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Solidification and melting characteristics of an enhanced LTES system for solar heat in industrial processes

José Muñoz-Cámara[1], Ridha Zitouni[2], Lucas Díaz-Moreno[2], Miguel Ángel Solano[2,] Saoussane Bachi Bensaad[2], José Pérez-García[2], Juan Pedro Solano[2*]

[1]Dpto. Ingeniería Mecánica y Energía, Universidad Miguel Hernández, Avda.de la Universidad s/n 03202 Elche (Spain)

[2]Dpto. de Ingeniería Térmica y de Fluidos, Universidad Politécnica de Cartagena, 30202 Cartagena (Spain)

* corresponding author: juanp.solano@upct.es

1. Introduction

Solar Heat for Industrial Processes (SHIP) is a rapidly growing field of solar thermal energy applications, aimed at decarbonizing industry processes. High temperature solar collectors, namely Fresnel-like and parabolic trough designs, are typically employed for the production of heat, using thermal oil as primary heat carrier.

These processes frequently require the coupling of the solar energy source with a thermal energy storage (TES) system, to accommodate the solar irradiance dynamics and its fluctuations with the eventually variable heat demand of the process. The most widely employed technologies for thermal energy storage are based on shell and tube heat exchangers, with a PCM stacked in the shell-side. In high temperature applications, nitrate salts are among the most appropriate PCM candidates [1].

The low thermal conductivity of the PCMs, and the slow motion of the material during melting and solidification yield low heat transfer coefficients, which results in poor overall heat transfer of the TES system. The use of extended surfaces is one of the techniques to enhance heat transfer in shell-and-tube tanks, although the increase of cost and weight, and the search of an optimal surface-to-volume ratio is an open issue for the design of this kind of equipment.

Based on a honeycomb design, a set of lightened inserts which keep the hexagonal perimeter across the extended surface have been built for increasing the outside area of the tubes [2]. Fast response characteristics are expected when the TES system is installed in series or parallel with a solar collector, using by-pass circuits that regulate the flow rate through the tubes while ensuring constant outlet oil temperature to the process.

The present paper describes the experimental facility built at Universidad Politécnica de Cartagena for testing the charging and discharging characteristics of the TES system, the preliminary tests and procedures for filling the tanks using a mixture of sodium and potassium nitrates and the two-phase dynamics that govern the air removal of the tubes during thermal oil filling.

2. Materials and methods

A sketch of the thermal energy storage tank is shown in Fig. 1-left. It consists of a cylindrical shell side with inner diameter D=910 mm and length L=1400 mm. A total number of 61 tubes with diameter 25,4×2,11 mm are connected in series, with the aim of ensuring turbulent flow of thermal oil through the tubes, promote high tube-side convective heat transfer coefficients and prevent fouling. Shell and tubes are manufactured in stainless steel AISI 316L. The hexagonal inserts are manufactured by casting of a Al-SiO_2 alloy, in the search of high thermal conductivity and corrosion resistance in contact with the nitrate salts. A total number of 360 inserts embrace the tubes, covering the overall shell volume. The tank stands upright to ease the initial filling of the shell with the PCM (see Fig. 1-right), and to promote buoyancy during the operation of the melting cycles.

A set of four long temperature sheaths with three different thermocouples each at different heights are inserted in the shell side through the upper tank lid. These sensors measure the temperature evolution during the charging and discharging cycles, and will be employed for data reduction purposes: computation of the instantaneous liquid fraction and the charging/discharging status of the accumulator. A removable insulation is installed around the tank, covering the lateral, top and bottom surfaces and the supports of the wheels, with 4 cm thickness of rockwool. The lateral surface is also insulated with an initial layer of 2 cm pyrogel.

Fig. 2 depicts a sketch of the thermal-hydraulic circuit that has been designed for testing the TES system under controlled conditions. A positive displacement pump moves thermal oil ‘Therminol 59’ through the closed circuit, which is insulated with 6 cm thickness rockwool. During the charging tests, the oil releases thermal energy to the energy storage tank as it flows through its serpentine tube path. After leaving the tank, the thermal oil is preheated using a 10 kW electrical resistance, which is controlled to ensure a temperature increase ΔT=5 K. A vortex flowmeter is employed for measuring the volumetric oil flow rate through the circuit. Piezorresistive gauge pressure sensors are located in the inlet and outlet of the TES system, to monitor the pressure drop across the serpentine. Inlet and outlet temperatures are measured with 2-wire PT-100 sensors immersed in the tubes. During solidification tests, colder thermal oil enters the accumulator and absorbs thermal energy from the PCM. The electrical resistance is disconnected and the flow is afterwards diverted to an air cooler, where a frequency-controlled fan allows the thermal oil to decrease its temperature ΔT=5 K.

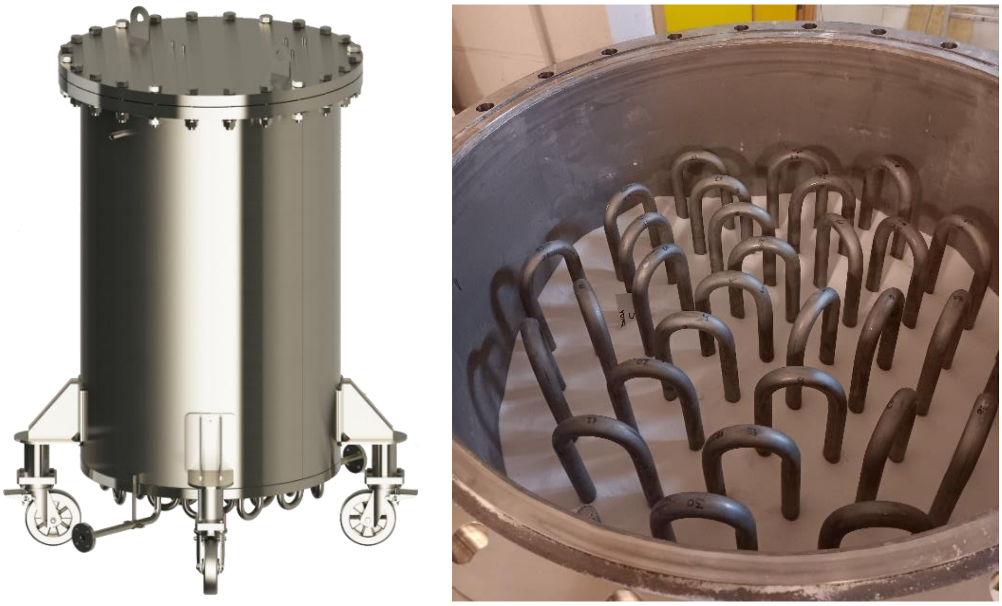

Figure 1. Sketch of the thermal energy storage tank. Left: final assembly. Right: Detail of the charged PCM

The start-up of the facility requires, however, two previous steps: a) the filling of the shell-and-tube tank with the PCM, and b) the filling of the pipe circuit with thermal oil. Fig. 3 represents the methodology for preparing the mixture. Potassium and sodium nitrates are delivered by the manufacturer in 25 kg bags. Owing to hygroscopic issues, caking of the material occurs, and mechanical grinding is necessary for the mixture of the two salts. The start-up of the test rig (Fig. 2) also requires a previous assessment of the thermal oil filling process: the existence of a vertical serpentine across the TES tank makes the exhaust of air difficult, as the purges of the facility are located in upper positions.

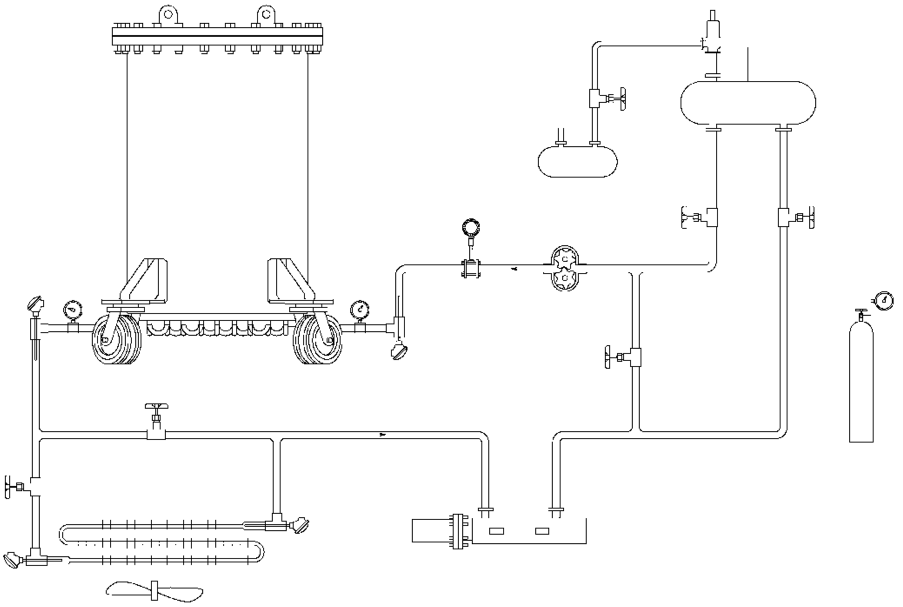

Figure 2: Test rig for latent thermal energy storage tanks

A visualization facility that mimics the serpentine geometry has been built (see Fig. 4), with the aim of: a) visualizing the flow phenomena of air removal during liquid filling; b) measuring the pressure drop during the process, in the search of a limit value that estimates a quality measure of liquid fraction in the circuit.

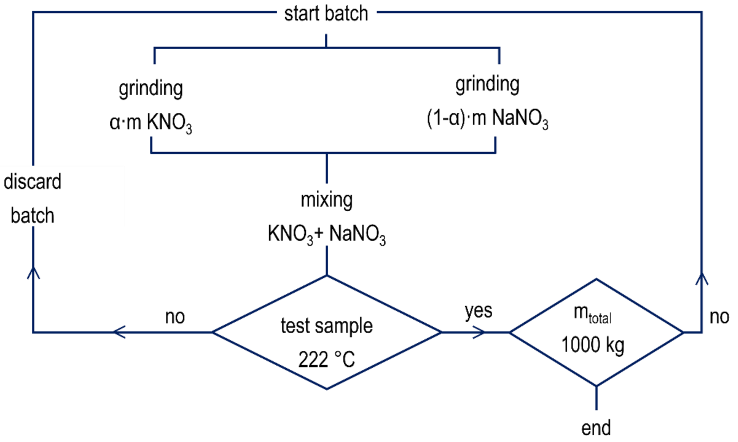

Figure 3. Methodology for preparation of the PCM mixture and filling the tank

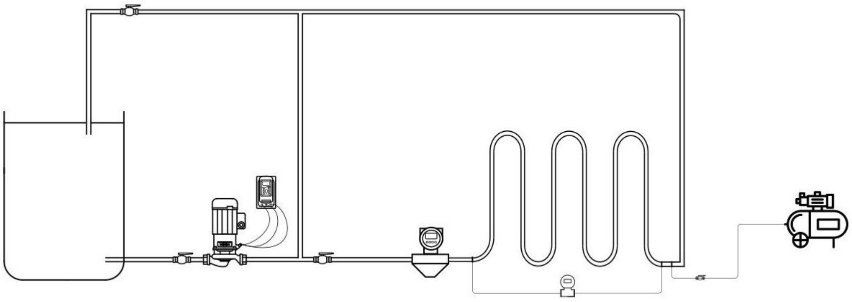

Figure 4. Auxiliary test rig for visualization of the gas-liquid flow during serpentine filling

3. Experimental results

The typical melting procedure of a test sample in an oven is shown in Fig. 5. The melting test starts at ambient temperature, and finishes when all the sample is liquid and overheated at T_{end}=250 °C. If the sample melts in the range T_{melt}=222 ± 0,5 °C, the whole batch is considered correctly mixed and the powder is poured into the TES tank.

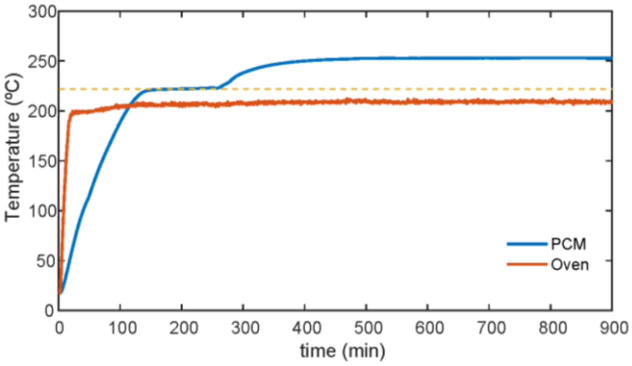

Figure 5. Temperature evolution in the PCM test sample and inside the oven during a typical melting test

A visualization detail of the gas-liquid mixture during the air removal process is depicted in Fig. 6. Higher flow rates and longer process durations favour the overall air removal. As the air is removed from the circuit, the pressure drop across the serpentine decreases towards an asymptotic value (see Fig. 7).

Figure 6. Snapshot of the gas-liquid mixing during filling

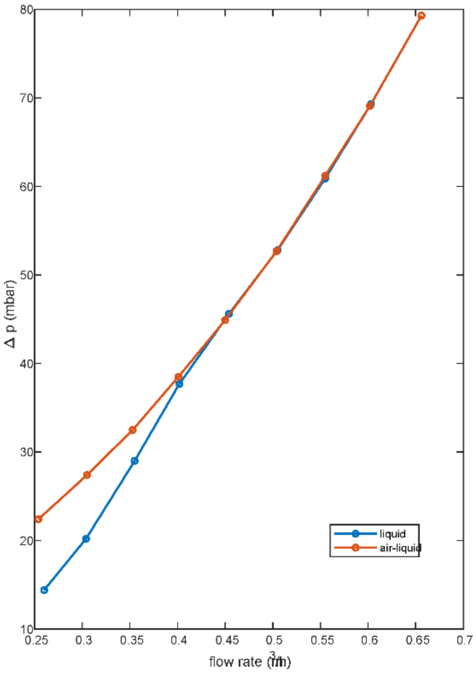

Figure 7. Pressure drop across the serpentine

4. Conclusions

The challenges of building and testing a TES system conceived for industrial demonstration purposes are outlined in this paper:

- The preparation of a PCM salt mixture and the filling of the tank require mechanical grinding and mixing, and sequential melting inside the tank.
- The high operational temperature requires high capital cost insulation systems, in order to reduce the thermal losses and control the overall efficiency of the system. Filling of the circuit with thermal oil is also subject to mechanical requirements to ensure the absence of air.

Acknowledgements

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