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COMPARATIVE STUDY OF TWO THERMAL STORAGE SYSTEMS USING SYNTHETIC OIL ALONE AND ROCKS AND OIL AS STORAGE MEDIA

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ABSTRACT

Due to the variable and non-continuous nature of the sun energy during a day and all over the year, solar thermodynamics installations need an energy storage device that will ensure the continuity of the process of the installation during non-sunny periods. Several storage technologies are implemented and thermal storage has proven to be the best solution given its efficiency, simplicity, reduced cost and non-harmful effect on the environment compared to other storage technologies.

The current work deals with a comparative study between two thermal storage systems: a system containing thermal oil alone (thermal oil as a storage media) and a system containing oil and rocks (rocks as storage media). Some criteria have been adopted to justify the choice of one technology over another.

NOMENCLATURE

ρ	density (kg/m ³)
u	axial velocity (m/s)
v	radial velocity (m/s)
μ	dynamic viscosity (Pa·s)
p	pressure (Pa)
g	gravitational acceleration (m/s ²)
T	temperature (K)
cp	specific heat capacity of fluid (J/kg·K)
λ	conductivity (W/m·K)
m	mass flow rate (kg/s)
Re	Reynold number
t	time (s)
D	diameter (m)
H	height (m)

INTRODUCTION

The non-continuous nature of solar energy requires the use of a thermal energy storage systems to ensure the continuity of the production and hence to improve the thermal performance of solar systems. For solar thermal systems, many storage technologies are studied; some are profitable and have been commercialized while many of them require more exploration to enhance their competitiveness.

The aim of the present work is to investigate the thermal behaviors of two thermal storage systems (a system containing thermal oil alone, and a system containing oil and rocks) under the same operation conditions, through a numerical simulation. The interest of introducing rocks is to reduce the amount of thermal oil used. The mass, momentum and energy conservation equations are solved using the commercial software ANSYS Fluent. The numerical results are validated with experimental data available in the literature

CFD MODELS

1. COMPUTATIONAL DOMAINS

A cylindrical tank containing oil alone and another one with the same dimensions containing oil and rocks which structured in a simple-cubic form; are the two systems subject of this work. For the first tank containing oil alone, the flow and the thermal fields are assumed to be axisymmetric, so a 2D analysis is then adopted to simplify the mathematical

model and gain in terms of calculation time. For the second one containing oil and rocks, only 1/4 of pattern is considered. The schematic of both storage tank considered in the present study is illustrated in Figure 1.

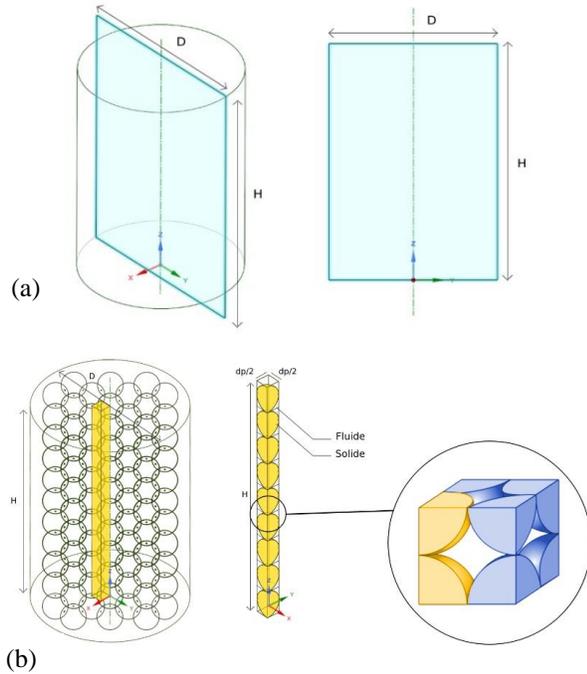


Figure 1. Schematic diagram of (a) tank containing oil alone and (b) tank containing oil and rocks

2. GOVERNING EQUATIONS

The thermal behavior and fluid flow inside the both of thermal storage tanks are governed by the time-dependent mass, momentum and energy conservation equations. These equations are based on the following assumptions:

- The fluid is isotropic, homogenous, incompressible and Newtonian;
- The flow is laminar;
- The thermo-physical properties of fluid and rocks are independent of the temperature;
- The viscous dissipation in the fluid is neglected.

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u}) = 0 \quad (1)$$

$$\frac{\partial (\rho \vec{u})}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u} \vec{u}) = -\vec{\nabla} \cdot p + \mu \vec{\nabla}^2 \vec{u} + \rho \vec{g} \quad (2)$$

$$\frac{\partial (\rho h)}{\partial t} + \vec{\nabla} \cdot (\rho h \vec{u}) = \lambda \vec{\nabla}^2 T \quad (3)$$

where, ρ is the fluid density, \vec{u} is the velocity, μ is its dynamic viscosity, p is the pressure, C_p is the specific heat capacity of the fluid, T is the fluid temperature, h is the enthalpy and λ is its thermal conductivity.

3. BOUNDARY AND INITIAL CONDITIONS

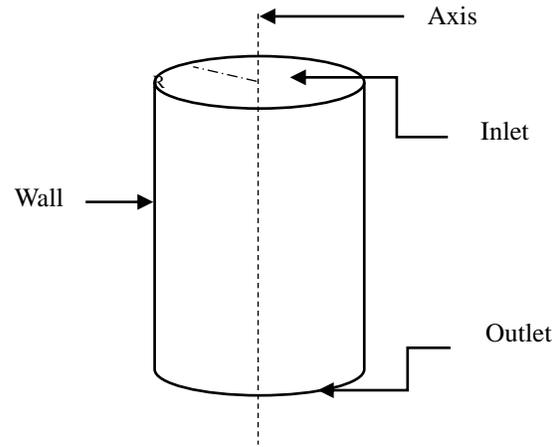


Figure 2. Schematic diagram of tank's boundary

For both systems, the tank wall is assumed to be adiabatic, thus a zero-heat flux boundary condition type is imposed on the wall. The inlet temperature and velocity of the fluid are assumed constant. The flux continuity boundary condition is imposed at the interface fluid-particles. The boundary conditions are given as follows:

At the inlet ($z=H$),

$$u|_{z=H} = u_{in} \text{ (axial inlet velocity)}$$

$$v|_{z=H} = 0 \text{ (radial inlet velocity)}$$

$$T|_{z=H} = T_{in} \text{ (inlet fluid temperature)}$$

At the outlet ($z=0$),

$$P_{out} = P_{atm} \text{ (Pressure outlet)}$$

At the wall ($r=R$),

$$u|_{r=R} = 0 \text{ and } v|_{r=R} = 0 \text{ (No slip condition)}$$

$$\frac{\partial T}{\partial r} \Big|_{r=R} = 0 \text{ (Adiabatic wall)}$$

During the charging phase, a hot thermal oil enters from the top opening, therefore $T_{in} = T_h$. Initially the temperature of the thermal oil and the rocks inside the storage tank is set equal to $T(t = 0, r) = T_c$

ANSYS Fluent (2022 R2) software is used to perform numerical simulations of the fluid flow and heat transfer in the thermal energy storage tank. It implements the finite volume method, in order to solve the discretized equations associated to the previous model.

The SIMPLE algorithm is used to manage the pressure-velocity coupling. The convective and diffusive terms in the energy conservation equation are discretized using second-order upwind interpolation. The simulations are considered converged when the residuals of all the governing equations are less than 10^{-6} .

VALIDATION OF THE RESULTS

The results of the experimental work of Mawire [1] were chosen to validate the first CFD model (tank containing oil alone). Simulations were made considering the same geometry and under the same operating conditions.

The predicted and experimental axial temperature profiles of the average temperature (between the axis and the wall) are compared. Figure 3a presents the temperature profiles different time intervals.

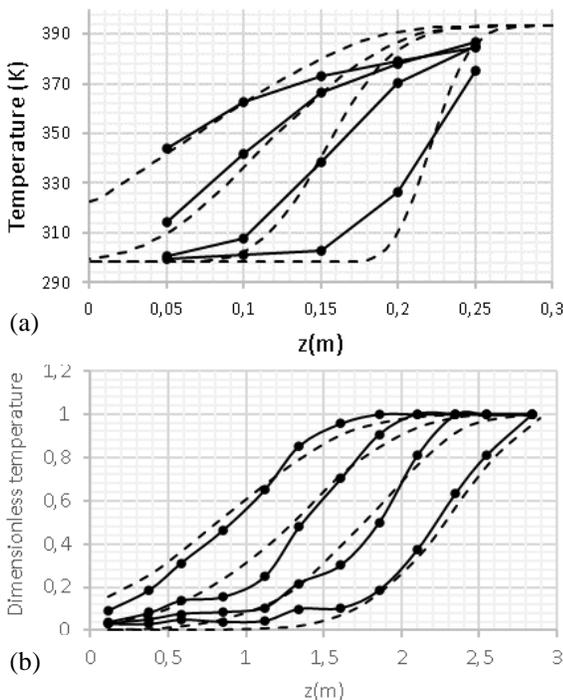


Figure 3. Simulated —●— VS experimental - - - temperature profiles for both systems

Figure 3b compares the results of the second CFD model (reservoir containing the oil and the rocks) with the experimental results measured by the CEA [2] during a charging process.

As can be seen from the figure, the numerical results follow the same trend as the experimental results for both of the models. However, they show relative small difference. For the tank containing oil alone, this difference is due to the fact that in experience, they take into account the losses through the walls while in the simulations we consider adiabatic walls. For the tank containing oil and rocks, the difference is due to the fact that the distribution of rocks in the tank adopted in the experiment is random while in the simulations is well ordered (simple cubic).

RESULTS AND DISCUSSIONS

The two tanks simulated in this study have the same dimensions (a height H of 3m and a diameter D of 1m). For the tank containing oil and the rocks, the diameter of the rocks is $d_p=0.03m$ and the porosity is $\epsilon=0,47$.

Thermal oil and rocks are used for this study. There thermo-physicals properties are listed in Table 1. The operating conditions are summarized in Table 2

Table 1: Thermo-physicals properties of used thermal oil

Properties	Thermal oil	Rocks
Density ρ (kg.m-3)	921,7034	3388,9
Specific heat C_p (J.kg-1.K-1)	2055,8	900
Thermal conductivity λ (W.m-1.K-1)	0,1194	0,1
Dynamic viscosity μ (kg.m-1.s-1)	0,0012	

Table 2: Operating conditions

Hot temperature T_h (K)	523,15
Cold temperature T_c (K)	373,15
Inlet velocity (m/s)	3.839×10^{-4}

1. MESH CONVERGENCE

For the first model, the computational domain is discretized using the adaptive mesh technique with inflation near the wall where there are large gradients. For the second one, polyhedral mesh is used. In order to avoid mesh problems close to the

contact point between spherical rocks, a cylindrical bridge with diameter of 20% d_p is added between the rocks.

The mesh convergence study shows that for a mesh M1 for the tank containing oil alone and M2 for the tank containing oil and rocks, the temperature and velocity profiles remain unchanged (the difference in terms of relative error does not exceed 0.5%). The following table presents the details of the converged meshes.

Table 3: Converged meshes details

	M1	M2
Elements	2000	206 517
Element type	Quadrilateral	Polyhedral
Quality Min	1	0.2

2. COMPARATIVE STUDY

2.1. STORAGE PERFORMANCE CRITERIA

One of the criteria commonly used to quantify the thermal performance of the thermocline storage tank, is the tail factor ϵ [3][4]. It reflects the slope of the outlet temperature time variation curve. It is calculated by the following relation where t_x is the time required by the outlet temperature to reach $T_x = T_c + 0.01x (T_h - T_c)$.

$$\epsilon = \frac{T_{80} - T_{20}}{t_{80} - t_{20}}$$

It should be noticed that a high value of the tail factor means that the shape of the outlet temperature time variation curve is closer to a step function, which implies that the storage tank is operating close to the ideal condition. The definition of the tail factor excludes the influences of the nature of the fluid used and their thermo-physical properties (for example C_p), therefore it's direct and practical to calculate. By comparing the tail factor value of a real charging process with that of the ideal case ($\epsilon = \infty$), the stratification level can then be quantified.

Another very important criterion for evaluating the behavior of storage systems is the storage capacity, it's calculated by integrating over the entire volume of the tank the energy stored in an elementary volume.

The tank with the oil and the rocks contains a volume percentage of 47% of oil unlike the tank with the oil alone. 53% of the storage volume is then filled with rocks which are basically an available and cheap material.

2.2. TEMPERATURE PROFILES

Figure 4 presents the simulated temperature profiles at different times for the two tanks under the same operating conditions as mentioned before.

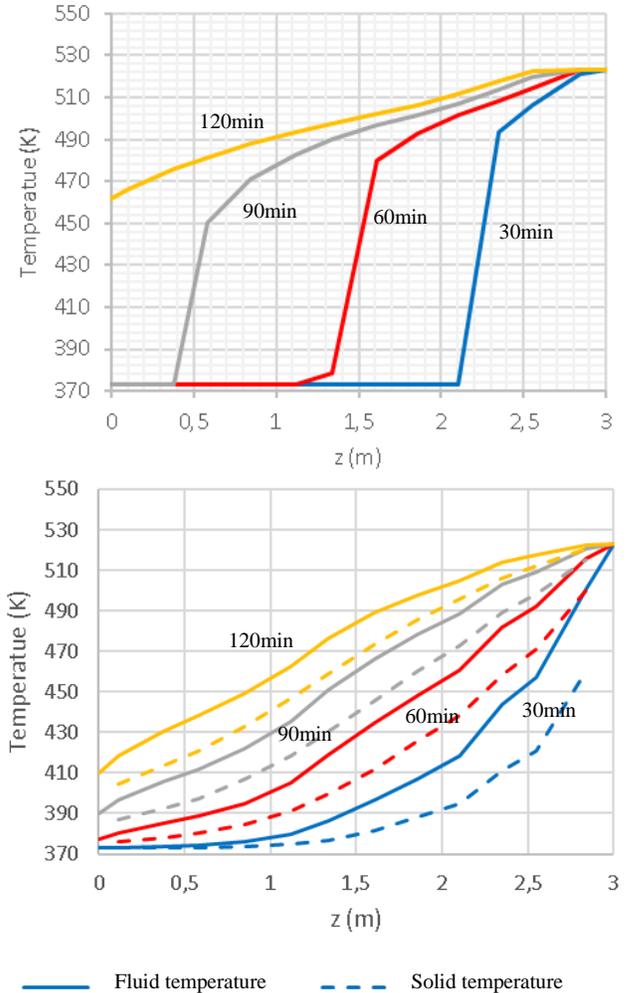


Figure 4. Simulated Axial profile of average temperature on a given z for (a) tank with oil only (b) tank with oil and rocks

As can be seen in the figure 4, the two graphs present different profiles in terms of temperature gradient in the thermocline zone. Indeed, in the tank containing oil and rocks, the temperature drops slowly unlike the tank containing oil alone, and this disturbs the stratification into the tank and therefore affects the storage performance.

2.3. OUTLET TEMPERATURE EVOLUTION

As mentioned, the tail factor gives an idea about the stratification degree in a thermal storage tank. It represents the slope of the time evolution curve of the temperature at the outlet position of the tank. The figure 5 represents the evolution over time of the temperature at the outlet position of the two tanks that we are studying.

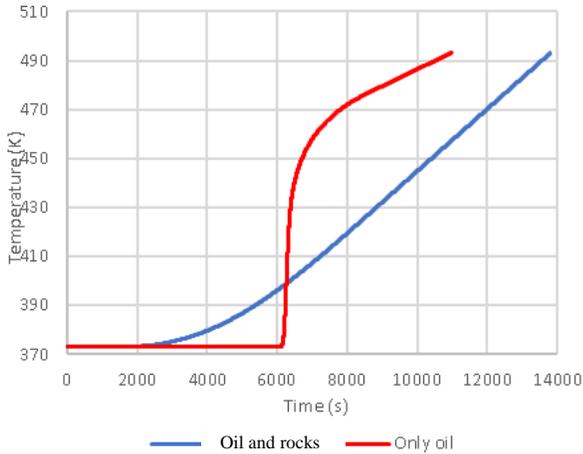


Figure 5. Temperature evolution at the outlet of the tanks

A tail factor equal to 0,01918 is calculated for the case of the tank containing oil alone, thus a tail factor of 0,01257 is calculated for the case of a tank containing oil and rocks. that means the stratification is better when the rocks are absent.

2.4. STORED ENERGY

The energy aspect is very important to evaluate the storage performance. The following figure represents the total energy stored in the both tanks.

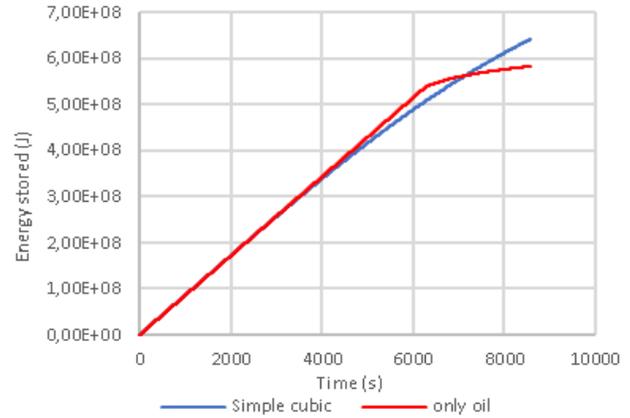


Figure 6. Evolution of the total energy stored in the both tanks

We can see in the figure 6 that the tank containing oil alone reaches the saturation point after 6650s while the other tank containing oil and rocks is not saturated yet, it is then able to store more. This is due to the fact that the rocks have too high ρC_p product compared to that of the thermal oil.

CONCLUSION

Numerical simulations are carried out for two thermal storage systems (a system containing thermal oil alone, and a system containing oil and rocks) under the same operation conditions. Numerical simulations were performed to compare the performances of both systems based on certain criteria.

The study shows us that the system containing oil and rocks is able to store more energy than the system with oil alone. The system containing oil and rocks is also favorable due to its lower cost because it uses materials available in nature. The study also showed that the system containing oil and rocks has a much more degraded stratification compared to the system containing oil alone.

There are many other parameters that affect the stratification, namely the diameter of the rocks, their arrangement in the reservoir, etc. The aim of the next study will be to improve the stratification in a storage system containing oil and rocks

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