

Packed-bed sensible thermal energy storage system using demolition wastes for concentrated solar power plants

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Abstract. This paper presents a study on development of a packed-bed storage system for CSP applications. In this system, demolition wastes from urban regeneration projects in Turkey has been investigated as potential STESM for cost effective storage systems. Schumann's two-phase one-dimensional model was used to evaluate the optimal design parameters. Effect of operational and geometrical design parameters such as mass velocity, porosity, aspect ratio of packed bed, packing diameter were assessed on storage performance. The system showed the best performance with low bed void fraction, low mass flow rate and low Re_p .

1. Introduction

Solar thermal energy has a huge potential as renewable energy source. In addition to heating and cooling use of solar thermal, electricity can be generated through a thermal cycle by concentrated solar power (CSP) plants. CSP technologies concentrate sun light and heat transfer fluid (HTF) in the temperature range between 250°C – 1000°C. Solar power towers, parabolic trough collectors, dish stirling reflectors and linear Fresnel collectors are some of the main components in CSP used for harnessing solar energy. Together with these technologies, sustainable and cost-effective storage systems to ensure continuous and efficient power production are needed.

Sensible thermal energy storage (STES) systems provide solutions to improve potential of CSP plants for both short-term and long-term storage. Parameters for system design, optimization and choice of storage medium depend on CSP technologies and operating temperature range.

Several sensible thermal energy storage materials (STESM) have been tested for CSP applications. The properties of STESMs which can be used for CSP applications are given in Table 1. Among these are molten salt, alumina, rock and high temperature concrete are the most preferred ones. There are some limitations of these STESMs. Molten salts can be corrosive and can be degraded above 600°C. Rock and concrete are not considered sustainable, since they depend on depletion of natural materials. In addition, finding uniform sized rock particles for efficient packing ratio may be problematic and expensive.

Table 1. Properties of STESMs that can be used for CSP applications

Materials	Density, ρ (kg/m ³)	Thermal Conductivity, k (W/mC)	Specific Heat, Cp (kJ/kgK)	Ref.
Solar Salt (NaNO ₃ :KNO ₃ 0.6:0.4)	1900	0.59	1.575	[18]
Silica	2500	0.1	0.90	[10]
Gneiss Rock	2740	3.0	0.82	[15]
Alumina balls	3350	30	0.90	[16]
Basalt	2644	2.08	0.77	[17]
Cofalit	3120	2.1	0.80	[18]
Concrete	2200	1.5	0.85	[19]
Coal Fly Ash	2600	1.3	0.7-1.3	[18]

In this study, demolition wastes from urban regeneration projects in Turkey has been investigated as potential STESM [1]. Valorization of these demolition wastes can help efficient utilization of solar energy and reduce solid wastes, which is becoming a huge problem in metropolitan areas. Using abundant and cheap STESM with high energy density is very important for cost-effective CSP applications.

Although using cheap storage material is important criteria, there are a lot of design parameters that effect the storage performance. According to Marti et al [14], mass flow, inlet temperature, particle diameter, bed void fraction and packed bed dimensions are main operational and geometrical parameters that need to be determined for storage design. Khan et al [5] have determined that fluid velocity and particle dimensions are effective on solid storage system behavior in CSP plants. Elouali et al [2] investigated the influence of different design parameters on packed-bed performance. Results showed that decrease of particle size and increase of the mass velocity of HTF increase the storage performance of packed-bed. Lugolole et al [6] also performed a study to evaluate the effect of HTF velocity and particle diameter. The system with small pebbles of 10.5 mm diameter and low HTF velocity of 4ml/s showed the best storage performance. Tiskatine et al [4] analysed different rock types to determine their potential as STESM in CSP plants. Results showed that physical and mechanical properties of dolerite, granodiorite, hornfels, gabbro and quarzitic sandstone are the most suitable ones for high temperature applications.

Bataineh and Gharaibeh [7] studied optimum design parameters for solid sensible storage system for a parabolic trough power plant. For constant storage tank volume, height to diameter ratio of storage tank did not show a big effect on storage performance. Buscemi et al [3] designed concrete thermal energy storage system integrated to Linear Fresnel Collectors for a pasta factory in Southern Italy. Stored energy was used in the pasta drying process with 87 % efficiency.

Zhao et al [8] developed a one-dimensional enthalpy-based dispersion-concentric (D-C) model to investigate efficient tank size of packed-bed system for concentrated solar power with a storage capacity of 2000 MWht. Nandi et al [9] developed three-dimensional numerical computational fluid dynamics (CFD) model to optimize design parameters of thermocline thermal energy storage system.

In this study, the aim is to investigate the optimum design parameters of a packed-bed storage system using demolition waste as STESM for CSP applications. Schumann's two-phase one-dimensional model was used to evaluate the effects of parameters such as mass velocity, porosity, aspect ratio of packed bed, packing diameter on storage performance.

Nomenclature	
C_p	Specific heat ($Jkg^{-1}K^{-1}$)
D_p	Diameter of particle (m)
D_T	Diameter of tank (m)
f	Fluid
h_v	Heat transfer coefficient ($Wm^{-2}K^{-1}$)
k_f	Fluid thermal conductivity ($Wm^{-1}K^{-1}$)
m	Mass flow rate (kgs^{-1})
p	Particle
s	Solid
t	Time (s)
T	Temperature ($^{\circ}C$)
T_{in}	Inlet Temperature ($^{\circ}C$)
T_o	Outlet Temperature ($^{\circ}C$)
u_{sup}	Superficial fluid velocity (ms^{-1})
v_f	velocity (mms^{-1})
η_c	Charging efficiency (%)
ρ	Density (kgm^{-3})
μ	Dynamic viscosity ($kgm^{-1}s^{-1}$)
ϵ	Bed void fraction
Re_p	Reynolds Particle

2. Packed Bed Storage System

2.1 Design Parameters

The packed bed TES system will be investigated numerically under different operating conditions. In this design, the packed bed column will be a cylindrical storage tank of 1.0 m diameter and 3.0 m height with aspect ratio of 3. Synthetic thermal oil (Therminol 66) will be used as HTF for storing heat up to 350 °C for CSP plants. Properties of Therminol 66 oil varying with temperature and temperature dependent correlations are given in Equation 1, 2 and 3.

$$\rho_f = -0.614254 T - 0.000321 T^2 + 1020.62 \quad (1)$$

$$C_{p_f} = 0.003313 T + 0.0000008970785 T^2 + 1.496005 \quad (2)$$

$$k_f = -0.000033 T - 0.00000015 T^2 + 1.496005 \quad (3)$$

Demolition wastes from an urban regeneration project in Turkey will be assessed as STESM with a heat capacity of 3200 kJ/m³K [1]. The ranges of the operating parameters of the packed-bed system is given in Table 2.

Table 2. TES design parameters and ranges

Design Parameters	Range of Parameters
Inlet Temperature, °C	200 – 350
Fluid Velocity, mm/s	0.5-3
Bed void fraction	0.2-0.6
Packing Diameter (D_T/D_p)	20-40
Density of particle, kg/m ³	2190
Specific heat of particle, Jkg ⁻¹ K ⁻¹	1340
Reynolds Particle, Re_p	15-150

2.2 Numerical Analysis

One-dimensional two-phase Schumann’s model was used to define design parameters of a packed-bed storage system for CSP applications. Following assumptions were considered in modelling:

- Heat conduction occurs only in axial direction
- No heat exchange between particles
- Heat exchange occurs from particles to HTF
- The system is well insulated and there is no heat loss

Governing equations can be written for solid and liquid phases as given in Equation 4 and 5, respectively [11, 12]:

$$\varepsilon \rho_f C p_f \frac{\partial T_f}{\partial t} + \varepsilon u_{sup} \rho_f C p_f \frac{\partial T_f}{\partial x} = h_v (T_s - T_f) \quad (4)$$

$$(1 - \varepsilon) \rho_s C p_s \frac{\partial T_s}{\partial t} = h_v (T_f - T_s) \quad (5)$$

Where ρ_f and ρ_s are density of fluid and solid phase and $C p_f$ and $C p_s$ are specific heat of fluid and solid phase, respectively. u_{sup} is superficial fluid velocity inside the packed bed, calculated based on porosity in Equation 6 [13]:

$$u_{sup} = \frac{\dot{m}}{\rho_f \pi \frac{(D_T)^2}{4} \varepsilon} \quad (6)$$

Volumetric heat transfer coefficient h_v are given by Equation 7 where particle Reynolds number is greater than 15 [10]:

$$h_v = \frac{6(1-\varepsilon)k_f[2.0+1.1*Pr^{\frac{1}{3}}*Re_p^{0.6}]}{D_p^2} \quad (7)$$

According to Cardenas et al [20], Prandtl number (Pr) is calculated by Equation 8.

$$Pr = \mu_f C p_f / k_f \quad (8)$$

Reynolds number based on particle diameter (Re_p) indicates the flow regime in the storage tank and defined as [10]:

$$Re_p = \frac{\rho_f u_{sup} D_p}{\mu_f \varepsilon} \quad (9)$$

3. Results and Discussion

The effects of operating parameters on thermocline storage system efficiency is defined by Nandi et al [9] based on the first law of thermodynamic. According to this, charging and discharging efficiency at any time can be found from Equation 10.

$$\eta = \frac{(m_f c_{pf} + m_s c_{ps}) |T_{avg} - T_0|}{(\dot{m}_f) c_{pf} t |T_{in} - T_0|} \quad (10)$$

Table 3 shows the effect of HTF velocity on charging efficiency at t:30 minutes with 0.45 bed void fraction and 250 °C inlet fluid temperature. Charging efficiency drops dramatically over 1.5 mm/s velocity. Unsteady laminar flow starts when Re_p is higher than 150 [14] and for the system analysed here, Re_p is close to 150 at 3.0 mm/s velocity. As seen in Figure 1, stratification of thermocline starts to be destroyed after 1.5 mm/s. Lower velocity shows better stratification and charging efficiency. On the other hand, it increases total charging time.

Table 3. Effect of velocity on charging efficiency and Re_p

Velocity, v_f , mm/s	Charging efficiency, η_c ,	Re_p @250 °C
0.5	98.8	22
1.0	98.3	45
1.5	97.9	67
2.0	91.9	90
2.5	80.6	112
3.0	69.4	135

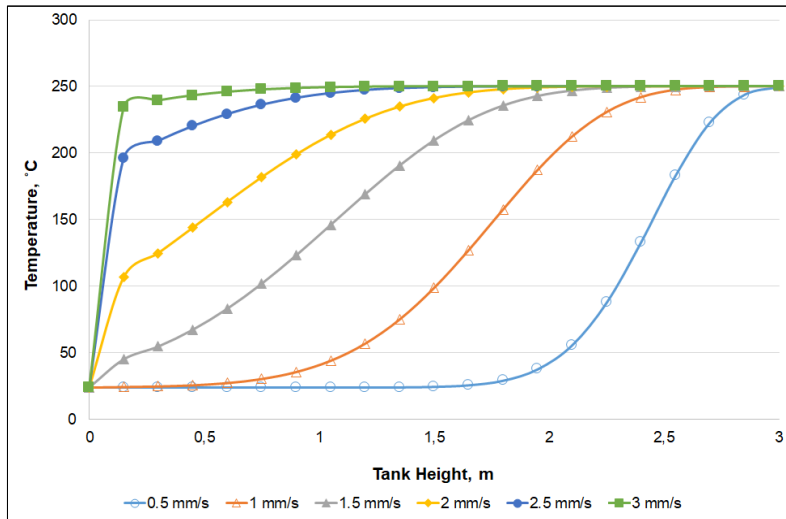


Figure 1. Change in stratification with velocity

According to Bruch et al [10], choosing the ratio of diameter of the tank to the characteristic diameter of packing is an important design parameter to have negligible wall effects. Figure 2 shows the effect of D_T/D_P ratio on system performance. At constant bed void

fraction, changing D_T/D_p ratio did not show significant effect on both storage efficiency and stratification behaviour. However, it is expected that increasing D_T/D_p ratio by decreasing particle diameter can decrease bed void fraction and Re_p . Thus, the system efficiency is also expected to increase.

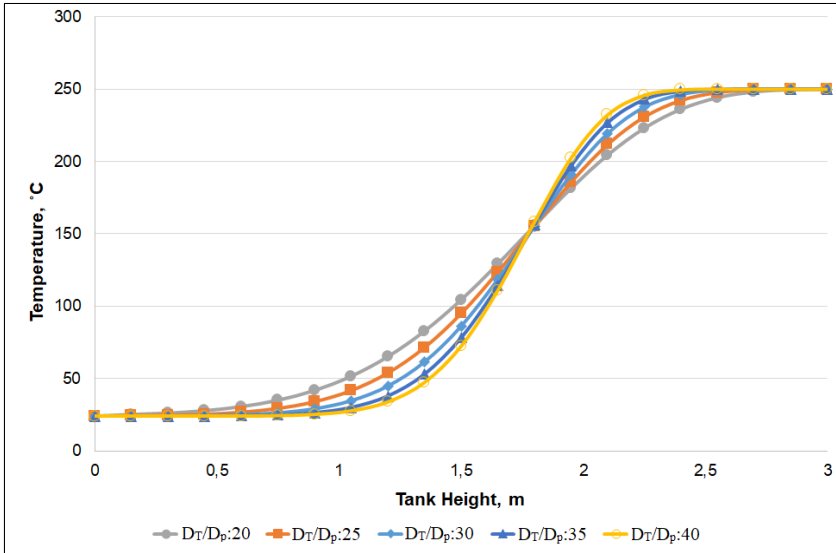


Figure 2. Change in stratification with the ratio of tank diameter to packing diameter ($D_T/D_p:20$)

As decreasing the packing diameter would also decrease, bed void fraction. storage tank can be filled with more packing material. Figure 3 shows the effect of bed void fraction on stratification behaviour. When the bed void fraction decreases, stratification behaviour starts to enhance. The effect of bed void fraction on charging efficiency is shown in Table 4. Although storage efficiency increases with decreasing bed void fraction, the effect on efficiency is less.

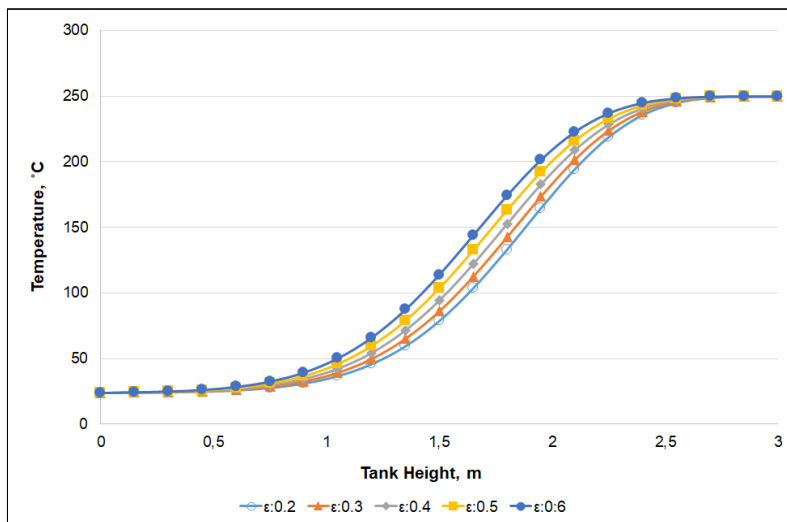


Figure 3. Change in stratification with bed void fraction

Table 4. Effect of bed void fraction on charging efficiency and Re_p

Bed void fraction, ϵ	Charging efficiency, η_C , %
0.2	98.9
0.3	98.8
0.4	98.5
0.5	98.4
0.6	98.3

Gibb et al [21] defined the total system energy storage capacity as sum of solid phase and sum of the components. Based on this definition, total stored energy is calculated by Equation (11) and (12).

$$Q_{\text{stored}} = Q_{\text{solid phase}} + Q_{\text{components}} \tag{11}$$

$$Q_{\text{stored}} = m_s c_{p_s} (T_{\text{avg}} - T_{t:0}) + m_f c_{p_f} (T_{\text{avg}} - T_{t:0}) \tag{12}$$

The change in accumulated stored energy by solid and fluid phases with time is given in Figure 4. Total energy stored during charging step, which reaches steady state after 100 min, is 376 kWh.

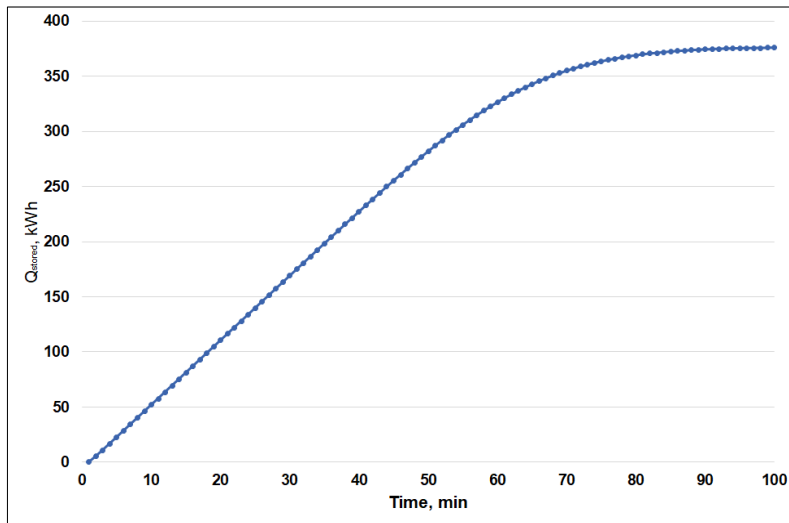


Figure 4. The change of accumulated stored energy with time

4. Conclusion and Outlook

The packed bed storage system for CSP plants was numerically studied by using Schumann’s model. In this system, demolition wastes as STESM and Therminol 66 as HTF was assessed. Mass velocity, bed void fraction, packing diameter and Reynolds number were defined critical design parameters. When the variable design parameters were evaluated by numerical model, it was found that laminar flow regime with low Re_p and low mass velocity

are the main criteria to reach high efficiency and smooth thermocline profile. In this study, the best storage performance was obtained when fluid velocity was 0.5 mm/s and the ratio of tank diameter to packing diameter (D_T/D_P) was 40. Storage efficiency reached to 98.5 % with bed void fractions up to 0.4. In further studies, effects of pressure drop, wall effect and temperature change on the system efficiency will be investigated. Moreover, scale-up of the packed bed storage system based on real operational CSP parameters need to be considered for future studies.

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