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Packed-bed Thermal Energy Storage Analysis: Quartzite and Palm-Oil Performance

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Abstract

A packed bed for solar energy storage in the form of sensible heat has been investigated using two-phase continuous model. The system contains Quartzite as the filler material and Palm oil as the heat transfer fluid. The aim of this work is to propose an eco-friendly storage system which uses natural concrete and certified sustainable oil for medium temperature thermal storage. Using the developed model, the performance of the Palm oil has been compared with two different synthetic oils which has shown that the Palm oil could efficiently be used as a heat transfer fluid for a working temperature below 300°C.

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Keywords: sensible heat; energy storage; packed bed; continuous model; Quartzite; Palm oil.

1. Introduction

Solar energy is one of the sustainable solutions to limit the greenhouse gases emitted by conventional energy systems. Great efforts have been devoted in this field for small and large scale development. However, the alternative character of solar energy still represents a real challenge for scientific research. In this context, energy storage is one of the promising key to correct partially the variability of the solar radiations by enlarging the operating hours of the solar system and improving its autonomy.

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Research in the field has shown that concentrated solar power technologies are easily coupled with thermal energy storage systems [1]. Among the existing types, sensible heat storage has been the most suitable, in terms of thermal efficiency and cost effectiveness, for concentrated solar power systems (CSP). While molten salt and synthetic oil are widely used for utility scale [1], different researches are progressing in other thermal energy storage types.

Actually, the present work is part of the COLDSUN project which aims to study theoretically and experimentally the coupling of solar Fresnel field to double effect absorption machine to produce air conditioning. In order to improve the reliability of the installation, the system has sensible heat thermal energy storage (SHTES) unit to store excess energy during the day time and restore it when the solar radiations are insufficient to run the absorption cycle. In this paper, the focus is on the thermal storage system (TES), which is a one tank thermocline with a packed bed of rocks and has oil as the heat transfer fluid (HTF).

Nomenclature

a_{sf}	specific surface area [m^{-1}]
Bi	Biot number
C_p	thermal heat capacity [$JKg^{-1}K^{-1}$]
D	diameter of the bed [m]
d_p	equivalent rock diameter [m]
h_{sf}	interstitial convective heat transfer coefficient [$W/m^{-2}K^{-1}$]
H	height of the bed [m]
k	thermal conductivity [$W.m^{-1}K^{-1}$]
K	permeability [m^2]
m_f	mass flow rate [$Kg.s^{-1}$]
Re	Reynolds number
T	temperature [K]
ΔP	pressure drop [Pa]
t	time [s]
v	velocity [$m.s^{-1}$]
z	axial coordinate [m]
	Greek letters
ε	porosity of the bed [m]
μ	dynamic viscosity [Pa.s]
ρ	density [$Kg.m^{-3}$]
	Subscripts
f	fluid
in	inlet
re	recovering
s	solid
st	storage
0	initial

The reduced cost of the one tank thermocline comparing to the two tanks indirect TES has attracted several studies [2,3,4]. While many previous works have considered air as the heat transfer fluid [5,6], in this study, the Palm Oil with Quartzite have been investigated. The choice of the working fluid is actually motivated by the eco-friendly aspect of using natural and certified sustainable oil instead of conventional or synthetic oils that impact the environment. Furthermore, Quartzite is a low cost and widely abundant rock that has been identified as a good filler material, being suitable for direct thermal storage and providing appropriate thermo-physical properties [7,8].

The analysis presented in this paper is based on two-temperature transient model which has been numerically solved using explicit scheme. Simulations have been run to test the performance of the Palm oil and the filler material considering different design parameters. The paper presents also a performance comparison between the Palm-Oil and two different synthetic oils.

2. Methodology

2.1. System description

The packed bed storage system is a porous media consisting of multiple solid packed particles that store thermal energy delivered by the hot fluid and restore it when in need. Actually, the porosity allows the circulation of the fluid inside the bed, so when charging, the hot HTF, coming from the solar field, enters from the top of the bed and transfers energy to the solid particles. In the recovering,

the flow is reversed and the cold HTF is pumped from the bottom of the tank to be heated up by the energy previously stored in the solid particles as it is shown in Fig.1.

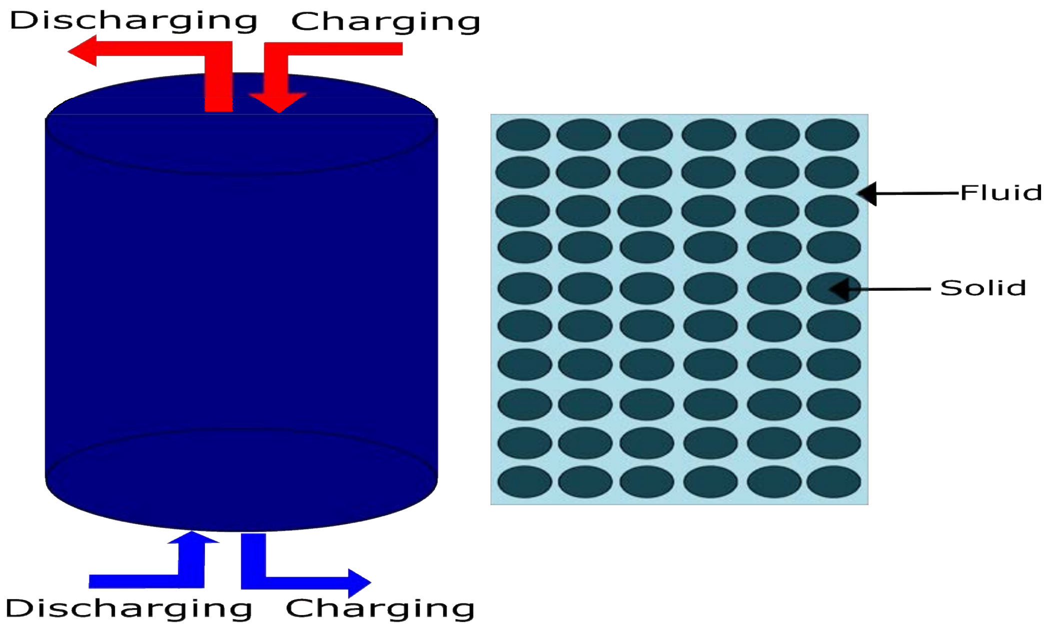

Fig. 1. Schematic of the packed bed thermal energy storage system.

2.2. Heat transfer model

The modelling was carried out using a transient two-temperature model with respect to the following assumptions*:*

- Unsteady state temperature model;
- Local thermal non-equilibrium;
- Homogeneous, isotropic and non-deformable porous media;

- The fluid flow is incompressible;
- The flow field is steady state;
- The velocity is fully developed;
- Darcy law is applied for Re<1 and Ergun equation for Re⩾1;
- Homogeneous intra-particle temperature distribution (Bi<1);
- Heat transfer by radiation and heat losses to the surrounding are neglected.

The model is based on two phase unsteady energy conservation equations Eq.(1) and Eq.(2), the pressure drop has been expressed by Darcy's law Eq.(3) for small Reynolds number and with the Ergun equation Eq.(4) for higher Reynolds. Energy equations were discretised using explicit finite volume scheme and then coded in C language with respect to the stability conditions [9].

$$\rho_f C_{p,f}\varepsilon\frac{\partial T_f}{\partial t}+\rho_f C_{p,f}v_f\frac{\partial T_f}{\partial z}=\varepsilon k_f\frac{\partial^2 T_f}{\partial z^2}-h_{sf}a_{sf}(T_f-T_s) \quad (1)$$

$$\rho_s C_{p,s}(1-\varepsilon)\frac{\partial T_s}{\partial t}=(1-\varepsilon)k_s\frac{\partial^2 T_s}{\partial z^2}+h_{sf}a_{sf}(T_f-T_s) \quad (2)$$

$$\Delta P=\frac{\mu}{K}\,v_f H \quad (3)$$

$$\Delta P=150\mu H\frac{(1-\varepsilon)^2 v_f}{\varepsilon^3 {d_p}^2}+1.75\rho H\frac{(1-\varepsilon)\,{v_f}^2}{\varepsilon^3 d_p} \quad (4)$$

3. Results and discussion

The developed code has served to simulate the performance of a packed bed SHTES system filled with Quartzite particles and had Palm oil as the working fluid. The conducted simulations considered two different volume capacities of the tank: $5m^3$ and $100m^3$. On the other hand the performance of the Palm oil was compared to industrial synthetic oils up to a maximum working temperature of 573 K.

3.1. Performance study

In the following section, we present the simulation results of the developed model using the Palm oil and Quartzite. The solid and fluid temperature distributions have been simulated and presented in figures 2 and 3. In addition, the storage and recovering efficiencies were given for different mass flow rate values. The simulation parameters for figures 2, 3 and 4 are presented in the table below:

Table 1. Simulation data inputs for the packed bed energy storage system.

Parameter	Value
Solid material	Quartzite
HTF	Palm oil
$T_{f,in}$	533 K
T_{s0}	298 K
m_f	0.3 $Kg.s^{-1}$
H	6 m
D	4.6 m
d_p	0.02 m
ε	0.35
t_{st}	8 hours
t_{re}	3 hours

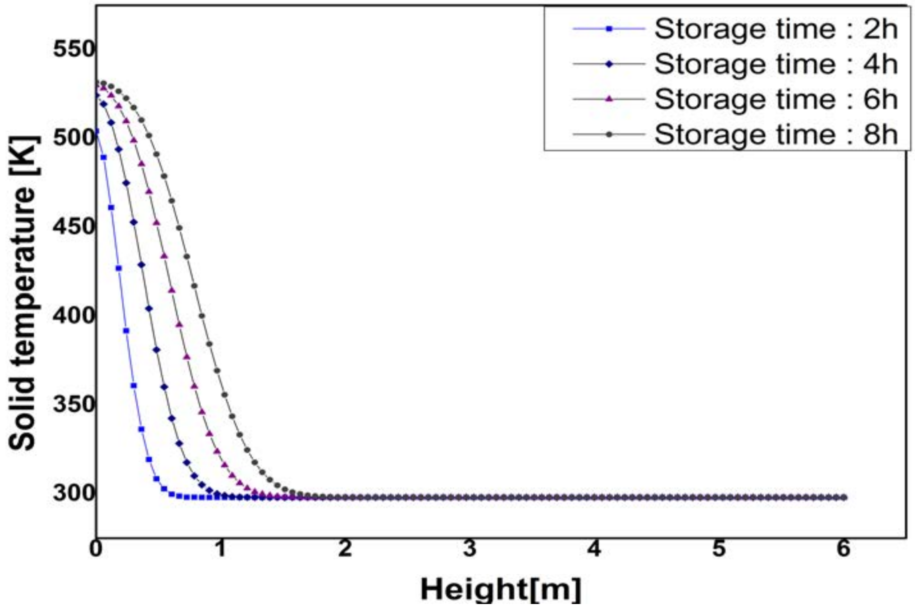

Fig. 2. Solid temperature axial distribution for different charging periods.

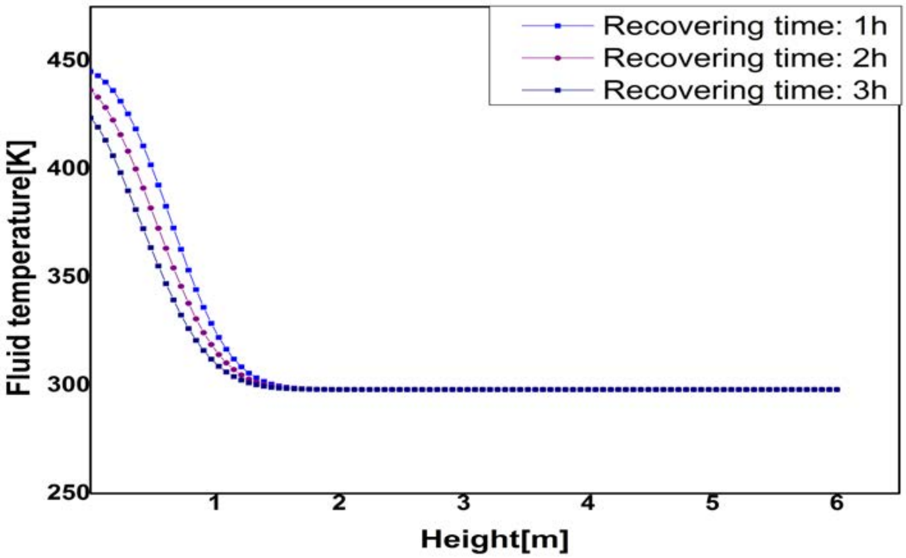

Fig. 3. Fluid temperature axial distribution for different recovering periods.

Fig.2 illustrates the axial distribution of the solid temperature inside the bed for different charging times. As it can be seen, the temperature decreases from high values at the top of the bed to low temperatures at the bottom, which points out the thermal stratification character of the thermocline, the figure shows also the increase of the solid temperature when increasing the charging periods.

Fig.3 shows the fluid temperature distribution during the recovering period, the HTF is heated up when flowing inside the bed, its temperature increases from 298 K, to 420 K at the end of the discharging time.

Fig.4 gives the storage and recovering efficiencies for varying mass flow rates of the HTF, the storage efficiency varies from 0.74 to 0.59 and decreases when increasing the mass flow rates. In other hand, the recovering efficiency varies from 0.36 to 0.53 and increases with higher values of the mass flow rate. The efficiencies mentioned earlier are for a one cycle of charge and discharge.

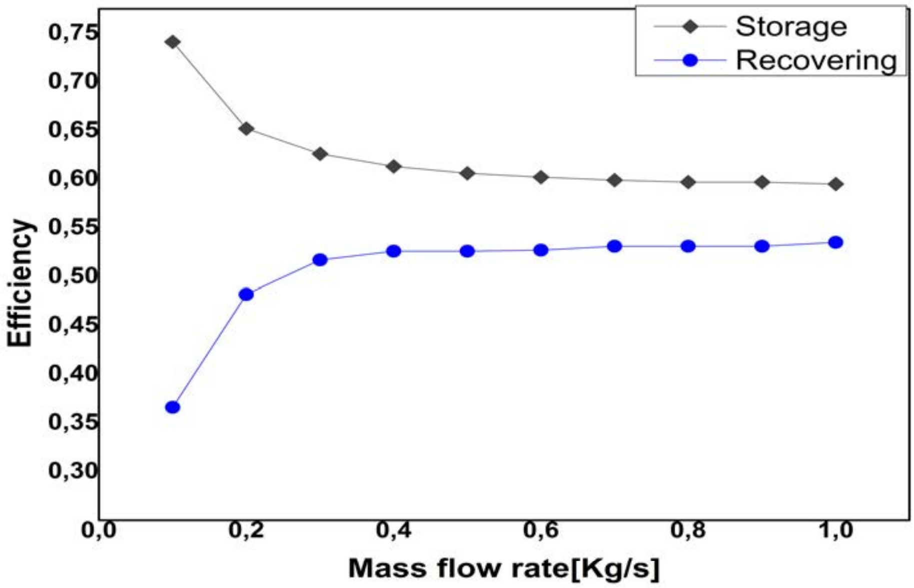

Fig. 4. Efficiencies of one cycle of charge (8h) & discharge (3h) for different mass flow rates

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3.2. Comparison with other fluids

In this section, we have compared the performance of the Palm Oil with two different synthetic oils that have been successfully used in concentrated solar power plants around the world: The first oil is Therminol-VP1, used in Genesis solar energy project- USA and the second one is the DowthermA used in both Nevada Solar One- USA and Noor I- Morocco.

Thermal parameters used in the simulation are for a fixed fluid temperature equal to 533 K, taken from the industrial available tables in literature:

Table 2. Thermal parameters of the HTFs used in the simulations at 533 K temperature.

Parameter	Palm	DowthermA	TherminolVP-1
$\mathbf{C_p}$ ($JKg^{-1}K^{-1}$)	2680	2245	2207
$\boldsymbol{\rho}$ ($Kg.m^{-3}$)	789.4	849	858
k ($W.m^{-1}K^{-1}$)	0.1575	0.1003	0.104
$\boldsymbol{\mu}$ (Pa.s)	$1.674\ 10^{-3}$	$0.27\ 10^{-3}$	$0.272\ 10^{-3}$

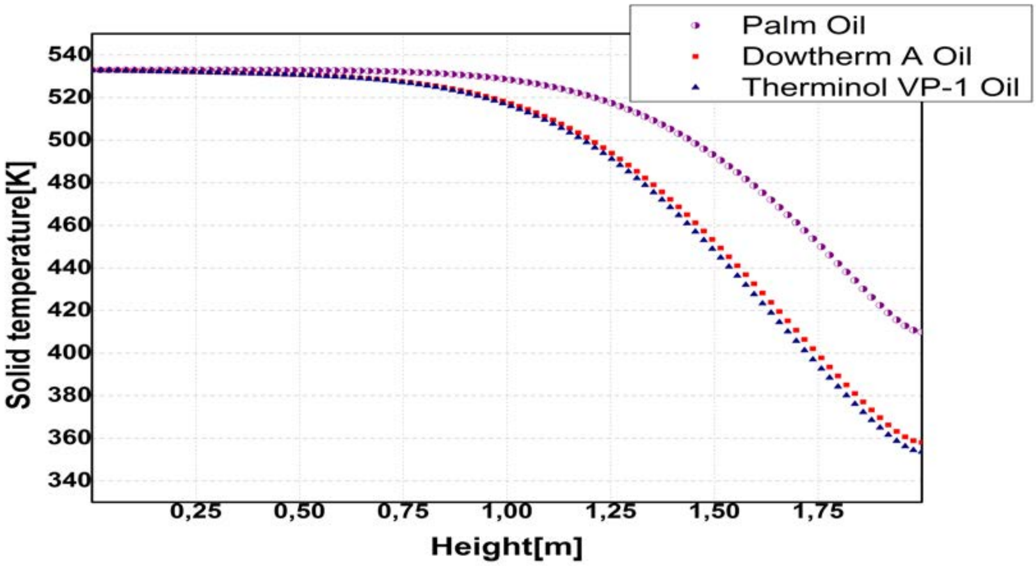

Fig. 5. Solid temperatures distributions for varying HTFs ($m_f = 0.1\ \mathrm{kg.s^{-1}}, D = 1.78\mathrm{m},\ \mathrm{H} = 2\mathrm{m}$).

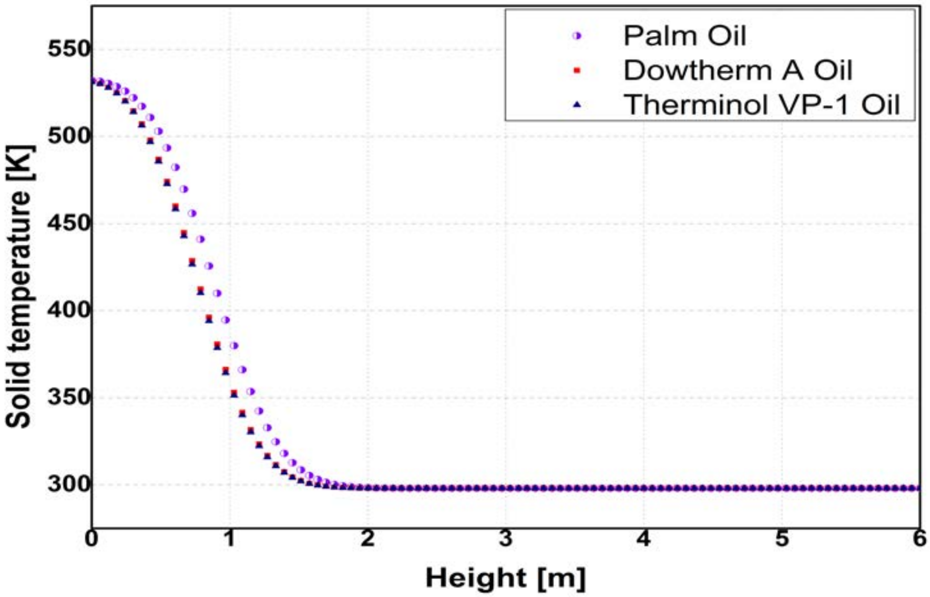

Fig. 6. Solid temperatures distributions for varying HTFs ($m_f = 0.3\ \mathrm{kg.s^{-1}}, V = 100m^3$).

Fig.5 and Fig.6 show the axial solid temperature distribution across the bed after 8 hours of charging for the three different oils, the results are obtained using the simulation parameters in table 1 with the difference that Fig.5 is for ($m_f = 0.1\ \mathrm{kg.s^{-1}}, V = 5m^3$) and Fig.6 is for($m_f = 0.3\ \mathrm{kg.s^{-1}}, V = 100m^3$).

In Fig.5 the temperature distribution obtained using the Palm oil shows a rapid convergence to the steady state conditions comparing to the synthetic oils, while in Fig.6 the solid temperatures are approximately the same for the three different oils.

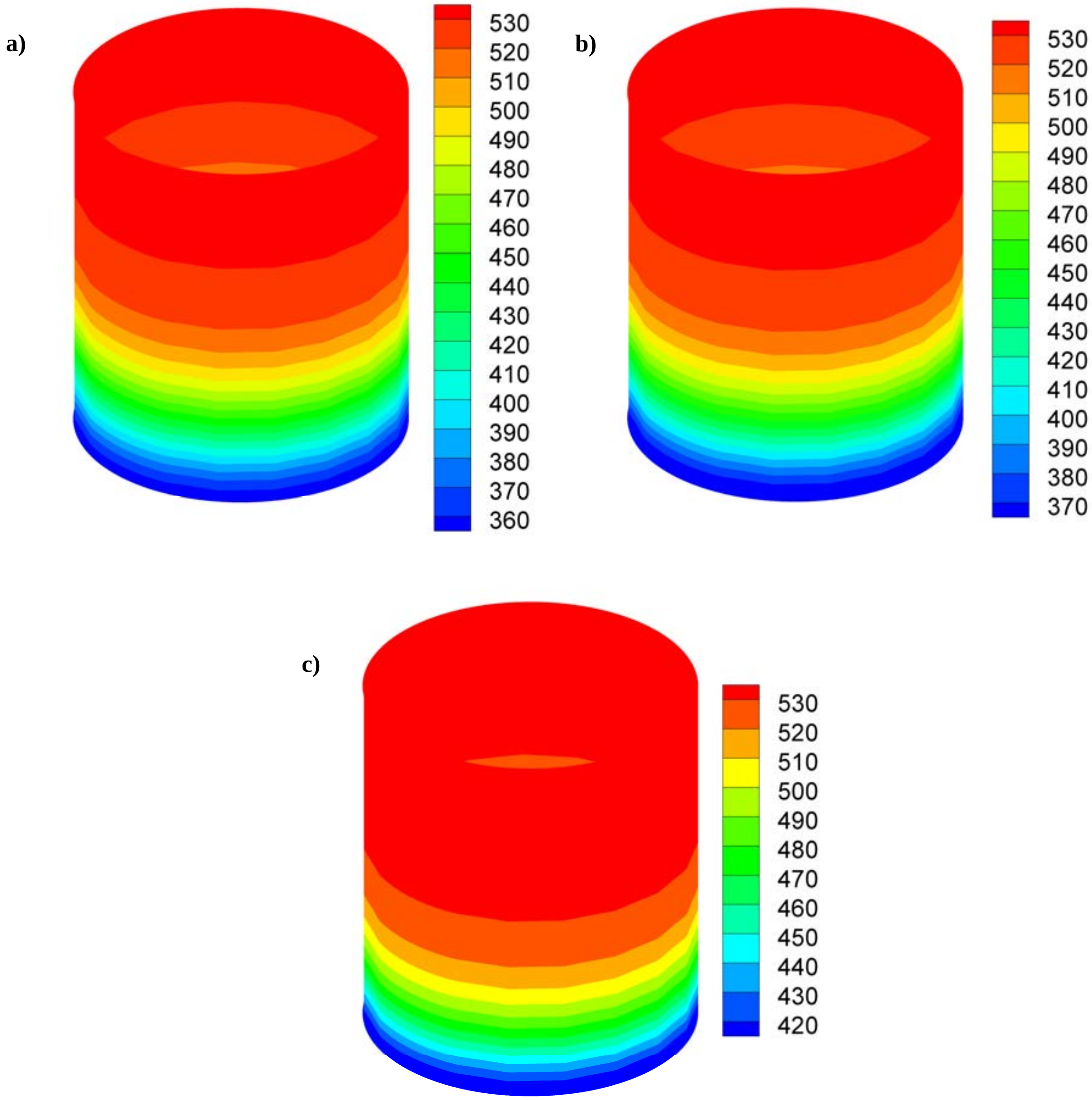

Fig. 7. 3-D axial solid temperatures for different HTFs: a) Therminol VP-1; b) Dowtherm A; c) Palm.

Fig.7 shows the 3-D axial solid temperature inside the packed bed, the printed figures (a, b and c) correspond to the simulation parameters given in table 1 and table 2, with a mass flow rate of 0.1 $kg.s^{-1}$, a total bed volume of $5m^3$ and a charging period equal to 9 hours.

As it can be seen, the temperature distribution for the tank (c), using the Palm oil, shows a higher temperature gradient than the solid temperatures inside the other tanks (a & b), using synthetic oils, this means that the Palm oil can insure the same performance with lower inlet fluid temperature or reduced charging time.

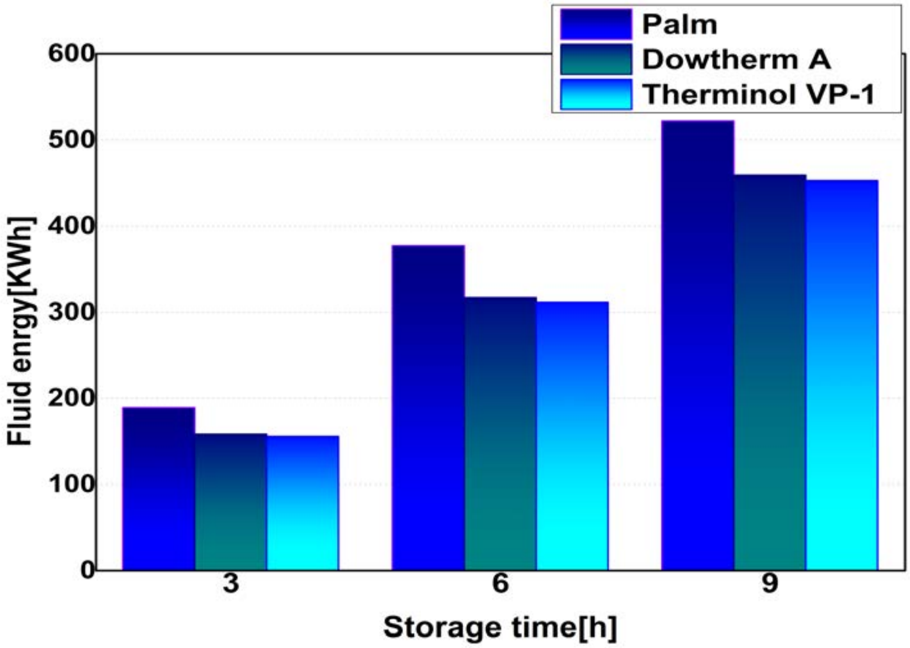

Fig. 8. Fluid energy for varying HTFs at different storage periods ($m_f = 0.1\ \mathrm{kg.}s^{-1}, D = 1.78\mathrm{m},\ \mathrm{H} = 2\mathrm{m}$)

Fig.8 illustrates the flow energy given by the studied HTFs for varying charging periods. As it can be seen, the energy delivered by the Palm oil is higher than the energy given by the DowthermA oil, which is slightly higher to the flow energy of the Therminol VP-1.

Actually, the amount of energy transferred by the Palm oil is 16% higher than the amount transported with other HTFs at the same fluid temperature, which indicates the ability of the Palm oil to be used as a heat transfer fluid in thermal energy storage systems.

4. Conclusion

A two phase dynamic model of packed bed thermal energy storage has been presented. The model has been used to test the performance of the Palm oil as the heat transfer fluid in a packed bed of Quartzite. A comparison study with other working fluids used in industrial scale concentrated solar power systems has also been presented. The results show higher solid temperature distribution when charging with the Palm oil than when charging with the other synthetic oils. Simulations have shown efficiencies of storage and recovering between 0.35 and 0.75 for a one cycle of charge and discharge. This study should be completed with an experimental investigation of the chemical properties of the Palm oil as a function of temperature.

Acknowledgements

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