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SOLAR HEAT FOR INDUSTRIAL PROCESSES (SHIP): MODELING AND OPTIMIZATION OF A PARABOLIC TROUGH PLANT WITH THERMOCLINE THERMAL STORAGE SYSTEM TO SUPPLY MEDIUM TEMPERATURE PROCESS HEAT

María V. Guisado[1], Fritz Zaversky[1], Irene Santana[1] and Ana Bernardos[1]

[1] National Renewable Energy Centre (CENER), Navarra (Spain)

Abstract

This paper presents the development of a simulation tool for a Solar Heat for Industrial Processes (SHIP) plants, based on Parabolic Though technology and equipped with direct thermocline Thermal Storage System (TES). The model developed is a one–dimensional model, based on the Modelica language, which allows the transient performance evaluation of the plant.

Key-words: Solar heat, Industrial process heat, Transient simulation, Modelica, Thermocline.

1. Introduction

This work have been carried out within the project ANTHOPHILA, a project of the Call RETOS-COLABORACIÓN 2014 of the R&D National Program of Research, Development and Innovation, funded by the Ministry of Industry, Energy and Tourism and with Ingeteam and CENER as partners. The main objective of this project is the research and development of new technologies that allows the procurement of a new concept of a hybrid solar thermal for industrial heat application.

Globally, industrial process heat accounts for more than two-thirds of total energy consumption in industry, and half of this demand is low-to-medium temperatures (<400ºC) (Kempener et al., 2016). This means that there is a big potential market for the application of solar thermal energy. Currently there are already installed 188 plants worldwide (AEE-INTEC, 2016) providing solar heat to industrial processes.

Due to the diversity of industrial processes and solar heat supply options, more detailed and accurate models for each of the plant components as well as transient simulation of the plant as a whole are required, in order to achieve efficient configurations.

This paper is focused on the application of a well-structured and flexible model, able to satisfy the requirements of the different industrial heat process plants. The model applies Modelica (Elmqvist and Mattsson, 1997) as modeling language and Dymola (Dassault-Systèmes, 2012) as simulation environment. The model has been applied in a small scale thermal plant for the hybridization of solar thermal and conventional combustion process for SHIP plants. The solar thermal process includes as TES a thermocline single-tank option, proposed by various authors in order to reduce costs, and which is hardly analyzable using the conventional quasi-steady state models.

2. Modelica Description and in-house model library

Modelica is a multi-purpose physical system modeling language which models the dynamic behavior of technical systems and it has been developed in an international effort in order to unify already existing

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similar modeling approaches and to enable developed models and model libraries to be easily exchanged. The concept is based on non-causal models featuring true ordinary differential and algebraic equations, i.e. differential-algebraic equation (DAE) systems (Elmqvist and Mattsson, 1997).

The object-oriented approach, the possibility of multiple inheritance and the re-declaration feature lead to a clear model structure, avoid multiple definitions of frequently used code and offer an incredible model flexibility. The code syntax and application guidelines are defined in the regularly updated Modelica Language Specification (Modelica-Association, 2012). Furthermore, the use of Modelica clearly decouples the modeler from the equation system solving. Instead of developing a specific solving algorithm for each modeling task, the Modelica tool reads the developed Modelica code, performs symbolic manipulations of equations and translates the Modelica model into numerical simulation code, using state-of-the-art algorithms developed for general application. Thus, developed models and model libraries are exchangeable, i.e. can be read and simulated using different Modelica environments. Today, commercial, as well as open-source Modelica environments are available (Dassault-Systèmes, 2012; Open-Source-Modelica-Consortium, 2013).

Based on the Modelica Standard Library (MLS), the Solar Thermal Energy Department of the Spanish National Renewable Energy Centre (CENER) has developed an in-house model library for the simulation of Concentrating Solar Thermal Plants (CSTLibrary).

The library is based on a one-dimensional fluid flow modeling approach, implemented according to the finite volume method (FVM) (Franke et al., 2009). The library includes a variety of components of thermal solar systems such as, solar collectors with different geometry and thermal loss models, several thermal energy storage solutions, including indirect and direct storage systems with two tanks and thermocline single-tank options, as well as heat exchangers and other thermo-hydraulic components: pipes, pumps, valves, etc., needed for a whole plant simulation. The transient models allow a detailed analysis of the components. Besides, any operation strategy can be integrated.

The modeling approach and the validation of single component models have been previously published in several works, e.g. (Zaversky et al., 2013; Zaversky, 2014; Hernández Arriaga et al., 2015).

3. Industrial Process Description and Model Implementation

The great flexibility of the models allows analyzing a wide variety of industrial heat processes. Concretely, in this work, the model has been applied to an industrial process consisting of a drying unit for the agricultural sector, whose heat is provided by a solar thermal system with parabolic trough technology working at medium temperature (100-250 °C), and an auxiliary fossil fuel boiler. The solar thermal plant also incorporates a storage system, whose size has been optimized considering the number of loops, with the objective to cover as much as possible the heat required by the process.

In order to demonstrate the flexibility of the model and at the same time, to analyze the technical feasibility of the industrial process, two types of thermal storage have been tested, the conventional two-tank storage system and a thermocline storage tank, which can provide a costs reduction but is hardly analyzable using the conventional quasi-steady state models. In addition, two absorber tubes of the same dimensions but different degrees of vacuum have been also analyzed in this work.

Fig.1 shows a basic scheme of the plant, which can be divided into three main systems: solar field, storage system and steam generator. The plant includes an auxiliary gas boiler in order to cover the thermal demand of the industrial process when the solar energy is not available.

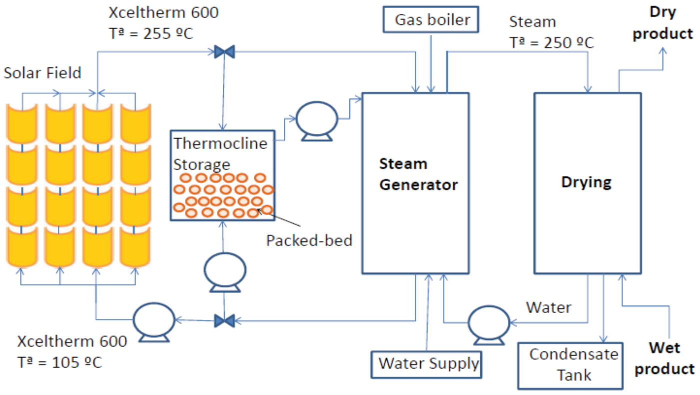

Fig. 1: Diagram of the reference plant with thermocline packed-bed storage

The following sub-sections show a brief description of the models used for each of the main systems mentioned above. They are described detailed in Zaversky (2014).

3.1. Solar Field

The solar field of a parabolic trough collector plant is composed of a number of solar collector loops of identical characteristics. A cold header pipe supplies the thermal fluid to the loops where the thermal fluid is heated by the solar energy and it drains into the hot header pipe. Each loop consists of solar collector assemblies (SCAs) connected in series and each solar collector assembly is composed of the basic solar collector components, as the parabolic mirrors and the solar absorber tubes, i.e. the heat collector elements (HCEs).

Fig. 2 shows a scheme of the solar field model used in this work. It consists of one representative solar collector loop, tow mass flow gains, and two additional dynamic pipe models that represent the cold and the hot header. Basically, the model is based on a 1-D approach according to Forristall (2003),and it discretizes the solar collector loop into a certain number of control volumes according the finite volume method. To correctly reproduce the dominant dynamics and the steady-state behavior, a certain minimum number of control volumes per loop are required.

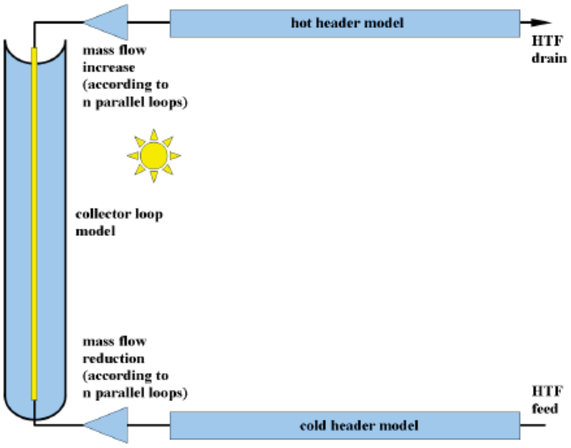

Fig. 2: The end-loop model of the parabolic trough collector field (Zaversky, 2014)

The total thermal power of the solar field is simply achieved via multiplying the mass flow of one loop by the number of total parallel loops.

The number of collectors per loop, and thus the final length of one loop, is defined by the plant´s operating conditions, such as the solar field´s nominal inlet and outlet temperature and the desired HTF mass flow rate for a given solar irradiance level.

Regarding the linear absorber of a parabolic trough collector, it is modeled as a straight steel pipe featuring a selective coating at the tube´s outer surface. It is discretized into a number of finite control volumes, and for each of them, the basic equations for mass and energy conservation are solved (see Fig. 3).

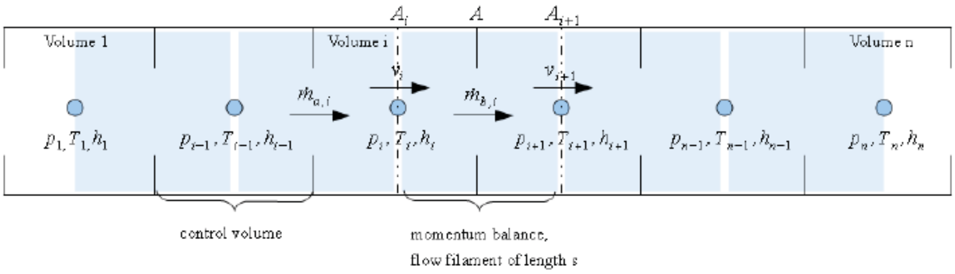

Fig. 3: Finite volume discretization scheme (Tummescheit, 2002)

In order to simplify the model, some assumptions are taken into account. Thus, the absorber tube as well as the glass envelope is assumed to have uniform circumferential temperatures and a uniform circumferential solar heat input. The glass envelope is considered opaque to infrared radiation (Forristall, 2003).

All solid material properties, thermal conductivity, density, and specific heat capacity are assumed to be constant and homogeneous. The heat conduction in longitudinal direction within the absorber tube and the glass envelope is neglected.

Finally, regarding the solar field sub-model, the thermal oil used is not yet available in open Modelica libraries, so these features have been newly implemented. It is modeled as incompressible fluid according to Radco-Industries-Inc. (2014).

Within the MSL, all specific media property functions are decoupled from the library components by defining a replaceable "medium package" in each of them. Basically, all fluid property function names and interfaces are defined within the base class "partial medium". In order to allow a full replaceability, each specific medium model extends from this base class the "partial medium" and defines the specific media related relationships by re-declaring each necessary medium property function. Thus, every single component of the library can easily be adapted for the use of different fluids, by simply replacing the default medium package when instantiating the final model.

3.2. Thermal Storage System

Regarding the thermal storage system, as it has been indicated previously, two types of systems have been analyzed, a conventional two-tank storage system and a single-tank thermocline with filler material. In both cases, the storage is a direct system in which the heat transfer fluid, thermal oil, is used as thermal storage fluid too.

Following sub-sections show a brief description of the main characteristics of each thermal storage system model.

3.2.1 Direct two-tank storage system

The active direct two-tank thermal energy storage system is composed of two tanks, physically separated such that the cold fluid is stored in one of them and the hot fluid in the other one. During charging, the thermal oil leaves the cold tank and it absorbs the energy provided by the solar field increasing its temperature and then it is stored in the hot tank. During discharging, the thermal oil from the hot tank provides heat to the steam generator when the energy from the solar field is not enough and the cold thermal oil is returned to the cold tank.

The basic components of a typical active direct two-tank system are the storage tanks (the hot tank and the cold tank).

The storage tank model is based on the assumption of having one representative thermal oil temperature. Hence, the thermal oil within the tank is modeled as a single control volume, defining an ideally mixed energy balance.

3.2.2 Direct thermocline storage system

Unlike the conventional two-tank storage system, in which the hot and cold fluid are stored in two different tanks, the thermocline storage system uses a single tank of slightly large dimensions in which the hot oil remains in the top of the tank and the cold fluid remains in the bottom, due to the thermocline effect.

The strongest temperature variation between these stratified layers occurs in a limited zone within the total thermal oil level height. For this reason, it is possible to provide almost constant thermal oil outlet temperatures, during a reasonable part of the discharging process. And vice versa, the cold thermal oil outlet temperature is almost constant during charging mode. About 69% of the total maximum thermal oil level height can be used for the actual storage capacity. Hence, about 31% of the thermal oil level height is required by the temperature gradient.

Furthermore, a packed bed is used in the thermocline tank as filler to increase the thermal capacity. The filler material avoids the convective mix and reduces the amount of fluid required for the storage system. The filler must have a high specific heat capacity, a minimal interstitial space, must be compatible with the storage fluid, and one should avoid toxic or hazardous materials.

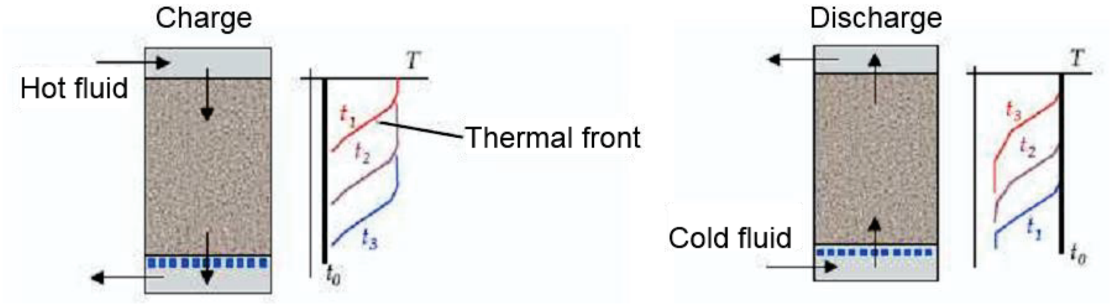

Fig. 4: Operation of a thermocline storage system with bed packed

The thermocline storage space can be divided into three zones. Starting from the bottom, the first zone is a rather constant low temperature zone (i) ranging from the bottom area of the tank up to the beginning of the pronounced temperature gradient zone. This temperature gradient zone (ii) is characterized by significant temperature changes of the storage fluid and the filler material. Finally, the temperature gradient zone is followed by the rather constant high temperature zone (iii) at the top of the tank (Yang and Garimella, 2010).

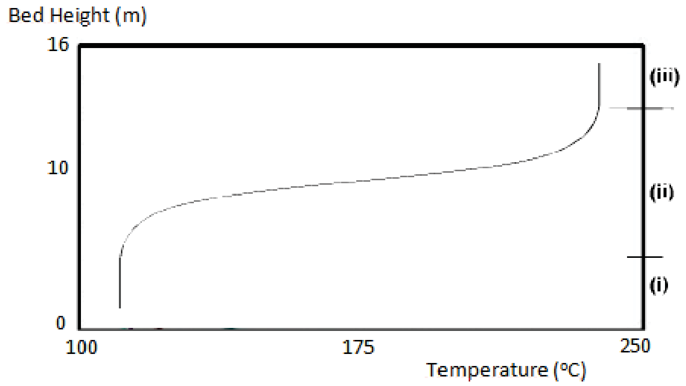

Fig. 5: Thermocline zones (i, ii, iii)

While discharging and charging, the temperature gradient zone moves towards the exit piping, leaving behind an expanding constant low temperature zone (discharging), or high temperature zone (charging), respectively.

In the constant temperature zones, the filler material is completely cooled or heated, providing a thermodynamic equilibrium between the thermal oil and the filler material. In the temperature gradient zone, the thermal energy is either transferred to the filler material (charging), or, in the case of discharging, to the thermal oil.

The thermocline problem can be described by the following set of coupled partial differential equations (PDEs), based on the pioneering work of Schumann (1929).This set of PDEs has to be discretized in order to obtain a set of ordinary differential equations (ODEs) suitable for the model formulation in Modelica. This has been done according to the finite volume method (FVM). In particular, the developed model is based on well-proven and freely available model structures and base classes, as provided by the Modelica Standard Library (MSL) (Modelica-Association, 2010). For a detailed model description, the interested reader is referred to Hernández Arriaga et al. (2015).

$$M_f c_f \frac{\partial T_f}{\partial t} + M_f c_f v \frac{\partial T_f}{\partial x} = h_{fs} P_{fs}\left(T_s - T_f\right) + k_{fe} A_c \frac{\partial^2 T_f}{\partial x^2} - U\, P_w\left(T_f - T_a\right) \qquad \text{(eq. 1)}$$

$$M_s c_s \frac{\partial T_s}{\partial t} = h_{fs} P_{fs}\left(T_f - T_s\right) + \; k_{se} A_c \frac{\partial^2 T_s}{\partial x^2} \qquad \text{(eq. 2)}$$

where

$$M_f = \epsilon\, A_c \rho_f \qquad \text{(eq. 3)}$$

$$M_s = (1 - \epsilon) A_c \rho_s \qquad \text{(eq.4)}$$

$$v = \frac{\dot{m}_f}{\rho_f\, \epsilon\, A_c} \qquad \text{(eq.5)}$$

3.3. Steam generator

The steam generator is modeled in quasi-steady manner, applying steady-state heat exchanger models implemented according to the logarithmic mean temperature difference method (Shah and Sekulic, 2003). The water medium model is implemented according to Wagner and Kruse (1998).

3.4. The transport system model, the control model and operation strategies

All sub-models for different systems of the plant are connected by the transport system model. The transport system model has the task to correctly distribute the mass and energy flows between the solar thermal plant's components. Further-more, the pumping power for the HTF circuit has to be estimated.

Basically, the transport system model consists of a steady-state pump model, an expansion vessel model, instances of a T-junction model and the corresponding connecting equations between the power plant components.

Next, the control of the plant model will be roughly outlined. Transient Modelica models of thermal processes where certain process variables need to be controlled, typically feature continuous feedback proportional-integral (PI) control. The solar field model´s mass flow control additionally features a feedforward term that uses a simple steady-state model of one representative loop, in order to predict a reasonable mass flow signal depending on the current direct normal irradiance.

Furthermore, besides the control loops for the nominal solar field outlet temperature, a defocusing control loop is implemented as well, in order to avoid overheating of the heat transfer fluid. In this work, this defocusing control is implemented using a simple PI feedback structure. Thus, whenever the HTF temperature exceeds a maximum value of 260^{o}C, the loop is defocused in the model. Not that the set point for the solar field outlet temperature is 255ºC.

In a solar thermal system with thermal energy storage, the current solar field mass flow rate does not automatically define the thermal load of the steam generator, since a fraction of the solar field mass flow can either be used for storage system charging, or, in storage system discharging mode, a certain mass flow top-up can be supplied to the power block by the thermal energy storage system. Thus, for a solar thermal plant with storage, the desired thermal load of the steam generator is controlled via charging or discharging of the thermal energy storage system, of course, if the current state-of-charge of the storage system allows the desired operation. The solar field will be defocused if the storage system is full and the solar field provides more power than the steam generator is able to handle.

The top-level control block implements the operating strategy of the plant model, i.e. it acts as a virtual operator of the plant that defines allowed minimum and maximum mass flow rates, the solar field recirculation mass flow, the thermal load set point of the steam generator as well as the thermal energy storage system´s operation.

An important point of the operation strategy control block is that it features discrete time variables that change their values at certain events during simulation, so, any arbitrary operating strategy can be implemented that defines certain variable set points according to specific operating directives.

4. Results and Conclusions

4.1. Plant Description – Technical parameters

The solar field of parabolic trough collectors consists of loops of 300 m. Each loop is composed of 74 collectors of 4 m length each of them. The thermal oil used as heat transfer fluid and thermal storage fluid is XCeltherm 600, which is an adequate fluid for the working temperatures. The absorber tubes are tubes of 2 meters length and have an inner diameter of 37 mm. The number of loops of the plant is a parameter which is going to be optimized.

In the case of the thermocline single-tank, the storage system includes a filler material in order to improve the thermal efficiency. After analysis of several materials, Cofalit has been selected for this study. It is a post-industrial commercial ceramic obtained from industrial processing of asbestos and waste. It shows good properties for the storage of thermal energy in the form of sensible heat up to 1100 °C. It has a specific heat of 0.860 kJ / kg K and its cost is very low.

The storage size, analyzed in a range of 1-8 hours, has been technically optimized during the design process in order to cover the thermal demand of the drying process as long as possible. An initial objective is that at least in the months of June, July and August, the auxiliary boiler should not be necessary.

The auxiliary boiler with fossil fuel is used to provide heat to the drying process when the thermal power provided by the solar field and/or storage system is not enough to cover the thermal demand.

The operation strategy consists of an annual demand of 3170 MWh distributed hourly such as is shown in Table 1 knowing that 100% of the demand is 1.5 MWt. It has been stablished as an initial target that at least in the months of June, July and August it is not necessary to start-up the boiler.

Tab. 1:Hourly demand

Month / Day	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Jan	0,58	0,61	0,63	0,66	0,68	0,69	0,79	0,81	0,81	0,60	0,45	0,31	0,22	0,18	0,15	0,13	0,11	0,13	0,22	0,30	0,38	0,46	0,51	0,54
Feb	0,57	0,60	0,62	0,64	0,66	0,66	0,76	0,77	0,75	0,53	0,39	0,29	0,25	0,21	0,18	0,16	0,15	0,16	0,19	0,27	0,35	0,43	0,50	0,53
Mar	0,48	0,53	0,57	0,60	0,61	0,63	0,76	0,78	0,67	0,38	0,22	0,12	0,06	0,02	0,00	0,00	0,00	0,00	0,02	0,12	0,20	0,30	0,40	0,45
Apr	0,19	0,24	0,29	0,32	0,34	0,37	0,48	0,50	0,47	0,23	0,07	0,02	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,03	0,09	0,13
May	0,07	0,12	0,17	0,21	0,25	0,28	0,40	0,42	0,39	0,10	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,03
Jun	0,02	0,07	0,10	0,13	0,16	0,18	0,29	0,31	0,26	0,03	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Jul	0,04	0,07	0,10	0,12	0,14	0,16	0,27	0,28	0,25	0,04	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01
Aug	0,07	0,12	0,17	0,21	0,23	0,25	0,36	0,37	0,36	0,10	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01
Sep	0,09	0,13	0,16	0,18	0,21	0,23	0,33	0,35	0,35	0,14	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,06
Oct	0,37	0,42	0,47	0,51	0,54	0,58	0,69	0,71	0,71	0,45	0,16	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,03	0,14	0,24	0,31
Nov	0,56	0,60	0,63	0,67	0,70	0,72	0,83	0,85	0,75	0,41	0,19	0,05	0,00	0,00	0,00	0,00	0,00	0,00	0,06	0,17	0,30	0,39	0,46	0,52
Dec	0,69	0,73	0,78	0,83	0,85	0,88	0,98	1,00	0,94	0,62	0,37	0,16	0,05	0,02	0,00	0,00	0,00	0,00	0,13	0,23	0,37	0,50	0,57	0,62

The model has been run over a year at Valladolid in Spain (Latitude 41.65^{o}) with a specific weather input file.

4.2. Results

The detailed transient analysis carried out by this software allows extracting and analyzing a large number of variables for the different systems and connections of the plant. The output variables such as power, energy, temperature, enthalpy, pressure, mass flow or charge states of the storage systems can be obtained for any instant of simulated period.

Results from these detailed simulations allow an accurate evaluation of the annual performance of the different alternatives, thereby providing a powerful and reliable tool for heat process plant designers.

Fig. 6 shows some of these variables for a clear day.

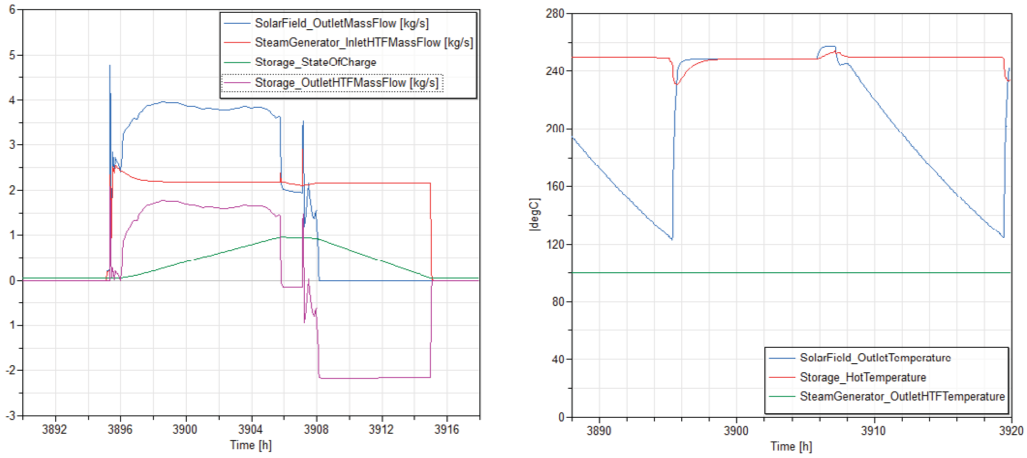

Fig. 6: Some variables provided by the software

During the optimization process, solar fields of 3-6 loops (1-1.5 MWt) and storage sizes of 1-8 hours have been analyzed, establishing as main aim to cover the demand of June, July and August. From this process, it can be concluded that, in order to cover that demand and due to that most of energy is required during the night, it is more profitable an increase of the storage size than an increase of the number of loops. So, among the options studied, a solar field with 3 - 4 loops and 8 hours of storage has been chosen as a technically optimal option. An increase in the number of loops would increase the defocusing and thus, would decrease the net plant performance but, it wouldn´t improve the coverage of the heat demand.

So, from the previous optimization process, several options have been analyzed including the different types of absorber tubes (Tube A and Tube B, which has a lower vacuum degree) and storage systems previously described.

The following tables show the main results for the options analyzed, from which can be observed that with a solar field of 4 loops, despite the annual energy generation decreases around 10-12% using the Tube B and a thermocline TES system, the power demand of June, July and August can be achieved.

So, in a next optimization stage, not included in the scope of this work, a detailed cost analysis for all components must be included in order to perform the techno-economic optimization of the complete plant and to confirm the potential feasibility of this TES system and the each type of tube for an industrial heat process.

Tab. 2:Results

	Two Tanks				Thermocline			
	Tube A	Tube B	Tube A	Tube B	Tube A	Tube B	Tube A	Tube B
Number of loops	3	3	4	4	3	3	4	4
Storage (h)	8	8	8	8	8	8	8	8
Energy Generation (MWh)	941	895	1072	1039	772	730	966	910
Annual Demand Coverage (%)	29.7	28.2	33.8	32.8	24.4	23.1	30.5	28.7
June, July and August Coverage (%)	100	96	100	100	89	87	98	98

Subsequently, in order to show the detailed analysis that the software can provide for each one of the systems, several figures of the storage systems and the absorber tube behavior are included.

Fig. 7 shows the behavior of the thermocline storage system for two different days. For one of them, the storage is partially filled and for the other one, it can be completely filled. To carry out the simulations, the thermocline tank has been divided on 40 nodes and the full storage graph shows that, as described in the thermocline sub-model, about 69% (28 nodes) of the total maximum thermal oil level height is in the hot zone and can be used for the actual storage capacity.

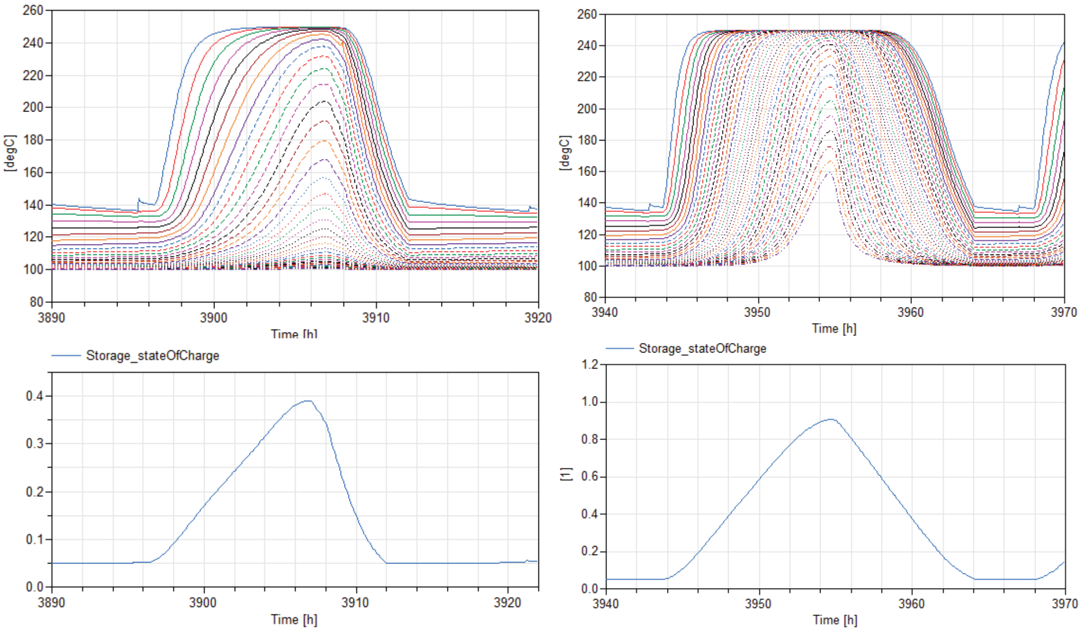

Fig. 7: Thermocline behavior

Finally, Fig. 8 shows the behavior of each type of absorber tube analyzed. It can be seen that the absorber tube B, which has higher thermal losses due to the lower vacuum degree, needs more time to achieve the output temperature (250ºC). Furthermore, nocturnal losses are bigger in this tube.

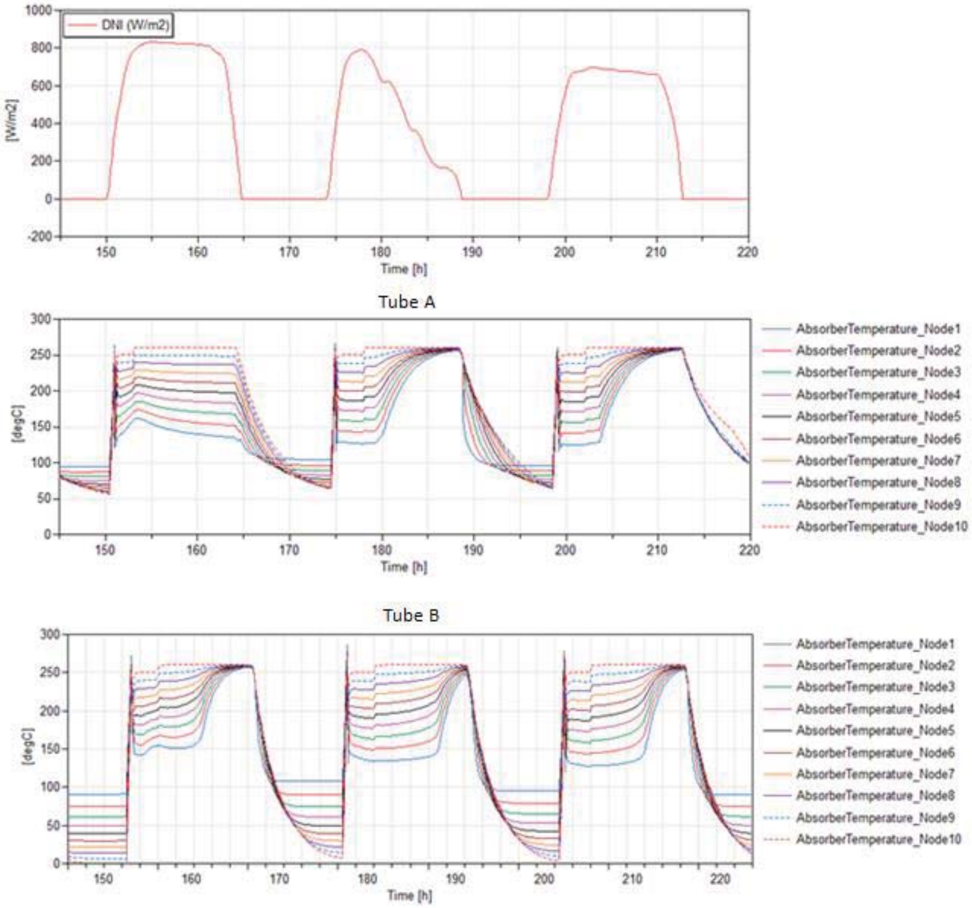

Fig. 8: Absorber tubes behavior

4.3. Conclusions

This work presents a well-structured and flexible model of a solar powered industrial process heat plant. In particular, the model has been applied on a small-scale hybridized SHIP plant, providing thermal power to a drying unit for the agricultural sector. The model applies Modelica as modeling language and Dymola as simulation environment. CENER's in-house model library (CSTLibrary) has been applied to model the system.

The transient analysis allows the evaluation of systems such as a thermocline single-tank storage, which has been proposed by various authors in order to reduce costs, and which is hardly analyzable using the conventional quasi-steady state models for process simulation.

Two types of thermal energy storage, the conventional two-tank concept, and the innovative single-tank thermocline option have been evaluated. Additionally, two types of solar collectors with different levels of vacuum have been analyzed.

The results of the simulations carried out show that with a solar field of 4 loops, despite the annual energy generation decreases around 10-12% using the Tube B and a thermocline TES system, the power demand of June, July and August can be achieved.

Future work will have to continue the optimization process also including costs to perform a techno-economic optimization.

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