MODELLING OF A SOLAR HEAT FOR INDUSTRIAL PROCESS (SHIP) SYSTEM USING FRESNEL COLLECTORS

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Abstract: *The Solar Heat for Industrial Process (SHIP) systems has been pushed forward in recent years as an option to achieve the goal of decarbonizing the industrial sector. In this way, it is possible to partially cover the heat necessities from the industry with these systems and then save fuel consumption. Fresnel solar energy concentrators have proved to be a state-of-the-art technology to be implemented for heat generation in SHIP systems. In this work, a quasi-dynamic model for the simulation of operation and performance of a SHIP system with Fresnel collectors solar field and the dynamics and inertia of a kettle reboiler has been developed. The preliminary validation of the model has been performed using experimental data obtained from the SOLPINVAP experimental plant in Almazora, Spain.*

Keywords: Solar Heat for Industrial Processes (SHIP), Fresnel solar collector; quasi-dynamic modelling; Renewable Energy Integration

1. INTRODUCTION

Solar Heat for Industrial Process (SHIP) is based on the integration of proven solar technology, which can be concentrating or not concentrating, to harness the incident irradiation from the sun and deliver it in the form of heat to an industrial process. The useful heat is transmitted by the means of a heat transfer fluid, which usually is thermal oil, water, or steam. In SHIP systems it is of great interest to predict the behaviour of the system under different demand, control conditions, and integration with the heat demand [1]. A quasi-dynamic model that simulates a SHIP system, with a modular Fresnel collector field and a modified kettle reboiler, able to simulate its dynamics, has been developed under the SOLPINVAP project [2]. In this work, the presented model has been first validated with measurements carried out in the SOLPINVAP experimental facility, located in Almazora, Spain.

2. METHODOLOGY

2.1. System model

The model has been built using the object-oriented programming environment of MatLab. Each object represents the physical components of the system. The objects form a set of differential-algebraic equations (DAE), solved with MatLab's built-in libraries for DAE systems. All the objects interact in-between, i.e. the outputs from one object are the inputs for the next.

The full model comprises a shell and tubes heat exchanger named kettle reboiler, a row of Fresnel solar collector modules, a circulation pump, a steam extraction valve, and pipelines.

2.2. Kettle reboiler model

The kettle reboiler that has been installed at the experimental platform has been modified to be able to function in two modes: Indirect Steam Generation (ISG) and Direct Steam Generation (DSG). Models where the 2- phase fluid is considered two separated fluids can be found in the literature. Though more complex, those models allow the state and properties of each phase to be known at any given time step. However, those models are useful when the steam and liquid water have different temperatures [3], [4]. Whereas in SHIP systems that is rarely the case. In this work, a simplified tank model has been developed, where the 2-phase fluid inside the kettle reboiler is considered to be in thermodynamic equilibrium at each time step. The state of the 2-phase fluid can be known by its specific internal energy u and density ρ. Equations (1) and (2) define the thermodynamic state of the kettle reboiler at each time step.

$$\frac{d\rho}{dt} = \frac{\sum \dot{m}_{in} - \sum \dot{m}_{out}}{V_{total}} \quad (1)$$

$$\frac{du}{dt} = \frac{\sum \dot{Q}_{in/out} + \sum(\dot{m}_{in} \cdot h_{in}) - \sum(\dot{m}_{out} \cdot h_{out}) - u(\sum \dot{m}_{in} - \sum \dot{m}_{out})}{\rho V_{total}} \quad (2)$$

Where $\dot{m}_{in}$ and $\dot{m}_{out}$ are the inlet and outlet mass flow rates, respectively, of the kettle reboiler, and V_{total} is the total volume of the tank. $\dot{Q}_{in/out}$ is any other heat flow entering to/going out from the kettle reboiler, for example, an input heat from the tubes heat exchanger or/and a heat loss to the ambient.

2.3. Fresnel collector model

The Fresnel modules have been modelled using a simple Incidence Angle Modifier (IAM) based model. The transversal and longitudinal IAM have been calculated with the Ray Tracing software Tonatiuh [5]. Thus, the incident energy on the absorber tubes can be calculated with the longitudinal and transversal IAM [6].

3. EXPERIMENTAL FACILITY

The experimental platform, called SOLPINVAP, is located in Almazora, Spain (39,958, -0,074). The facility comprises a single row of 6 collector modules connected in series. Each module has 3 receiver tubes, for a total of 9 tubes. The Fresnel solar collector modules have been manufactured by Solatom [7]. Each module has a reflective aperture area of $26{,}4\ m^2$. The optical efficiency of the collector modules has been calculated in Tonatiuh, resulting in $65{,}1$ %. The kettle reboiler is located inside a skid structure at the southern side of the solar field. The solar field is north-south oriented, with a deviation of $32°$ northeast (being north $0°$ and south $180°$). In Figure 1a and 1b the experimental solar facility SOLPINVAP is shown.

a) b)

Figure 1. SOLPINVAP experimental facility. In a) the Fresnel collector modules solar field, and in b) the kettle reboiler inside the skid with the hydraulic system.

4. RESULTS AND DISCUSSION

The experimental data has been acquired during summer 2021. The experimental facility was set to work in indirect steam generation. This means, the kettle reboiler receives the heat absorbed from the solar field through the tubes heat exchanger. The measurements made on June 24, 2021, have been selected for the preliminary validation of the model. On June 24, the weather behaved as clear sky conditions, as shown in Figure 2. Figure 2 shows the global, direct normal, and diffuse irradiation measurements at Valencia Airport in Manises on June 24, 2021. Although the SOLPINVAP facility is 63 km away from Valencia Airport, it has been assumed that the weather does not significantly change around the same region. Thus, a clear sky irradiation model has been used to predict the direct normal irradiation (DNI) at each time step on the simulation. The fluid used as heat transfer fluid through the solar field is pressurized water.

The measurements made on June 24, 2021, are shown in Figure 3a and 3b. Where $T1$ and $T2$ are the inlet and outlet temperatures of the Fresnel modules solar field, respectively, and T_{tank} is the temperature inside the kettle reboiler. The steam extraction has been done through a steam valve controlled by a PID control scheme, and the mass flow is shown in Figure 3a as steam mass flow. The water level inside the tank is shown as well in Figure 3a. As observed in Figure 3a, on June 24, 2021, there was only heat absorbed in the solar field, evaporation and steam extraction. The filling water pump was activated manually only for 5 minutes during the measurements, as observed in the kettle reboiler water level in Figure 3a.

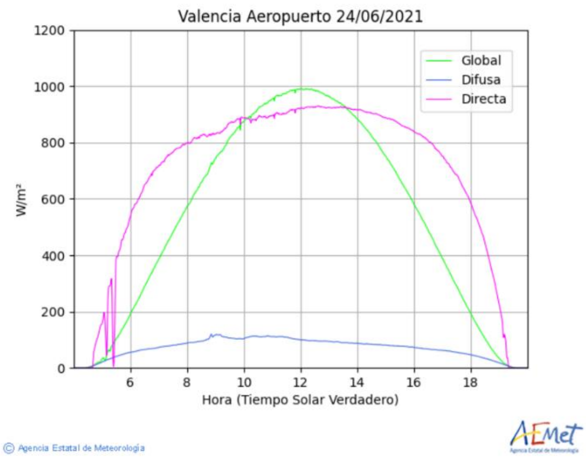
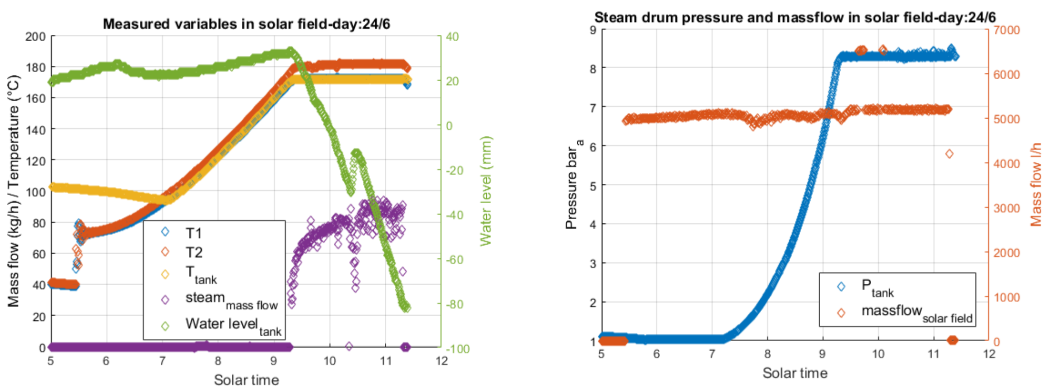


Figure 2. Global, direct and diffused irradiation measured at Valencia airport (taken from the Agencia Estatal de Meteorología – AEMET, Gobierno de España).



a) b)

Figure 3. Measurements made at the SOLPINVAP facility: a) shows Temperatures at the inlet and outlet of the solar field and the kettle reboiler temperature, the kettle reboiler water level and the steam outlet mass flow; in b) the kettle reboiler pressure and the solar field mass flow.

The model is intended to simulate the system under normal working conditions with different control schemes and heat demands. For the model's preliminary validation, in Figure 3a and 3b the period where the system is in steady-state conditions has been selected, which is between 9:30 and 11:30 solar time.

First of all, the Fresnel solar collector module model has been validated against the measurements made on June 24, 2021. The collector model has been adjusted through a clean factor, representing how clean the solar field mirrors are. The value of the clean factor has been taken as 0,59 for the analyzed period. Therefore, the inlet temperature and water mass flow of the solar field experimental data, and the clear-sky model, have been used as inputs for the Fresnel model to predict the outlet temperature. Figure 4 shows the predicted outlet temperature $T2_{sim}$, the measured outlet temperature $T2_{exp}$, and the measured inlet temperature $T1_{exp}$ from the Fresnel solar field.

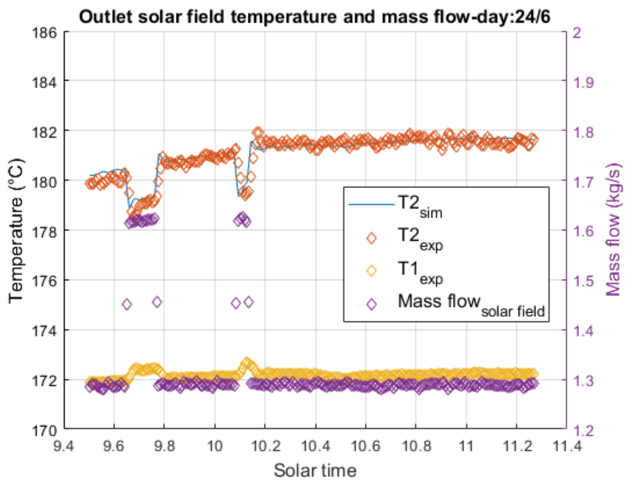


Figure 4. Resulting predicted outlet temperature and measured outlet temperature, the measured inlet temperature, and the solar filed water mass flow.

As observed from the measurements, an abrupt increment in the water mass flow decreases the temperature difference between the inlet and outlet temperatures. The model has been able to follow the change in the predicted outlet temperature. The mean root square error between the predicted and measured outlet temperature has been calculated to be 0.297 ℃. Figure 4 also shows no significant thermal inertia in the collector tubes.

A simulation implementing the full model has been carried out for the same steady-state period. Throughout the simulation, the filling water enters at 50 ℃. The simulated steam extraction has been carried out by a proportional control based on the kettle reboiler pressure. The results are shown in Figure 5a, 5b, and 5c. Figure 5a shows the inlet and outlet temperatures, both predicted by the model and measured in the facility. The model predicts the decrease in temperature difference between the inlet and outlet of the solar field with the sudden increment in water mass flow. However, due to the introduction of the filling water, there is a sudden drop in the kettle reboiler predicted pressure. The latter can be observed in Figure 5b, where the kettle reboiler pressure, both simulated by the model and the measured, and the calculated and measured water level are shown.

The sudden simulated pressure drop also affects the predicted inlet temperature and, in consequence, the outlet temperature of the solar field. In Figure 5c, the extracted steam mass flow, both simulated and measured, is displayed. In the simulation result and the measurements, the steam mass flow decreases when cold water is introduced into the kettle reboiler In Figure 5b, the difference between the measured and simulated tank pressure is because the model considers that, at every time step, the 2-phase fluid inside the kettle reboiler is in thermodynamic equilibrium; this means that the introduced cold water instantly mixes, whereas this is not true in reality. Thus, the model predict a decrease in pressure of 0,343 bar. The pressure sensor does not detect this effect because, in reality, stratification in the liquid phase is created when cold water is introduced into the kettle reboiler. Therefore, in reality the pressure drop may be smaller. Nevertheless, the pressure drop does not greatly affect the generated energy predicted by the model.

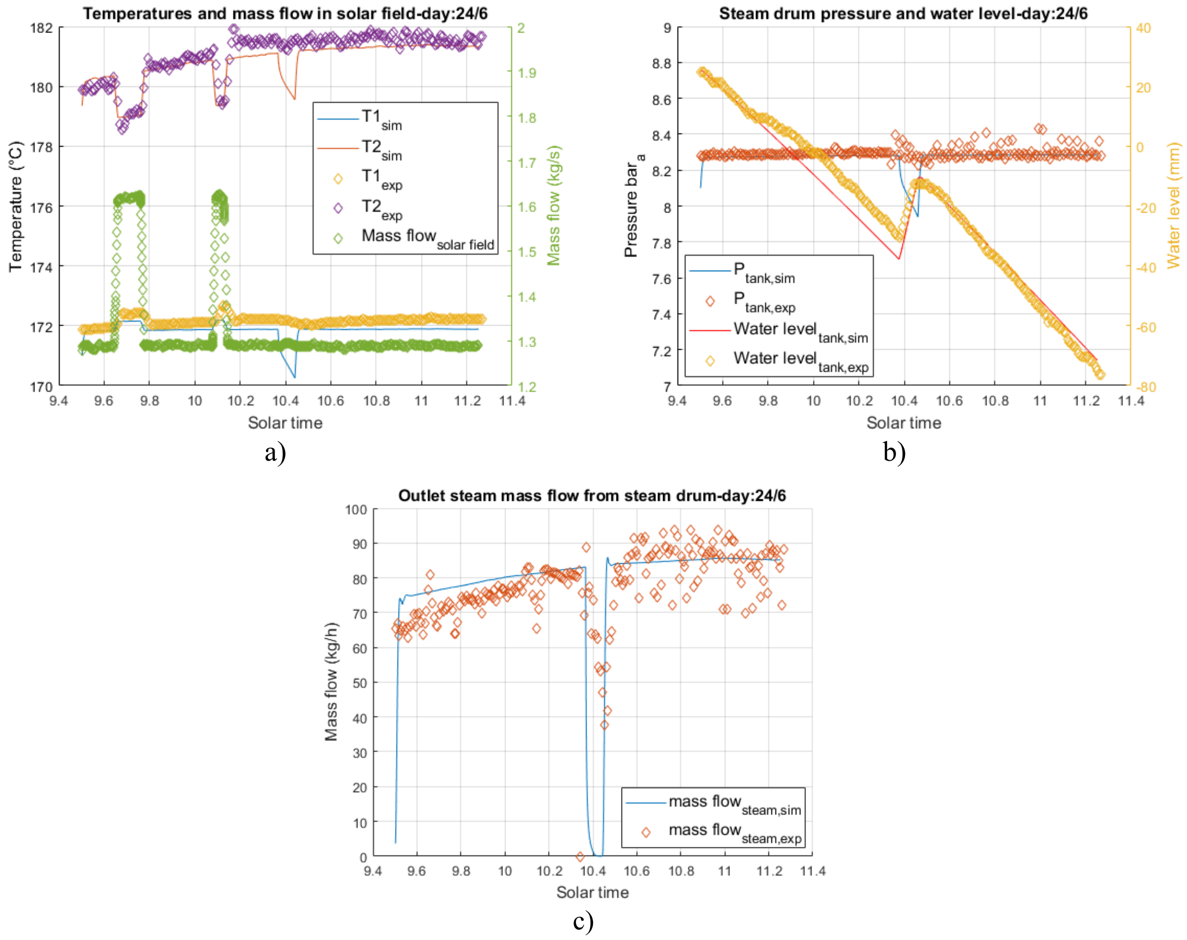


Figure 5. Simulation results in steady state. a) inlet and outlet temperatures, and water mass flow of the solar field; b) kettle reboiler pressure and water level; c) steam extraction mass flow.

5. CONCLUSIONS

The developed quasi-dynamic model that predicts the dynamic behavior of a SHIP system has been preliminarily validated with measurements carried out in the solar field located in the SOLPINVAP facility. During the steady-state working period, the model well predicts the inlet and outlet temperature of the Fresnel collector solar field. The model also follows the change in temperature difference when a sudden increase and decrease of water mass flow occurs. The simulated pressure has the same behavior during the analyzed period, except when cold water is introduced into the kettle reboiler. This difference is due to the stratified liquid phase after the tank has been filled. Moreover, the pressure drop may be smaller in reality. However, the measurements of extracted steam mass flow decrease when the tank is filled as well as the simulated extracted steam mass flow. Thus, there was a decrease in pressure which was not reflected in the measurements carried out by the pressure sensor. Nevertheless, it was acknowledged by the PID proportional control that controls the opening of the steam extraction valve. Continuous validation with more measured days in the facility is ongoing. Including the metal inertia of the tank is one of the next steps in the development of the model to consider the transient period.

ACKNOWLEDGEMENTS

Thanks to the company SOLATOM CSP, for all the information and operatoinal data from the SHIP facility used in the present work. This work was partially supported by the Research and Development Aid Program (PAID-01-20) of the Universitat Politècnica de València for receiving the Research Fellowship FPI-UPV- 2020. This publication has been carried out in the framework of the project "DECARBONIZACIÓN DE EDIFICIOS E INDUSTRIAS CON SISTEMAS HÍBRIDOS DE BOMBA DE CALOR", funded by the Spanish "Ministerio de Ciencia e Innovación (MCIIN)" with code number PID2020-115665RB-I00.

REFERENCES

[1] M. Berger, M. Meyer-Grünefeldt, D. Krüger, K. Hennecke, M. Mokhtar, and C. Zahler, "First Year of Operational Experience with a Solar Process Steam system for a Pharmaceutical Company in Jordan," *Energy Procedia*, vol. 91, pp. 591–600, Jun. 2016, doi: 10.1016/j.egypro.2016.06.209.

[2] INDERTEC, "Indertec desarrolla SOLPINVAP: Energía SOLar de Media Temperatura para procesos INdustriales con demanda de VAPor." https://indertec.com/2020/01/19/indertec-desarrolla-solpinvap-energia-solar-de-media-temperatura-para-procesos-industriales-con-demanda-de-vapor/ (accessed Jun. 08, 2020).

[3] V. D. Stevanovic, B. Maslovaric, and S. Prica, "Dynamics of steam accumulation," *Applied Thermal Engineering*, vol. 37, pp. 73–79, 2012, doi: 10.1016/j.applthermaleng.2012.01.007.

[4] B. Sun, J. Guo, Y. Lei, L. Yang, Y. Li, and G. Zhang, "Simulation and verification of a non-equilibrium thermodynamic model for a steam catapult's steam accumulator," *International Journal of Heat and Mass Transfer*, vol. 85, pp. 88–97, 2015, doi: 10.1016/j.ijheatmasstransfer.2015.01.120.

[5] CENER, "Tonatiuh, Monte Carlo Ray Tracer Software." https://iat-cener.github.io/tonatiuh/ (accessed Feb. 21, 2022).

[6] G. Morin, J. Dersch, W. Platzer, M. Eck, and A. Häberle, "Comparison of Linear Fresnel and Parabolic Trough Collector power plants," *Solar Energy*, vol. 86, no. 1, pp. 1–12, 2012, doi: 10.1016/j.solener.2011.06.020.

[7] Solatom, "SolatomCSP." http://www.solatom.com/ (accessed Jun. 08, 2020).