POLYPHEM
Small-Scale Solar Thermal Combined Cycle

Report on the design and specifications for the integration of the whole TES in the POLYPHEM system

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This document is the deliverable D3.2 of the project POLYPHEM, where the issues related to the physical and virtual integration of the thermal storage system in the whole Polyphem plant are discussed.

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The POLYPHEM project is a research and innovation action funded by the European Union’s H2020 program. It is implemented by a European consortium of 4 research centres and 5 industrial partners. The aim is to increase the flexibility and improve the performance of small solar tower power plants. The concept of POLYPHEM consists in implementing a combined cycle formed by a solarized micro gas-turbine and a Rankine organic cycle machine, with an integrated thermal storage device between the two cycles. The need for cooling is minimal.

Developed from a patented technology by CNRS and CEA, the pressurized air solar receiver is integrated in the micro-turbine cycle. The thermal efficiency targeted for the receiver is 80% with a cost of 400 €/kW. The innovative thermal storage uses thermal oil and a single thermocline tank with a technical concrete filler material.

The main expected impact of this project is to enhance the competitiveness of low-carbon energy production systems through the technology developed. The expected progress is a better fitting of electricity generation to variable local needs, an overall conversion efficiency of solar energy into electricity of 18% for an investment cost of less than 5 €/W and a low environmental impact. By 2030, the cost of electricity production targeted by the POLYPHEM technology is 165 €/MWh for an annual direct normal irradiation of 2600 kWh/m²/year (North Africa and Middle East) and 209 €/MWh under 2050 kWh/m²/year (Southern Europe). In addition to decentralized power generation, other applications are considered for the deployment of this technology used in poly-generation: industrial heat production, solar heating and cooling, desalination of seawater or brackish water.

A prototype plant of 60 kWel with a thermal storage of 1300 kWh is designed, built and installed on the site of the experimental solar tower of Themis in Targasonne (France). The objective of the project is to validate the technical choices under test conditions representative of actual operating conditions.

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<th>Acronym/abbreviation</th>
<th>Meaning/full text</th>
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<tbody>
<tr>
<td>AALB</td>
<td>Aalborg CSP</td>
</tr>
<tr>
<td>ARRA</td>
<td>Arraela S.L.</td>
</tr>
<tr>
<td>CA</td>
<td>Consortium Agreement</td>
</tr>
<tr>
<td>CEA</td>
<td>Commissariat à l’Energie Atomique</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CIEMAT</td>
<td>Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas</td>
</tr>
<tr>
<td>CNRS</td>
<td>Centre National de la Recherche Scientifique</td>
</tr>
<tr>
<td>CO</td>
<td>Confidential: only for members of the consortium (including the Commission Services)</td>
</tr>
<tr>
<td>C&lt;sub&gt;p&lt;/sub&gt;</td>
<td>Specific heat capacity</td>
</tr>
<tr>
<td>CSP</td>
<td>Concentrated Solar Power</td>
</tr>
<tr>
<td>D</td>
<td>Deliverable</td>
</tr>
<tr>
<td>ETC</td>
<td>Effective Thermal Conductivity</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>EURO</td>
<td>Euronovia</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Model</td>
</tr>
<tr>
<td>FISE</td>
<td>Fraunhofer Institute for Solar Energy Systems, ISE</td>
</tr>
<tr>
<td>HTF</td>
<td>Heat Transfer Fluid</td>
</tr>
<tr>
<td>KAE</td>
<td>Kaefer Isoliertechnik GmbH</td>
</tr>
<tr>
<td>M</td>
<td>Month</td>
</tr>
<tr>
<td>MS</td>
<td>Milestone</td>
</tr>
<tr>
<td>ORC</td>
<td>‘Orcan Energy AG’ or ‘Organic Rankine Cycle’</td>
</tr>
<tr>
<td>PU</td>
<td>Public</td>
</tr>
<tr>
<td>STE</td>
<td>Solar Thermal Electricity (equivalent to Concentrated Solar Power)</td>
</tr>
<tr>
<td>TES</td>
<td>Thermal Energy Storage</td>
</tr>
<tr>
<td>WP</td>
<td>Work Package</td>
</tr>
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1. INTRODUCTION

This deliverable presents the issues related to the integration of the thermal storage system (TES) in the Polyphem plant. These questions are in relation to the physical integration of this TES, so engineering details are exposed, and also to the simulation model for the thermohydraulic behaviour of the storage tank, based on which the temperature gauges number and locations are defined. According to the work already done in WP4, control scheme of the TES is kept out of the TES subsystem, so it is not included here.

This report uses the main outcomes and results of D3.1 Report on the designs and specifications of filler, tank and foundations.

2. CONSTRUCTIVE INTEGRATION OF THE TES IN THEMIS

The thermocline tank position is determined by the available area around the tower. After the analysis of different positions, taking into account security and safety conditions (as the holding tank for oil leakages, evacuation routes, distance to the tower) it was decided to place the unit in an existing platform made in concrete around 5 m away from the tower, as illustrated in Figure 1.

![Figure 1: Distribution in Themis plant](image)

The thermocline tank was designed in deliverable D3.1. It is cylinder shaped **1.30 m in radius and 3.20 m in height** (inner dimensions) supported by an insulating slab. The thickness of the different elements was set to:

- Walls $\rightarrow 0.50$ m
- Roof $\rightarrow 0.40$ m
- Bottom slab $\rightarrow 0.40$ m
- Insulating slab $\rightarrow 0.40$ m

A cross section of the tank structural elements is shown below:
Both the roof and the walls are covered with refractory insulating plates 0.20 m thickness. This thermal insulation can be modified under demand by changing the conductivity of the material or the thickness.

In particular the isolating slab was designed with air chambers crossing from top to bottom the whole concrete section. The idea is decreasing the conductivity of the slab by including air volume in the structure:

![Figure 2: Structural schema of the thermocline tank](image1)

![Figure 3: Air chambers in the isolating slab](image2)
The materials used in this prototype are those already chosen according to deliverable D3.1, i.e. HEATEK-RV and HEATEK-RC for tank walls and insulating slab, respectively, and 3CR12 or B500S steel for the reinforcement bars.

Additionally, a thermal sealant will be used in the contact faces of pipes (both for inlet/outlet connections and for enclosing the required thermocouples for model validation –see section 4-) and the concrete. The sealant reduces the hydraulic gradient along these contact surfaces, avoiding oil leakage. The datasheet of this material and some of pictures and results obtained when it was tested at Arraela are in Annex 1, where it can be seen that the working temperature is up to 1500 ºC.

Attached to this report can be found the constructive drawings of the tank (Annex 2). We want to remark following aspects:

1) In order to comply with the HAZOP requirements of the plant, a holding deposit for oil leakages has been designed and presented in the drawings:

![Figure 4: Holding deposit for oil leakages](image)

The volume of this security reservoir is a 10% larger than the oil volume inside the thermocline tank.

2) In order to create the cylinder-shape air chambers in the insulating slab, the bottom slab of the tank cannot be built directly in its final position; otherwise the concrete flows inside and fills the hollows below. The solution comes through an independent construction, including frameworks, steel bars and concrete pouring, and once the slab has the appropriate resistance (14 days) will be uplifted and placed on the insulating slab, as a precast unit. This is shown in Figure 5.
3) The top slab has been designed as a removable unit, so it will be built as a precast unit and assembled to the head of the walls thanks to a step-shape in the contact surface. With this geometry, both the slab and the wall can deform together during the heating and cooling processes, not communicating structural efforts between them:

During the operational modes, the top slab can be removed thanks to 4 wrenches embedded in the concrete:
The datasheet of these wrenches is at the end of this document (Annex 3).

4) Steel pipes for enclosing thermocouples will be embedded in the concrete walls of the tank. In order to avoid any oil leakage, a sealant will be used. Also we will weld two washers to the tube so the length of the theoretical route of the oil from the inner to the outer side will be much longer. As the expansion coefficients of the concretes and steel used are the same, (see D3.1), no cracks are foreseen during the thermal deformation of the whole structure.

![Figure 8: Cross section of the thermocouples in the tank wall](image)

5) During construction, an intensive test campaign will be performed, not only to control the quality of the materials, but also to perform a geometrical checking for all the faces of the tank. The reason is that the values shown in the drawings are those considered in the bars calculations; also these are the accurate ones to secure that concrete thickness is enough to control the crack width (always lower than 0.20 mm).

### 2.1 Additional Testing for Long Term Performance of the Developed Concrete Formulations

According to the results of the tests carried out with HEATEK-RC and HEATEK-RV concretes and steels alloys during the first part of the project, we foresee a test campaign for these materials on site during the construction process. The idea is to obtain probes of the concretes (RV and RC) during the pouring process, in order to:

1) Develop **destructive and non-destructive tests** as summarized in the Table 1 below. According to the results we can accept or refuse the material. In the first case everything keeps forward according to the schedule; in the second case new structural studies have to be done in order to evaluate whether if it is feasible to study reinforcements or if the lot has to be definitely rejected and replaced by a new one.

2) Reproduce in a laboratory the same thermal conditions than those the concretes will support in the prototype unit. This way we will be aware of any unexpected change in the evolution of the behaviour of the material during the span life (oil perfusion, cracks, and loose aggregates).
For the reinforcement bars, a validation of the origin of the material (steel casting) and an additional characterization of the thermal yield strength at design temperature (330 °C) will be done.

### 2.1.1 Test Campaign

For the control of the thermal concretes poured on site, we propose the breakdown of the structure in 4 parts and 5 lots for acceptance or reject:

- Insulating foundation, in HEATEK-RC, 1 lot.
- Bottom slab of the tank, in HEATEK-RV, 1 lot.
- Walls of the tank, in HEATEK-RV, 2 lots (lower and upper ring).
- Top slab of the tank, in HEATEK-RV, 1 lot.

Next table shows the type of tests to be done in the lots above.

#### Table 1: Tests to perform in the concretes during construction

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Units</th>
<th>Size</th>
<th>Nº of samples per lot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Compression resistance</td>
<td>MPa</td>
<td>10x10x10 cm³</td>
<td>2</td>
</tr>
<tr>
<td>2) Flexural strength</td>
<td>MPa</td>
<td>60x15x15 cm³</td>
<td>2</td>
</tr>
<tr>
<td>3) Thermal conductivity</td>
<td>J/gr.K</td>
<td>Ø30 x 15 cm</td>
<td>1</td>
</tr>
<tr>
<td>4) Expansion coefficient</td>
<td>ºC⁻¹</td>
<td>Ø30 x 15 cm</td>
<td>1</td>
</tr>
<tr>
<td>5) Impact sclerometer (test hammer)</td>
<td>MPa</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>6) Laboratory samples</td>
<td>-</td>
<td>10x10x10 cm³</td>
<td>1</td>
</tr>
</tbody>
</table>

The types of tests proposed are not the usual in standard construction projects. In this case we need to validate both mechanical (1, 2) and thermal (3, 4) properties. Also we include non-destructive tests after construction, so we can follow the evolution of the material properties in a long term:

- Impact sclerometer to obtain the compression resistance of the concrete and its variation along the time.
- Samples of the concretes in a laboratory, subjected to the same thermal conditions than the proper tank and in contact with the oil.

For the control of the reinforcement steel, there will be 2 lots: one for the walls and other for the slabs. The only test proposed is the yield strength under the maximum design temperature, 330 °C.

### 2.1.2 Results to be validated

As presented in the deliverable D3.1, the mechanical and thermal values considered in the design of the thermocline tank were according to those values obtained during the test campaign developed in the laboratory. These are the values to be validated in the materials on site:

- **HEATEK-RV**: according to its resistance properties at high temperatures and the demonstrated compatibility with the thermal oil, has been the one chosen for the structure of the tank. Main parameters are following:
  
  - Compression resistance (330 °C) \( \rightarrow \) 50 MPa
  - Tension resistance (330 °C) \( \rightarrow \) 5MPa
  - Density \( \rightarrow \) 3.0 t/m³
  - Young modulus \( \rightarrow \) 40.50 GPa (@25°C) and 14.50 GPa (@700°C)
  - Poisson coefficient \( \rightarrow \) 0.20
  - Thermal expansion coefficient \( \rightarrow \) 13 \( 10^{-6} \) ºC⁻¹
Thermal conductivity $\rightarrow$ see Figure 9

Figure 9: Effective thermal conductivity of HEATEK- RV

- **HEATEK-RV**: its resistance properties do not improve to RV, however the thermal conductivity is lower, so is the one chosen for the insulating slab. These are the values considered:
  
  Compression resistance (330 ºC) $\rightarrow$ > 18 MPa  
  Tension resistance (330 ºC) $\rightarrow$ > 1.80 MPa  
  Density $\rightarrow$ 1.85 t/m$^3$  
  Young modulus $\rightarrow$ 18.00 GPa (@25ºC) and 10.50 GPa (@500ºC)  
  Poisson coefficient $\rightarrow$ 0.20  
  Thermal expansion coefficient $\rightarrow$ 12 $10^{-6}$ ºC$^{-1}$  
  Thermal conductivity $\rightarrow$ see Figure 10

Figure 10 : Effective thermal conductivity of HEATEK- RC

- Reinforcement steel U-3CR12 or B500S (depending on the availability in the market):  
  Yield strength (330 ºC) $\rightarrow$ > 400 MPa  
  Density $\rightarrow$ 7.68 t/m$^3$  
  Young modulus $\rightarrow$ 231 GPa (@100ºC) and 150 GPa (@500ºC)  
  Thermal conductivity $\rightarrow$ 30.0 W/m·K (@100ºC) and 40.0 W/m·K (@500ºC)  
  Thermal expansion coefficient $\rightarrow$ (0 to 500ºC) 12.3 $10^{-6}$ ºC$^{-1}$
Once validated the results with the tests on site, and according to the parametrization of the properties we did in the models studied for the deliverable D3.1, if in one lot there are differences higher than ±10% by comparison with the ones above, we will update the CFD study with the real values and analyse the structural and thermal performance of the tank. As said before, according to the evaluation of the model, the lot under study can be approved or removed and replaced by a new one.

### 3. CURRENT SIMULATION MODEL FOR THE TES

Current Ciemat’s model for studying the thermohydraulic behaviour of a thermocline storage tank with filler is an analytical model based on sigmoid curves, which are mathematical solutions of the energy balance equation. The parameters of this analytical model have been obtained by fitting its mathematical expression to a well validated Ciemat’s numerical model, [1]. This numerical model considered a single effective storage medium inside the thermocline tank (liquid or liquid with packed-bed) whose temperature $T$ varies with time (unsteady) along the tank height, $z$ (one-dimensional).

The one-dimension differential energy balance equation that describes the behaviour of a thermocline storage tank with a single effective storage medium, and for which thermal losses can be neglected is [1]:

$$\frac{\partial T}{\partial t} + v_{TC} \frac{\partial T}{\partial z} = \alpha_{eff} \frac{\partial^2 T}{\partial z^2}$$  \hspace{1cm} (Eq. 1)

Where $v_{TC}$ corresponds to the velocity at which thermocline zone moves inside the tank and $\alpha_{eff}$ is the effective diffusivity of the storage media. These parameters can be expressed in terms of the assumed thermo-physical properties of the effective storage medium which are:

$$v_{TC} = \frac{(\rho C_p)_{\text{liquid}}}{(\rho C_p)_{\text{eff}}} v_m$$

$$(\rho C_p)_{\text{eff}} = \varepsilon (\rho C_p)_{\text{liquid}} + (1 - \varepsilon)(\rho C_p)_{\text{solid}}$$

$$\alpha_{eff} = \frac{k_{eff}}{(\rho C_p)_{\text{eff}}}$$

$$k_{eff} = \varepsilon k_{\text{liquid}} + (1 - \varepsilon)k_{\text{solid}}$$

$$(\rho C_p)_{\text{eff}} = \frac{(\rho C_p)_{\text{liquid}}(\rho C_p)_{\text{solid}}}{\varepsilon (\rho C_p)_{\text{liquid}} + (1 - \varepsilon)(\rho C_p)_{\text{solid}}}$$  \hspace{1cm} (Eq. 2)

Where $v_m$ is the superficial liquid velocity (oil velocity in Polyphem’s case), which can be calculated from the oil mass flow, $\dot{m}$, with the oil density and the tank diameter (D):

$$v_m = \frac{\dot{m}}{\rho_{\text{liquid}} 0.25 \pi D^2}$$  \hspace{1cm} (Eq. 3)

If (Eq. 1) is written with dimensionless variables the resulting expression is:

$$\frac{\partial \phi}{\partial t^*} + v^* \frac{\partial \phi}{\partial z^*} = \frac{\partial^2 \phi}{\partial z^{*2}}$$  \hspace{1cm} (Eq. 4)

With the following transformations

$$\phi = \frac{T - T_{\text{min}}}{T_{\text{max}} - T_{\text{min}}}, \quad z^* = \frac{z}{L}, \quad t^* = \frac{t \alpha_{eff}}{L^2}, \quad v^* = \frac{v_{TC} L}{\alpha_{eff}}$$  \hspace{1cm} (Eq. 5)

Both (Eq. 1) and (Eq. 4) can be solved either numerical [1] or analytically [2]. However, independently on the solving method, the solution of (Eq. 1) is a set of sigmoid curves that represent the temperature variation as a function of time.
and tank height. When analytical methods are applied for solving either Eq. (1) or Eq. (4), the solutions found in the literature are sigmoid functions used in the field of statistics. In previous works we chose either logistic curves [2] or algebraic sigmoids [3] as solutions. Both kinds of sigmoids have two parameters ($z_c^*$ and $\beta z^*$) and their expressions for the temperature evolution in dimensionless coordinates are:

Logistic
\[ \phi = \frac{1}{1 + e^{-4 \beta z^* (z - z_c^*)}} \]  
(Eq. 6)

Algebraic
\[ \phi = \frac{1}{2} \left\{ 1 + \left[ \frac{1}{4 \beta z^* z} (z - z_c^*)^2 \right]^{1/2} \right\} \]  
(Eq. 7)

Where $z_c^*$ indicates the position of the thermocline zone centre, and $\beta z^*$ is the slope of the temperature curve in that position [2].

According to Polyphem proposal, the storage tank has an effective storage capacity of 2 MWh, which implies, as explained in D3.1, 2.6 MWh gross storage capacity. Since it is a single tank system, there will be some tank volume occupied by the thermocline region that will not be useful.

In Deliverable 3.1 the size of this volume was estimated using CIEMAT’s model by assuming a design oil flowrate of 0.7 kg/s. According to this simulation, around 25% of the tank volume was expected to be occupied by the thermocline region. Therefore, a conservative risk margin of 30% was considered so that a tank with a storage capacity of 2.6 MWh was chosen appropriate. On the other hand, the operation modes that are going to be considered will take into account that part of the energy available at moderate temperature in the thermocline region may be used for preheating the ORC engine and even to generate electricity. So 2.6 MWh was a conservative value.

In this deliverable, some more calculations have been performed for predicting the thermocline zone behaviour inside the tank. For these calculations, tank parameters and thermophysical properties recorded in Table 2 have been used. It is worth mentioning the very low oil velocity which is expected in the closed storage loop. This velocity is given by the heat and mass balance with the primary polyphem loop.

### Table 2. POLYPHEM tank parameters and thermophysical properties of oil and filler.

<table>
<thead>
<tr>
<th>Oil properties @ 200 °C</th>
<th>Filler properties</th>
<th>Tank parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Jarytherm DBT</td>
<td>Material</td>
</tr>
<tr>
<td>$\rho$ (kg/m$^3$)</td>
<td>914</td>
<td>$\rho$ (kg/m$^3$)</td>
</tr>
<tr>
<td>DBT (J/kg K)</td>
<td>2100</td>
<td>$C_p$ (J/kg K)</td>
</tr>
<tr>
<td>k (W/m K)</td>
<td>0.113</td>
<td>k (W/m K)</td>
</tr>
<tr>
<td>$\mu$ (m$^2$/s)</td>
<td>$8.20 \times 10^{-7}$</td>
<td>$\varepsilon(\cdot)$</td>
</tr>
</tbody>
</table>

In order to predict the variation of the temperature curve slope $\beta z^*$ as thermocline zone moves inside the tank, analytical model already developed by Votyakov and Bonanos has been applied [4]. These authors proposed the following variation of the sigmoid slope with time:
\[
\beta_z^* = \frac{L}{\sqrt{4\pi D^* \alpha_{\text{eff}} t}}
\]

(Eq. 8)

Where \( D^* \) is a parameter that depends on the thermophysical properties of the liquid and the filler and on dimensionless numbers like Re, Pe, Bi and Nu. Therefore, this \( D^* \) parameter strongly depends on the filler particle diameter and so does the value of the sigmoid slope, which is directly related to thermocline zone thickness. In Figure 11, the variation of the sigmoid slope with time has been calculated with (Eq. 8) and the corresponding data taken from Table 2 for fillers with different particle size (1, 3 and 5 cm) but the same porosity \( \varepsilon=0.4 \).

\[\beta_z^* \]

\( \varepsilon=0.4 \, \text{m} \]

\( z_c=2.5 \, \text{m} \)

\( t \, (\text{min}) \)

\( 0 \, 50 \, 100 \, 150 \, 200 \, 250 \, 300 \, 350 \, 400 \, 450 \, 500 \)

\( \beta_z^* \)

\( 0 \, 5 \, 10 \, 15 \, 20 \)

\( z_c=2.5 \, \text{m} \)

\( t \, (\text{min}) \)

\( 0 \, 50 \, 100 \, 150 \, 200 \, 250 \, 300 \, 350 \, 400 \, 450 \, 500 \)

\( \beta_z^* \)

\( \varepsilon=0.4 \, \text{m} \)

\( d_p=1 \, \text{cm} \)

\( d_p=3 \, \text{cm} \)

\( d_p=5 \, \text{cm} \)

Figure 11: Variation of the sigmoid slope with time according to Votyakov and Bonanos model \cite{4} for fillers with different particle size (1, 3 and 5 cm) but the same porosity \( \varepsilon=0.4 \).

As expected, the smaller the particle size, the smaller the thermocline region is. This can be seen more clearly in the curves of Figure 12, which represent the temperature profile inside the tank when thermocline zone attains the upper part in a discharge process performed under the conditions recorded in Table 2. These curves have been plotted by using the logistic expression of (Eq. 6).

\[T (\degree \text{C}) \]

\( T (\degree \text{C}) \)

\( z \, (\text{m}) \)

\( 0.0 \, 0.5 \, 1.0 \, 1.5 \, 2.0 \, 2.5 \, 3.0 \)

\( T (\degree \text{C}) \)

\( 100 \, 120 \, 140 \, 160 \, 180 \, 200 \, 220 \, 240 \, 260 \, 280 \, 300 \)

\( d_p=1 \, \text{cm} \)

\( d_p=3 \, \text{cm} \)

\( d_p=5 \, \text{cm} \)

Figure 12. Temperature variation curves showing the influence of filler particle diameter when thermocline zone centre is at 2.5 m from tank inlet in a discharge process.
4. DESIGN OF MONITORING FOR VALIDATION OF THE TES SIMULATION MODEL

The thermocline tank at Polyphem project is filled with oil and a filler material. Pressure in the tank is foreseen to be ambient pressure, being the tank connected to an expansion tank and to a nitrogen injecting system. This last system should guarantee the pressure regulation in the tank, avoiding the necessity of a pressure gauge directly installed in the tank. According to the provider, the oil vapour pressure at maximum working temperature is below 100 kPa (absolute pressure) [5]. Oil vapour pressure formation is hence negligible and no pressurizing system is needed. The presence of the filler material, and the connection to the expansion tank, makes unnecessary the use of a level measurement system.

Temperature is expected to be in the range of -15 (ambient temperature) to a maximum of 320°C, and hence thermocouples type J have been selected. Thermocouples are preferred compared with PT100 because of the lower durability of PT100 in an environment where vibrations are frequent. J thermocouples can measure in the -40 up to 750°C range.

According to the IEC 60584.2, the measurement error for class 1 J type thermocouples is:

\[
\begin{align*}
\pm 1.5 \degree C & \text{ for temperatures in the range } -40 \text{ to } 375 \degree C \\
(\pm 0.004 \cdot T) & \text{ for temperatures in the range } 375 \text{ to } 750 \degree C
\end{align*}
\]

In order to validate the model described in the previous section, 49 thermal gauges (thermocouples) will be allocated in contact with the oil within the tank at different vertical positions and angles (see Figure 13). With such a distribution, 7 temperature measurements will be available at the tank axis (so nearly every 0.5 meters) for checking the model results. The thermocouples at different angles and distances from the axis will serve to quantify losses through the tank walls and also thermohydraulic symmetry. Several thermocouples will be inserted in the inlet and outlet pipes. Thermal losses through the tank foundation will be evaluated by using 3 thermocouples placed at the tank foundation axis and thermal losses through tank walls will be evaluated using 3 thermocouples placed at the tank external surface, covered by a protective foil.

Thermocouples inside the tank will be inserted via 4 nozzles placed at the tank walls upper part, where a nitrogen chamber is foreseen. The thermocouples names and relative positions to the tank bottom centre are listed in Table 3.

![Figure 13: Thermal gauges assignment and location within the storage tank.](image-url)
Table 3: Thermocouples names and positions

<table>
<thead>
<tr>
<th>Nozzle, (Height)*</th>
<th>Sensor name (location*)</th>
<th>Tank centre</th>
<th>20cm from tank centre</th>
<th>40 cm from tank centre</th>
<th>Tank walls</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, (10)</td>
<td>T11 (0,0,10)</td>
<td>T12 (20,0,10)</td>
<td>T13 (40,0,10)</td>
<td>T14 (125,0,10)</td>
<td></td>
</tr>
<tr>
<td>1, (110)</td>
<td>T31 (0,0,110)</td>
<td>T32 (20,0,110)</td>
<td>T33 (40,0,110)</td>
<td>T34 (125,0,110)</td>
<td></td>
</tr>
<tr>
<td>1, (210)</td>
<td>T51 (0,0,210)</td>
<td>T52 (20,0,210)</td>
<td>T53 (40,0,210)</td>
<td>T54 (125,0,210)</td>
<td></td>
</tr>
<tr>
<td>1, (310)</td>
<td>T71 (0,0,310)</td>
<td>T72 (20,0,310)</td>
<td>T73 (40,0,310)</td>
<td>T74 (134,0,310)</td>
<td></td>
</tr>
<tr>
<td>2, (10)</td>
<td>T15 (0,20,10)</td>
<td>T16 (0,40,10)</td>
<td>T17 (0,125,10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2, (110)</td>
<td>T35 (0,20,110)</td>
<td>T36 (0,40,110)</td>
<td>T37 (0,125,110)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2, (210)</td>
<td>T55 (0,20,210)</td>
<td>T56 (0,40,210)</td>
<td>T57 (0,125,210)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2, (310)</td>
<td>T75 (0,20,310)</td>
<td>T76 (0,40,310)</td>
<td>T77 (0,125,310)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3, (60)</td>
<td>T21 (0,0,60)</td>
<td>T22 (-20,0,60)</td>
<td>T23 (-40,0,60)</td>
<td>T24 (-125,0,60)</td>
<td></td>
</tr>
<tr>
<td>3, (160)</td>
<td>T41 (0,0,160)</td>
<td>T42 (-20,0,160)</td>
<td>T43 (-40,0,160)</td>
<td>T44 (-125,0,160)</td>
<td></td>
</tr>
<tr>
<td>3, (260)</td>
<td>T61 (0,0,260)</td>
<td>T62 (-20,0,260)</td>
<td>T63 (-40,0,260)</td>
<td>T64 (-125,0,260)</td>
<td></td>
</tr>
<tr>
<td>4, (60)</td>
<td>T25 (0,-20,60)</td>
<td>T26 (0,-40,60)</td>
<td>T27 (0,-125,60)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4, (160)</td>
<td>T45 (0,-20,160)</td>
<td>T46 (0,-40,160)</td>
<td>T47 (0,-125,160)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4, (260)</td>
<td>T65 (0,-20,260)</td>
<td>T66 (0,-40,260)</td>
<td>T67 (0,-125,260)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower oil inlet</td>
<td>T01 (in pipeline, central exit)</td>
<td>T02 (in pipeline, centre)</td>
<td>T03 (in pipeline, wall)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper oil inlet</td>
<td>T04 (in pipeline, central exit)</td>
<td>T05 (in pipeline, centre)</td>
<td>T06 (in pipeline, cover wall)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basement</td>
<td>T07 (up)</td>
<td>T08 (middle)</td>
<td>T09 (down)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation</td>
<td>T101 (wall-bottom)</td>
<td>T102 (wall-middle height)</td>
<td>T103 (wall- top)</td>
<td>T104 (tank cover)</td>
<td></td>
</tr>
</tbody>
</table>

(* Positions referred to tank bottom centrum. Distances in centimetres)
5. ANNEX 1: THERMAL SEALING

DESCRIPTION:
Mono-component refractory putty based on inorganic resins.

PROPERTIES:

• Mono-component, ready for use.
• Excellent adhesion on metals, stone and concrete.
• Resists high temperatures and fire.
• Does not contract or crack.

APPLICATIONS:

• High temperature resistant sealant up to 1,500 ° C. Suitable for joints subjected to high temperature and direct fire.
• For permanent repair and sealing of joints in:
  • Cracks.
  • Refractory elements.

INDICATIONS OF USE:

Apply on clean and dry surfaces. If necessary, in addition to a mechanical treatment, it is convenient to clean with a non-fatty solvent such as acetone.

NOTE: It should not be applied in rainy weather or threat of rain, as well as with temperatures below +5 ° C.

TECHNICAL CHARACTERISTICS:

• Appearance: Homogenous fine paste
• Density (23°C DIN 53217): 1.80 g / cm3
• Lift (ISO 7390): <5 mm
• Temperature resistance: 1,500 °C Max.
EXAMPLE OF TESTS CARRIED OUT

- A cylindrical vessel is constructed with HEATEK® RV parts glued with the resin tested.
- It is filled with the thermal oil used up to about 7 cm from the upper edge.
- A thermo-regulated resistance is introduced at 335 °C, some days, waiting for oil diffusion samples through the concrete.
- Once the controls have been analyzed, there is a greater resistance to the diffusion of thermal oil through the resin than through the concrete itself.
- Likewise, a good adhesion can be seen between the pieces between which the resin has been used without any adverse reaction being observed.
6. ANNEX 2: DRAWINGS OF THERMAL ENERGY STORAGE TANK
D3.2 Report on the design and specifications for the integration of the whole TES in the POLYPHEM system
D3.2 Report on the design and specifications for the integration of the whole TES in the POLYPHEM system
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### 7. ANNEX 3: DATASHEET OF WRENCHES USED TO ADJUST THE TOP SLAB

#### Data sheet for the Spherical head transport anchor system

**PHILIPP GROUP**

#### Table 2: Dimensions Spherical Anchor (mm without slippage)

<table>
<thead>
<tr>
<th>Type</th>
<th>Length</th>
<th>Outer Diameter</th>
<th>Inner Diameter</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>25</td>
<td>30</td>
<td>20</td>
<td>0.5</td>
</tr>
<tr>
<td>B</td>
<td>30</td>
<td>35</td>
<td>25</td>
<td>0.7</td>
</tr>
<tr>
<td>C</td>
<td>35</td>
<td>40</td>
<td>30</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**ANNEX 3: DATASHEET OF WRENCHES USED TO ADJUST THE TOP SLAB**

**Figure 1**

**Figure 2**

**Figure 3**