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MODELLING AND SIMULATION OF A SUSTAINABLE THERMAL ENERGY STORAGE SYSTEM FOR CONCENTRATING SOLAR POWER (CSP) PLANT USING ECO-MATERIALS

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Abstract

This paper addresses industry sector like concentrating solar power (CSP) plant used for electricity generation. Up till now, this technology is not affordable for developing countries where CSP potential is good. To contribute on the improvement of CSP technology, ceramic balls using sand clay and industry waste (coal bottom ash) have been developed for sensible heat storage. In this paper, the one dimensional two phase model has been chosen to predict the behaviour of the ceramic oil and vegetal oil (Jatropha curcas oil) thermal energy storage system. The results show that high porosity (> 45%), filler material with big size and high fluid velocity are not required for thermal energy storage because of the degradation of the thermocline. Taking into account a tank ratio H/D of 2.5 and a total stored energy of $2MWh_{th}$, the results show a possibility to reach a discharge time of 9 hours with discharge efficiency of more than 90%. The thermocline thickness variation under the variation of fluid velocity, particle diameter, tank porosity shows that for an effective thermal energy storage system, the thermocline maximal thickness is around one third of the packed-bed height. To conclude, the developed ceramic ball and Jatropha curcas oil could be considered as an innovative and cost-effective for thermal energy storage in CSP or other applications like solar cooker.

1. Introduction

Renewable energy is anticipated to play a vital role in the future as global energy demand is growing and conventional sources like petroleum and coal are depleting. One promising renewable resource technology is that of concentrating solar power (CSP) plants [1, 2]. This explains the high initial investment of 15% to 20% associated with the two-tank storage system and the high price of heat transfer fluid (HTF) like synthetic and mineral oil also used as storage medium at the SEGS plant since 1984 [3].

Besides, mineral oil is highly flammable, for instance, in the 2009 fire event at the solar field of the Andasol CSP plant in Spain [4]. As an intermediary solution, an engineering study in 2004 shows a possible reduction of 10% of levelized electricity cost using molten salt in the storage medium [3], which became the most effective thermal energy storage material used in most CSP plants like Andasol and Ouarzazate [5, 6]. The molten salt is also compromised due to its high melting temperature and the complex management of its thermal stability [4, 7, 8]. A better option is the possibility to have a greater reduction of CSP cost of about 33% to 35% by cancelling one tank of the storage system and using eco-materials such as natural rocks, stone and industrial waste as filter materials [9, 10]. This one-tank technology called *thermocline energy storage* uses a single tank to store thermal energy [5, 11-14] and is reviewed by [15].

This paper, thus, aims to assess numerically the behaviour of a new storage system under thermal cycling as experimentally and numerically done in [16] with phase change material (PCM) and quartzitic and rapeseed oil. Ceramic balls are first developed using sand, clay, and coal bottom ash (CBA) [17] and put in contact with Jatropha curcas oil for three months (see Figure 1) in the framework for sensible heat storage. Then a numerical performance analysis is carried out on the ceramic balls-JCCO thermocline energy storage system to access the behavior of the new storage system.

Figure 1. Aspect of some ceramic balls (right) and JCCO before or during heat (left) treatment.

The article is organized into sections: Section 1 introduces thermal energy storage while Section 2 describes the model. Section 3 presents the numerical simulations while Section 4 focuses on model validation. Finally, the conclusion is presented in Section 5.

2. Model Description

Different numerical models are often used to assess the performance of storage systems [15, 16]. Most of these models have been developed based on the Schuman model since 1929 [14] depending on assumptions and the number of dimensions. There are two broad categories depending on whether a significant thermal gradient inside the solids is considered or not. Then differentiation can be made according to the number of phases (fluid, solid, walls) accounted for or the number of dimensions (1D or 2D) [15, 18]. All these models are developed either to reduce the computation time or to achieve better prediction of experimental results. For example, 1D-1phase model can compute faster than 1D-2P and the one-dimensional intra-particle conduction model while the last two give better results taking, respectively, the overall heat exchange between solids and fluids and, in addition, to the increasing conduction resistance inside solids [18]. In this study, the performance of the ceramic ball-JaCCO packed-bed TES system is assessed using the 1D-2P model.

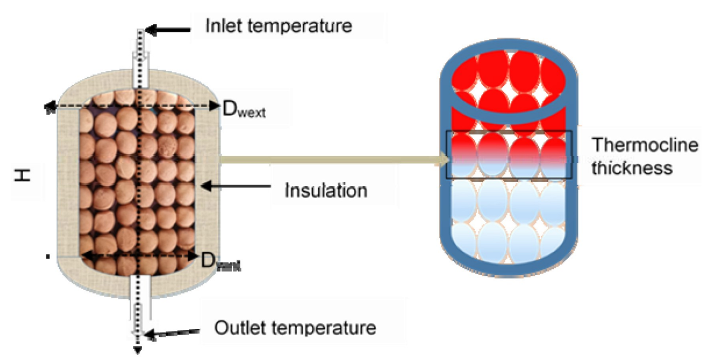


Figure 2. Ceramic balls and JCCO thermal energy storage model.

In literature, vegetal oil like rapeseed oil and quartzitic thermocline systems have been numerically analysed and implemented [10]. Jatropha curcas thermal stability has been assessed in several studies without any thermal performance assessment like storage and discharge efficiencies, and effect of the different parameters such as fluid velocity, particle diameter, tank porosity and volumetric heat capacity on the TES performance. The TES model is presented in Figure 2. Equations (1) and (2) are used to describe the energy balances occurred in the system.

The liquid phase energy balance

$$\varepsilon(\rho c_p)_f\left(\frac{\partial T_f}{\partial t} + u\frac{\partial T_f}{\partial z}\right) = \lambda_{feff}\left[\frac{\partial^2 T_f}{\partial z^2}\right] + h_v(T_p - T_f) + 4\frac{U_w}{V_{total}}(T_{ext} - T_f). \quad (1)$$

The solid phase energy balance

$$(1-\varepsilon)(\rho c_p)_s\left(\frac{\partial T_s}{\partial t}\right) = \lambda_{peff}\frac{\partial^2 T_s}{\partial z^2} + h_v(T_f - T_p), \quad (2)$$

where T_f is the fluid temperature, T_p the filler material or solid particle temperature, ε the tank porosity, ρ the density, c_p the specific heat capacity, f for the fluid, s for the solid, λ_{eff} the effective thermal conductivity, h_v the interstitial heat transfer coefficient, and U_w the heat loss.

The equations were obtained with the following assumptions:

- Fluid velocity and temperature distribution are only in axial direction:

$$\overrightarrow{u_r} = \vec{0}, \quad \frac{\partial T}{\partial r} = 0. \quad (3)$$

- HTF flows through the packed-bed in laminar regime.
- Particle bed porosity in the tank is homogenous.
- Properties of the solid particle are independent of temperature.
- Inlet temperature is constant. Also, the velocity is constant.
- For solid, filler materials are spherical with a very small contact surface, so that there is no heat conduction between the particles.

- Heat conduction occurs in fluid phase in axial direction.

- The properties of the fluid are computed at the film or average temperature.

The velocity of the fluid inside the filler bed is calculated from the density of the fluid, the tanks' cross-sectional area and the mass flow rate data as in equation (4):

$$u = \frac{\dot{m}}{\rho_f \times \left(\varepsilon\pi\left(\frac{D}{2}\right)^2 \right)}. \quad (4)$$

The key thermo-physical properties used to estimate the heat transfer inside the packed-bed system are the effective thermal conductivities of HTF and solid fillers, respectively, λ_{feff} and λ_{peff}. The various effective thermal conductivity models that have been set up over the past few years are presented in [19]. In this paper, the effective thermal conductivities (equation (5)) are considered to study the impact of different effective thermal conductivities:

$$\lambda_{feff} = \varepsilon \times \lambda_f, \quad \lambda_{peff} = (1 - \varepsilon) \times \lambda_p. \quad (5)$$

The interstitial heat transfer coefficient h_v between solid and fluid is calculated using (6) as follows [19]:

$$h_v = \frac{6(1 - \varepsilon)k_{f[2+1.1\times Re_p^{0.6} pr^{1/3}]}}{d_p^2}. \quad (6)$$

The global heat transfer coefficient U_w for evaluating thermal losses to the environment in W/K is given by

$$U_w = \frac{1}{R_{th}}, \quad (7)$$

where

$$R_{th} = \frac{1}{h_{ext} \times A_{w,ext}} = \frac{\ln\left(\frac{r_{w,ext}}{r_{w,int}}\right)}{2 \times \pi \lambda_{insul} \times H} + \frac{1}{h_{air} \times A_{w,ext}}. \tag{8}$$

Boundary and initial conditions

Initial conditions of discharge are as follows:

$$T_f(t = 0) = T_p = T_{exp}(t = 0). \tag{9}$$

Since the numerical models consider one-dimensional media, the boundary conditions during a discharge consider only one on the top and the other on the bottom of the tank. The cold heat transfer fluid enters the tank from the bottom, which means inlet temperature and velocity for the fluid conditions and an adiabatic condition for the solid and the wall. On the bottom:

$$T_f(z = 0) = T_L, \tag{10}$$

$$\frac{\partial T_f}{\partial z}(z = 0) = \frac{\partial T_p}{\partial z}(z = 0) = 0. \tag{11}$$

The hot heat transfer fluid leaves the tank in an adiabatic condition for the solid and the fluid:

$$\frac{\partial T_f}{\partial z}(z = H) = \frac{\partial T_p}{\partial z}(z = H) = 0. \tag{12}$$

3. Numerical Method

The difference finite method was used to numerically discretize different equations. The backward differencing scheme was used for the first order derivative term, an implicit scheme was used for time discretization while the central differencing scheme was used for the second order derivative terms. The solution was found using an iterative approach based on the Gauss-Seidel computational method to compute one or two temperature vectors (particle and fluid) for each time step, at the same time. The convergence criterion was 10^{-3}. To simplify the model and to reduce the computational time, the fluid properties were computed at the mean temperature. The numerical model was coded and computed using an open access software FORTRAN force2. The technical specifications of the Lenovo Thinkpad used include an 8 GB 1600 MHz DDR3, memory, 2.6 GHz Inter ® core™ i5-3320M CPU, and 168 GB SSD hard disk.

4. Results and Discussion

4.1. Model validation

To assess the ability of the 1D-2phase model to provide reasonable predictions of the model described above, we compare and contrast with experimental results. The numerical results are validated using the experimental results of Hoffmann et al. and Pacheco et al. based, respectively, on 8.3kWh$_{th}$ lab scale packed-bed quartzite rapeseed oil and 2.3MWh$_{th}$ pilot scale packed-bed molten salt thermocline storage systems [10, 20]. Figure 3 illustrates the axial temperature profiles of the rapeseed oil and molten salt in storage tanks of the experimental and numerical results and Table 1 compares the different errors.

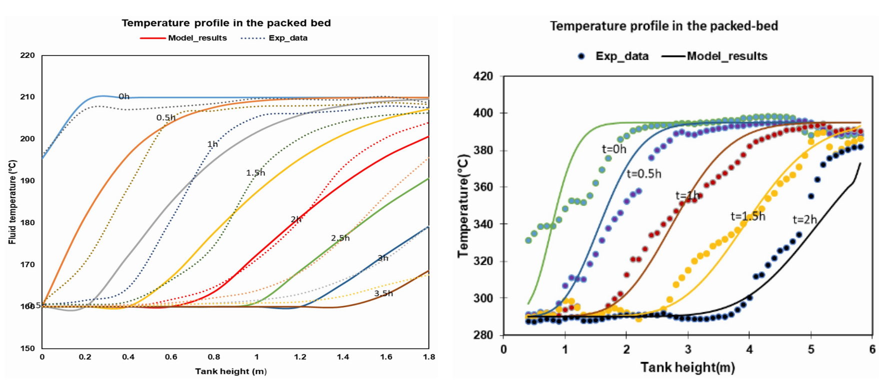


Figure 3. Model validation against experimental data from Hoffmann et al. (left) and Pacheco et al. (right).

The model errors, root mean square error (RMSE) and relative error are computed using the following equation [4]:

$$\text{RMSE} = \frac{1}{n} \times \sum \left(\frac{T_{exp} - T}{T_{exp}} \right)^2, \tag{13}$$

$$\text{relative error} = \frac{\text{experimental value} - \text{model value}}{\text{experimental value}}. \tag{14}$$

Table 1. Different errors of the model

Experimental data sources	1D-2P model	Mean error (°C)	Maximum error (°C)	RMSE
Hoffmann experimental data [21] (temperature profile)	Hoffmann model	3.58	13.77	1.4×10^{-4}
Hoffmann experimental data [21]	Our model	3.59	6.44	2×10^{-4}
Pacheco et al. experimental data [20] (temperature profile)	Our model	1.79	2.41	3.4×10^{-4}
Hoffmann experimental data [21] (outlet temperature)	Hoffmann model	2.11	4.52	1.9×10^{-4}
Hoffmann data	Our model	3.59	6.45	1.5×10^{-4}
Pacheco et al. experimental data [20]	Our model	1.75	2.33	3.2×10^{-4}

The simulation uses the properties in Table 2 of ceramic balls [17] developed.

Table 2. Thermal properties of ceramic balls

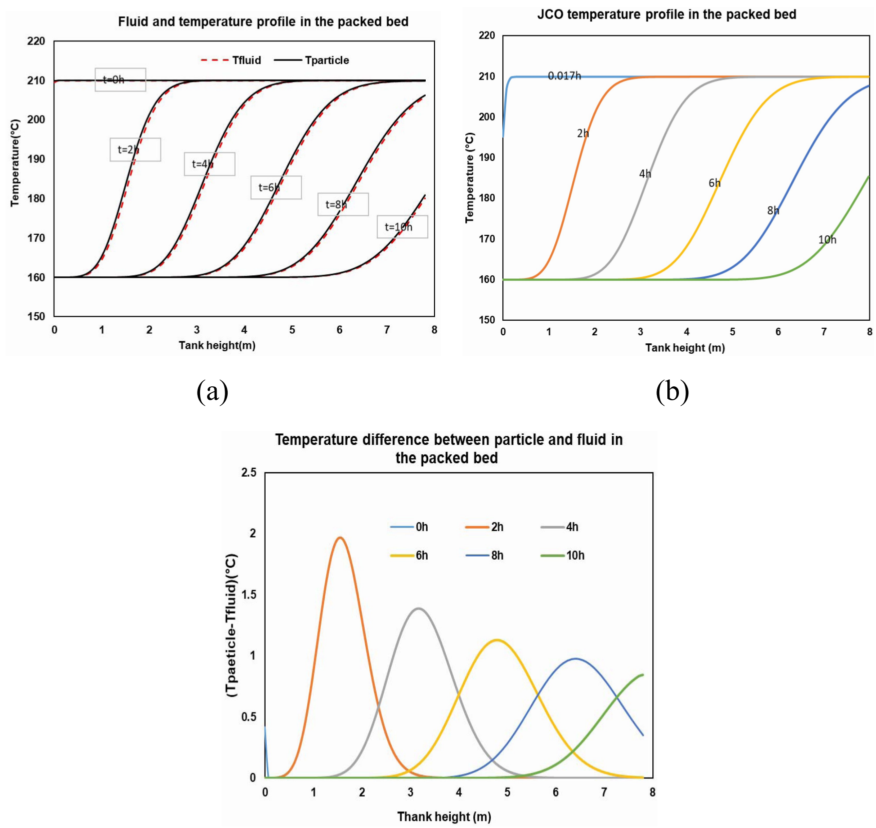
Properties	λ_p (W/m.K)	D (mm^2.s^{-1})	pCp (MJ.m^{-3}.K^{-1})	Cp (J/kg.K)
Ceramic balls	0.347	0.143	2.429	1026

Table 3. Thermal properties of Jatropha curcas oil [22] and authors

Dynamic viscosity (Pa.s.K^{-1})	$\mu_f = (14227.1512293829 \times (T_f)^{-1.63689632357044})/(1000000) \times \rho_f$
Density (kg.m^{-3})	$\rho_f = -0.7392 \times T + 933.47$
Specific heat capacity (J.kg^{-1}.K^{-1})	$c_{pf} = (2.262T^4 - 10.423T^3 + 12.947T^2 + 0.441T + 1.9608) \times 1000$
Thermal conductivity	$\lambda_f = 2.80T^2 - 2.258T + 0.1736$

4.2. Heat transfer profile between Jatropha curcas oil and ceramic balls

In this subsection, the general behaviour of heat transfer between JCCO and spherical ceramic during the discharging process is presented. The solid ceramic ball developed and used is of diameter 2.88. Figures 4(a) and 4(b) show the variations of (i) the fluid temperature profile, and (ii) fluid and solid temperatures at particle surface, respectively, with the discharging time, while Figure 4(c) is (iii) describes the temperature differences between them for 2MWh$_{th}$ ceramic balls-JCCO TES system.



(c)

Figure 4. (a) Fluid and temperature profile in the packed-bed, (b) JCO temperature profile and (c) temperature differences between fluid and particles.

4.3. Effect of fluid velocity, particle diameter and tank porosity on thermocline thickness and storage efficiencies

In idealized storage systems, hot and cold regions are perfectly separated ensuring no heat losses, and all thermal energies (Q) charged can be discharged at the same temperature level. In practice, however, performance degradation can occur due to heat losses to the environment as well as internal thermal diffusion inside the tank. To represent these effects, the discharge and storage efficiencies are as follow:

$$\eta_{discharge} = \frac{Q_{discharge}}{Q_{charge}} = \frac{\int_0^{t_{dischg}} \dot{m}C_{p,f}(T_{out} - T_{\min})dt}{\int_0^{t_{chg}} \dot{m}C_{p,f}(T_{\max} - T_{\min})dt}, \quad (15)$$

$$\eta_{storage} = \eta_{discharge} \times \eta_{charge} \text{ with } \eta_{charge} = \frac{Q_{charge}}{Q_{total}}. \quad (16)$$

Figures 5 and 6 present the effect of fluid velocity, particle diameter and tank porosity on thermocline storage performance. The effect of fluid velocity shows that for high fluid velocity u, JCCO flows faster through the packed-bed, indicating a larger heat discharging rate with discharging time less than 1.5h. The thermocline thickness is more stable when the fluid velocity decreases. When the inlet velocity decreases, the discharging time increases significantly for higher than 9h (see Figure 5(a)). However, the effect of JCCO inlet velocity affects slightly the storage efficiencies (see Figure 5(b)). Therefore, the increase of particle diameter can decrease the storage efficiencies of 3.17% (Figure 6(a)) when the diameter increases from 1cm to 3cm and the discharge and storage efficiencies show a decrease of 3.83% and 5.7% when the tank porosity increases from 40% to 50% as illustrated in Figure 6(b). However, Figure 6(b) shows that the tank porosity should be less than 45%.

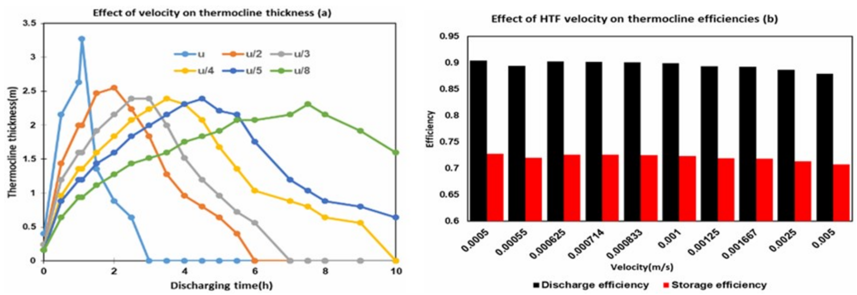


Figure 5. Effect of fluid velocity on thermocline thickness and thermocline energy efficiencies.

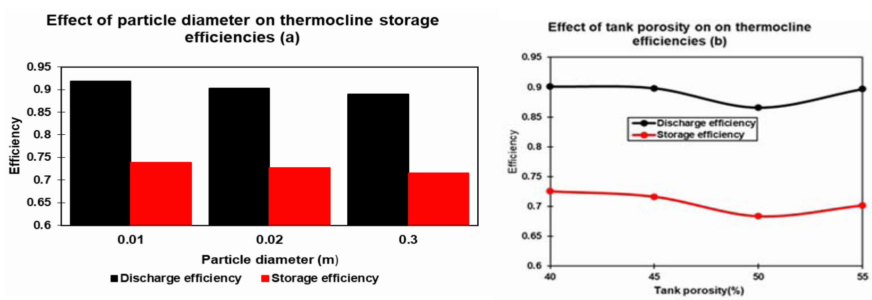


Figure 6. Effect of particle diameter and tank porosity on thermocline efficiencies.

5. Conclusion

In this paper, a one dimensional two phase simple model has been developed to study the performance of packed-bed thermal energy storage system. The model validation shows maximum relative errors of 6.44% and 2.41%, respectively, for rapeseed oil and molten salt as heat transfer models. After the validation of the model, the performance of new thermocline energy storage system (ceramic balls-JCCO) has been accessed. The results show that low fluid velocity is required to avoid larger heat discharging rate and faster degradation of the thermocline thickness. High particle diameter and tank porosity decrease the thermocline energy storage efficiency. The implementation of this new TES system could be applied in addition to CSP plants to solar cooker, air washer and solar drier [23-25].

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