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DEVELOPMENT OF A SMALL SOLAR THERMAL POWER PLANT FOR HEAT AND POWER SUPPLY TO DOMESTIC AND SMALL BUSINESS BUILDINGS

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ABSTRACT

The small solar thermal power plant is being developed with funding from EU Horizon 2020 Program. The plant is configured around a 2-kWel Organic Rankine Cycle turbine and solar field, made of Fresnel mirrors. The solar field is used to heat thermal oil to the temperature of about 240 ºC. This thermal energy is used to run the Organic Rankine Cycle turbine and the heat rejected in its condenser (about 18-kWth) is utilized for hot water production and living space heating.

The plant is equipped with a latent heat thermal storage to extend its operation by about 4 hours during the evening building occupancy period. The phase change material used is Solar salt with the melting/solidification point at about 220 ºC. The total mass of the PCM is about 3,800 kg and the thermal storage capacity is about 100 kWh. The operation of the plant is monitored by a central controller unit. The main components of the plant are being manufactured and laboratory tested with the aim to assemble the plant at the demonstration site, located in Catalonia, Spain. At the first stage of investigations the ORC turbine will be directly integrated with the solar filed to evaluate their joint performance. During the second stage of tests, the Latent Heat Thermal Storage will be incorporated into the plant and its performance during the charging and discharging processes will be investigated. It is planned that the continuous filed tests of the whole plant will be performed during the 2018-2019 period.

INTRODUCTION

Micro CHP technologies run on fossil fuels such as natural gas have been intensively developed over the last several decades and these were based on small Stirling engines, Internal Combustion gas engines, steam and ORC turbines and reciprocating engines, fuel cells etc. [1].

Thermal engines, such as steam, ORC and Bryton turbines, are usually deployed for conversion of solar energy or other types of renewable energy and waste heat on a large scale [2,3]. Kalina cycle systems are also attractive for solar and waste energy utilization [4].

A very limited number of technologies have been tested to provide heat and power for individual houses or small business with utilization of solar and other types of renewable energy and these include small medium temperature Stirling Engines [5] and PV-T technology. Due to relatively low-level temperatures, the overall heat-to-electricity conversion efficiency in small Stirling engines is very low. Additionally, this technology still carries a number of unresolved engineering issues such as the high level of thermal losses, use of expensive materials, sealing of internal gas circuit, reliability in exploitation, large dimensions and excessive weight. The PV-T technology, which converts non-concentrated solar energy, normally cannot provide sufficient amount of hot water and meet heating requirements of dwellings and, therefore, is used for pre-heating in domestic hot water supply systems. The micro ORC turbine could provide feasible solution for generation heat and power with the use of solar energy if technical problems on maintaining the acceptable level of energy conversion efficiency could be resolved at such micro scale. This work describes collaborative activities of several SME and Universities on the development of a small solar heat and power plant (Innova MicroSolar) built around solar energy concentrating collectors, 2-kWel micro scale ORC turbine and latent heat thermal storage system. The importance of the project lies in the opportunity to estimate the technical-economical and environmental performance of such technology in conditions of real exploitation and evaluation of its feasibility compared to other existing and potential competing technologies.

NOMENCLATURE

Abbreviations

AR	Anti Reflective
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CSP	Concentrated Solar Power
HTF	Heat Transfer Fluid
LFR	Linear Fresnel Reflector
LHTES	Latent Heat Thermal Storage
PCM	Phase Change Material
P & ID	Piping and Instrumentation Diagram
TES	Thermal Energy Storage

SOLAR PLANT

The Innova MicroSolar system is being constructed to utilize solar energy to produce electricity and heating for domestic and small business buildings, see Fig 1. The system consists of three main components: a solar field, which is solar power concentrating system (CSP), latent heat thermal energy storage system (LHTESS) and Organic Rankine Cycle (ORC) turbine.The CSP system is based on the Linear Fresnel Reflector (LFR) technology. This CSP system uses long segments of almost flat mirrors to focus the direct solar radiation upon a tubular receiver, which is mounted in the focal line of mirrors. The ORC turbine is driven by solar energy or thermal energy, accumulated in the TES by solar salt used as a phase change material (PCM). The TES is charged during the day in parallel to operation of the ORC turbine. The design feature of TES is that heat is charged and discharged using the Heat Transfer Fluid (HTF) via horizontally installed reversible (bi-directional) heat pipes.

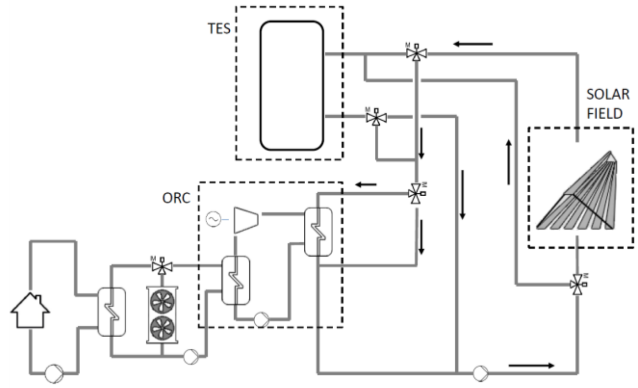


Fig. 1: The schematic of the Innova MicroSolar Plant

Solar Concentrating Collector

In order to have the LFR collector's structure sufficiently small and lightweight, Elianto's team has applied a new type of manufacturing technology for both the primary reflector and the frame components of the LFR assembly. Elianto's R & D team also run computer simulations to identify geometric dimensions of the new LFR collector.

The schematic of the Innova Micro Solar LFR collector's design is shown in Fig. 2.

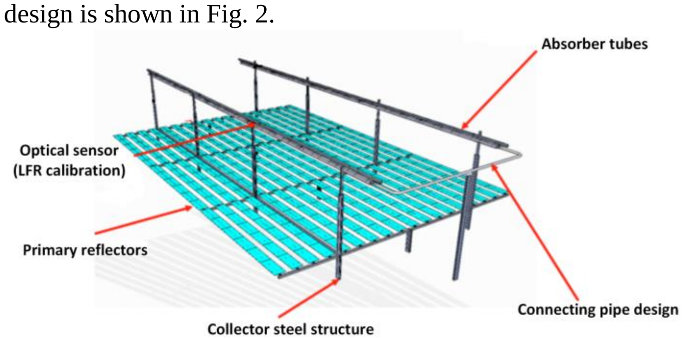


Fig. 2: The schematic of the Innova Micro Solar LFR collector's design

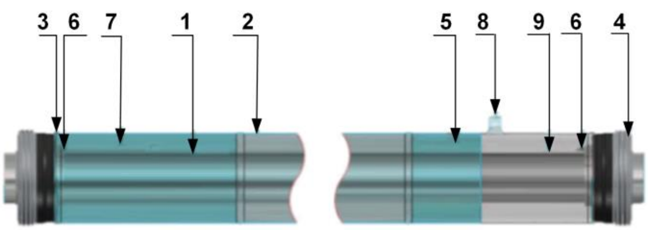
In parallel to the computer simulation activity, extensive optical numerical modelling was carried out to design the mirrors-receive system, capable to demonstrate high performance. Structural modelling was also performed, so the construction will withstand high winds. The system consists of two modules with its own line of receivers, mounted at the height of 3 m above the ground level. Each module is made of 9 primary reflector units and 5 receiver tube units. The total length and width of the module is about 20 and 6 m, respectively, and it covers a ground area of around 120 m2. The total net mirror surface area per module is 146 m2, which at nominal conditions with the Direct Normal Irradiance equal to 900 W/m2 delivers a peak thermal power of 80 kW. Mirror laminas are of the high efficiency and reliability and primary mirror reflectors are made of unbreakable solar grade aluminium. The two LFR collector modules are connected to form a single hydraulic loop. The HTF used is diathermic oil

Therminol 62, which can be exploited at temperatures over 340 °C. The Innova Micro Solar field is equipped with a fully automatic pumping unit, which is controlled using electric valves and an array of process sensors, located in different parts of the plant. These sensors measure pressures, temperatures, mass fluxes and sun irradiation. All units of the plant are connected to each other using thermally insulated piping network.

Incorporation of a mirror cleaning maintenance system is possible with the chassis, which permit installation of the optional automatic robot for washing primary reflectors.

The design of the collector has a very high mirror density per unit of the ground area. The system operates in the fully automatic mode.

The commercially available evacuated receiver of standard dimensions (70 mm in the dimeter) was selected for the new LFR collector, see Fig. 3. It's maximum operating temperature is 400 °C and, at the operating temperature of the Innova Micro Solar project equal to 300 °C, this component achieves the efficiency of 90% in transferring solar flux energy to the HTF.



1. Stainless steel absorber tube with spectrally selective coating;2. Glass jacket with Anti Reflective (AR) coating; 3. Glass to metal seals; 4. Thermal expansion compensators; 5. Vacuum annulus;6. Non-evaporable Getter (NEG) pills; 7. Barium getter; 8. Pump nipple; 9. Serial number.

Fig. 3: Innova MicroSolar evacuated receiver tube technology for the LFR collector

The selected evacuated absorber tube technology uses a spectrally selective coating deposited on the steel tube. This is a thin-film multilayer structure, including a layer of metal, reflecting the infrared radiation, and a superior layer of antireflective (AR) ceramic material. A graded ceramic-metallic material guarantees a high absorptance in the solar wavelength range and a low emittance behavior at the operational temperature of the solar receiver up to 400 °C. The external glass has an AR coating on both surfaces in order to minimize the reflection losses. The thermal expansion compensators are required between the metallic absorber tube and external glass envelope. In order to maintain vacuum inside the glass envelope, the compensators are installed using a special glass-to-metal seal. The tube getter provides the safe and efficient operation during the expected receiver's lifetime, absorbing the residual gases on the metal and glass surfaces inside the annulus. Furthermore, it has been designed to capture HTF hydrogen molecules, penetrating the steel tube.

Overall, the technical characteristics of the solar filed are as follows: the lowest net optical efficiency for the entire solar field is 60%; the lowest net thermal receiver tube efficiency is 70%; the solar peak thermal power is 60 kWth with the maximum HTF allowable outlet temperature of 290 °C.

ORC Turbine

The design of ORC turbine was developed by Enogia to generate electricity at the rate of 2 kW. The Piping and Instrumentation Diagram (P & ID) of the complete assembly of the ORC unit is shown in Fig. 4. This P & ID presents installation and connections of all components, actuators, pumps and sensors, which are mounted together on the single steel framework.

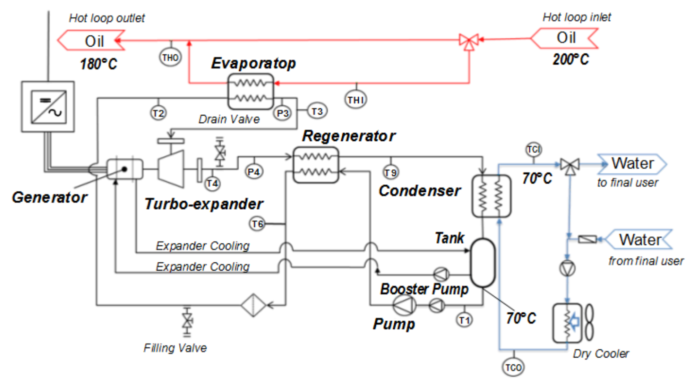


Fig. 4: Piping and Instrumentation Diagram of the ORC unit

It can be seen in this figure that the working fluid flows from the tank to booster pump and then it is pressurized by the main pump. Further, the working fluid passes through the regenerator/recuperator to be preheated and then is boiled in the evaporator. The working fluid vapour is directed to the turbine blades and after expansion process it flows to the regenerator for precooling. Finally, the vapour passes to the condenser and the formed fluid is taken to the tank. The working fluid is also used to cool the generator.

Among various working fluids, two were identified as suitable for this project: NOVEC 649 and Cyclopentane. These two fluids have characteristics and properties, which mostly satisfy project and ORC design requirements. The NOVEC 649, commercialized by 3M, is an HFE. It is environmentally friendly, easy to handle as it is considered to be non-hazardous fluid: it is not flammable and is not toxic. This fluid was identified as the first choice working fluid for the use in ORC prototype. The Cyclopentane is the second working fluid, which has a certain potential for the use in the ORC unit in this project. It has even superior thermodynamic properties, compared to NOVEC 649, but this substance is flammable, which leads to a number of constraints in the prototype design.

For the above reasons, the ORC prototype is designed to operate using both NOVEC 649 and Cyclopentane.

Table 1 shows calculated theoretical performance of the ORC unit using NOVEC 649 and Cyclopentane. The system will operate at the temperature of 200 °C, achieved in the "heating" loop of the plant (solar field and heat storage). For the first prototype, NOVEC 649 is chosen as the final working fluid.

Table 1. Theoretical estimation of the ORC unit performance

	Units	NOVEC 649	Cyclopentane
Heating Loop			
Thermal Power	kW	22	22
Inlet Temperature	ºC	200	220
Outlet Temperature	ºC	180	180
Mass flow of thermal oil	kg/s	0.44	0.22
Specific heat of thermal oil	kJ/kg K	2.5	2.5
Rankine Cycle			
Boiling temperature	ºC	170	188
Superheating degree	ºC	5	5
High pressure	MPa	1.7	2.2
Specific Enthalpy	kJ/kg	433.79	574.83
Condensing temperature	ºC	73	73
Low pressure	MPa	0.22	0.21
Specific Expansion enthalpy	kJ/kg	415.4	473.17
Sub-cooling degree	ºC	1	1
Mass flow	kg/s	0.216	0.049
Gross Electric power production	kW	2.38	2.99
Efficiency		0.108	0.136

The ORC turbine's rotor and stator were designed and dimensioned using 3-D CFD simulations, see Figs. 5 and 6. In simulations the rotor blades are considered to be in rotation at the speed of 43,500 rpm. A polyhedral type of mesh has been used in the computational domain with a very fine mesh being deployed in the vicinity of walls. The number of cells in the computational mesh is 580,000. Since the performance of a small turbines is very sensitive to various types of losses, this type of simulations is used to identify elements in the design, causing losses due to separation of the flow and improve the geometry of the turbine blades.

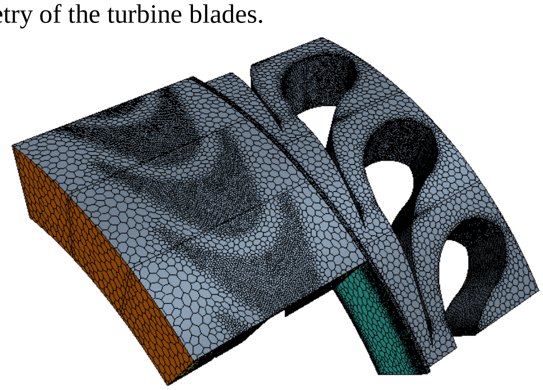


Fig. 5: Computational mesh for the stator-rotor assembly

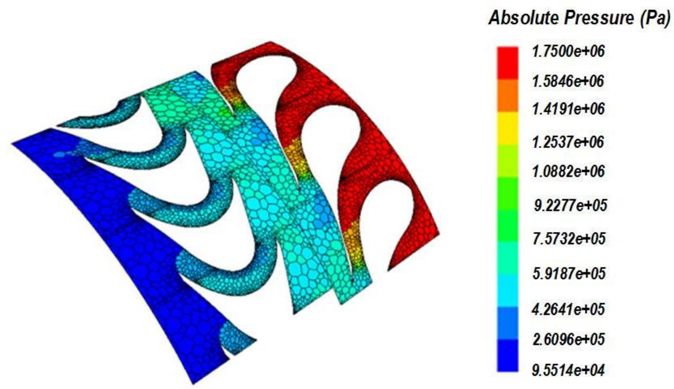


Fig. 6: CFD simulation results on pressure variations in the NOVEC 649 vapour, flowing through the stator-rotor assembly

After completion of CFD simulations of the turbine's stator and rotor blades, the volute and housing components of the ORC turbine were designed. The structural analysis of these components was performed to finalize the selection of materials, so to ensure that deformations in the geometry of components due to pressure, inertia and thermal loads during operation will not exceed critical levels, causing mechanical destruction or seizure of rotating parts. Using high grade or stainless steel for manufacturing turbine components, capable to withstand the high temperatures and pressures, would result in these components being too heavy. This, in turn, would result in the excessive inertial load on the rotor and necessity to use larger bearings. For these reasons, the titanium alloy Ti6AlV4 was selected as the material to manufacture rotor blades and the volute. The use of the titanium alloy also makes it possible to keep the thermal expansion of components at the low level, which is critical to maintain small gaps between the volute and tips of blades of the turbine. Figs. 7 and 8 show the 3-D CAD assembly of ORC unit and its view from the top. The dimensions of the steel framework are 1470 x 800 x 750 mm (height x width x depth).

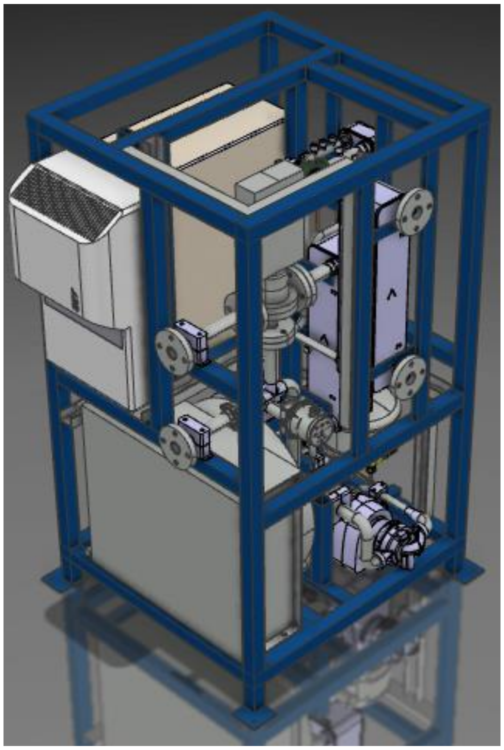


Fig. 7: 3-D CAD design of the ORC unit assembly

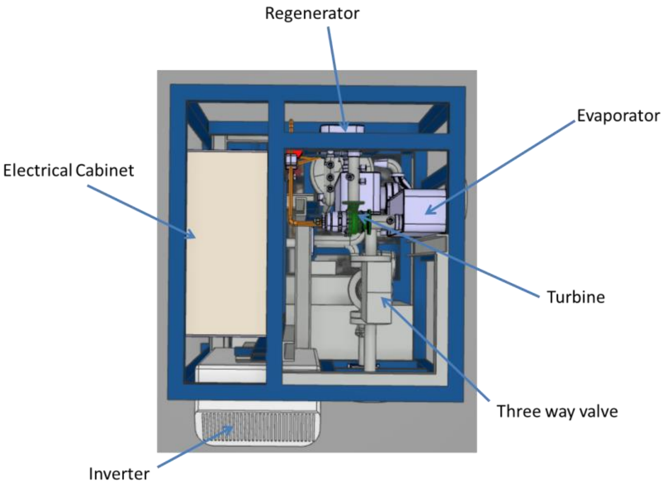


Fig. 8: 3-D CAD design of the ORC unit assembly: view from the top

Fig. 9 shows the photograph of the manufactured 2-kWel ORC assembly and Fig. 10 presents experimental results from preliminary tests of the ORC unit using thermal oil with maximum temperature of 140 °C. At these conditions, the ORC units produces about 700 W of electricity. Currently, the design of the turbine is being modified and preparations are underway for tests with the temperature of thermal oil up to 220 °C.

Fig. 9: The manufactured and assembled ORC unit

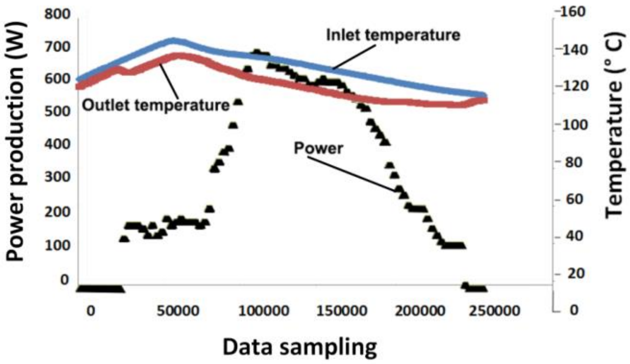


Fig. 10: Experimental results on the ORC performance at the temperature of heating thermal oil equal to 140 °C

LHTES System

The purpose of the LHTES system is to accumulate and then provide the thermal energy for operation of the ORC turbine over a 4-hour period, when there is no solar energy is available (at the night-occupancy time). The thermal energy should be supplied to the ORC at the rate of 25 kWth so its storing capacity is 100 kWh.

Out of several PCMs, tested for the use in LHTES system of the Innova MicroSolar Plant, solar salt was selected for the thermal energy storage at the temperature of 220 °C. Thermo-physical properties of solar salt were measured using the Differential Scanning Calorimetry technique and thermal conductivity meter. This data is presented in Table 2.

Table 2. Solar salt physical properties

Property	Formula	Units	Ref.
$T_{solidus}$	218	°C	PW*
$T_{liqvidus}$	230	°C	PW
H_{fusion}	94.3	kJ/kg	PW
ρ_{liquid}	2106 -0.680 T (°C)	kg/m^3	[6]
$C_{pliquid}$	1620	J/kg °C	PW
k_{liquid}	0.380 + 3.452·10^{-4} T (°C)	W/m °C	[6]
η_{liquid}	1/(–0.263 + 0.0020 T (°C))	cP	[7,8]

* PW is present work

The main disadvantage of the PCM is its low thermal conductivity, which makes it difficult to complete the discharging and charging processes in the required 4-hour period. Therefore, various methods to enhance the heat conduction were investigated. The heat transfer enhancement in the LHTES system can be divided into two groups, namely increasing the PCM thermal conductivity by adding high thermal conductive particles and by placing high thermal conductivity insertions into the PCM (e.g. metallic fins, heat pipes, and others) [9]. The approach selected in the project is the use of reversible (bi-directional) heat pipes in a combination with metallic inserts.

Figs. 11, 12 and 13 show the general design of LHTES system's single module. The module is divided into two main volumes: the first volume is the oil reservoir with the inlet and outlet for the HTF with the second volume being PCM chamber. An array of stainless steel cartridges horizontally run through oil and PCM chambers. These are used to house the bi-directional heat pipes and also to transfer heat from the condensing zone of the heat pipes to the vertical metallic insertions, which are used as fins. The pitch between these vertical fins is between 8 and 10 mm.

The HTF, flowing from the solar field, passes heat to the array of horizontally mounted heat pipes through their smaller fins, welded to pipes in their evaporative zone, see Fig. 14. Heat is then transferred to the PCM via vertical fins – metallic insertions in the PCM chamber. When it is necessary to deliver heat from the PCM storage to the ORC unit, these heat pipes work in the opposite direction. Their longer condensing zone operates as the evaporative zone and the part of heat pipes, located in the oil chamber, turns into the condensing zone. The length of heat pipes in the oil chamber is approximated 0.1m. The PCM chamber of the LHTES system has internal dimensions of 1000 mm x 660 mm x 470 mm. The mass of the PCM in the module is about 600 kg. The length of heat pipes, embedded into the PCM, is about 450 mm. One of the challenges in designing the LHTES system is the selection of the configuration of these metallic inserts to maximize the capacity and performance with the minimum increase in the weight and cost.

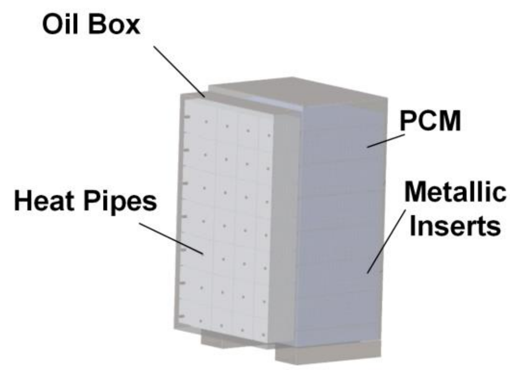


Fig. 11: Design of the single module of the LHTES

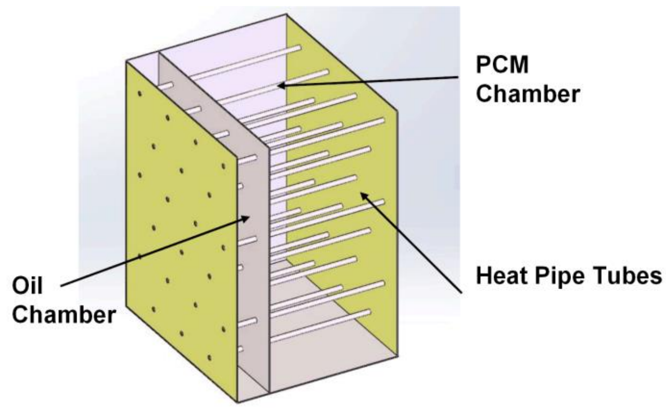


Fig. 12: Thermal oil and PCM chambers in the single module of the LHTESS

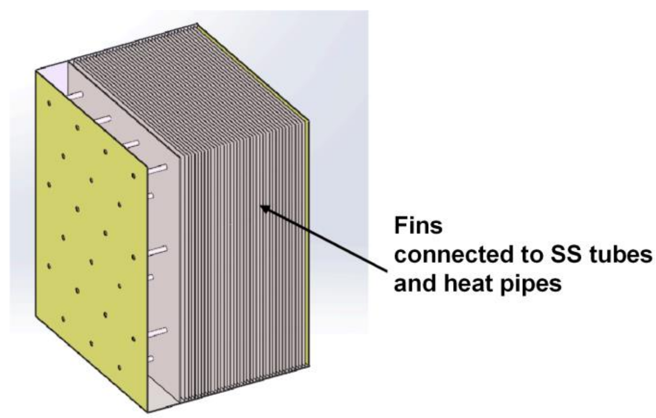


Fig. 13: The single module of the LHTESS with vertical fins (metallic instertions).

In order to store the amount of thermal energy, sufficient to run the ORC plant for 4 hours, the mass of solar salt is approximately 3.8 tons with the volume of the LHTESS being 2 m3. A modular design concept of the LHTESS is adopted in order to have between 6 to 10 modules as is shown in Fig 15.

Fig. 14: Fins welded to the part of heat pipes in the oil chamber

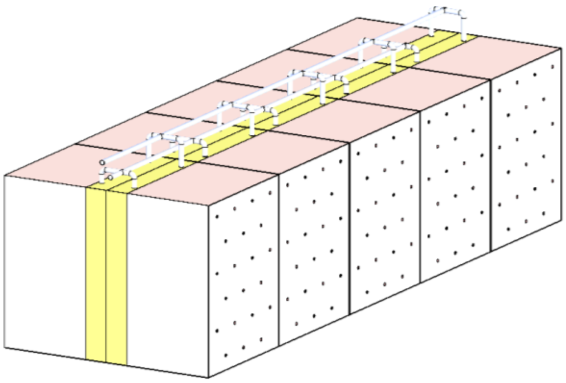


Fig. 15: The modular design of the LHTESS

The heat pipes, developed by Aavid Thermacore, are made of 70 Cu (Copper) & 30 Ni (Nickel) alloy with the working fluid being water. The operational pressure is about 70 bar at the temperature of 285 °C, see Fig. 16

Fig. 16: Reversible (bi-directional) heat pipe.

The experimental tests of heat pipes revealed that these can transfer a maximum power of 120 W each and the temperature difference across the pipe' length does not exceed 10.4 °C at the heating temperature of 290 °C, see Fig. 17.

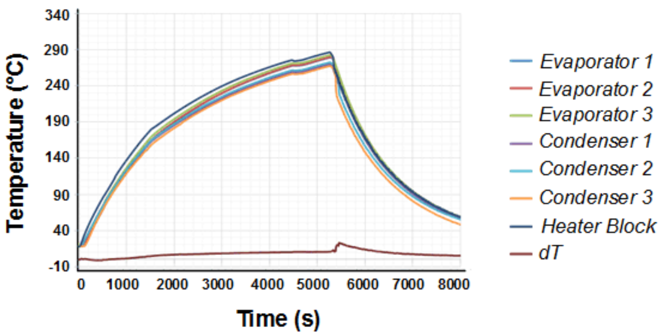


Fig. 17: Tests of horizontally mounted heat pipes

The Central Control System

The Control system was designed by STRATEGIE S.R.L. to monitor the overall system and to control and supervise interaction between plant's individual components. The Control system carries out pre-operational checks, start-up, operation monitoring, scheduling, controlled or emergency shut-downs, solar tracking, monitoring of charging and discharging processes in the thermal storage and on- and off-grid modes of operation of the power plant. The control system uses specially developed built-in software. The control algorithms have been created to fully satisfy the domestic hot water and space heating demand and to achieve the highest possible energy and carbon savings. This goal is to prioritize the operation of ORC unit at high solar irradiation and the recharging process of the thermal storage. Another goal is the use of thermal storage for running the ORC unit at periods, when solar irradiation is not sufficient to run the plant. The developed central control system does not provide detailed control over single subsystems, but collects information on their status through a fieldbus connection. The control unit uses the collected information to achieve an efficient management and better integration of all subsystems. Smart integration with a domestic boiler has been implemented in order to provide the domestic user with hot water even when there is no sufficient solar energy, optimizing the energy consumption. Furthermore, the smart control interface has been developed to ensure full compatibility with the state-of-the-art home/building automation control solutions.

Control procedures are organized in two separate and parallel layers. The lower layer is responsible for system safety: if the system is not in a safe state to operate, the control will not generate the enabling signal for different subsystems, blocks control procedures and deactivates supervision policies. As the system returns into the safe state, all functionalities will be enabled again. The upper layer is responsible for the system control. The whole system can work in eight different configurations, depending on the actual status of its sub-systems. Each of such configurations is identified with a specific phase identifier. Transitions between different phases are regulated by the corresponding control strategies. Process parameters (mass flows, temperatures and other variables) are also regulated in this applicative layer.

The heat rejected in the ORC turbine is used to produce domestic hot water and for heating purposes. Therefore, the ORC unit is integrated with the domestic boiler. The boiler provides additional heat, if the user requires higher thermal output than that produced by the ORC unit. In this case the boiler is switched on to reach the desired temperature level. If the amount of heat, produced by the ORC unit is sufficient, then the boiler remains switched off. The control system provides the user with the option to preconfigure timing of the hot water production and also hot water pre-heat, which allows the boiler to deliver hot water more quickly. When the heating is on, the optimizer function calculates the time needed for the boiler to start in order to reach the correct temperature at the programmed times.

The CSP field and ORC unit are equipped with their own internal alarm and warning systems, which display actual status of a set of parameters, and active alarms and warnings through Modbus fieldbus. Therefore, the central control system monitors the CSP field and ORC unit internal statuses and prevents situations, when the whole system does not operate properly. When the central control detects an alarm condition in the CSP or ORC unis, these are isolated from the other components of the plant. Additionally, an alarm will be generated for the operator via the management interface in order to facilitate the system safety maintenance.

Smart optimization logics were developed with the aim to improve the system performance and two different approaches, that may be applied at the same time in a synergistic way, were considered. The first approach consists of a fuzzy based controller, which acts on the higher level with respect to the temperature regulators, used in the system by changing the temperature setpoint in an adaptive manner. Basically, given a desired setpoint and following some linguistic rules, a fuzzy controller adds a positive or negative ΔSetpoint in order to increase the convergence speed. ΔSetpoint is changed in the adaptive way, i.e. it is larger in the magnitude if the actual temperature differs greatly from the setpoint value. This technique was developed for the case, in which it is assumed that the temperature and flow regulation is performed internally for the solar field and in which the central controller does not have direct access to the subsystem. In this case, the fuzzy approach is one of the few valid and robust methods for controlling and optimization.

For the case in which the flow and temperature regulations are performed by the central control unit, the global aspects have to be taken into account and this cannot be achieved by only using the subsystems control. Therefore, the optimization could be performed by acting directly on the parameters of these regulators.

However, the preference was given to maintain a hierarchical control architecture because of a top-down approach, where low level regulators are static and programmed only for the system setup, while the supervision layer is dynamically configurable and is responsible for global optimization.

Other alternative approaches are also possible, which ensure that the basic architecture of the fuzzy optimizer is unchanged. For example, when the enthalpy control is used rather than a temperature one, new functions for fuzzification and de-fuzzification should be developed and new rules should be identified, but the approach structure, as mentioned above, remains unchanged. Another approach is to improve the system regulators performance. This could be done in two different ways, namely by performing a gain scheduling policy or using a hybrid fuzzy-PI technique. Both techniques implement nonlinear adaptive control, for which it is not necessary to have detailed information on the system model.

Gain scheduling involves the definition of several working points and the tuning of proper gains in each of these working conditions while the benefit of the fuzzy-PI controller is that it does not use the specific operating point. The rules evaluate the difference between the measured value and the set value, which is the error signal. The rules also evaluate the trend in variation of the error signal to determine whether to increase or decrease the control variable input.

The control system software architecture was developed, following the SMoRES standard (Scalable, Modular, Reusable, Extensible and Simple). Several independent modules were developed and tested using the queued state machine design pattern. The interaction between modules was realized with an exchange of messages and this approach allows an easy integration of additional features without changing the basic ones, which were already tested. In the experimental plant such features are essential because not all technical specifications are defined at the project stage and during the development and setup phase re-definition of some management policies might be required.

Software modules have different roles and run independently, adding specific functionalities to the complete system. Modules communicate with each other using messages, exchanged through software queues, and share data using dedicated structures designed to avoid the data corruption.

The following software modules have been designed:

- Enogia System (ORC) Interface module: this module is responsible for communication with the Enogia system, which reads sensor signals and actuator status and active alarm codes or set actuator status.
- Elianto System (CSP) Interface module: the module is responsible for communication with the Elianto system, which reads sensor signals and actuator status and active alarms codes or set actuator status.
- WAGO System management module: this is responsible for communication with WAGO distributed I/O system.
- Safety Management module: this manages safety of the whole system and ensures that all systems are in the correct operating conditions prior to start up.
- Automatic Management:
  - Control - this module implements all the system control logics such as regulations and phase switching.
  - Optimization - this module implements the optimization policies when the system is in a consonant working condition.
- Datalog - this module implements configurable datalog. The user can configure this by specifying which system variables should be logged and the acquisition rate.
- User Management: this module implements user management such as login and logout features and roles and permission management.

- Alarms Management: this module implements a central alarm management detecting error signals from the several subsystems and implementing the proper safety procedures.

Manual interface has been developed as a separate upper layer because it requires input from the operator and it is optional, while other modules are needed for the correct management of the system. Fig. 18 shows the draft version of the operator manual interface.

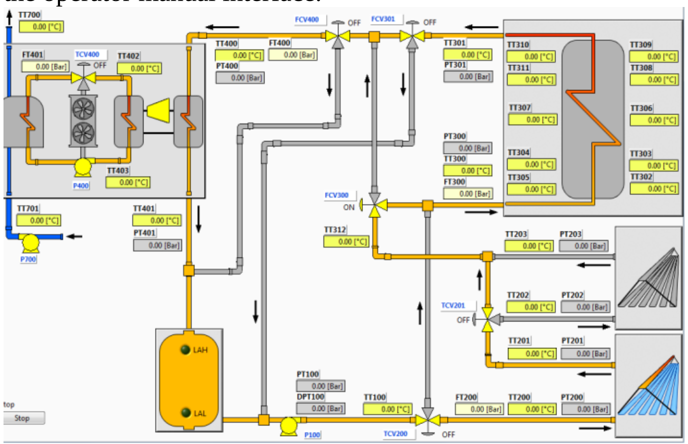


Fig. 18: The operator manual interface

All system sensor measurements are presented in real time and it is also possible to manually activate pumps and proportional valves. Pipes are coloured depending on the measured temperature in order to give to the user an immediate information on the system status.

The control cabinet's electrical design was produced for the control system as a priority for the realization of the scalable and robust system. The control system central unit is an embedded fan-less industrial PC with the role to monitor each subsystem and carry out the central management of the whole system. The hardware architecture of the control system is presented in Fig. 19. Here the embedded PC is connected through the main switch to the external component (the ORC and CSP units) using Modbus TCP-IP open standard protocol. The WAGO unit is placed inside the control cabinet and connected to the field bus to provide the management of digital and analogue inputs/outputs. In the first version of the cabinet just one digital input/output module with eight isolated inputs and eight isolated outputs was installed in accordance with the specifications received from other project partners, but an extension of its capacity can be easily carried out.

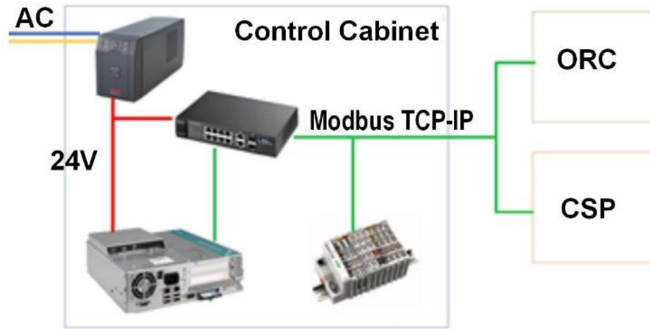


Fig. 19: Control cabinet's block scheme

The cabinet's dimensions are 600 mm in length, 1000 mm in width and 250 mm in depth, see Fig. 20. The choice of these dimensions and geometry selection was made with the purpose to accommodate all electrical components, allowing sufficient ventilation and leaving 25% of the internal space available for further modification, as required.

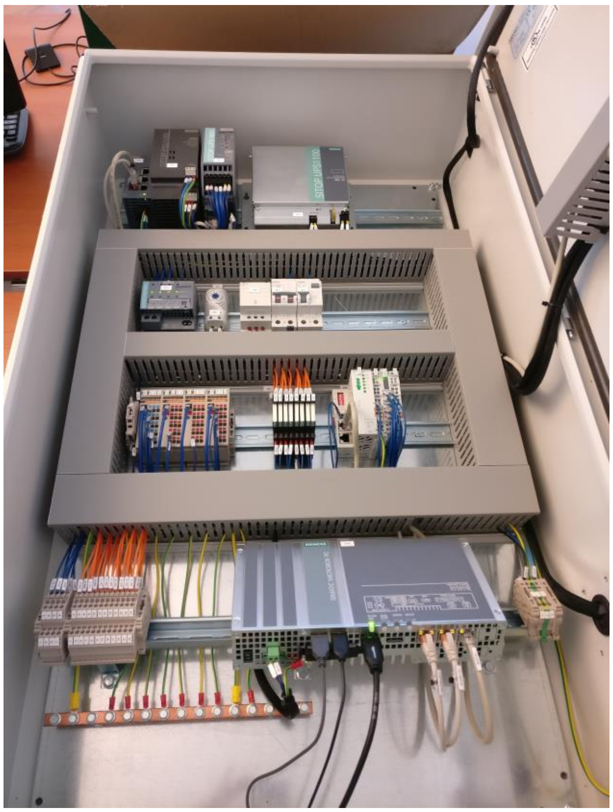


Fig. 20: Electrical Cabinet

The forced ventilation system is installed in order to allow the sufficient air circulation for cooling of installed electronic components and to maintain the optimal operating temperature. Components are arranged internally in such a way that the equipment, that generates heat most intensively, is located at the top of the cabinet to avoid an early deterioration of the most sensitive electronic components such as the PC and WAGO central unit.

An UPS was used to prevent voltage drops that could cause the sudden shutdown, resulting in the PC damage. In case of the power failure, the control system will perform all procedures to bring the system into the safe status.

The connection between the PC/tablet and control system is performed through a standard WIFI connection. Both open standard (RESTful Web Service) and proprietary standard were taken into account for the information exchange between PC/tablet and the central control system. The choice between the two techniques has to be made after the setup phase; one of the strengths of the open solution is a possibility of greater flexibility in future, allowing some instruments to be replaced with lower cost substitutes.

CONCLUSIONS

The design of components of the small solar heat and power plant had been completed. The main subsystems of the plant were manufactured with some of them passing preliminary laboratory tests for estimation of their individual performance.

Laboratory scale measurements confirmed the high optical performance of Fresnel reflector segments.

The 2-kWel ORC unit was developed and preliminarily tested using heating oil with the temperature of 140 ºC. Currently, preparations are underway for further tests of the ORC turbine with the temperature of heating oil close to 200 ºC.

The tests of the horizontally mounted heat pipes were completed which demonstrated their capacity to transfer heat in both directions.

Solar salt was selected as the PCM for LHTES system and its thermo-physical properties were measured to obtain data for LHTES system designing. The configuration of the single LHTES module was numerically simulated in order to rationalize its design. A smaller version of the single module of the LHTES system is being built to experimentally evaluate its dynamic characteristics such as the thermal energy charging and discharging rates.

Hardware and software of the central control system's functionality was tested in laboratory conditions using Matlab Simulink for imitation of all system components and various operational scenarios.

Currently, the plant is being assembled in the Catalan Region of Spain. At the first stage of demonstrations the simplified version of the plant, in which the solar field is directly connected to the ORC turbine, will be tested. Later on it is planned to extend the plant's configuration by including the thermal storage and its integration into electrical grid and hot water & heating system of a small hostel.

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REFERENCES

[1] K. Mahkamov. Chapter 18: Thermal-engine-based small and micro combined and power (CHP) systems for domestic applications: modelling micro-CHP deployment. (pp 459-513) in the book by R. Beith (Editor), "Small and Micro combined heat and power (CHP systems: Advanced design, performance, materials and applications", ISBN 978-1-84569-795-2, Woodhead Publishing Limited, 2011, 528 p.

[2] Manuel Blanco Lourdes Ramirez Santigosa (Editors). Advances in Concentrating Solar Thermal Research and Technology (1st Edition). ISBN:9780081005163, Woodhead Publishing, 2017, 494 pages.

[3] https://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=8315 (Assessed on 17 December 2017).

[4] Rogdakis, E. and Lolos, P. Kalina Cycles for Power Generation (DOI: 10.1002/9781118991978.hces014). Pages 1–25. In: Handbook of Clean Energy Systems. John Wiley & Sons, 2015.

[5] http://www.digespo.eu (Assessed on 17 December 2017)

[6] W. Zhai, B. Yang, M. Li, S. Li, M. Xin, J. Lin, L. Wang. Preparation of Multi nitrate molten salt and its properties tests. In Proceedings of International Symposium on Materials, Energy and Environment Engineering (ISM3E 2015). Changsha, China on November 28-29, 2015.

[7] C.E. Fawsitt. CXXIV.—Viscosity determinations at high temperatures. J Chem Soc, Trans, vol. 93, pp. 1299-1307, 1908.

[8] Y. Jin, J. Cheng, X. An, T. Su, P. Zhang, Z. Li. Accurate viscosity measurement of nitrates/nitrites salts for concentrated solar power. Sol Energy, vol. 137, pp.385-392, 2016.

[9] J. Chen, D. Yang, J. Jiang, A. Ma, and D. Song. Research Progress of Phase Change Materials (PCMs) Embedded with Metal Foam (a Review). Procedia Mater Sci, vol. 4, pp. 389-394, 2014.