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TRANSIENT SIMULATION OF A MOLTEN SALT TWO TANK THERMAL STORAGE SYSTEM

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Abstract. *Solar energy is an inexhaustible clean source of energy, however the capacity factor of these plants are low if compared to other sources, such as hydro and nuclear. Among the renewables, the solar thermal is able to retain the excess of energy in thermal storage systems and thus use this energy in periods of cloudiness and after dusk, when the incidence of sunlights are not enough to generate power. This work attempts to simulate a two-tanks sensible heat thermal storage system using the molten salt as heat transfer fluid, which is the most used in solar power plants. The analysis consists of a transient simulation of the heat exchange mechanisms in the storage tanks fully charged and discharged. The simulation is performed for the climatic data of the Brazilian semi-arid region and the heat loss results are compared to actual situations available in the literature.*

Keywords: *Thermal energy storage, solar power energy, two tanks storage system*

1. INTRODUCTION

The concern of the nations about the pollution and deterioration of the ozone layer caused by greenhouse gas emissions has raised interest in alternative energy sources. Recent accidents at nuclear power plants such as Fukushima, Japan, has led the countries that have this source as main means of power generation to seek energy alternatives with lower environmental effects.

Renewable energies are gaining more space and becoming competitive in the energy market. However, the capacity factor of these plants are lower when compared to other non-renewable sources, such as thermoelectric by gas and coal. Among renewables, thermal solar energy, which uses thermal energy from the sun to generate power, has great potential for developing Thermal Energy Storage systems (TES). That way, it is possible to generate electricity during periods of cloudiness and after dusk, an alternative that it is not present in wind farms (with the lack of wind) and photovoltaic panels (in the absence of sunlight) (Duffie and Beckman, 2013).

The so-called Thermal Storage systems consist at storing thermal energy by three different means: By sensible heat where there is not phase change; By latent heat, where there is a phase change; And by chemical reactions, where the heat is used to conduct chemical reactions. Among the plants that are in operation, the most popular and acceptable mean of thermal storage are by direct sensible heat two tanks (Kuravi *et al.*, 2013). This system consists of heating a heat transfer fluid (HTF), and therefore stored in the hot tank, where in periods of cloudiness or after dusk, the energy is used to generate steam for the turbines, then the HTF goes to a cold tank and returns to the heat receiver. Figure 1 sketches a TES layout for direct sensible heat two tanks.

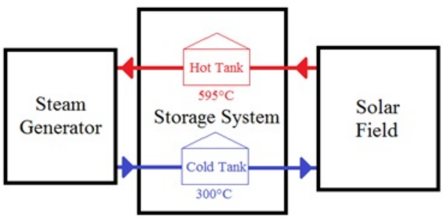


Figure 1. Sketch of a TES by direct heat sensitive two tanks.

Such TES can reach a storage capacity of 15h (Gemasola, Sevilla - Spain) and can provide power 24 hours a day. Overall, solar energy is an inexhaustible renewable source with great potential for energetic exploitation. This paper seeks to provide a reliable and quick solution tool for simulation of thermal storage tanks, using finite volume method allied with the heat transfer mechanisms to achieve these objectives.

2. METHODOLOGY

The development of new technologies depends on the physical comprehension of these systems. Therefore, this paper aims to quickly and easily analyze the thermal losses of a thermal storage tanks. The system was analyzed considering the period of one day of storage, which was considered a characteristic day for the monthly average wind currents and solar radiation. Thus the decay of the HTF temperature after one day of storage is known.

2.1 Tank Properties

The analyzed system consists of operating temperatures of 560°C for the hot tank and 295°C for the cold tank. According to Kuravi *et al.* (2013), in applications with temperatures less than 400°C using carbon steel are acceptable, and for applications with higher temperatures, stainless steel should be used for tank components. The insulation material should be selected based on the operating temperature ranges.

Zaversky *et al.* (2013) states that the thermal conductivity is the governing factor of heat loss from tanks. The insulating material used for this article to the tanks' walls consists of mineral wool, foam glass and calcium silicate board and to the tanks' roof consists of silicate board, since the relationship between the thermal conductivity and the temperature are known (Zaversky *et al.*, 2013) and is given by Eq. (1) and Eq. (2) for the tanks' walls and roof, respectively.

$$k = k_0 + k_1 \cdot (T - 273.15) \tag{1}$$

$$k = 0.0674 + 4 \cdot 10^{-5} \cdot T + 6 \cdot 10^{-8} \cdot T^2 + 9 \cdot 10^{-12} \cdot T^3 \tag{2}$$

k – Thermal conductivity [W/mK];

k_0 – Thermal conductivity coefficient of correlation [W/mK]

k_1 – Thermal conductivity coefficient of correlation [W/mK]

T – Operating temperature [°C]

The inner and outer surface of the insulating material are protected by metal layers, however these are not modeled, as the inertial and thermal resistance of these materials can be neglected. The k_0 and k_1 values for the insulation material are $0.037W/(mK)$ and $2 \cdot 10^{-4}W/(mK)$, respectively (Zaversky *et al.*, 2013).

2.2 Heat Transfer Fluid Properties

The HTF must be determined in order to be compatible with the storage type and capable of operating across the temperature range. For solar plants that use the TES two tanks sensible heat the most used HTF is molten salts (Kuravi *et al.*, 2013). For this work, we used the molten nitrate salt (60% $NaNO_3$, KNO_3 40%), also known as solar salt, which is widely used in solar central receiver power for operations at high temperatures (290°C to 565°C). Apart from that, data as thermal conductivity, thermal diffusivity, and others are easily available at Kreith *et al.* (2011).

2.3 Tank Modeling

The tank was modeled according to a layout similar to proposed by Zaversky *et al.* (2014a), which was considered all the heat transfer mechanisms. Figure 2 outlines the proposed model. The solar salt exchanges heat by convection with tank's inner walls, with the tank's bottom and with the atmospheric gas, the radiation emitted by the salt surface to the not wet tank's walls have also been considered in the analysis. The atmospheric gas exchanges heat by convection with the non-wetted walls and the tank's roof. Finally, conduction was considered from the tank's inner to the outer surfaces (wet wall, non-wetted wall and roof) and convection with the surroundings. The emitted radiation and the solar incident were also included in this analysis.

The heat transfer between molten salt and the tank's walls and bottom were modeled as natural convection. Movements related to pumps were neglected in this analysis. The dimensionless natural convection correlations (Nusselt number, Nu) was obtained from Kreith *et al.* (2011). For natural convection between the wall and molten salt it was used the Eq. (3) applicable for the Rayleigh number (Ra) intervals from 10 to 10^8, and Eq. (4) for Grashof number (Gr) above 10^9, these correlations are applied to hot fluid in contact with cold vertical surface.

$$Nu = 0.68Pr^{1/2} \cdot \frac{Gr^{1/4}}{(0.952 + Pr)^{1/4}} \tag{3}$$

Where Pr is the Prandtl number.

$$Nu = 0.68Ra^{1/3} \tag{4}$$

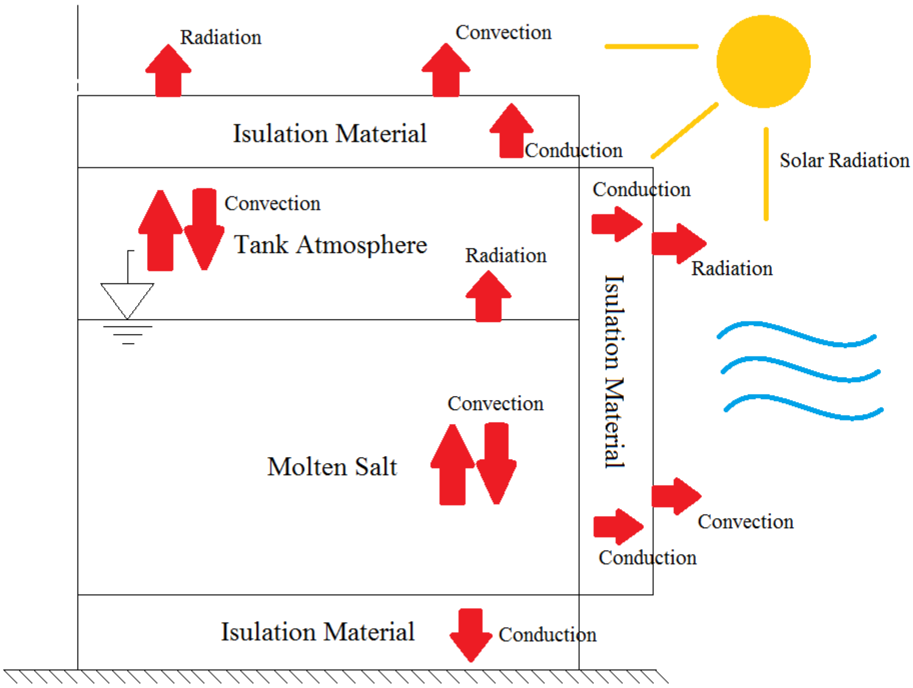


Figure 2. Schematic illustration of a thermal storage tank

The natural convection between the molten salt and the bottom of the tank was calculated using the correlation, Eq. (5) for hot fluid in contact with the lower cold plate for Rayleigh number ranges between 10^5 to 10^{10}.

$$Nu = 0.27Ra^{1/4} \tag{5}$$

The heat transfer mechanism between the molten salt and the gas was modeled as a thin cold gas plate in contact with a lower hot liquid (Zaversky *et al.*, 2013). The Equation (6) represents the correlation for this mechanism to intervals of Ra from 10^5 to 10^7 and the Eq. (7) for intervals from 10^7 to 10^{10}.

$$Nu = 0.27Ra^{1/4} \tag{6}$$

$$Nu = 0.15Ra^{1/3} \tag{7}$$

Similarly, these correlations can be applied to the atmosphere of the tank and the non-wetted wall.

The tank's atmosphere was modeled as a cavity, where the surfaces radiative energy balance were calculated. The correlation for calculating the form factor of the salt surface and the tank's roof was the same used between the two concentric disks, given by Eq. (8). To the form factor between salt surface and the tank walls was used the relationship between the form factors, Eq. (9).These equations were obtained in Çengel and Ghajar (2012).

$$F_{1\to 2} = 1 + \frac{1 - \sqrt{4R^2 + 1}}{2R^2} \tag{8}$$

$$F_{1\to 3} = 1 - F_{1\to 2} - F_{1\to 1} \quad (9)$$

Where $F_{1\to 2}$ is the form factor between the salt surface and the tank's roof, $F_{1\to 3}$ is the form factor between the salt surface and the tank's walls and $F_{1\to 1}$ is the form factor between the salt surface and itself, which is null for that case.

To the outer surface was considered a mixed convection (natural and forced) and radiation emitted and received from the surface. The natural convection was modeled as a hot plate, due to its large diameter, in a cool medium Eq . (3), and the forced convection as a hot cylinder in contact with a cold air flow, Eq. (10). The Equation (11) models the mixed behavior, where the factor n in this case is three.

$$\begin{array}{ll} Nu = 0.911 Re^{0.330} Pr^{1/3} & for\ 0.4 < Re < 4 \\ Nu = 0.989 Re^{0.385} Pr^{1/3} & for\ 4 < Re < 40 \\ Nu = 0.683 Re^{0.466} Pr^{1/3} & for\ 40 < Re < 4000 \\ Nu = 0.193 Re^{0.618} Pr^{1/3} & for\ 4000 < Re < 40000 \\ Nu = 0.027 Re^{0.805} Pr^{1/3} & for\ 40000 < Re < 400000 \end{array} \quad (10)$$

$$Nu_{comb} = (Nu^n_{forced} + (Nu^n_{natural}) \quad (11)$$

The radiation emitted by the outer surface of the tank was modeled by the following Eq. (12).

$$Q_{rad} = \epsilon_{wall} \cdot A \cdot T_s^4 \quad (12)$$

Where ϵ_{wall} is the emissivity of the tank wall, 'A' is the tank's outer surface area e T_s is the outer surface temperature.

The incident solar radiation in the tank, as well as the ambient temperature and wind speed were obtained through the acquisition data system from solar energy laboratory of the Federal University of Rio Grande do Norte. For each half-hour intervals such values are measured. The Figure 3 shows the variation of these parameters over time.

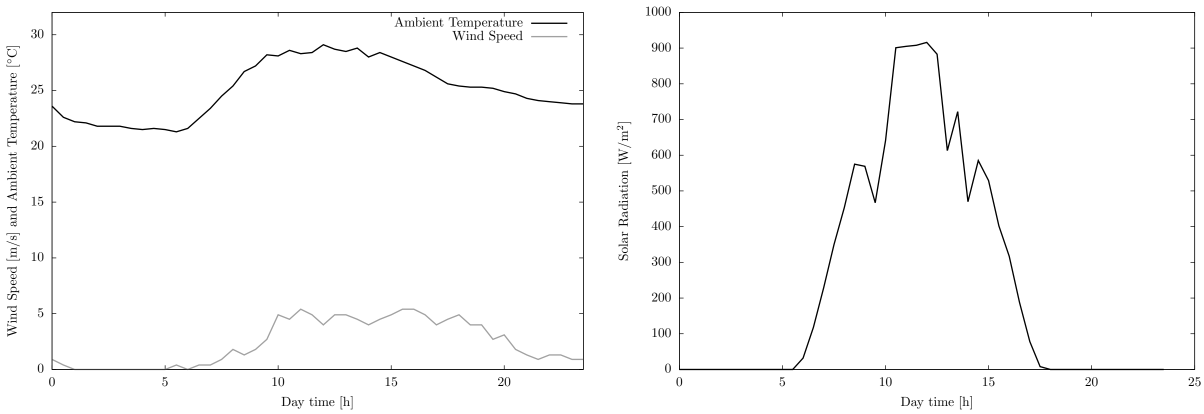


Figure 3. Wind speed, ambient temperature and solar radiation data.

The conduction between the inner and outer surface of the tank was modeled by finite volume method Fig. 4, in which the wall thickness was divided into small volumes(Zaversky *et al.*, 2014b). Initially it was considered an isothermal wall and the by the time that the outer surface loses heat to the environment a temperature gradient appears. The boundary conditions were the heat flow from the salt to the inner walls of the tank and the heat flux from the walls to the external medium. It was also considered that the finite volume store heat in the process.

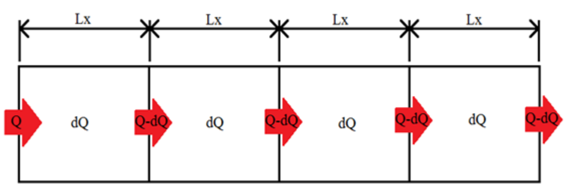


Figure 4. Layout of the finite volume method.

It was selected an august characteristic day to perform the simulation. In possession of such data, it was used the C++ programming language to calculations effect.The computational procedure consisted in the application of finite volume to the walls, roof and bottom of the tank. Each element was divided into small elements (130 units) resulting in a system of ordinary differential equations (ODEs). Such system was solved using an implementation of the Runge Kutta method of fourth order.

The temperature of the solar salt was set to 595°C for the hot tank. The system was considered fully insulated to initial conditions. As stated previously, data such as ambient temperature, wind speed and solar radiation were used as system boundary conditions. Finally, the temperature drop per day were determined for the fully charged hot tank.

3. RESULTS AND DISCUSSION

Due to the isothermal initial condition, the first two days were not considered from the analysis because they represent only the heat loss of the wall to the environment. From the third day the solar salt presents some temperature drop. Figure 5 and 6 shows a graph with the temperature drop and a comparison between the heat loss data from this paper and Zaversky *et al.* (2013) versus time.

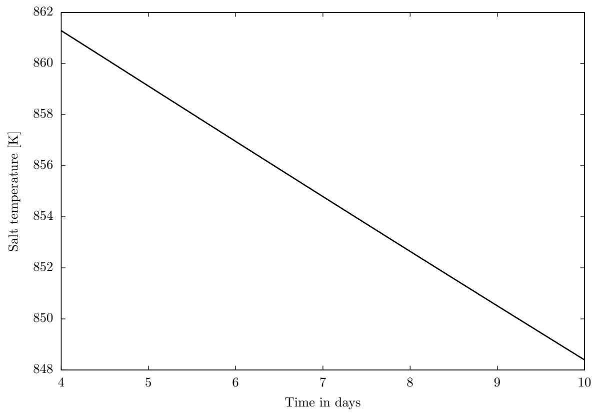
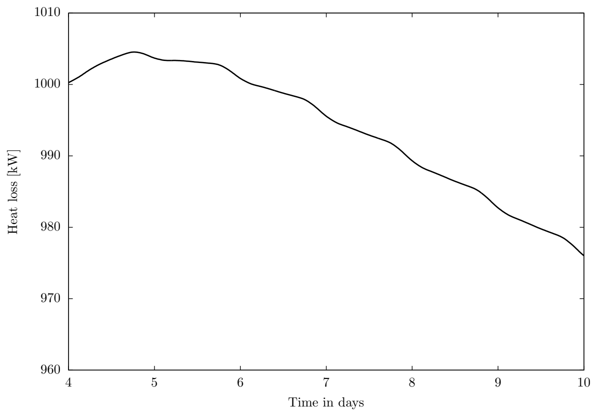


Figure 5. Temperature variation.



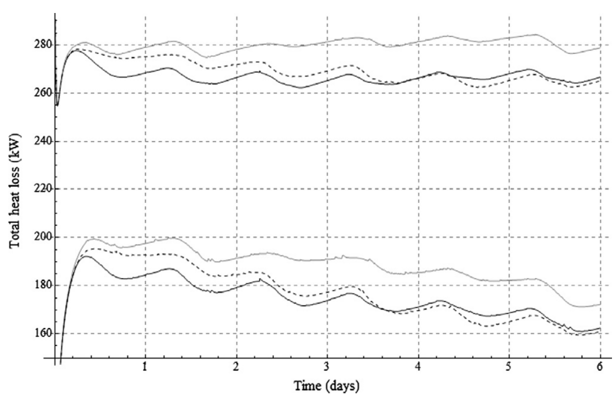


Figure 6. Total heat loss A. Araújo, G. Tápia and J. Farias Filho (left side) and Total heat loss Zaversky *et al.* (2013) (right side)

Throughout the day, there was a drop in temperature equal to $2K/day$ for the hot tank. Zaversky *et al.* (2013), presents similar results, with temperatures drops around $1.1K/day$ for fully charged hot tank, and $5.4K/day$ for the cold tank. Unlike the Zaversky *et al.* (2013) work, the tank proposed by this paper showed a maximum heat loss around 1MW, however the heat loss decreases rapidly, since the tank's outer surface temperature reaches values close to ambient temperature. The large difference between these two papers might be the different approach of both works and the calculation of the heat transfer coefficients and tank's dimensions.

4. CONCLUSIONS

Thermal storage tanks have acceptable energy losses for theirs application, since they are used when the solar supply cannot meet the energy demand for power generation. Thus, the rate of temperature decay around $2K/day$ is satisfactory.

The thermal storage is one of the main strengths of solar thermal energy. The comprehension of heat transfer mechanisms is fundamental to the development of new storage technologies. The use of reliable tools that enable the study and analysis of such systems helps in this role. This work reached satisfactory results for heat loss in storage tanks by sensible heat.

More detailed analyzes of the heat transfer mechanisms and efficient methods may further enhance this analysis. The design and selection of materials for thermal storage tanks can be included for comparative analysis. Initial and boundary conditions must be reviewed in order to obtain reliable results in comparison with the conditions encountered in practice.

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