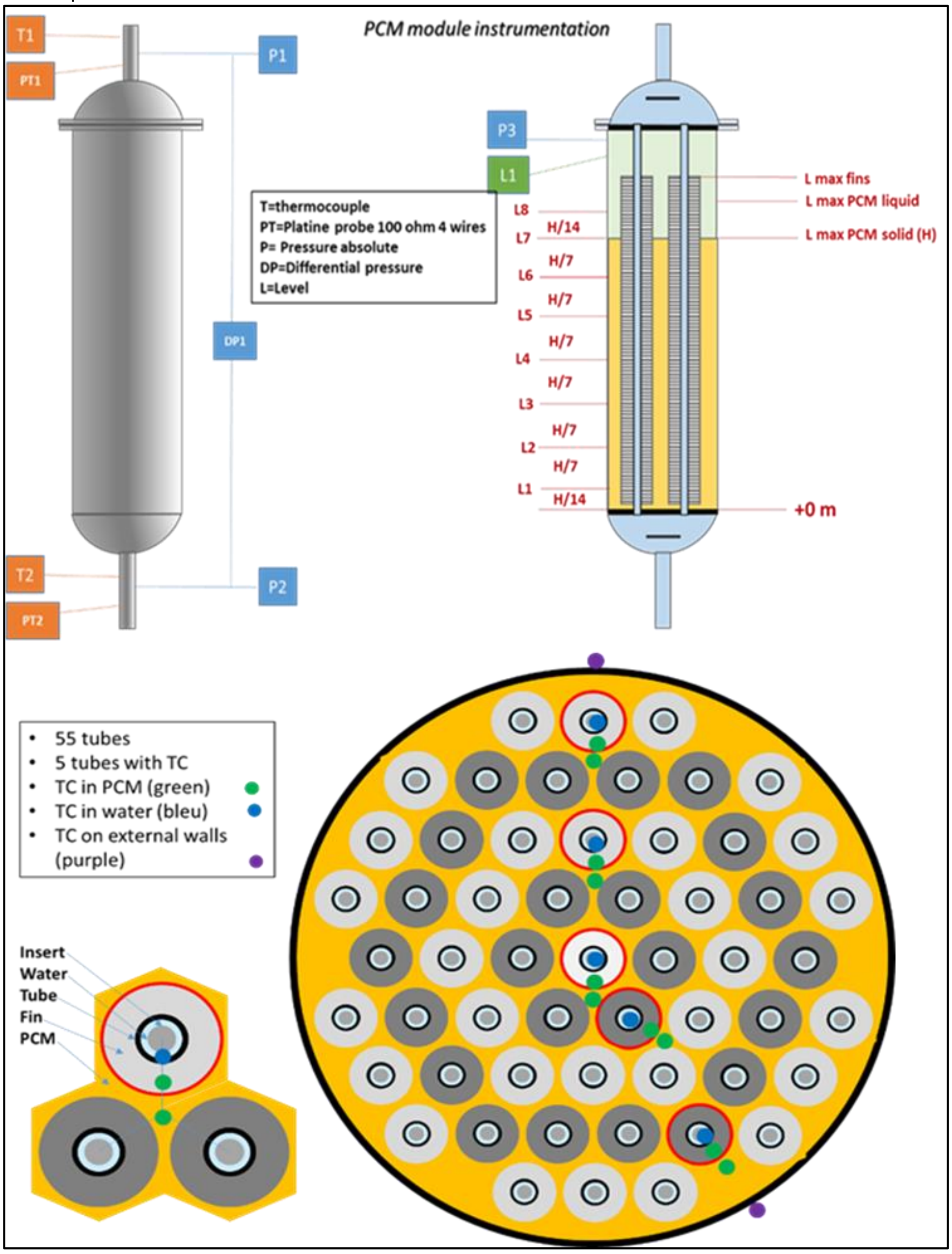


Figure 6. Instrumentation scheme of the PCM module with 55 tubes

When it was decided that the hydraulic inserts were not suitable due to the scaling risk at the end of December 2021, CEA proposed another design to avoid the inserts, which will be detailed in the next section.

2.2 Detailed design 2

The new design aims to avoid the hydraulic inserts, in order to increase the flowrate by tube, the number of tubes was reduced. This was obtained by increasing the amount of PCM around each tube and enhancing the heat exchange in the PCM by adding aluminium profiles (FIOCCO) in the PCM zone (Figure 7).

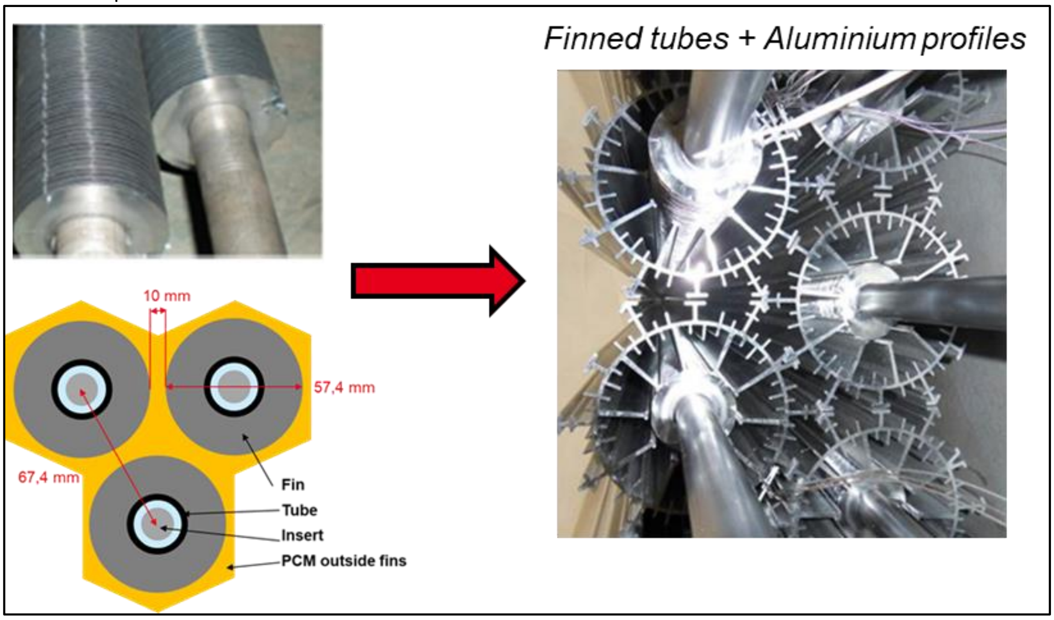


Figure 7. Scheme explaining the two designs of the PCM module: With aluminium profiles and without hydraulic inserts

This design results in an increase of the Reynolds number in each tube, and allows escaping from the transition zones between the natural convection flow and the forced convection flow (unsteady and hardly predictable zones) (c.f. deliverable D2.2).

Figure 8 shows the first 3D and 2D drawings of the PCM module with 19 tubes. As the previous study was almost complete, the diameter of the shell was retained for this study (0.61 m). This resulted in a module of 19 tubes (same finned tubes as study 1), with a pitch between two fins of 60 mm (aluminium profiles diameter 117.4 mm) and without hydraulic inserts inside the tubes.

For the demonstrator, the pitch between two fins will be 70 mm. However, the conservation of the shell diameter from the previous study led to a pitch between two fins of 60 mm (with 19 tubes) for the small-scale module.

The 3D drawing shows the complete module details. The shell, the top and bottom collectors, the connections, the skirt, the retention tray, the ground base and the compensator are used from the previous study. The main differences are the number of tubes and the addition of aluminium profiles in order to avoid the hydraulic inserts in the tubes.

The design pressure on the heat transfer fluid side is 14 bar, and the design temperature is 196°C. The shell is designed for 0.5 bar and 196°C to avoid being subject to the pressure equipment regulation.

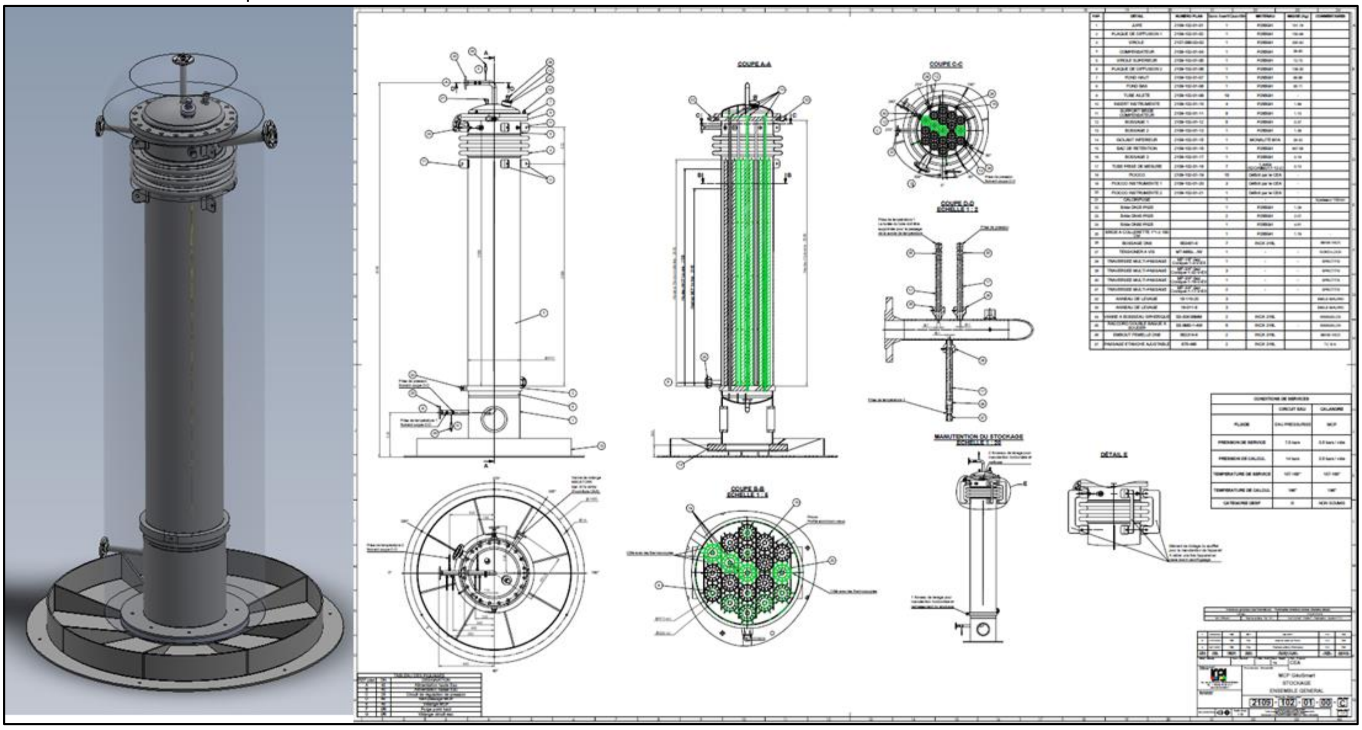


Figure 8. 3D and 2D drawings of the PCM module with 19 tubes

Figure 9 shows the geometry of the profiles around the tubes (19 profiles), and the profiles in the periphery (12 profiles), these profiles enhance the thermal conduction in the PCM around the tubes and in the periphery close to the shell.

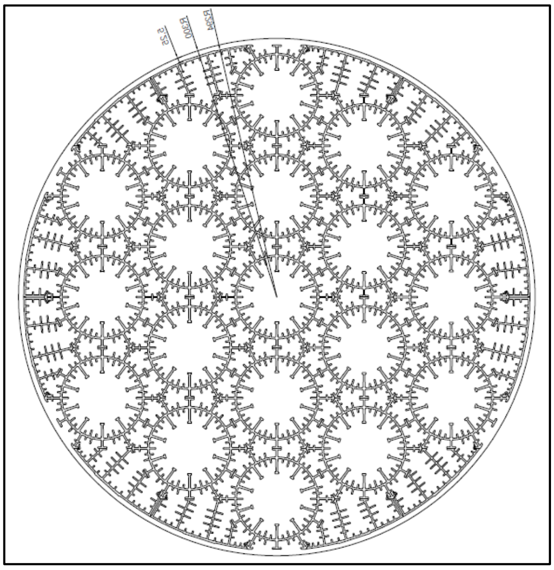


Figure 9. Drawing of the aluminium profiles in the GeoSmart PCM module

One of the detailed design difficulties is the instrumentation of the module. It should be dense, as this is a test module. Therefore, the major issue is to place the thermocouples and to take out the connection cables.

The instrumentation cables exit the top of the module through tight SPECTITE connectors; there are no connectors along the PCM height in order to minimize PCM leaks. In order to open easily the upper flange, the thermocouples in the PCM exit below the flange, and the thermocouples in the tubes or in the upper domed end exit above the flange. The thermocouples in the bottom dished end leave by the bottom of the module.

The instrumentation of the module is shown in Figures 10 and 11. Temperature and pressure sensors are installed at the inlet and outlet of the module in order to measure the inlet and outlet HTF conditions, a mass flowmeter is also installed upward the module on the experimental loop to measure the HTF flowrate. Four finned tubes are instrumented on eight height levels as follows: 1 thermocouple (TC) in the heat transfer fluid, 1 TC in the PCM between fins and 1 TC in the zone PCM + aluminium profiles. The shell is also instrumented with 1 TC at each level. On the PCM side, the TCs are held on the aluminium profiles. In the water tubes, they are held on a small vertical support with a minimal flow section.

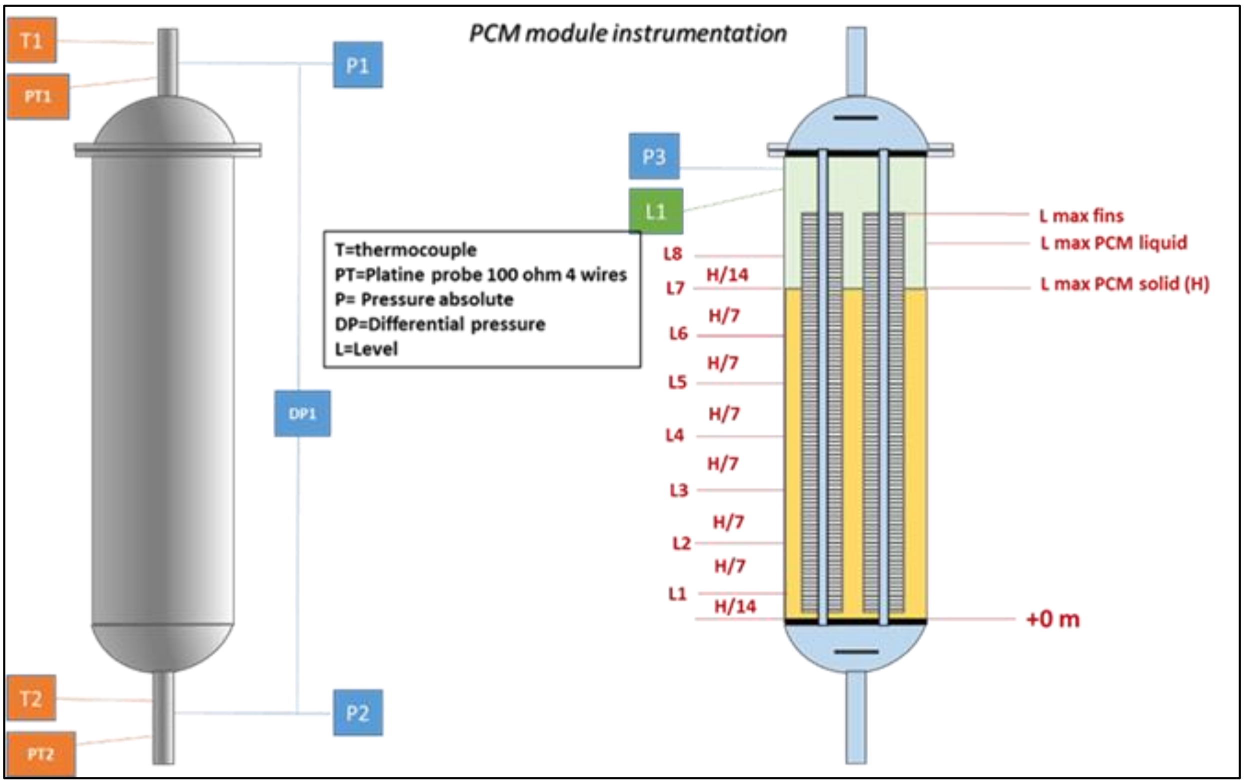


Figure 10. Instrumentation of the PCM module

The top and bottom collectors are also instrumented, to estimate the homogeneity of the heat transfer fluid. The TCs are held on small rods that are welded on the domed ends. The position of these TCs is consistent with the flow inlet pipe and with the entrance of the tubes.

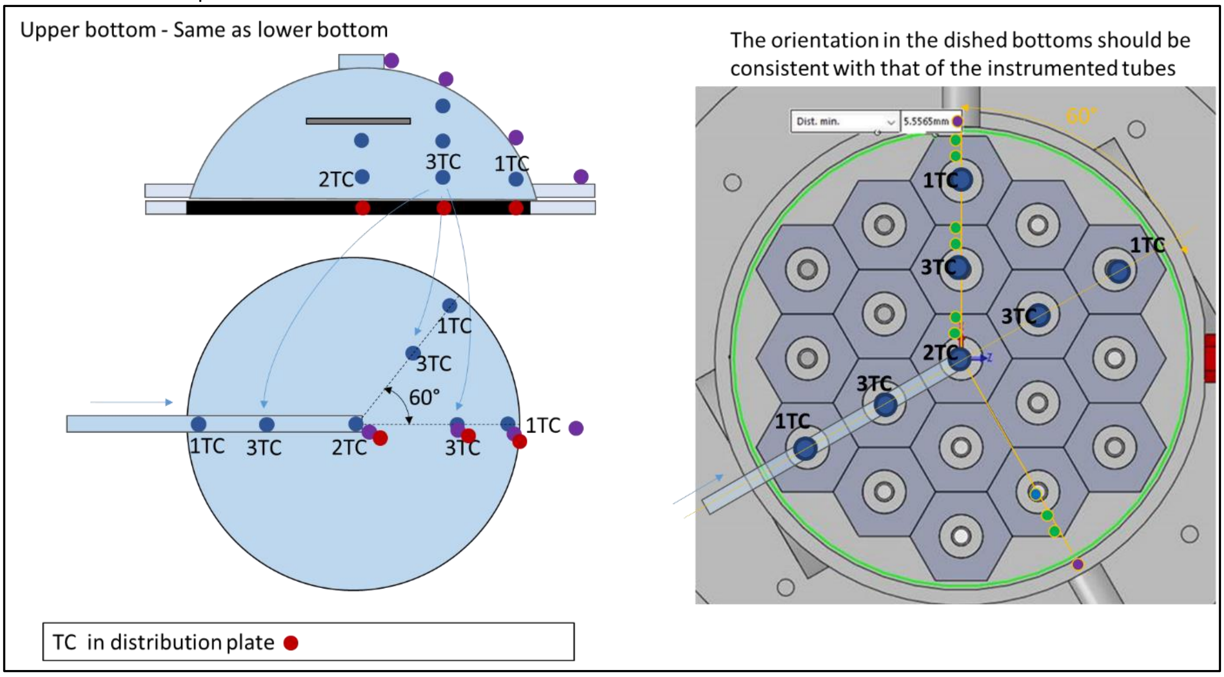


Figure 11. Instrumentation of the domed ends

The upper distribution plate includes also a few TCs to evaluate its thermal inertia.

Figures 12 and 13 show the instrumented supports inside the tubes (8 levels on the HTF side), and the instrumented aluminium profiles: 8 levels at the end of the fins and the end of the aluminium profiles.

Four finned tubes and aluminium profiles will be instrumented in this module. One profile close to the shell will be instrumented too.

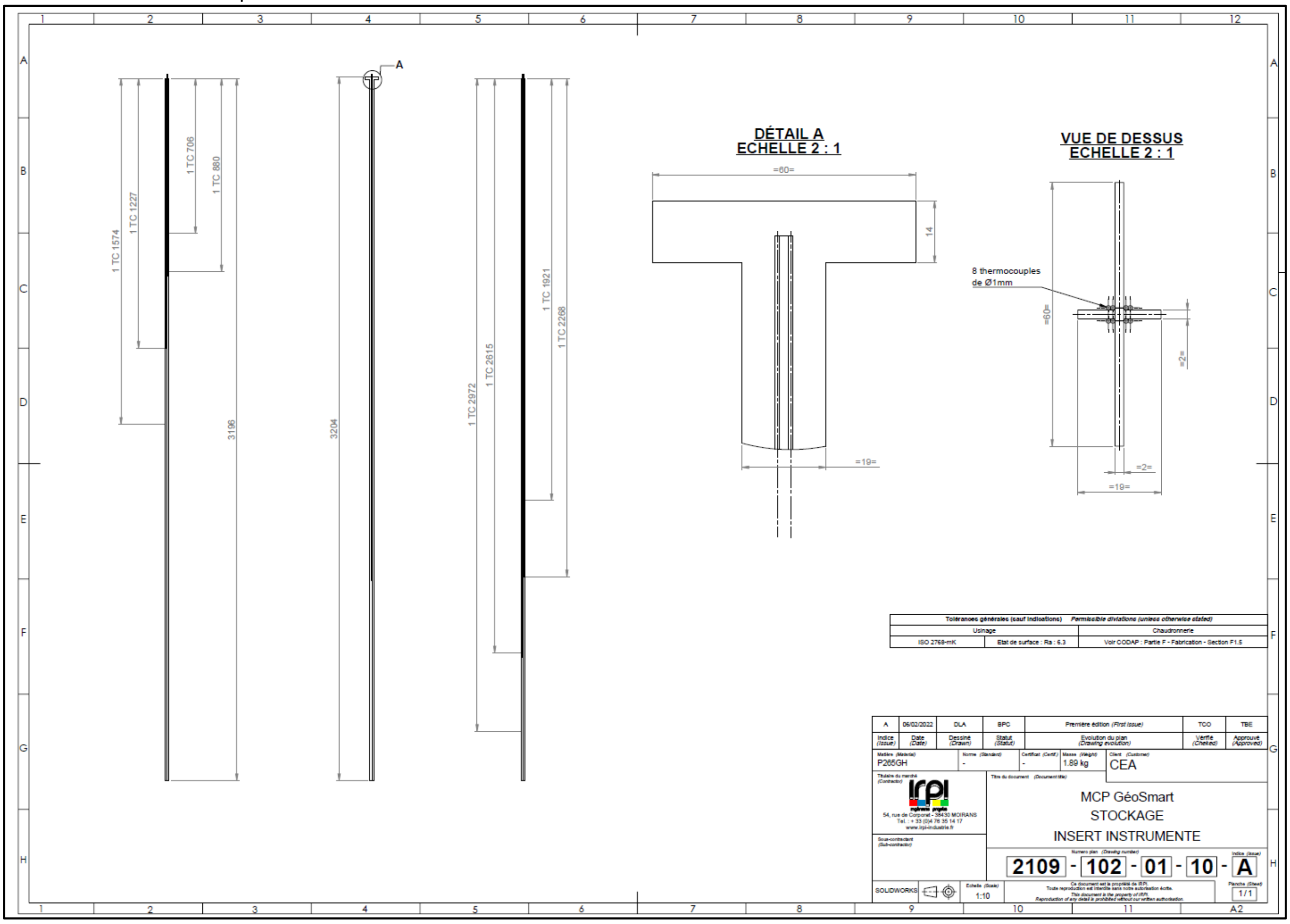


Figure 12. Instrumentation of the inserts on the HTF side

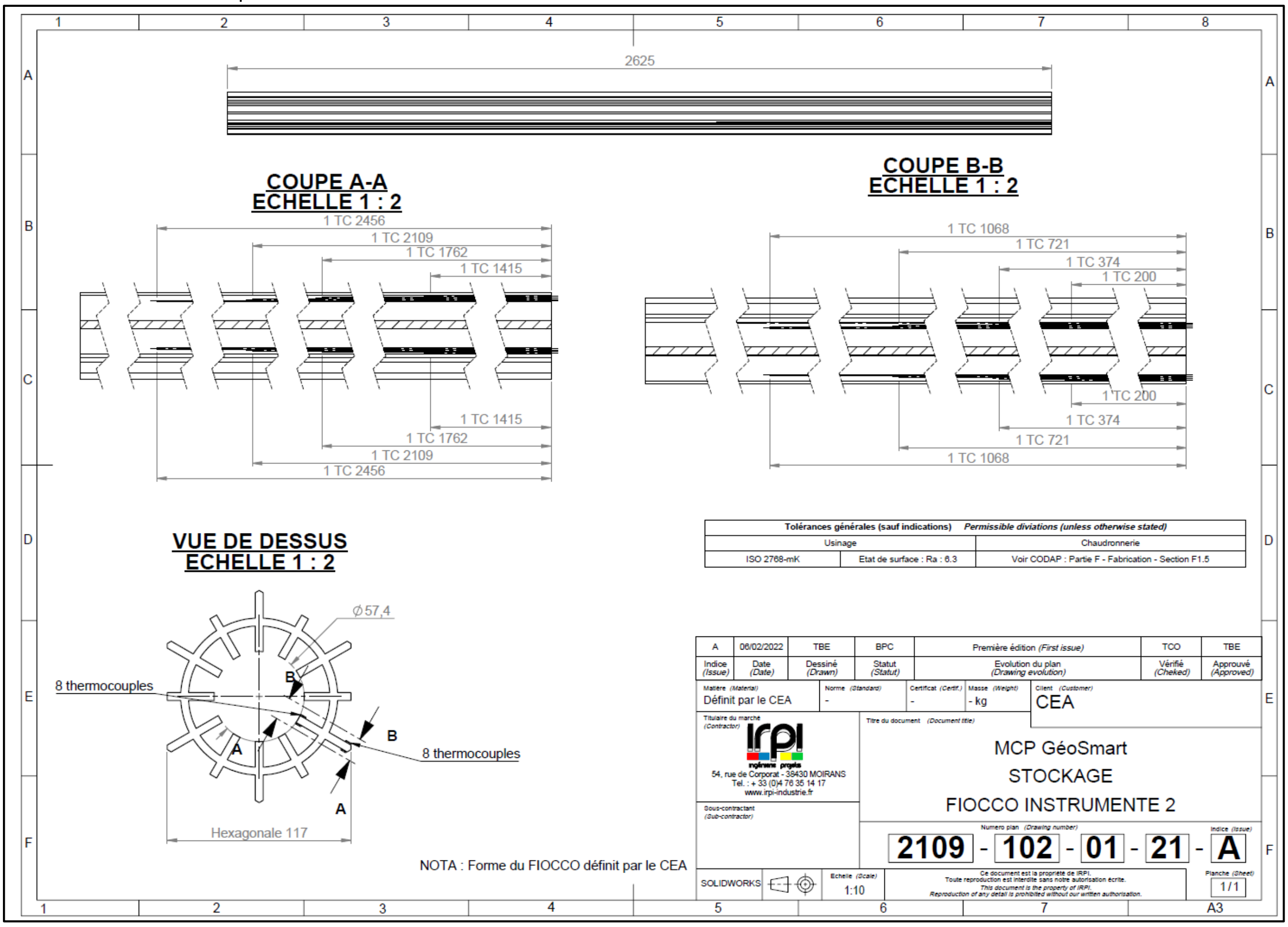


Figure 13. Instrumentation of the aluminium profiles

For a diameter of 0.61 m, the total height of the module is 4.36 m. The tubes total length is 3.19 m, including 2.625 m of finned part, 0.5 m at the top of non-finned part and 0.065 m of non-finned part at the bottom (gap between fins and distribution plate) (Figure 14). The non-finned part at the top of the tubes is dedicated the gas sky of the module.

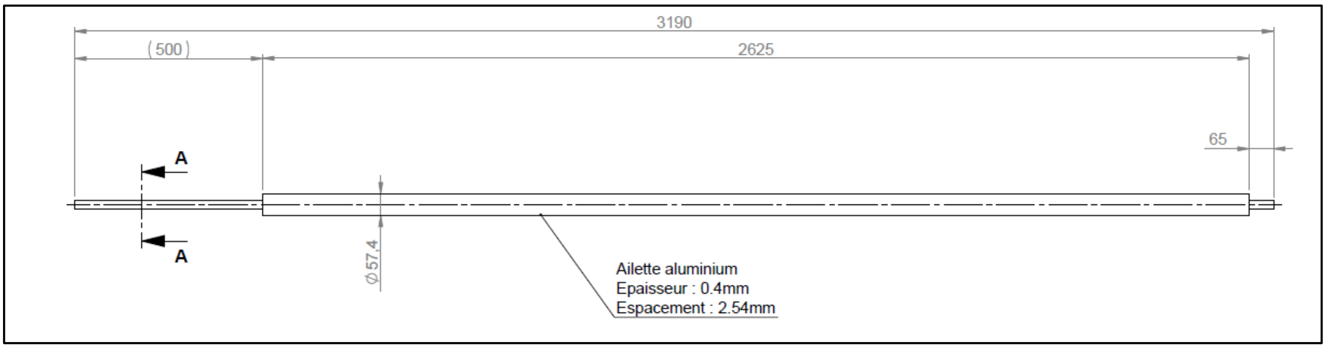
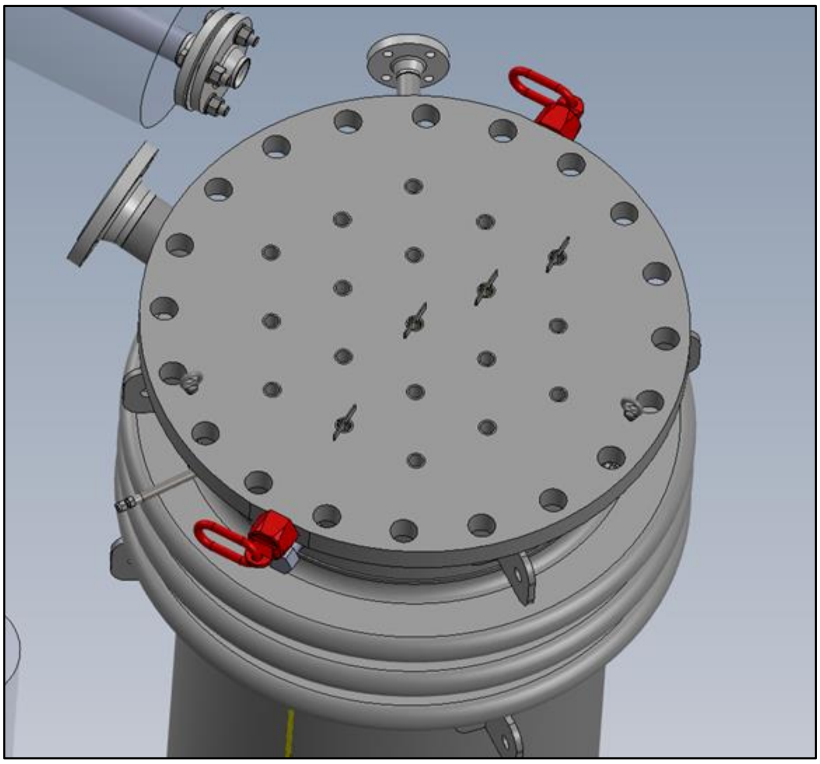


Figure 14. Drawing of the finned tubes

Figures 15, 16, and 17 show the detailed drawings of the distribution plate and the top / bottom collectors of the module.



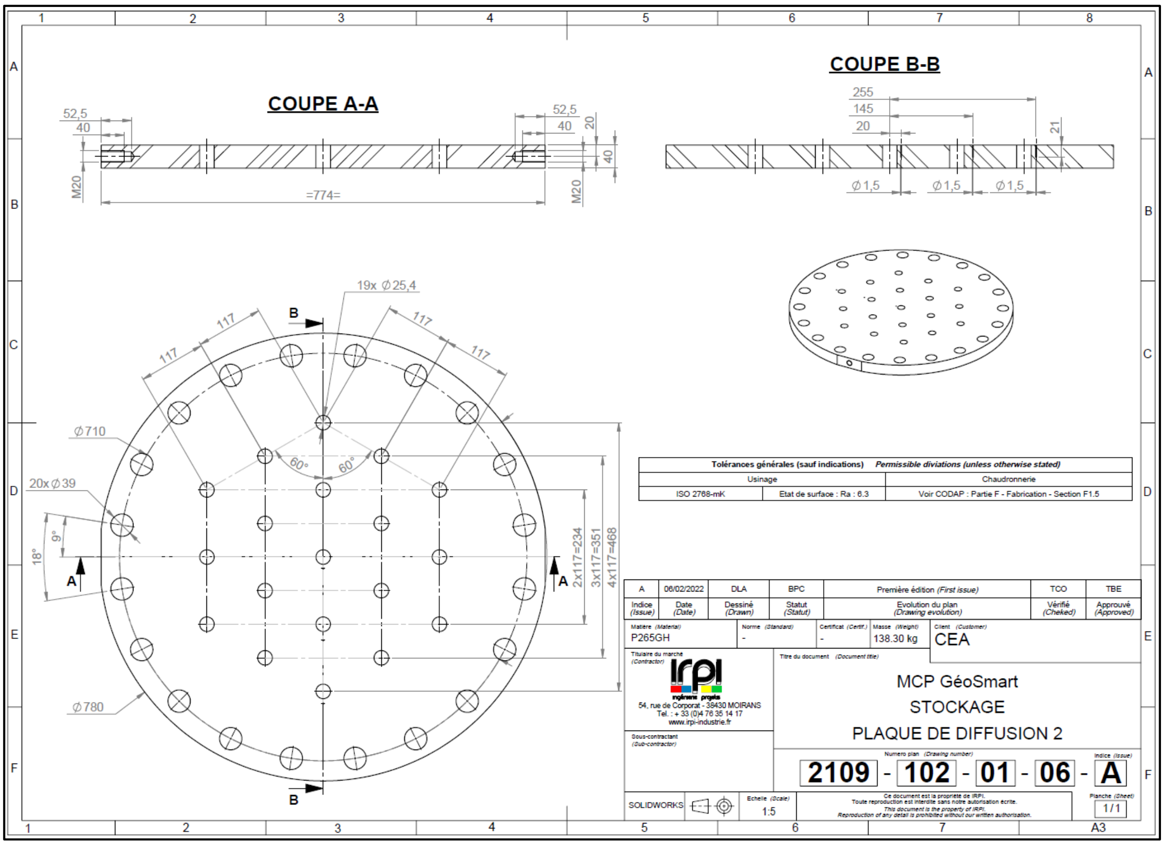


Figure 15. 3D and Drawing of distribution plate

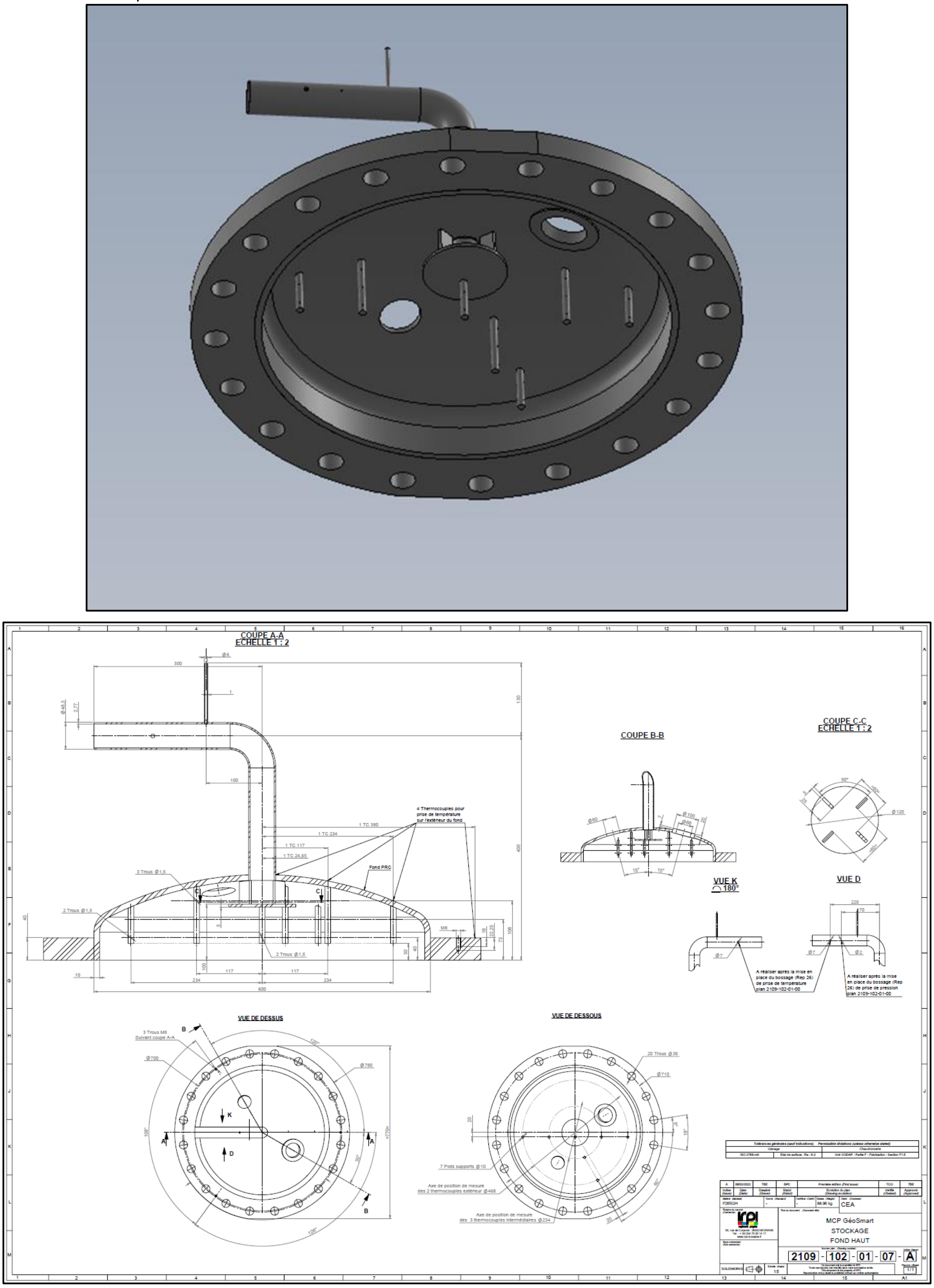


Figure 16. 3D and drawing of the top collector including the TCs supports

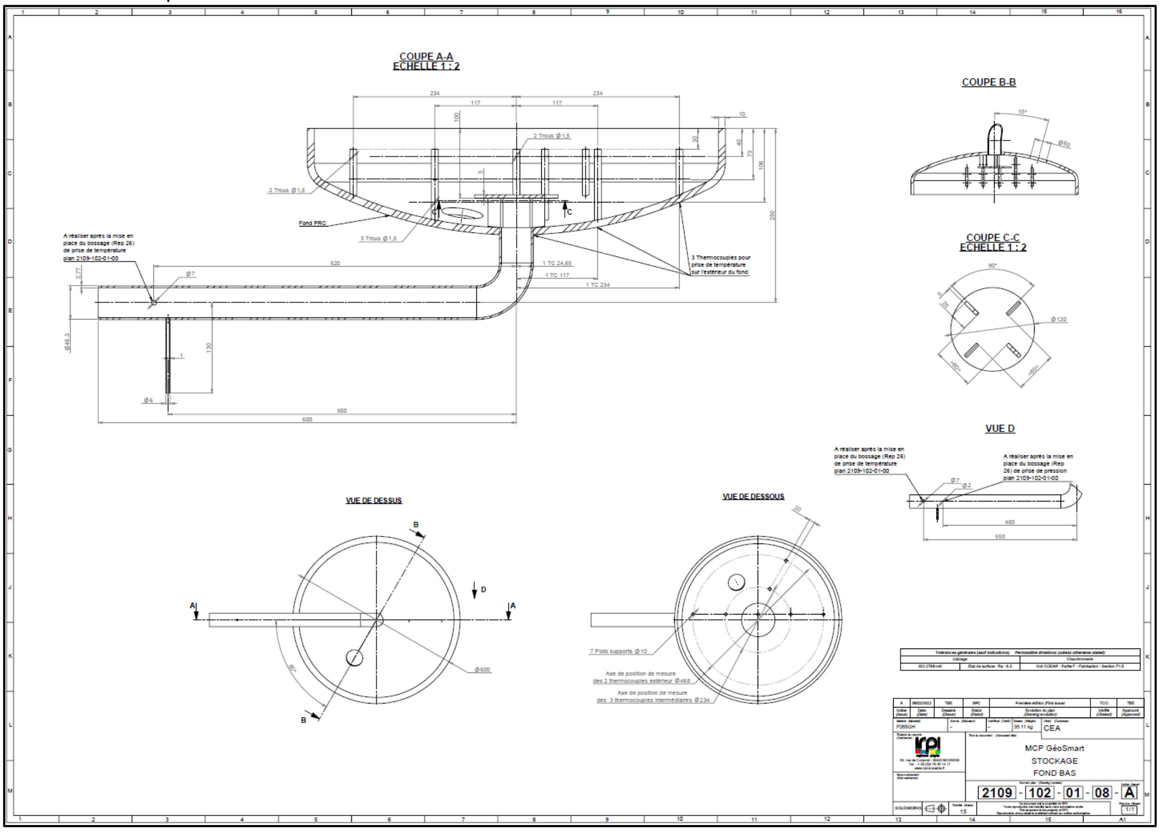


Figure 17. Drawing of the bottom collector including the TCs supports

After the installation on the CEA site, the PCM module will be filled with solid PCM using a large pipe at the top of the shell (Figure 18). The PCM will melt thanks to the water circuit. At the end of the test campaigns, the module can be emptied thanks to a small pipe at the bottom of the shell, equipped with an on/off valve. These pipes and valves will be electric traced to melt the solid PCM plug before emptying.

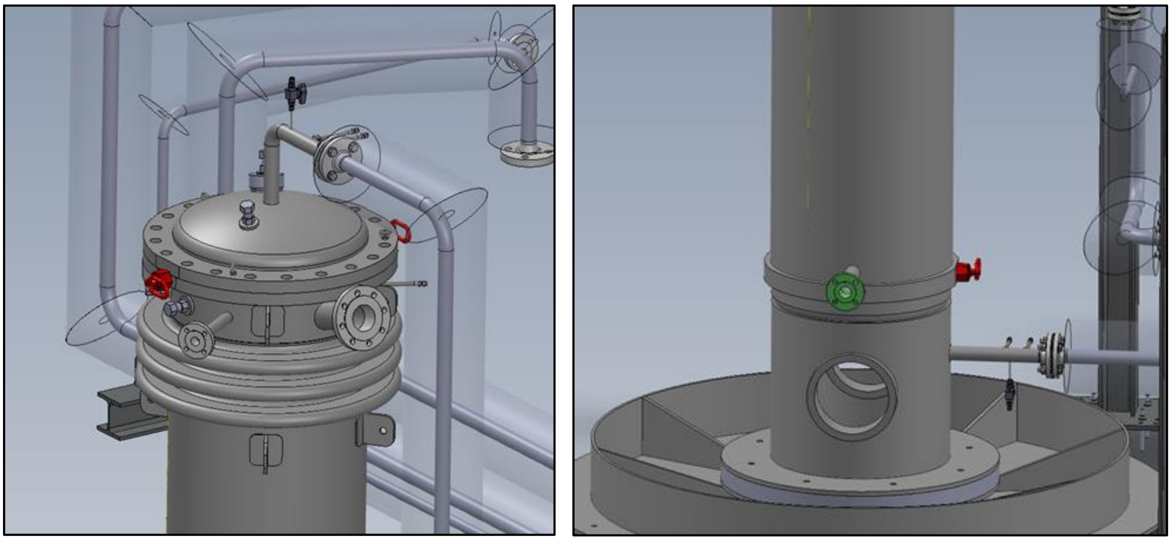


Figure 18. 3D view of the PCM filling (left) and emptying (right) piping

The mechanical engineering office did the calculations with Ansys 2020, to verify the mechanical strength of the module in service conditions: the deadweight and difference of temperature in the fluid circuit, stresses in service conditions, deadweight and shell pressure, dead weight, shell pressure and fluid circuit pressure, stresses during evacuation and the load drop of the module.

For example, the static load of this module is 30541 N along the vertical axis. Transverse forces are negligible. As the surface area of the retention tray is 3.46m², the average pressure on the basement is 883 kg/m², which is acceptable, the maximal load being 2000 kg/m².

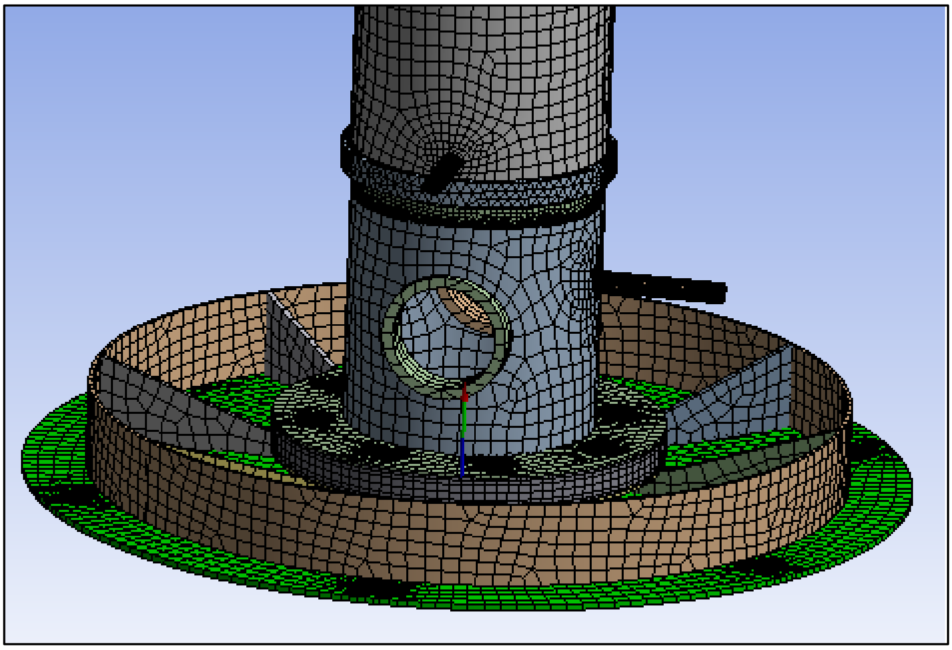


Figure 19. Calculation of the static load

2.3 Connections to the experimental facility (DESI)

The module will be tested on a superheated water facility (DESI), max 40 bar and 250°C, 200 kW built on CEA site. The GeoSmart project requirements are 8 bar and 165°C, ~50 kW.

Figures 20 show a 3D drawing of the DESI loop and where the PCM module will be installed.

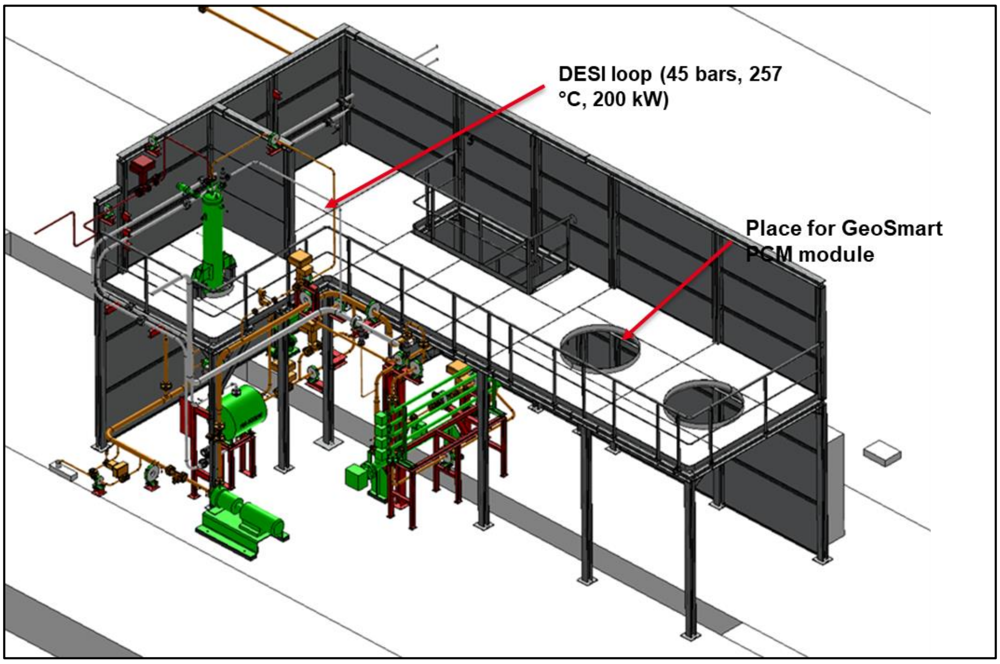


Figure 20. Drawing of the DESI loop with the GeoSmart PCM module place

Figure 21 shows the PCM module and the connection pipes on the DESI loop.

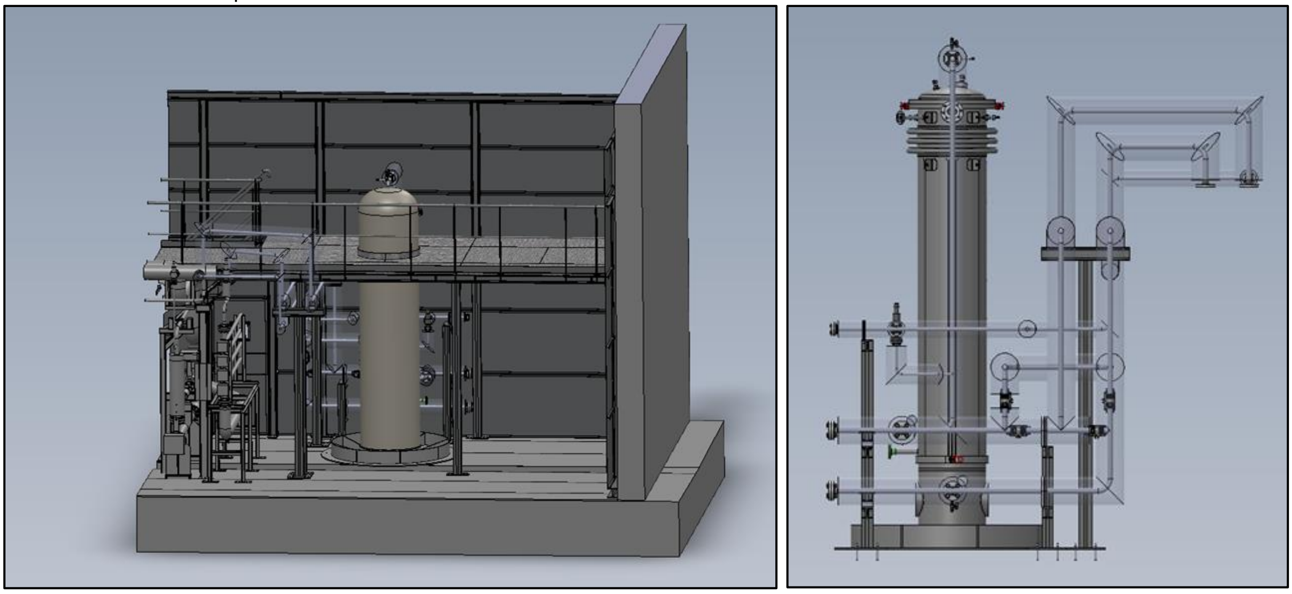


Figure 21. Drawing of the PCM module connected to the DESI loop with insulation (left) and without (right)

The pipes are equipped with 4 electro-pneumatic valves in order to change the HTF circulation inside the module, and with 2 manual valves in order to keep the module full of water during non-use periods.

Even if the module is designed at a lower pressure, the piping and the valves are designed for the DESI conditions, i.e. 45 bars and 257°C, they were calculated against the risk of pressure failure, similarly the piping flexibility during thermal cycling has been calculated too.

The coupling efforts due to the piping when submitted to temperature and pressure on the module connection flanges have been calculated and are acceptable; the piping supports have also been calculated.

3. CONCLUSIONS

Two detailed studies were initiated for the small-scale PCM module. The WP2 partners selected the second solution, 19 finned tubes with aluminium profiles and without hydraulic inserts inside the tubes.

The total height and diameter of the module will be respectively, 4.36 m and 0.61 m. The instrumentation as well as the connection to the experimental facility at CEA were defined.

The call for tender for the module manufacturing was launched in March and the answers were received beginning of May 2022. CEA is in the process of selecting the module manufacturer. The module manufacture is the critical pathway.

CEA has purchased the finned tubes in April 2022. The supplier is "PROFINS". The tubes should be delivered in June 2022.

CEA has purchased the aluminium profiles in April 2022. The supplier is "Tecnocll". The profiles should be delivered in September 2022.

CEA has launched a quotation in May 2022 for the 6 high-pressure valves on the PCM module pipes.

CEA has a quotation still outstanding for a safety valve, instrumentation, modification of the DESI control system to include the PCM module and module insulation.

The drawings and calculation reports were transmitted to Naldeo, as a reference for the detailed study of the large scale-demonstrator in WP7.

The small-scale PCM module will be manufactured and tested in Task 2.4.