Numerical Investigation of Thermal Storage System in a Single-Tank for CSP Plants

Mohamed Hajjaj[1], Aumeur El Amrani [2] and Abella Bouaaddi[1]

[1] *LGEMS,Dept.of Physics, National School of Applied Sciences, Ibn Zohr University Agadir, Morocco*

[2] *EPSMS,Dept.of Physics, FST B.P.509, Boutalamine, Errachidia, My ismail University, Morocco*

Keywords: Concentrating solar power, Thermal energy storage, Thermocline, Single- tank, Method of characteristics.

Abstract: To avoid the intermittency behavior in solar energy system due to unforeseen weather conditions and to improve the energy availability, thermal energy storage (TES) system remains inevitable. Thus, a single tank packed bed thermocline based TES system can provide an effective solution. This paper reports a study on the thermal energy storage in a thermocline tank having a solid filler material. A comprehensive one-dimensional non-thermal equilibrium model is considered and is solved using method of characteristics for the energy storage investigation in a single tank packed bed thermocline storage system. In this present study, the governing equations are approached from a new numerical method perspective. The governing equations are reduced to dimensionless forms, which allow a universal application of the solution. The dimensionless equations, which are as a system of hyperbolic type, are solved numerically by the method of characteristics.

1 INTRODUCTION

Many studies are underway on renewable energy related to the issue of fossil fuel depletion and the request of new energy sources. In particular, studies using solar energy have been actively conducted over the last few decades. In addition, CSP technologies generates electricity by transferring heat from solar receivers to a heat transfer fluid and then to steam, which is expanded through a turbine. Moreover, CSP not only supports the base load, but it also saves extra energy during the daytime. This energy can then be used at night, when solar power is lacking. Thus, thermal energy storage (TES) is a core technology that increases the total system efficiency by increasing the plant operation time. It is essential to develop a thermal storage tank with efficient thermal energy storage and energy discharge.

The important issue related to TES for CSP plants is high-temperature storage. Generally, high-temperature thermal storage is required to produce high-temperature steam, leading to enhanced power efficiency. However, the maximum temperature of a solar receiver at current CSP plants (i.e. Crescent dunes, Gemasolar) using molten salt is approximately 565°C (1050F), which may be related to the decomposition of the molten salt. In addition, price competitiveness is important in TES of CSP because TES is known to be responsible for approximately 20% of the total price. Therefore, the development of cost competitive high-temperature TES approaches is crucial for the commercialization of CSP technology.

For high-temperature storage, molten salt is generally used as the heat transfer fluid (HTF) because the decomposition temperature of molten salt (~550°C) remains higher than that of other types of HTF (i.e. oil). However, the relatively high melting temperature and material competitiveness are still concerns. ‘Hitec’ and ‘Solar salt’ are widely used as commercial HTFs [1].

In order to reduce the cost of TES, thermocline TES, which enables thermal storage and discharge in one tank, has been investigated. Thermocline TES refers to a means of storing high- and low-temperature fluids in a single tank by means of thermal stratification. The core technology is to prevent the mixing of the high and low-temperature fluids during the charge and discharge operations. The piping design and insulation technology associated with the thermal storage tank are the key technologies. Thermocline TES has not been put

El Amrani, A. and Bouaaddi, A.
Numerical Investigation of Thermal Storage System in a Single-Tank for CSP Plants.
DOI: 10.5220/0009775502910296
In *Proceedings of the 1st International Conference of Computer Science and Renewable Energies (ICCSRE 2018)*, pages 291-296
ISBN: 978-989-758-431-2

into practical use, but it is technically feasible in order to lower the TES cost.

In this paper, we will discuss some modelling approaches for single-tank thermocline storage having solid filler material for CSP plants. Several studies involving numerical analyses on solar-assisted thermal storage systems [2,3] and experimental studies of thermocline water storage systems [4,5] have been reported. However, there is limited information available on the thermocline TES using molten salt as a storage medium. In particular, feasibility testing of molten-salt thermocline TES was occurred, but most papers address numerical modeling [6–9] and filler compatibility with molten salt [10–15]. In addition, the experimental data pertaining to the transient behavior of molten salt TES by Sandia National Laboratory [13] remains the only experimental work thus far, whereas most numerical analysis papers use these results to verify their models.

As discussed above, the most important issues in relation to TES are high-temperature storage and cost-competitive storage. Moreover, there is very limited information in the form of experimental data pertaining to molten-salt thermocline TES. A single-medium (molten salt) thermocline TES system has been considered as a potentially feasible upcoming technology, and this paper the feasibility of single-medium thermocline TES is investigated. A study of thermocline TES was carried out and the thermal characteristics of a thermal storage tank according to the operating conditions (mainly the flow rate) at a high temperature (500°C) will be investigated in the next work.

2 SYSTEM DESCRIPTION

A sound key to substantially reduce the thermal energy costs is to use single-tank thermocline storage systems with molten salts as the direct heat transfer fluid. The thermocline storage system utilizes a single tank that is larger compared to tanks used in two-tank thermal storage systems. With the number of tanks reduced to one, the hot and cold fluid is contained in one tank; the storage tank relies on the buoyancy phenomena, to maintain thermal stratification. The filler material also plays the porous medium flow distributor role that mitigates irrelevant secondary velocities in the tank cross section which can cause de stratification of the hot and cold HTF regions.

A schematic of a concentrated solar power plant with TES is shown in Fig. 1. A single tank is used to store energy which has a thermal gradient that separates the hot fluid from cold fluid. Thus, a filler material is used which acts as heat reservoir and also replaces expensive HTF. A stratification of hot and cold fluids in a thermocline tank prevents convective mixing, which allows the maximum utilization of a single tank. During the charge cycle, hot molten salt from the collector field flows via from the top of into the tank, which it loses heat to the filler material, and finally exits the tank with a reduction in temperature through the bottom of the tank and is back to the collector field where further heating takes place.

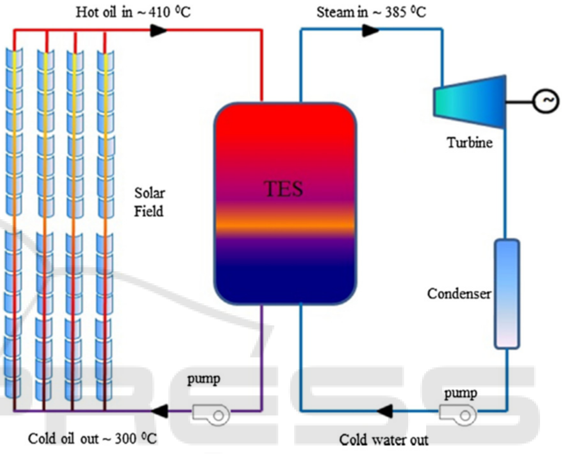

Figure 1: Schematic of a concentrated solar power plant with TES.

In this work, we present a mathematical model of the CSP plants, which is integrated by developing a program based on the method of characteristics. Section 2 of this paper gives a brief overview of the related works. Section 3 provides an overview of our methodology. Section 4 concludes the paper and provides an outlook into future work.

2.1 Mathematical Modeling

A comprehensive one-dimensional non-thermal equilibrium model is used to investigate the energy storage in a single tank thermocline storage system assuming constant average velocity inside the bed. The model is solved using method of characteristics, which could produce numerical solutions of high level of accuracy and stability with minimal computing time [16].

Brinkman- Forchheimer extended Darcy model is used to model the porous medium resistance.

The numerical model is simplified by implementing the following assumptions:

- A uniform radial distribution of the fluid flow and rocks through the storage tank is assumed to make the problem to a one dimensional problem along the axis, z, of the storage tank.
- The axial conduction inside the packed bed is neglected.
- The flow is considered incompressible and laminar.
- Contacts between rocks are point contacts and therefore heat conduction between rocks is negligible.
- There is no heat loss from the storage tank to the surroundings.
- The tank is considered to have a uniformly distributed spherical filler materials of same size as a porous matrix.

2.2 Governing Equations and Boundary Conditions

2.2.1 Fluid Energy Balance Equation

Based on the aforementioned assumptions and by performing a thermal energy balance on the control volume, the energy balance equation for the fluid and filler can be written as follows [16]:

The cross-sectional area of the tank associated to the fluid flow is assumed constant at all points along the axis of the tank and is:

$$a_f = \varepsilon \pi R^2 \tag{1}$$

With the flow velocity of U the thermal energy balance of the fluid in the control volume dz is giving by:

$$\rho_f \varepsilon \pi R^2 U(h_z - h_{z+dz}) + hS_r(T_r - T_f)dz = \rho_f C_f \varepsilon \pi R^2 dz \frac{\partial T_f}{\partial t} \tag{2}$$

Where the average fluid velocity in the packed bed is:

$$U = \frac{\dot{m}}{\rho_f a_f} \tag{3}$$

With substitutions for the definition of enthalpy and rearrangement of Eq. (2), the energy balance equation becomes as:

$$\frac{hS_r}{\rho_f C_f \varepsilon \pi R^2}(T_r - T_f) = \frac{\partial T_f}{\partial t} + U\frac{\partial T_f}{\partial z} \tag{4}$$

Introducing the following dimensionless variables:

$$\theta_f = \frac{(T_f - T_l)}{(T_h - T_l)} \ ; \qquad \theta_r = \frac{(T_r - T_l)}{(T_h - T_l)} \tag{5}$$

$$z^* = \frac{z}{H} \qquad ; \quad t^* = \frac{t}{({}^{H}/_{U})} \tag{6}$$

The dimensionless governing equation for heat transfer fluid can be expressed as:

$$\frac{\partial \theta_f}{\partial t^*} + \frac{\partial \theta_f}{\partial z^*} = \frac{1}{\tau_R}\left(\theta_r - \theta_f\right) \tag{7}$$

where

$$\tau_R = \frac{U}{H}\frac{\rho_f C_f \varepsilon \pi R^2}{hS_r}$$

Based on Assumption (2), the heat transfer surface area of rocks per unit length of the tank S_r can be calculated from the equation:

$$S_r = \frac{6(1-\varepsilon)\pi R^2}{d_r} \tag{8}$$

where d_r is the equivalent diameter of rock (m) and ε is the porosity.

The heat transfer coefficient h $(\mathrm{W/m^2\,°C})$ in the above equations is based on the analysis provided by [17] for porous media.

$$h = 0.191\frac{\dot{m}\ C_f}{\varepsilon \pi R^2} Re^{-0.278} Pr^{-2/3} \tag{9}$$

where the Re is the modified Reynolds number for porous media, defined as [17]:

$$Re = \frac{4Gr_{char}}{\mu_f} \tag{10}$$

where G is the mass flux of fluid through the porous bed expressed as:

$$G = \frac{\dot{m}}{\varepsilon \pi R^2} \tag{11}$$

and r_{char} is defined at the characteristic radius by [17] (sometimes defined as the hydraulic radius)

$$r_{char} = \frac{\varepsilon d_r}{4(1-\varepsilon)} \tag{12}$$

2.2.2 Energy Balance Equation for Filler Material

For the energy balance of the filler material (rocks), the same control volume dz was considered. The filler works only to deliver/extract heat to/from the passing fluid at the cost of a change in the internal energy of the filler. The energy balance equation is given by the following expression:

$$hS_r\left(T_r - T_f\right)dz = -\rho_r C_r (1-\varepsilon)\pi R^2 dz \frac{\partial T_r}{\partial t} \tag{13}$$

with substitution of dimensionless variables given in Eq. (5, 6), the above governing equation becomes as:

$$\frac{\partial \theta_r}{\partial t^*} = -\frac{H_{CR}}{\tau_R}\left(\theta_r - \theta_f\right) \tag{14}$$

where

$$H_{CR} = \frac{\varepsilon \rho_f C_f}{\rho_r C_r (1-\varepsilon)}$$

The dimensionless form of governing equations will also assist experimental test on a small-scale prototype thermocline system, which only values of τ_R and H_{CR} need to be matched to a real-size thermocline storage tank.

3 METHOD OF CHARACTERISTICS

3.1 Numerical Solution

The non dimensional energy balance equations for heat transfer fluid and rocks can be solved numerically along the characteristics [18]. Equation (7) can be reduced along the characteristic $t^* = z^*$, so that we can have:

$$\frac{D\theta_f}{Dt^*} = \frac{1}{\tau_R}(\theta_r - \theta_f) \qquad (15)$$

Separating and integrating along the characteristic,the equation becomes as:

$$\int d\theta_f = \int \frac{1}{\tau_R}(\theta_r - \theta_f)dt^* \qquad (16)$$

Similarly, Eq. (14) for the energy balance of rocks is reposed along characteristic $z^* = const$, so that

$$\frac{d\theta_r}{dt^*} = \frac{-H_{CR}}{\tau_R}(\theta_r - \theta_f) \qquad (17)$$

The solution for Eq. (17) is very similar to that for Eq. (15) but with an additional factor of H_{CR}. The term H_{CR} is simply a fractional ratio of fluid heat capacitance to rock heat capacitance. Therefore the equation for solution of θ_r will react with dampened speed than θ_f, as the filler material must have the capacity to store the energy being delivered to it, and vice versa.

Finally, separating and integrating along the characteristic for Eq. (17) as:

$$\int d\theta_r = \int \frac{-H_{CR}}{\tau_R}(\theta_r - \theta_f)dt^* \qquad (18)$$

There are now two characteristic equations bound to intersections of time and space. A discretized grid of points, laid over the time space dimensions, will have nodes at these intersecting points. Therefore, Eq. (16) can be definitely integrated numerically as:

$$\int_{v_{1,1}}^{v_{2,2}} d\theta_f = \int_{v_{1,1}}^{v_{2,2}} \frac{1}{\tau_R}(\theta_r - \theta_f)dt^* \qquad (19)$$

The numerical integration of the right hand side is performed via the trapezoidal rule and the solution is expressed as follows:

$$\theta_{f_{2,2}} - \theta_{f_{1,1}} = \frac{1}{\tau_R}\left(\frac{\theta_{r_{2,2}} + \theta_{r_{1,1}}}{2} - \frac{\theta_{f_{2,2}} + \theta_{f_{1,1}}}{2}\right)\Delta t^* \qquad (20)$$

where $\theta_{f_{1,1}}$ is the value of θ_f at $v_{1,1}$ and $\theta_{f_{2,2}}$ is the value of θ_f at $v_{2,2}$, and similarly so for θ_r .

The integration for Eq. (18) along $z^* = \text{const}$ is:

$$\int_{v_{2,1}}^{v_{2,2}} d\theta_r = \int_{v_{2,1}}^{v_{2,2}} \frac{-H_{CR}}{\tau_R}(\theta_r - \theta_f)dt^* \qquad (21)$$

The numerical integration of the right hand side is also performed via the trapezoidal rule and the solution is given by:

$$\theta_{r_{2,2}} - \theta_{r_{2,1}} = \frac{-H_{CR}}{\tau_R}\left(\frac{\theta_{r_{2,2}} + \theta_{r_{2,1}}}{2} - \frac{\theta_{f_{2,2}} + \theta_{f_{2,1}}}{2}\right)\Delta t^* \qquad (22)$$

Equations (20) and (22) can be reposed as a group of algebraic equations for two unknowns of $\theta_{f_{2,2}}$ and $\theta_{r_{2,2}}$, while θ_f and θ_r at grid points $v_{1,1}$ and $v_{2,1}$ are known will be demonstrated in the next work.

3.2 Simulation by TRNSYS

After its implementation in the TRNSYS16 TESS library, the model (type 536), was integrated into an evaluation project under different climatic zones in Morocco.

We use the TRNSYS16 software to simulate the prototype. All parameters of the CSP were introduced in the TRNSYS model shown in Fig. 2.

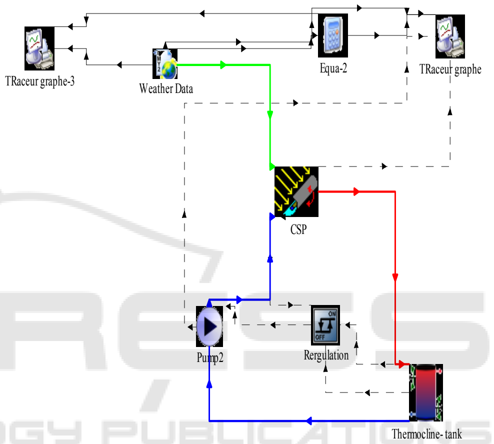

Figure 2: Simulation by TRNSYS of a CSP plants with Thermocline- Tank.

We use the TRNSYS16 software to simulate CSP system using Solar Salt as the HTF in the first case.

According to the objective of the present study that investigates the thermal performance of a thermocline TES system for CSP plants under the Moroccan meteorological data, the selected location is Errachidia city, which is the second most important insolation region in Morocco.

Fig. 3 shows the variation of the ambient temperature and the wind velocity through out the year for Errachidia site.

In the following section, the dynamic results are presented during a representative week (first week of July) and the variation of useful gain energy and direct normal irradiation are summarized throughout the year with different HTFs using in the first case Solar Salt.

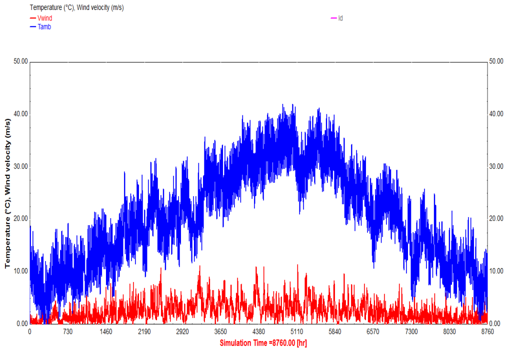

Figure 3: Annual ambient temperature and wind velocity

Fig. 4 shows the hourly variation of the outlet temperature of the CSP collector. It can be observed that HTF outlet temperature at the solar collector varies periodically with time and its minimum value can reach ambient temperature (Tamb) value during de day time.

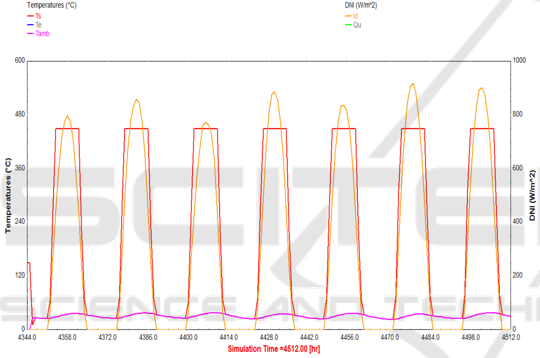

Figure 4: Variation of Solar Salt outlet temperature at the collector (CSP) and ambient temperature during the first week of July.

4 CONCLUSIONS

This paper describes a mathematical model of a thermocline TES system, which is expected to be a core technology for CSP plants.

A non-thermal equilibrium model is used for investigating the effect of different HTFs on the thermal performance of a thermocline thermal energy storage system using Therminol, Solar Salt and HITEC respectively as the HTFs and quartzite rock as the filler material. As future work, we prospect to study the performance and the simulation of our mathematical model by TRNSYS software and add the control of TES systems in the tank for concentrated solar power plants. And we prospect to study Thermal characteristics, including temperature profiles and discharge effectiveness of storage tank. In ordre to plot and to analyse charging and discharging curves at different porosity values for Therminol, Solar Salt and HITEC.

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