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Commissioning and Tests of a Mini CSP Plant

Lisa Willwerth[1a], Margarita Rodriguez[2], Esther Rojas[3], Ridha Ben Cheikh[4], Souha Ferchichi[4], Amani Jmili[4], Abdallah Baba[5], João Soares[6], Francesco Parise[7], Barbara Weinzierl[1] and Dirk Krüger[1]

[1]*German Aerospace Center (DLR), Institute of Solar Research, Linder Höhe, 51147 Cologne, Germany.*
[2]*CIEMAT-PSA; Carretera de Senes, 4.5km, 4500 Tabernas, Almería, Spain.*
[3]*CIEMAT-PSA; Av. Complutense 40, 28040 Madrid, Spain.*
[4]*Université Tunis el Manar, École Nationale d'Ingénieurs de Tunis, B.P. 37, Belvedere 1002, Tunis, Tunisia.*
[5]*Alternative Energy Systems, Avenue Tahar Sfar 29, 4002 Sousse, Tunisia.*
[6]*University of Porto- Faculty of Engineering, Rua Dr Roberto Frias, 4200-465 Porto, Portugal.*
[7]*Zuccato Energia Via della Consortia 2, 37127 Verona, Italy.*

[a)]Corresponding author: lisa.willwerth@dlr.de

Abstract. A small-scale hybrid power plant with CSP and biogas boiler was built at the University ENIT as a laboratory for research and education. The CSP system consists of parabolic trough collectors operating in direct steam generation (DSG) concept. An ORC turbine with a newly developed generator design generates up to 65 kW electrical from low temperature steam. Additionally, biomass anaerobic digestion and phase change storage are demonstrated. While the commissioning of the plant is scheduled for the end of August 2017, commissioning of the single components has already been successfully completed. Highlights and main results from installation and commissioning period are published within this paper.

INTRODUCTION

A small hybrid Concentrated Solar Power (CSP) plant has been erected at the premises of the École Nationale d'Ingénieurs de Tunis (ENIT) within the REELCOOP project. The plant includes many novel concepts and outputs. It is the first CSP plant in Tunisia and thus will contribute to enhance CSP knowledge and commercialization in the region. Steam is generated directly within the solar field, which is constituted by parallel loops of parabolic troughs, contributing to the know-how of CSP Direct Steam Generation, as well as for process steam technology. Due to low temperature and small-scale of the power plant an Organic Rankine Cycle (ORC) was chosen, allowing to set up the steam generation system as closed loop above ambient pressure, reducing air in-leakages and increasing the plant components lifetime (i.e. reducing corrosion).

One breakthrough output is the demonstration and optimization of CSP/Biomass hybridization. For the purpose a steam boiler driven by biogas is used. The anaerobic digestion of food waste from the university canteen will be demonstrated as well, showing a potential solution for food waste issues.

To complete the system a thermal storage could be integrated in the system in future, but up to now there is no phase change storage which would fit the plants requirements. Therefore, a latent heat storage prototype was built and tested at the Plataforma Solar de Almería (PSA).

Since the plant is located at a university it will not only be operated to gain experience for CSP, biomass and CSP/Biomass hybridization and to test components, but will also be used as a student laboratory. On top of that the facility is envisaged to demonstrate CSP to the MENA industry or to educate operational personal not only for CSP, but also for process steam technology.

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DETAILED PLANT LAYOUT

The solar electricity installation at ENIT has been erected to demonstrate the joint operation of a solar thermal field and a biomass boiler for electricity generation in small scale. The planning process resulted in a closed steam/condensate loop as displayed in Fig.1.

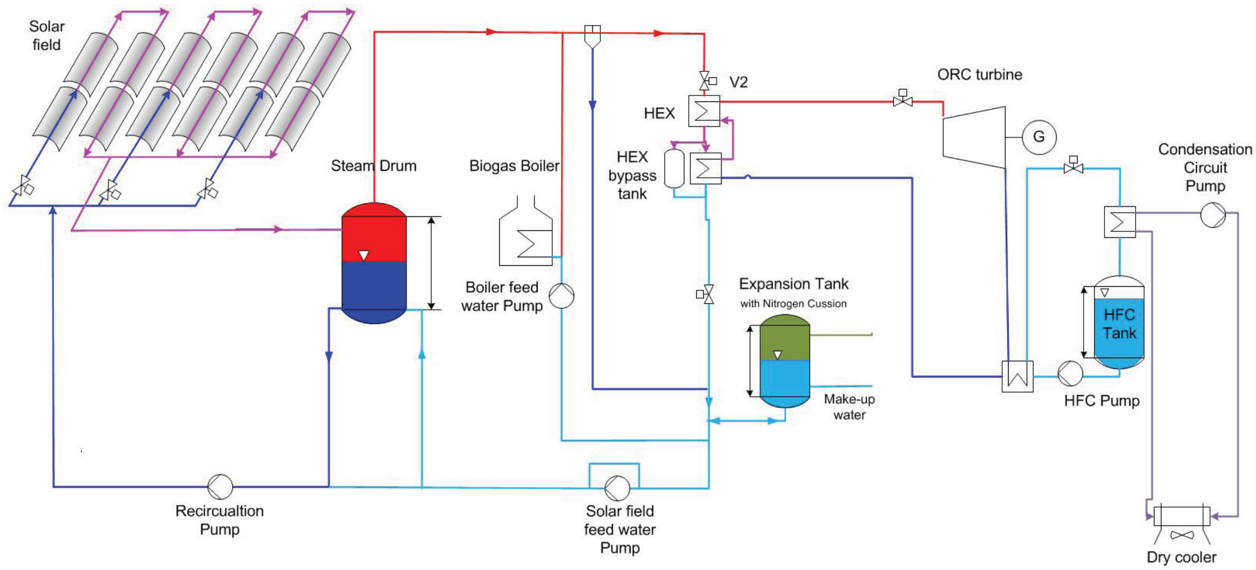


FIGURE 1. P&ID of the closed loop DSG system with solar field, biogas boiler and ORC

For technical data see [1]. Water from the Steam drum is pumped to the solar field where it is partially evaporated. The water and steam mixture is separated in the steam drum. While the condensate recirculates in the solar field, saturated steam at about 170°C flows to the heat exchangers (HEX).

In the first HEX saturated steam condensates, while on the other side the organic heat transfer fluid (HTF) evaporates. In the second HEX the condensate cools down, while the organic HTF is preheated. A bypass tank enables the measurement of the condensate level between the HEX. To optimize the heat transfer between the solar and biomass circuit and the ORC circuit and to hinder steam from entering the feed water pump, the condensate level should remain between both heat exchangers, but transients can cause changes in the level. A study [2] found, that pressure drops due to gaps in solar irradiation cause the expansion tank to balance pressures by pushing water into the system. This water volume may be too big to be instantly moved by the feed water pump and can increase the level between the HEX. A control strategy for the closed loop system was developed to balance the condensate level.

The organic HTF vapor drives the turbine and is condensed. The remaining heat in the condensate is used to preheat the organic HTF. Heat dissipation from the ORC condenser will be achieved through the use of a dry cooler. This device is a fluid-to-air heat exchanger, where fans blow ambient air over a series of finned tubes. A dry cooler was chosen because it does not consume water, which limits the risk of corrosion, clogging and dirt accumulation. Besides, the cooler is equipped with a frequency converter and thus power consumption is always proportional to the actual need. The equipment is currently under installation at ENIT.

As backup energy, a biomass system was proposed which feeds a boiler instead of the CSP system, in the absence of direct solar irradiance. However, to cover the ORC steam demand huge biomass amounts are required and consequently a big digester volume. Therefore, the installed boiler is able to operate on both, natural gas and biogas. To demonstrate the feasibility of the biomass system, a medium size digester was integrated. The one stage wet continuous digester with a volume of 3 m^3 will be fed with organic wastes from the university restaurant. The biomass system, consisting of digester, mixer and decanter, is currently in the installation phase next to the plant at ENIT.

CONSTRUCTION OF THE PLANT

Solar field, ORC, boiler and piping have been installed. A dry cooling system is being connected. Electrical connection works are ongoing. The combined commissioning of solar field and ORC is planned for August 2017. The main achievements in the construction phase are documented in the following.

Land Works and Fundaments

The soil at the construction site is challenging. Rain water used to accumulate on the site and lead to ground movement which caused cracks in neighboring buildings. Therefore, AES (Sousse, Tunisia) designed thoroughly a drainage system for the entire solar field and chose a special pylon type foundation to meet the structural requirements of the solar collectors (see Fig. 2).

(a) (b) (c)

FIGURE 2. Pictures from the construction site (a) drainage under solar collector, (b) pylon fundament (c) final solar field and building

Installation of Solar Field

The parabolic trough solar field was manufactured and provided by Soltigua, in Gambettola, Italy. Solar field main components were installed by the AES team, with support of ENIT and under Soltigua supervision. The collector design proved to be robust and simple, resulting in an easy installation (See Fig. 3a&b). The foundations level was constantly checked in order to guarantee the collectors specific installation tolerance. Subsequently, the solar field sensors were tested and GPS equipment was used to define and calibrate the exact solar collectors' orientation (see Fig. 3c). A quick tracking test was carried out to verify all operation parameters. At the end, the solar field was commissioned for operation.

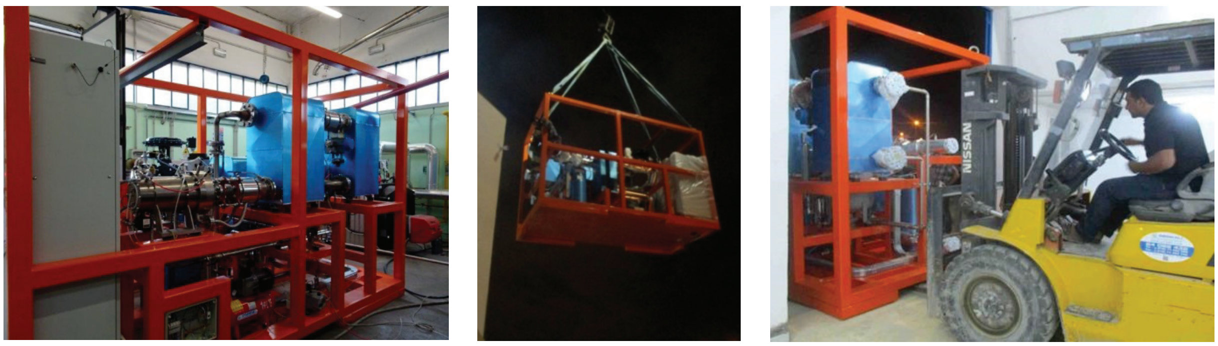
(a) (b) (c)

FIGURE 3. Pictures of solar field installation (a) Torque tubes handling, (b) attachment of mirrors, (c) calibrating collector orientation

Installation of ORC

The Organic Rankine Cycle Module was delivered by Zuccato Energia, in Verona, Italy. To meet the requirements of the solar field a new generator was designed. In tests with a first prototype, high temperatures exceeding demagnetization temperatures were observed due to high parasitic currents caused by internal current loops inside the magnets. Therefore, a new winding geometry was developed in a double three-phase configuration for turbogenerator, with the help of an expert in electric machine design from the University of Padua. Generator tests with the new winding geometry showed good results with temperatures remaining entirely in the acceptable range throughout the working envelope.

The complete ORC module (Fig. 4a) was easy to transport with a lifting crane (Fig. 4b) or a forklift (Fig. 4c) as a whole.



(a) (b) (c)

FIGURE 4. Pictures of ORC (a) commissioning at Zuccato, (b) lifting with crane, (c) moving into the building with forklift

COMMISSIONING OF COMPONENTS

As soon as the overall installation is finished, the complete plant will be commissioned. As a preparation, the main components were already commissioned alone. A pressure test for the piping was completed successfully, the ORC was commissioned at the manufacturer and the storage was tested at the PSA. These tests are described in the following. Also, the tracking of the solar collectors will be tested before the overall commissioning.

Pressure Test Solar Field and Piping

A pressure test of the piping was successfully performed using pressurized water. The design pressure of the system is 12.5 bar_{abs}. As the safety factor foreseen in Tunisia is 1.5 for steam installations in this pressure range, a testing pressure of 19 bar_{abs} had to be applied. First the piping was filled with water. The water was circulated for some minutes to vent the system. Then the vent valves were closed and an additional, external pump increased the pressure in the piping to 19 bar_{abs}. After small welding works, the piping and components proved to be tight and safe for the designed pressure. The safety valves were installed after the pressure test.

Commissioning of ORC

The ORC turbine has been tested for a few days at the premises of the manufacturer Zuccato Energia, Italy. Saturated steam at about 170 °C was provided by a boiler. The ORC machine started well within a few minutes. A relatively stable gross electrical power of 76 kW was delivered. The electrical output is measured behind the inverter. The thermal power has been calculated with the steam volume flow rate and temperature at the turbine inlet and condensate temperature at the turbine outlet. An efficiency of about 13% has been reached during first tests, which is in line with the calculated planning data for the ORC. After a thorough commissioning of the complete plant and an optimization of control, a higher efficiency is possible.

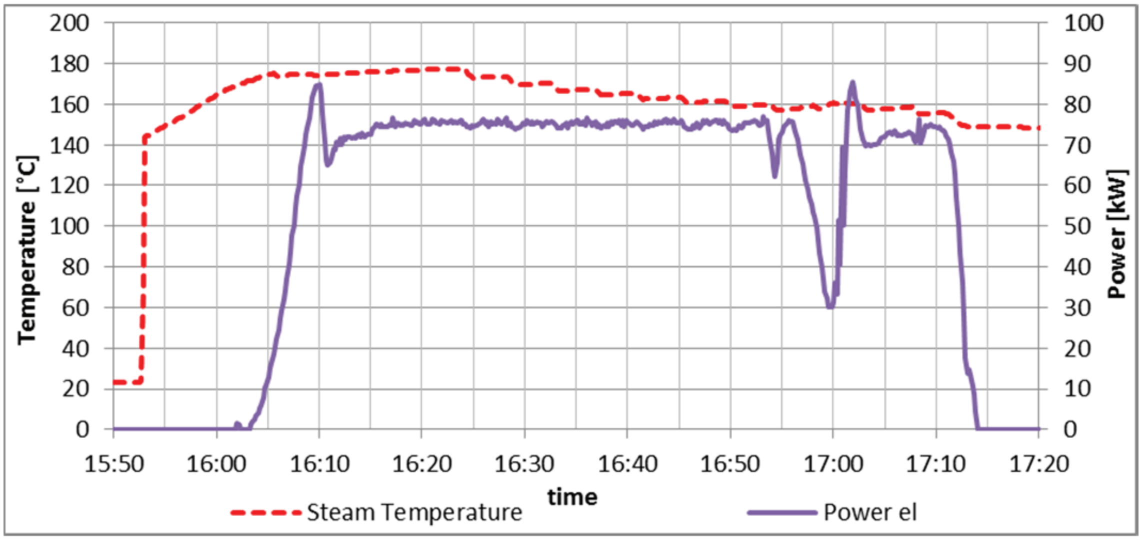


FIGURE 5. Commissioning of the ORC steam temperature and electrical power

In the first tests high variations in the condensate level in the tank were observed. As a result, the condensate reached below the minimum level and temperature reached 150°C at the outlet of the heat exchangers. The condensate level should not fall below the lowest level to avoid the feed water pump running with steam and it should not move to far up as this would reduce the heat transfer area for the steam. The fluctuation has been reduced by adapted control parameters for the steam control valve V-2 (see Fig.1).

Figure 5 shows the measurement data of a later ORC test on 13th of May 2016. The steam temperature before the control valve leaps to 140 °C at 15:53. Within 5 min it is increased to 175 °C. From 16:00 V2 opened gradually and accordingly the thermal energy provided increased. Simultaneously the ORC starts electricity generation. Only 7 min. later thermal power reaches a maximum of 700 kW while electricity generation reaches a maximum of 85 kW. Then thermal power is constantly reduced to 600 kW and electricity generation remains constant at about 76 kW as well. Small fluctuations in the power are due to an intervallic firing of the boiler. The drop in electrical power around 17:00 is caused by a drop in steam mass flow rate.

The quick start-up and fast adoption to part load without shutting off the ORC demonstrates its high flexibility, which will be beneficial for the combination with fluctuating concentrated solar power.

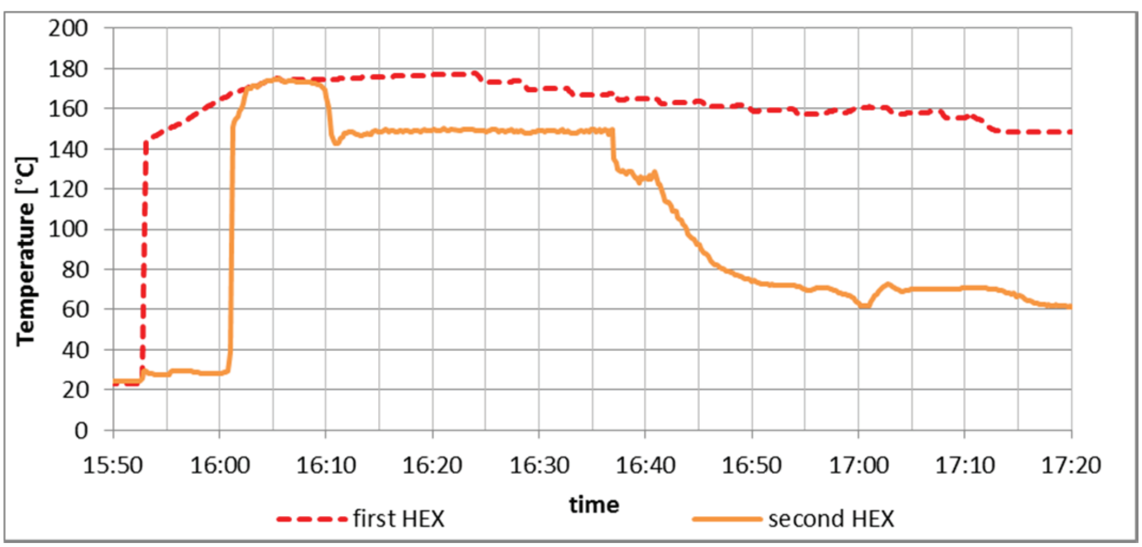


FIGURE 6. Commissioning of the ORC steam temperature before the first and before the second HEX

The water steam mass flow rate and thus the heat transferred, is regulated by the valve V-2. Additionally, it controls the temperature and pressure of the organic fluid entering the turbine. Figure 6 shows the water temperature before the first and the second HEX. While the steam temperature is already up over 140 °C, the temperature between the HEX is still low, indicating that V-2 is still closed and there is no mass flow through the HEX yet. At about 16:00 V-2 opens and the temperature between the HEX directly adopts the same temperature of the steam. The temperature between the HEX gives a hint on the condensate level between the HEX. As long as, the temperatures before and between the HEX are the same, the water is not fully condensed and didn`t start cooling down yet. So, the condensate level is below the second temperature measurement. At 16:10 the control narrows V2, and reduces the thermal power provided. The higher pressure losses cause a loss of exergy. This is not going to be very relevant during operation with a solar field, because its maximum thermal power is designed to be equal to the maximum power of the ORC, therefore a higher efficiency is to be expected for operation with the solar field. Furthermore, thermal energy part loads can be avoided trough the hybrid operation of the plant.

From 16:10 on, the temperature behind the first HEX is up to 30 °C less than the temperature before the first HEX due to V2 control. From 16:36 on, the temperature behind the first HEX decreases, which indicates, that the condensate level is rising and there is already condensate in the first HEX cooling down. The condensate level control will be studied during operation with the complete plant.

For comparison with later testing in the field, the cooling temperature must be considered. While wet cooling with low return temperatures has been used for commissioning in the facility, the cooling at ENIT will be performed with dry cooling to save water. The higher return temperature will have a significant influence on the turbine efficiency but fit better to the thermal output of the solar field and biomass boiler.

After the tests, the turbine wheel has been changed to adapt from 80 to 65 kW electrical output as to fit better to full and part load conditions at the ENIT installation.

Commissioning of Storage

The storage module has been tested at the Plataforma Solar de Almería. A modified spiral plate heat exchanger is used as latent storage module. As a phase change material Hitec® salt was chosen. The melting and freezing tests with the material, as well as the design of the storage module and the test set up are described in [3]. Saturated steam at different temperatures up to 170°C was provided by a steam boiler for charging and hot water up to 130ºC by a water heater for discharging.

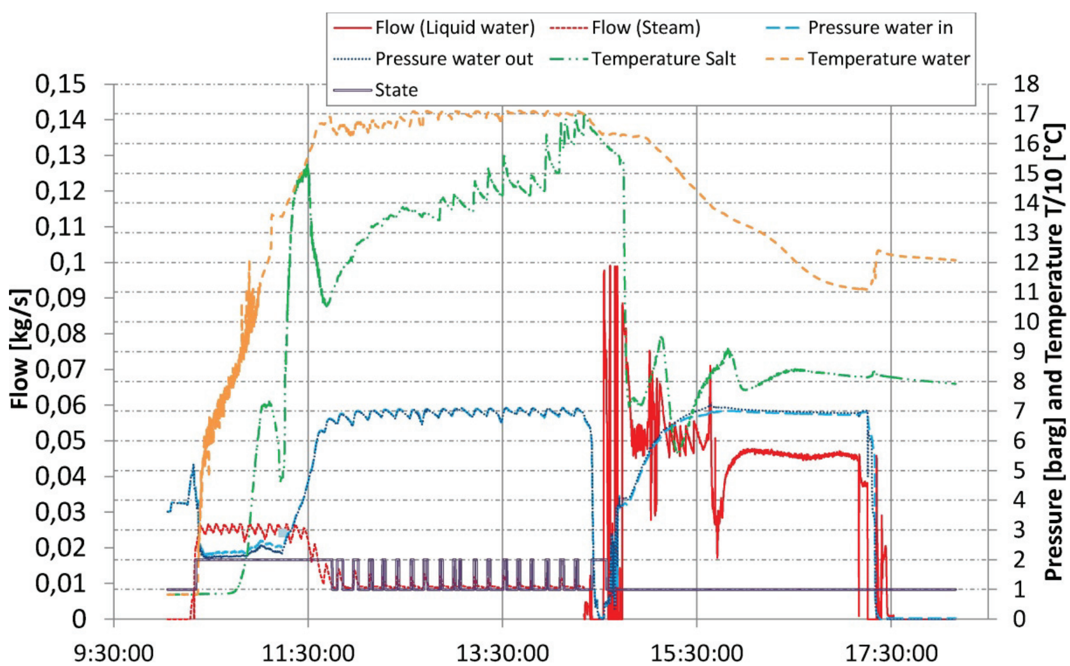


FIGURE 7. Diagram of Charging and discharging for 9/1/2017

In Figure 7, an example of charge and discharge process can be observed. Here, the inlet water flow in liquid state and steam state, the inlet and outlet pressures, and the water state are shown. Also, the temperature of the heat transfer fluid during discharge (charge), as well as, the mean temperature of three thermocouples at the HTF inlet (outlet) during the charge (discharge) are represented. Two main aspects have to be considered during the testing phase of the project: First, the steam boiler stopped providing constant steam and reduced the steam mass flow by 50 % whenever the pressure in the HTF loop went above 4 bar_g, providing steam in pulses that produce a charge in a saw-tooth profile; and second, the control of the pressurized tankless water heater failed at high temperature and pressure (see Fig. 7 from 14:38 to 15:30), being only possible to operate it in a regulated way below 90 °C.

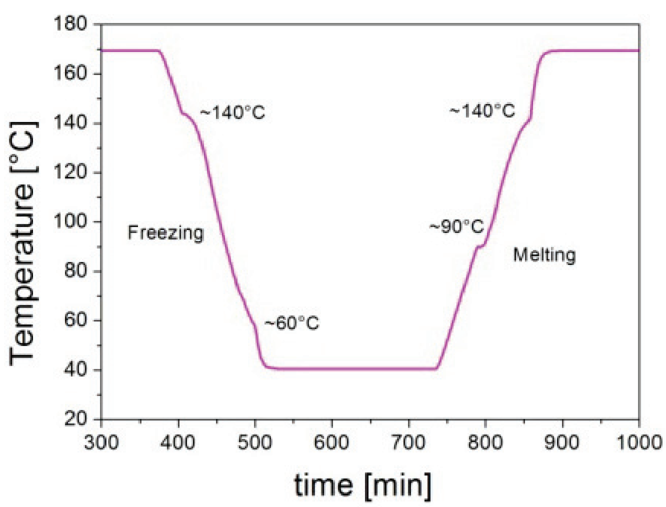
Several studies of the Hitec® salt as phase change material have been performed. As can be seen in Fig. 8a, during charging (melting process) two phase transitions can be observed in the PCM: one at 90 ºC, which may correspond to a solid to solid transition and another one at 140 ºC, corresponding to a solid to liquid phase change. During discharging (freezing the PCM) there are two transitions: one at 140 ºC (liquid to solid) and another at 60 ºC (solid to solid). The difference in the temperature, at which the solid to solid transition takes place, is due to the supercooling effect. Hence, there is not a clear definition of the point at which charging and discharging processes end, since the storage module does not behave as a whole.

In Fig. 9 the charging power for 9/1/2017 is shown, calculated by the mass flow measurement entering the TES module and the enthalpy change given by the HTF outlet conditions and HTF inlet conditions. The obtained saw-tooth profile is due to the steam boiler that provides steam at pulses.

At the end of the charging process at approximately 11:45, the HTF has supplied 94.4 kWh to the whole system. Part of this energy has been used for increasing the temperature of the storage module (sensible heat), part for dealing with thermal losses and part has been stored in form of latent heat, by changing the phase of the PCM from solid to liquid. For the calculation of the supplied energy it has been taken into account that the storage module is made of 1410 kg stainless steel (c_p=500 kJ/kg) and 410 kg of HITEC (c_p=1 560 kJ/kg), which means that steel mass is more than 3 times PCM mass, while its heat capacity is around three times lower, giving a similar thermal losses.

The calculated mean heat loss power is 1.45 kW, and the resulting energy for the latent heat is 1 kWh, which implies 9 kJ/kg specific latent heat of the PCM, which is much lower than expected up to now. This result, together with the solid to solid transitions detailed above and the relatively low enthalpy of fusion, make Hitec salt not the most appropriate candidate for its use as PCM.

The TES module used for the project (Fig. 8b) is a commercial spiral heat exchanger. In spite of the spiral geometry, the stream inertial forces that drag the steam along are not as large as expected.



(a)

(b)

FIGURE 8. (a) Hitec freezing-melting curves where two solid-solid transitions at 60 and 90 ºC can be observed and (b) picture of Thermal energy storage module

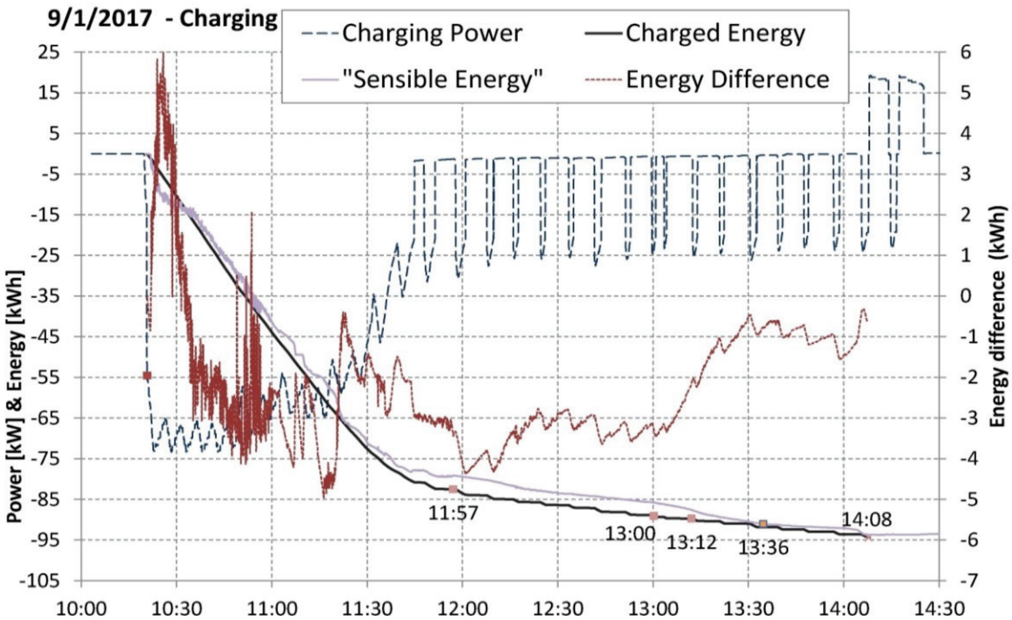


FIGURE 9. HTF charging power, energy supplied by the HTF and estimated energy used for sensible heat. Experimental data of 9/1/2017.

The storage module tested here did not allow including temperature gauges at different radial positions, but at the center and outer radius of the equipment. This would allow a better definition of the phase change moment for the different parts of the TES module, since one of the main conclusions of this work is the difficulty in defining ends of charging and discharging processes when inhomogeneous phase change processes take place.

In spite of the above mentioned problems, adequate enough approaches for evaluating the thermal performance have been found.

SUMMARY AND OUTLOOK

Within the REELCOOP Project a novel small-scale hybrid power plant with CSP, biogas boiler and ORC was built at the University ENIT. It will serve as a laboratory to examine hybridized small scale CSP power plants and additionally will be used for education. The construction works are almost finished and the main components are already commissioned. For the specific requirements of the CSP thermal power, a new turbo-generator design was developed. Also, a new phase change storage material was investigated and a novel storage design commissioned. The complete hybrid power plant is scheduled to be commissioned in August 2017. Furthermore, food waste anaerobic digestion will be demonstrated.

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