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DYNAMIC MODELING OF A THERMAL STORAGE SYSTEM
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Abstract. *In search of sustainable development, renewable sources are increasingly used in the production of clean energy. Solar energy is an example of renewable energy which is abundant in the ambient. Systems that use solar energy can have their energy stored in thermal energy storage (TES) system which keeps the heat of the working fluid for later use in processes such as: desalination; energy cycles; solar oven and others. Due to the variability of solar energy and seeking to minimize this effect in the process, it is important to understand the dynamics of the system as well as to identify how the manipulated variables and the disturbances influence the heat transfers. The objective of this work is to develop a dynamic model for the thermal energy storage system and solar collector of a thermo solar system in order to analyze how the time-dependent profile of the main input variables, as flow rate through collectors, influence the downstream process. The phenomenological model was validated with data from the literature and the results show that the system has a high overall efficiency and that a time-dependent flow rate through collector is required to ensure the temperature required by the downstream process.*

Keywords: *Thermal energy storage, solar collector, dynamic modeling, solar energy.*

1. INTRODUCTION

The world demand for energy grows with the increase of the population and consumption, and then it is necessary to seek alternative sources of energy to pursue the sustainable development. As a result, the use of renewable energy has been increasing faster than other sources of energy as fossil and nuclear and the forecast is that renewable energy will be responsible for almost 38.5% in the world energy share by 2050 (Mekhilef et al, 2011). Renewable energy as hydraulic, wind, tidal, biomass and solar, are clean sources with regenerative capacity. The solar energy is abundant in the environment and has high potential for use, as it covers the entire planet. The energy generated by the Sun reaches the Earth in the form of electromagnetic radiation due to the conversion of the energy released during the process of nuclear fusion. This energy can be used to generate electricity through a photovoltaic process or through energy cycles; in heating and cooling environments; in water heating and heliothermal energy generation (EPE, 2018). Photovoltaic panels and solar collectors are used to transform solar energy into electrical and thermal energy, respectively.

The use of photovoltaic panels is more common when compared to solar collectors. The use of photovoltaic solar energy in Brazil corresponds to 1.6% of the entire Brazilian energy matrix, with residential solar energy accounting for 72.6% of the total, followed by commerce and services companies (17.99%) and by rural solar energy (6.25%) (CRESESB, 2018). Besides the need to generate electricity for domestic and industrial use, there is also a need to generate thermal energy for these segments. About 13% of industrial and domestic thermal applications require thermal energy at temperatures up to 100 ◦C, 27% up to 200 ◦C, and the remaining applications require high temperatures in the steel, glass and pottery industries. To reach such temperatures, many sectors seek the use of flat and concentrated solar collectors for clean generation of thermal energy (Mekhilef, 2011). Thermal energy is defined as the part of the internal energy, whereas the internal energy is proportional to its absolute temperature and is increased or decreased by the transfer of energy. The increase in thermal energy implies an increase in internal energy and temperature within a system. Thermal energy can be used directly in applications where heat is required. For example, heating; conversion into mechanical energy, such as in combustion engines and transformation into electrical energy, as already mentioned. One way to obtain thermal energy is through solar energy (Khatib et al, 2012).

Solar energy is not continuously available 24 h a day, furthermore, the presence of clouds and the environmental conditions cause intermittency in the energy supply. In such cases, thermal energy storage (TES) system is used to store the solar radiation during sunny days for later use in systems such as: desalination; energy cycles; solar oven and others.

These systems can be classified according to the storage mechanism: in the form of sensitive heat, latent heat and thermo chemical reactions. The understanding of the dynamics of the system and how input variables and disturbances influence heat transfer mechanisms allows to create strategies to dampen the effects of frequent disturbances.

Studies of TES systems in the literature are extensive due to their application in many areas of science and engineering. Schulte-Fischedick et al. (2008), Al-Sulaiman et al. (2011), Gárcia et al. (2013) and Suárez et al. (2015) performed the analysis of storage tanks coupled to solar collectors taking into account the steady state. In these works, the fluids used in the thermal transfer were water, oil or molten salt. They evaluated the efficiency of such tanks with the variation of their area and materials, analyzing the heat losses to the ambient. These authors, however, did not evaluate the influence of inherent disturbances of the process, such as irradiation and ambient temperature, and yet, some of these authors did not analyze all the mechanisms of heat loss in the thermal system. Rodriguez et al. (2013) and Menendez et al. (2014) evaluated dynamic heat and temperature losses for TES system based in molten salt. Zaversky et al. (2013) and Bonila Javier et al. (2017) simulated a TES system using molten salt with a dynamic model of two tanks, investigating heat losses to the environment. Nevertheless these authors did not evaluate the influence of the inputs to the solar collector coupled to the tanks. Powell and Edgar (2012) proposed modeling and control of the thermal system in order to control the production of energy in addition to the outlet temperature of the collector.

Although some of these studies consider the dynamics of the process, they do not investigate the behavior of input variables of the solar collector, such as irradiation, ambient temperature and flow rate of heating medium. These input variables have a direct impact on the outlet temperature of the tank. Therefore, the objective of this work is to develop a dynamic model of a solar thermal system composed of two storage tanks and a solar collector, coupled to a desalination process, that uses water as a heating fluid, in order to analyze how the time-dependent profile of the main input variables influence the temperature and energy delivered to the downstream process. The importance of this study concerns the elaboration of control strategies and time-varying optimization in order to maximize the energy efficiency of the system. The paper is organized into four sections. The next section describes the system, its model and the methodology used. The model is validated with data from literature and the results discussed. The paper closes with conclusions about the study and future work.

2. MATHEMATICAL MODEL OF THE PROCESS

2.1 System description

The investigated system, illustrated in Fig. 1, operates with water as heat-transfer fluid then the solar energy is converted into thermal energy in the form of the sensible heat of water. The process flowsheet comprehends the field of solar collectors of type CPC (Parabolic Compound Concentrator), the thermal energy storage system that is composed by a cold- and hot-water tank, and the multi-effect distillation plant (MED) that is used in the desalination of sea water. The disturbances are solar irradiation (I) and ambient temperature (T_a). The flow rate of water that circulates in the collectors is the input variable which can be further manipulated to control the desalination system, damping low-frequency disturbances.

Cold water is heated in the solar collector and then feeds the hot-water tank to supply heat to the desalination (MED) with flow rate $m_0^v = 12$ kg/s. Thus, the thermal energy required by the MED plant is supplied by the hot water from the storage system. After losing heat in the desalination process, the water returns to the cold-water tank and is pumped to the solar collector, closing the cycle. In this cycle the flow rate to desalination (m_0^v) is considered constant, unlike the flow to solar collector (m_c).

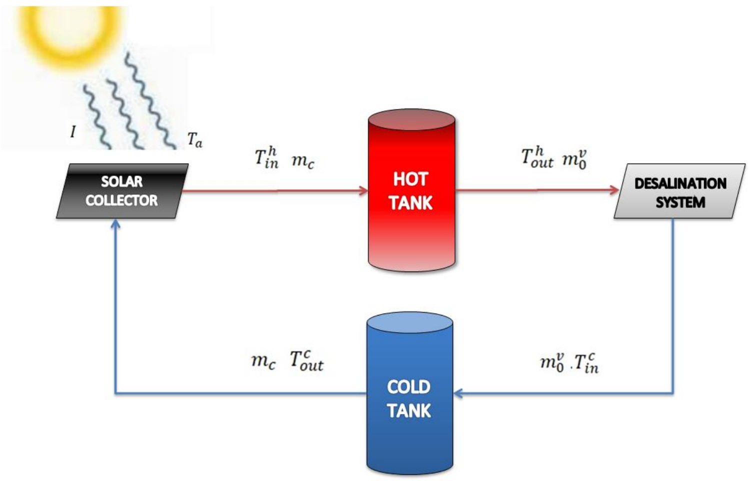


Figure 1. Process flowsheet.

The next section details the model for solar collectors and TES system. For more details regarding the MED, the reader should refer to Roca et al. (2008).

2.2 Solar collector

The phenomenological model for the solar collectors considers the following assumptions: the water specific mass and the specific heat are considered constant and thermal losses in equipment and accessories such as pumps and valves are neglected. The solar field is an association of plane collectors and each association has a number of n_p = 7 tubes. The mathematical model is based on the energy balance of the water flowing into the equivalent absorber tube of length $Leq = L \cdot n_p$, where L is the length of the CPC tube. The energy balance is represented to (González *et al*. 2014):

$$\frac{T_{in}^{h}}{dt} = \frac{1}{\rho \cdot Ac \cdot c_p} \cdot \left[\beta \cdot I - \frac{H}{Leq} \cdot \left(0{,}5 \cdot (T_{in}^{h} + T_{out}^{c}) - T_a\right)\right] - \frac{m_c \cdot \beta_F \cdot (T_{in}^{h} - T_{out}^{c})}{\rho \cdot Ac \cdot Leq} \tag{1}$$

where *t* is the time (s), ρ is the specific mass (975 kg/m³ at 65°C), T_{out}^{c} is the outlet temperature of the cold tank (°C), T_{in}^{h} is the inlet temperature of the hot tank (°C), c_p is the water specific heat (4190 J/kg°C at 65°C), β is a irradiance parameter (0.105 m), H is global thermal losses coefficient (4.7 J/s.K), Leq is the equivalent length of the absorber tube (5.67 m), L is length of the absorber tube (0.81m), Ac is the cross sectional area of the absorber tubes, where the diameter is equal to $5 \cdot 10^{-3}$m and β_F is solar field parameter equal to 0.002. The input variables are solar radiation (I), ambient temperature (T_a) and water mass flow (m^c).

2.3 Thermal Energy Storage System

The mass balance in the hot- and cold-water tanks are respectively given by:

$$\frac{dh^h}{dt} = \frac{m_c - m_0^v}{\rho \cdot A} \tag{2}$$

$$\frac{dh^c}{dt} = \frac{m_0^v - m_c}{\rho \cdot A} \tag{3}$$

where *t* is the time (s) , h^h and h^c are the levels of the hot- and cold-water tanks, respectively (m), m_c is the flow of water circulating in the collectors (kg/s), m_0^v is the outlet flow of the hot tank (12 kg/s), ρ is the specific mass (975m³/kg at 65°C) and A is the cross sectional area of the tank (113 m²).

The outlet temperature each tank is calculated through the energy balances, according to:

$$\frac{dT_{out}^{h}}{dt} = \frac{m_c \cdot c_p . T_{in}^{h} - m_0^v . c_p . T_{out}^{h} - Q_c}{\rho \cdot A \cdot c_p \cdot h^h} - \frac{T_{out,}^{h} (m_c - m_0^v)}{\rho \cdot A \cdot h^h} \tag{4}$$

$$\frac{dT_{out}^{c}}{dt} = \frac{m_0^v \cdot c_p . T_{in}^{c} - m_c . c_p . T_{out}^{c} - Q_c}{\rho \cdot A \cdot c_p \cdot h^c} - \frac{T_{out}^{c} (m_0^v - m_c)}{\rho \cdot A \cdot h^c} \tag{5}$$

where *t* is the time (s), h^h and h^c are the levels of the hot-water and cold-water tanks, respectively (m); m_c is the flow of water circulating in the collectors (kg/s), m_0^v is the outlet flow of the hot tank (12 kg/s), ρ is the specific mass (and A is the cross sectional area of the tank (m²), T_{out}^{h} is the outlet temperature of the hot tank (°C), T_{in}^{h} is the inlet temperature of the hot tank (°C), c_p is the water specific heat (4190 J/kg°C at 65°C), T_{in}^{c} is the inlet temperature of the cold tank (°C). The heat loss by conduction, Q_c (J), corresponds to the heat lost by radiation (Q_{rad}) and convection (Q_{conv}), according to:

$$Q_c = Q_{rad +} Q_{conv} \tag{6}$$

$$Q_c = 2 \cdot \pi \cdot li \cdot \frac{o}{ln \frac{ri}{rii}} + \frac{rii^2}{k} \cdot (\bar{T} - T_{so}) \tag{7}$$

$$\mathrm{Q_{rad}} = \Psi \cdot \sigma \cdot \mathrm{A_t} \cdot \mathrm{T_{so}}^4 - \mathrm{T_a}^4 \tag{8}$$

$$\mathrm{Q_{conv}} = \mathrm{hwt} \cdot \mathrm{A_t} \cdot (\mathrm{T_{so}} - \mathrm{T_a}) \tag{9}$$

where li is the conductivity index of the tank (1); o is the thickness of the tank cap (0.4 m); ri and rii are the external internal radius of the tank, respectively (6 and 6.15m); k is the thickness of the tank (0.15m); $\bar{T}$ is the average temperature of entering and leaving the tank; T_{so} is the temperature of the outer wall of the tank (°C); Ψ is the emission from the external surface of the tank (0.9); σ is a tank loss constant ($5.67 \cdot 10^{-8}$); A_t is the tank outer surface area (414 m²); T_a is the ambient temperature (°C). The convective heat transfer coefficient hwt is calculated according to (Al-Ajlan, 2003):

$$hwt = \frac{8{,}6 \cdot A_t \cdot V^{0{,}6}}{{L_t}^{0{,}4}} \tag{10}$$

where V is the wind speed in (3.19 m/s) and L_t is the cubic root of the tank volume (8.03 m).

The overall energy efficiency of the system (η_c), the energy stored by the tanks (E_s) and the useful energy of the solar collector (E_c) are calculated according to (Kumaresan et al, 2012):

$$\eta_c = \frac{E_s}{E_c} \tag{11}$$

$$E_s = E_c - E_{lost} \tag{12}$$

$$E_c = A_{CPC} \cdot (I - U \cdot \left(0{,}5 \cdot (T_{in}^h + T_{out}^c) - \mathrm{T_a}\right)) \tag{13}$$

where E_{lost} is the energy lost by conduction, Q_c, by the tank (kW); A_{CPC} is the total solar collector area (500 m²); I is the solar irradiation (W/m²); T_{in}^h is the inlet temperature of the hot tank (°C), T_{out}^c is the outlet temperature of the cold tank (°C), U is global heat exchange coefficient ($\frac{W}{m^2 \cdot °C}$) and $\mathrm{T_a}$ is the ambient temperature (°C).

The resulting model is represented by a Differential Algebraic Equation (DAE). The mathematical model was implemented in MOSAICmodeling, a free software, that generates codes for various simulation and optimization environments in different programming languages, such as MATLAB, gPROMS, Aspen, among others (MOSAIC, 2020). The model in MOSAICmodeling was exported to MATLAB, where it was solved with the native function ODE15s. The initial conditions of the Differential Equations are given in the Table 1.

Table 1. Initial condition of the Differential Equations.

Variable	Initial Condition
$T^h_{in\,(t=0)}$	65°C
$h^h_{(t=0)}$	3.3 m
$h^c_{(t=0)}$	2.1 m
$T^h_{out(t=0)}$	63°C
$T^c_{out(t=0)}$	60°C

3. VALIDATION AND RESULTS

The model of the solar collector was validated against the simulated data from González et al (2014), for a given ambient temperature, irradiation and water mass flow rate profile. It is important to emphasize that the data simulated by González et al (2014) were validated with experimental data. Figure 2 compares the outlet temperature of the solar collector predicted by the model with simulated data from González et al (2014). The results show very good fit of the model, with deviations of up to 4.49%.

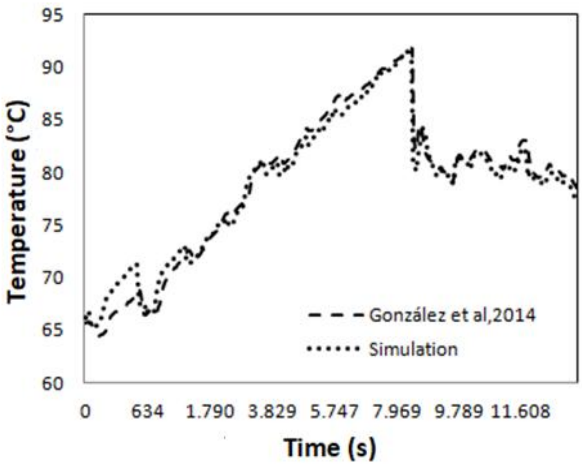


Figure 2. Validation of the solar collector model against simulated data from González et al. (2014).

A sensitivity analysis is carried out to investigate the behavior of the tank's level and outlet temperatures of the system regarding changes in the following input variables: irradiation (I); ambient temperature (T_a) and water flow to the collectors (m_c). Real irradiation and ambient temperature profiles, as shown in Fig. 3, were imposed to the model. The data were taken from Ayala et al (2011), who reported local conditions in Almeria on October 14th 2009. The simulation window considered a cycle of solar irradiation with 50,000 seconds.

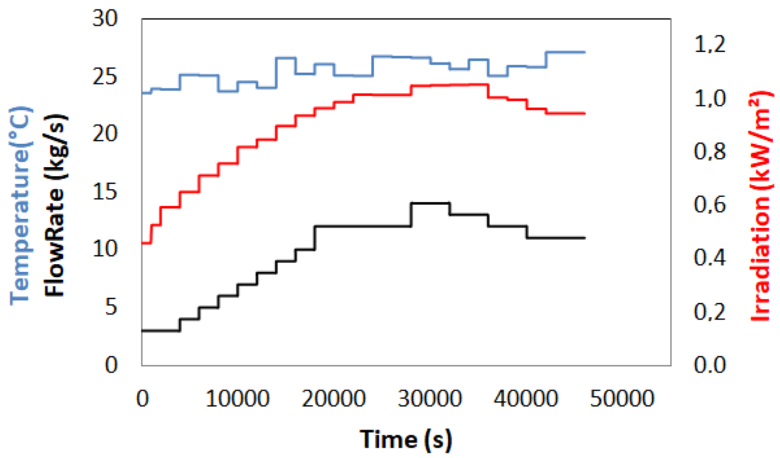


Figure 3. Inlet profiles of ambient temperature, water flow rate and irradiation.

The desalination process downstream of the thermal system requires that the outlet temperature of the hot tank ranges between 65 and 75 °C to ensure the production of distilled water, while maintaining the useful life of the plant's equipment and accessories. Since the water flow rate m_c is the potential manipulated variable to control the outlet temperature of the hot-water tank and, consequently, the production of fresh water from desalination, the profile of Fig. 4 was compared with a constant flow of $m_c = 8$ kg/s and the results are illustrated in Fig. 4. The time-dependent flow rate profile results in a more pronounced increase in temperature up to 10,000 seconds due to lower flow rates that attempt to balance lower irradiations. After this period, the outlet temperature of the tank gradually decreases, despite the increase in irradiation, due to the further increase in water flow. The time-dependent flow rate profile meets the outlet temperature restrictions of the hot-water tank after about 2,108 seconds (Fig. 4a). When a constant flow is imposed, the system is not able to maintain the temperature within the constraints, except during the period of from 10,000 to 20,000 seconds, as shown in Fig. 4b. This constraint violation can generate stress on fittings and tubes and cause unnecessary costs with maintenance of equipment as well as energy. Therefore, a time-dependent rate of water flow is mandatory to ensure that the outlet temperature of the solar collector meets the heat required for the desalination process without compromising the equipment.

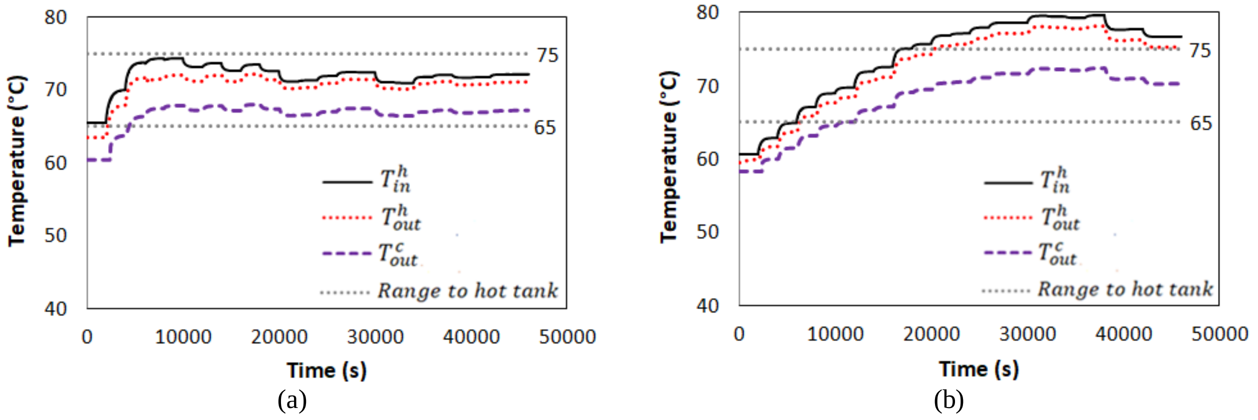


Figure 4: Outlet temperature profiles after disturbance on water flow rate ($\boldsymbol{m_c}$): (a) time-dependent profile according to Figure 3 and (b) constant profile with $\boldsymbol{m_c} = \mathbf{8}$ kg/s.

In order to optimize the efficiency of the collector and to avoid the wear of its materials, the temperature gradient in the collector must vary within 5 and 20°C (Ayala et al, 2011). The average temperature gradient within 2,000 and 10,000 seconds is around 6 to 7.5 ° C. After 10,000 seconds, this gradient stabilizes due to the compensation of irradiation with the flow profile presented, satisfying the constraint. To investigate the average temperature gradient in the collector, a sensitivity analysis was performed varying m_c (1, 5 and 9 kg/s) at constant I (700W/m²) and T_a (20°). According to the results in Table 2, it is observed that the temperature gradient is sensitive to the variation of the flow rate that circulates in the collectors. To fulfill the temperature constrain in the collectors (5 to 20°C), tough, the flow that circulates in the collectors must be between 1 and 5 kg/s for the irradiation and temperature conditions simulated.

Table 2. Sensitivity analysis of temperature gain in the solar collector.

Flow rate in the solar collector (kg/s)	Temperature gradient (°C)
1	18.42
5	5.21
9	4.74

The tanks are integrating systems because the outlet flow rates do not depend on their levels. When the time-dependent inlet flow rate is imposed, according to Fig. 3, until t =20,000s, m_c is lower than the flow rate required by the MED. Therefore, the hot-water tank's level decreases and the cold-tank's level rises, as Fig. 5 shows. From t =30,000s on, though, m_c is higher than the flow rate to MED, then the hot-water tank's level starts increasing and the cold-water tank's level decreasing accordingly.

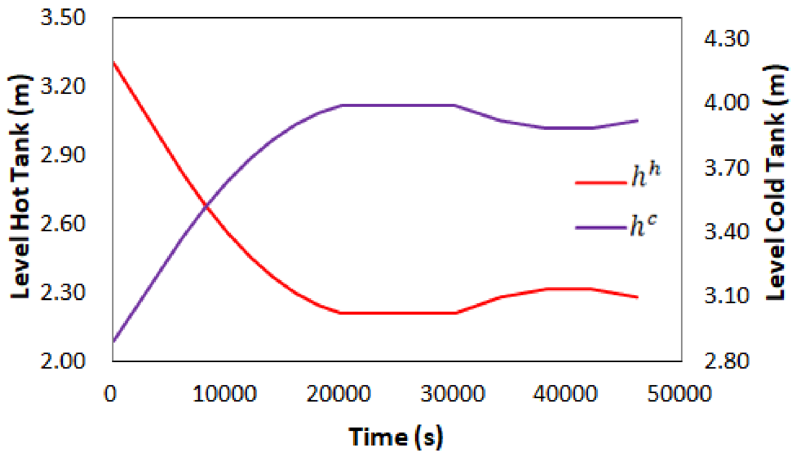
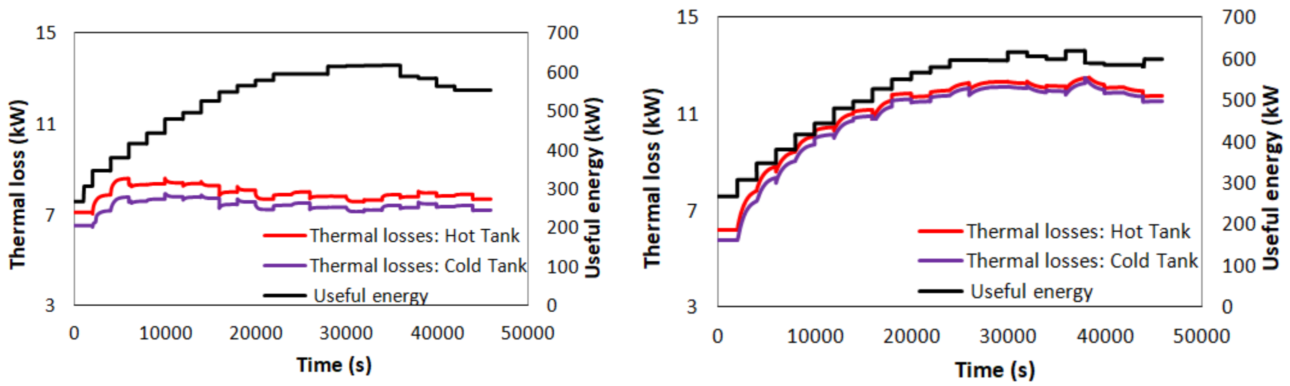


Figure 5: Tanks' level behavior due to transient disturbances in Fig. 3.

The efficiency of the system is illustrated in Fig. 6, which shows the thermal loss (Q_c) and useful energy of the solar collector (E_c), according to Eq. 7 and 13, respectively. The energy lost is much less than the energy received and the overall efficiency of the system varies between 90 and 95%. The loss of energy increases with the increase in the temperature of the tank, because, according to Eq. 7, 8 and 9, higher surface temperatures increase heat transferred by convection, radiation and conduction. In order to verify the useful energy of the collector and the outlet temperatures only of the thermal reservoir system, the desalination system was decoupled from the simulation and the same scenario presented in Fig. 3 was imposed. The results are shown in Fig. 6b and indicate that the useful energy of the collector without the MED (Fig 6b) is close to the energy of the collector coupled to the MED (Fig 6a). The energy loss of the tanks without the MED is slightly greater because of the higher temperatures, as shown in Fig. 7. Comparison between Fig. 7 (without MED) and Fig. 4a (with MED) confirms that the TES can efficiently store the energy from the solar collectors because the temperature of the stream leaving the hot-water tank can increase roughly 20°C.



(a) (b)

Figure 6: Tank's thermal losses and energy gain (a) with desalination system (MED) and (b) without desalination system (MED).

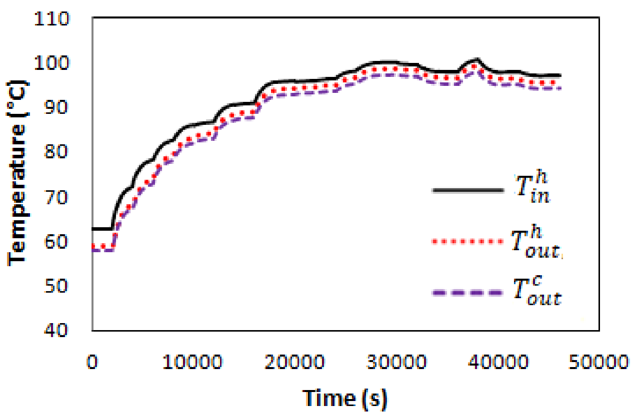


Figure 7: Outlet temperature profiles without desalination system (MED) after disturbance on water flow rate ($\boldsymbol{m_c}$) time-dependent profile according to Fig 3.

4. CONCLUSION

This work presented a dynamic model for the thermal storage system coupled with solar collectors and desalinization process, that was validated with simulated data from the literature with low deviations of 4.49%. The results show that a time-dependent flow rate through the collector is necessary to guarantee the temperature required by the downstream process. TES is necessary to dampen solar radiation, as it varies throughout the day. The system has a high overall efficiency because the heat losses are much lower than the energy gain. Future studies will investigate the optimization of the water flow profile for the collectors to maximize the productivity of fresh water in desalination, while ensuring the constraints of the TES system.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

AL-AJLAN. S.A, AL FARIS.H, KHONKAR.H.Al. **A simulation modeling for optimization of flat plate collector design in Riyadh, Saudi Arabia.** Renewable Energy, v. 28, n. 9, p. 1325–1339, 2003.

AL-SULAIMAN, FA, DINCER, I; HAMDULLAHPUR, F. **Exergy modeling of a new solar driven trigeneration system.** Solar Energy , v. 85, p. 2228–2243, 2011.

AYALA, CO, ROCA, L, GUZMAN, JL, NORMEY-RICO, JE, BERENGUEL, M, YEBRA, L. **Local model predictive controller in a solar desalination plant collector field.** Renewable Energy, v.36, p.3001-3012, 2011.

BONILLA J, MARGARITA M. RODRIGUES-GARCIA, LIDIA ROCA, ALBERTO CALLE. **Design and experimental validation of a computational effective dynamic thermal energy storage tank model.** Energy, v. 152, p. 840-857, 2017.

EPE. Energy research company. **Statistical Yearbook of Electricity 2017: Base Year 2016**. Rio de Janeiro (RJ), 2017. Accessed on: October 13, 2018. Available at: http://www.epe.gov.br.

GARCIA-BARBERENA J, ZAVERSKY F, SANCHEZ M, ASTRAIN D. **Transient molten salt two-tank thermal storage modeling for CSP performance simulations.** Solar Energy, v93, p294-311, 2013.

MANENTI F, RAVAGHI-ARDEBILI Z. **Dynamic simulation of concentrating solar power plant and two-tanks direct thermal energy storage.** Energy 2013;55:89-97.

MENÉNDEZ R, MARTINEZ R, MARTINEZ J, PRIETO M, BARCIA L, SANCHEZ J. **A novel modeling of molten-salt heat storage systems in thermal solar power plants**. Energies 2014; 7(10):6721-40.

SCHULTE-FISCHEDICK, J, HERRMANN, U, TAMME, R. **CFD analyzes of the cool down behavior of molten salt thermal storage systems** . Jacksonville, Florida - USA: Energy Sustainability, 2008.

SUÁREZ, C, IRANZO, A, PINO, FJ, GUERRA, J. **Transient analysis of the cooling process of molten salt thermal storage tanks due to standby heat loss.** Energy,v. 142, p. 56–65, 2015.

GONZÁLEZ R, ROCA L, RODRIGUEZ F. **Economic optimal control applied to a solar sea water desalination plant.** Computers and Chemical Engineering, v. 71, p554-562, 2014.

POWELL, K. M.; EDGAR , T.F. Modeling and control of a solar thermal power plant with thermal energy storage. Chemical Engineering Science, v. 71, p. 138-145, 2012. 58

RODRÍGUEZ I, PÉREZ-SEGARRA CD, LEHMKUHL O, OLIVA A. **Modular object-oriented methodology for the resolution of storage tanks for csp plants**. Applied Energy, v. 109, p. 402–414, 2013.

RODRIGUEZ GARCIA M-M. **First experimental results of a PTC facility using gas as the heat transfer fluid.** In: 15th SolarPACES conference, Berlin, Germany; 2009.

ZAVERSKY, F, SÁNCHEZ, JGBM, ASTRAIN, D. **Transient molten salt two-tank thermal storage modeling for csp performance simulations.** Solar Energy , v. 93, p. 294–311, 2013.

7. RESPONSIBILITY NOTICE

The authors, D.F.S.Paixão, V.V.Gomes, D.P.S.Cunha, K.V. Pontes, are the only responsible for the printed material included in this paper.