Sensible Thermal Energy Storage in Packed Bed for Industrial Solar Applications

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Abstract

This paper presents a study on development of sensible thermal energy storage in a laboratory scale packed bed for industrial solar applications. In the cylindrical storage tank with 0.30 m diameter and 0.90 m height, two different types of packing materials from waste materials are used. First one is produced from building demolition wastes, which are molded in different geometries. For the second one, hallow silane crosslinking of polyethylene (PEX-b) pipe, which are leftovers from pipe manufacturers are used. The system design includes cycles that simulates storage and recovery of heat controlled by temperature. In further studies the performance of the system will be tested at different operating conditions and life cycle assessment will be made. Inertiazing such waste materials are expected provide low-cost and sustainable sensible heat storage systems for industrial solar applications.

Keywords: Packed-bed, Solar Heat Industrial Applications, Sensible Thermal Energy Storage (STES), Solar Energy,

1. Introduction

Total energy consumption in the world is increasing rapidly. According to International Energy Agency (IEA), global energy consumption has increased more than twice over the last forty years. Industries consume 29% of the world's total delivered energy with energy systems generally using of fossil fuels (IEA, 2017). The use of fossil fuels in industry reduces the competitiveness in global market. In addition, the environmental impacts and increased CO2 emissions emphasizes the importance of the usage of renewable energy sources in industries. Although solar energy can be potentially used in many industrial processes, variability of sunlight is the main barrier for continuous utilization (EESI, 2011).

The mismatch between supply and demand of solar energy can be covered by thermal energy storage (TES) systems. There are three TES concepts, namely thermo-chemical storage, sensible heat storage and latent heat storage. The thermochemical storage is still being developed and it is not widely used in industrial applications. Sensible heat storage, utilizes temperature changes of storage materials. Latent heat storage using phase change materials (PCM) has higher storage capacity than sensible heat storage materials, but the cost of PCMs, especially at temperatures above 150℃ is very high (Mawire and McPherson, 2009). Due to the technical difficulties and high price of PCM, latent heat storage is costly for industrial applications. Sensible heat is the most preferable TES concept in industrial applications, due to the availability and low-cost sensible thermal energy storage materials (STESM). Basalt, aluminum, carbon steel, and iron are among the well known sensible heat storage materials. Also, recently, inertized products such as by-products of mining and metallurgical industry, asbestos-containing wastes, and post-industrial ceramic are being developed for high temperature. The properties of other STESMs in literature are given in Tab. 1.

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Tab. 1: Properties of sensible thermal energy storage materials (STESM) in literature

Materials	Density,(ρ) (kg/m³)	Thermal Conductivity,(k) (W/mC)	Specific Heat, (Cp) (kJ/kgK)	Heat Capacity,(ρ.Cp) (kJ/m³K)	Ref.
Brick	3200	0.1	0.80	2560	Kuravi et al, 2013
Silica	2500	0.1	0.90	2250	Bruch et al, 2014
Gneiss Rock	2740	3.0	0.82	2260	Jemmal et al, 2016
Alumina balls (Al_2O_3≥89.5 wt %)	3350	30	0.90	3020	Cascetta et al, 2015
Basalt	2644	2.08	0.77	2040	Tiskatine et al, 2017
Cofalit (asbestos containing waste)	3120	2.1	0.80	2490	Motte et al, 2015
BOF-Slag (By-product generated in steel industry)	3972	-	0.91	3460	Grosu et al, 2018
Municipal waste glass	2962	1.16	0.71	3430	Gutierrez et al, 2016

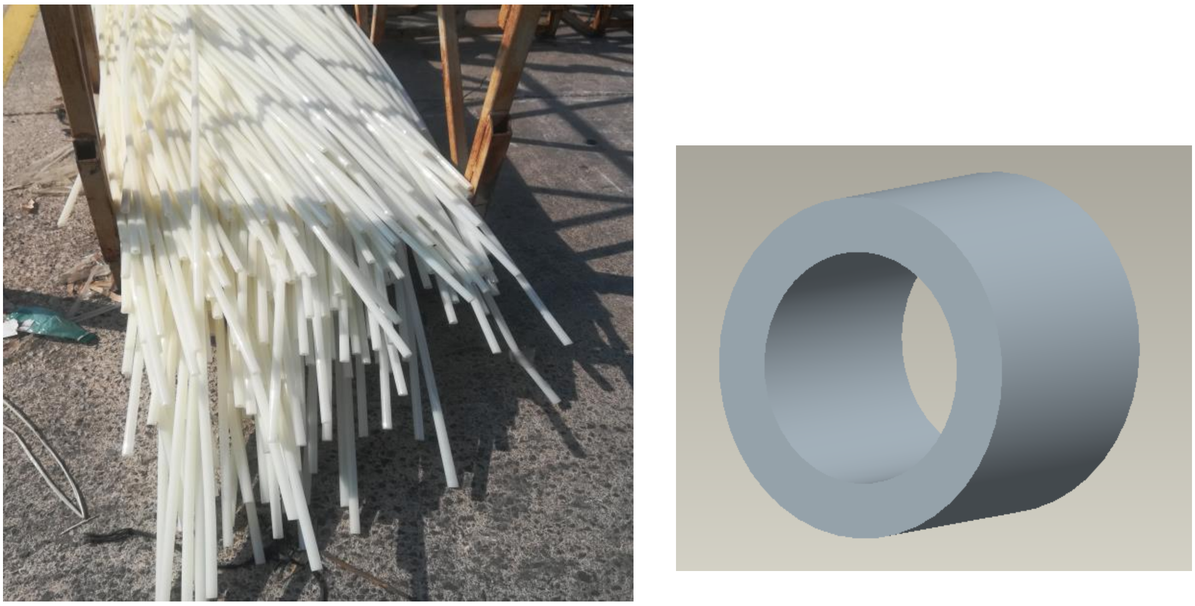
TES systems provide alternative solutions to benefit from renewable energy sources in various sectors in a sustainable way (Paksoy, 2007). In recent years, TES systems have been investigated to reduce energy consumption and effective use of solar energy for industrial applications. The balance between supply and demand of solar energy can be ensured through the use of TES systems (Brunch et al, 2014).

In most of the recent studies, numerical evaluation of packed bed TES for industrial solar applications have been reported, but only a few studies are on experimental demonstrations, especially using liquid heat transfer fluids (Brunch et al, 2014).

In this study, laboratory scale packed bed TES system is designed with the purpose of storing heat at 130 – 180 °C that will be suitable for industrial solar applications. Two new packing materials developed from waste materials will be tested in this TES system for a more sustainable operation.

2. Sensible Thermal Energy Storage Materials (STESM)

Providing storage material with cheap and high energy density is very crucial for low-cost and high-efficient thermal energy storage systems. For this reason, using waste materials as STESM is a better option in TES systems. Two types of STESM developed from waste materials, which are shown in Fig.1 and Fig.2 will be used in this study. Building demolition wastes from urban development projects are processed and molded into different geometries to obtain STESM. PEX-b pipe leftovers in pipe manufacturers cannot be recycled and re-used in pipe production. PEX-b durable to high temperatures can be utilized as packing material to store high temperature heat.



(a) **(b)**

Fig. 1: PEX-pipe as STESM, a)Scrap of PEX-pipe, b) Section of PEX-pipe

(a) **(b)**

Fig. 2: Demolition waste as STESM, a) Demolition wastes from urban development projects, b)Demolition waste after processed as STESM

The most important parameters for storage materials are high specific heat capacity and density, capability for operating at suitable temperature range, good thermal conductivity and low cost (Klein et al, 2015). The properties of two types of STESM developed in this study are given in Tab. 2.

Tab. 2: Properties of sensible thermal energy storage materials (STESM) used in this study

STESM	Density, (ρ) (kg/m^3)	Specific Heat, (Cp) (kJ/kgK)	Heat Capacity, (ρ.Cp) (kJ/m^{3}K)
Demolition Waste	2100	1.53	3213
Waste of PEX-b pipe	930	2.3	2139

Their heat capacities vary from 2100 to 3200 kJ/m^{3}K. The heat capacities of STESM developed in this study from waste materials are comparable to the previous studies with values in the range of 2000 to 3500 kJ/m^{3}K as given in Tab.1.

3. Design of Packed Bed Thermal Energy Storage System

The laboratory scale packed bed TES system is developed based on the scheme shown in Figure 3 (Bruch et al., 2014). This system consists of charging and discharging cycles for storing and recovering solar heat in packed bed column. In the charging cycle to the left of the packed bed column, a heat transfer fluid (HTF) bath with a heater is used to simulate solar heat. The stored heat is recovered in the discharging cycle through a heat exchanger shown to the right of the packed bed column. The system includes pump, flowmeter, valves and thermocuples to control and collect data from experiments.

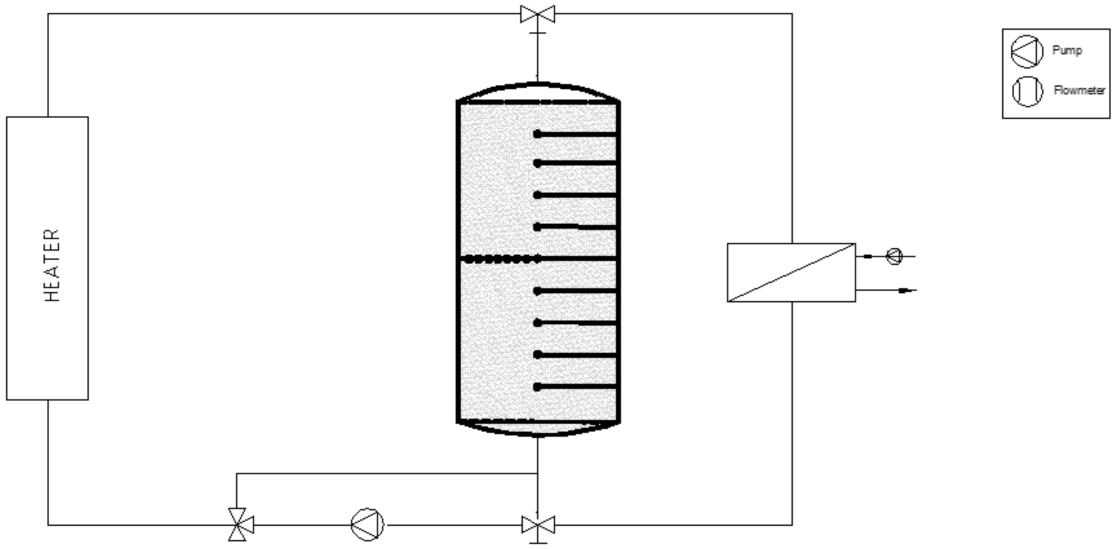


Fig. 3: Scheme of packed bed TES system

The real system constructed based on this scheme is shown in Fig.4. The packed bed column is a cylindrical storage tank of 0.30 m diameter and 0.90 m height made of stainless steel with aspect ratio of 3. The tank is insulated with 0.02 m glass wool. Demolition wastes developed in different geometries and PEX-b pipe leftovers will be tested for the first time as STESMs. The ratio the diameter of the tank to the characteristic diameter of packing was chosen to be greater than 30, i.e. $D_{tank}/D_s > 30$, to have negligible wall effects (Bruch et al, 2014). Synthetic thermal oil (Therminol 66) is be used as HTF for storing heat between 130 – 180°C. For storing heat below 100 °C water is used as HTF. Twelve thermocouples (PT100 type) with a precision of ±0.5°C are used in the system for temperature measurement. Ten of them are placed inside the packed bed column to measure the porous media temperature on vertical and axial lines and two of them are located at the inlet and outlet of the heat exchanger. HTF bath with 50 L capacity includes a 2 kW electric heater for simulating solar heat at desired temperature. The Oil pump, a maximum rotation speed of 1500 rpm, used for circulating HTF in the system is manufactured by KUPARPUMP. Direction of HTF flow is controlled by 2-way and 3-way ball valves, which are operated based on temperature measurements by data logger. For the discharge cycle a plate type heat exchanger from HTF to water was used for heat recovery. Flow rate of HTF can be controlled by QTLD turbine flow meter. Oro et al (2013) designed a packed bed column with capacity of 4.0 L filled with spherically encapsulated PCM and water as HTF. Their experimental results analyzed with different numerical models showed that constant velocity profile gave better performance than variable one. TES system parameters are summarized in Tab. 3. Charging and discharging experiments will be carried out with constant fluid velocity up to 12 mm/s for laminar flow to allow the Reynolds number (Re) given in eq.1 to be less than 2300.

$$Re = \frac{\rho_f V_0 D_P}{\mu_f} = \frac{V_0 D_P}{\nu_f} \qquad \text{(eq.1)}$$

The density (ρ_f), kinematic viscosity (ν_f) and the specific heat capacity (Cp_f) of the synthetic thermal oil vary with temperature and are represented with eq.2, eq.3 and eq. 4, respectively.

$$\rho_f \left(\frac{kg}{m^3}\right) = -0.614254 * T\ (°C) - 0.000321 * T^2\ (°C) + 1020.62 \quad \text{(eq.2)}$$

$$v_f \left(\frac{mm^2}{s}\right) = e^{\left(\frac{586.375}{T\ (°C)+62.5}\right)-2.2809} \quad \text{(eq.3)}$$

$$Cp_f \left(\frac{kJ}{kgK}\right) = 0.003313 * T\ (°C) + 0.0000008970785 * T^2 (°C) + 1.496005 \quad \text{(eq.4)}$$

Fig. 4: Laboratory scale packed bed TES system

Tab. 3: TES system parameters

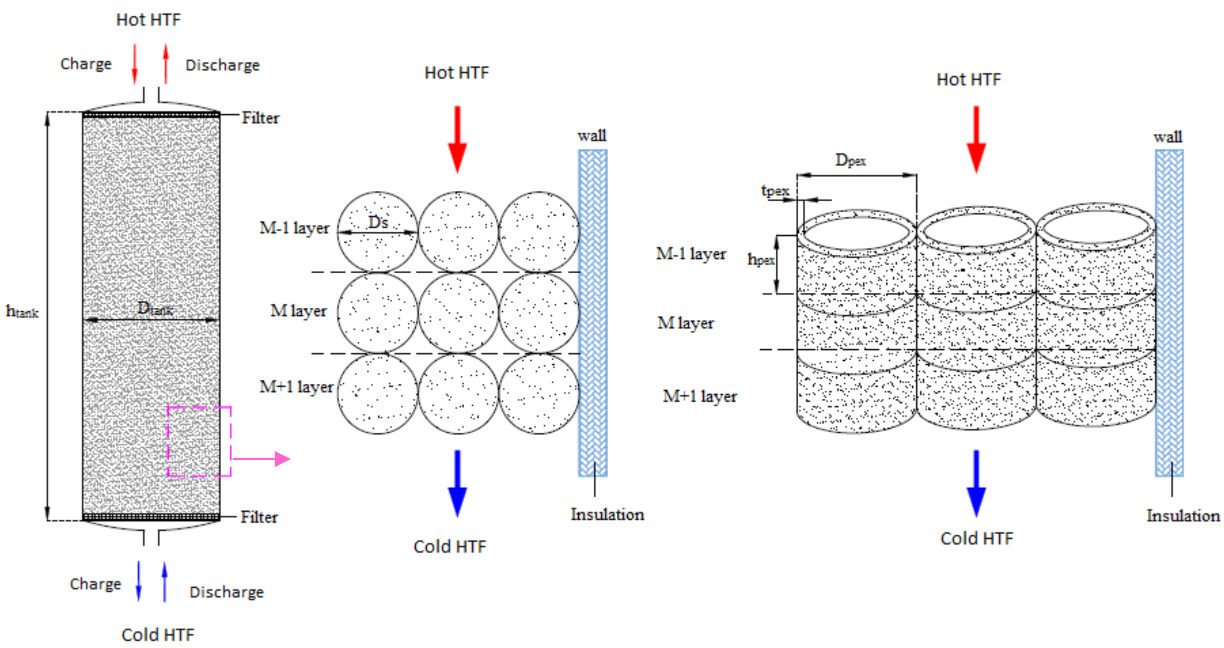
Parameter	Value
Height of storage tank; h_{tank} (m)	0.90
Diameter of storage tank; D_{tank} (m)	0.30
Inlet temperature range (°C) for demolition waste	130 – 180
Inlet temperature range (°C) for Pex-b pipe	50-80
Diameter of demolition waste as STESM, D_s (mm)	10
Diameter of PEX pipe, D_{pex} (mm)	16
Thickness of PEX pipe, t_{pex} (mm)	2.0
Fluid velocity range; V_0 (mm/s)	0 – 12
Density of Therminol 66 as HTF, ρ_f	Given by eq. 1
Specific heat of Therminol 66 as HTF, Cp_f	Given by eq.3
Density of water as HTF, ρ_w (kg/m^3)	1000
Specific heat of water as HTF, Cp_w (kJ/kgK)	4.187

During the charging process, hot HTF flows into top of the storage tank. STESM absorbs heat from the hot HTF and thus heat is stored in STESM by increasing temperature of storage material. While during the discharging process, cold HTF enters through bottom of the tank and hot STESMs are releasing heat to the cold HTF. STESMs with same diameter are packed in the cylindrical storage tank and HTF flows through the void space of the storage tank. The void fraction of the storage tank filled with STESMs will be calculated according to eq.5.

$$\varepsilon = V_{HTF}/V_{tank} \quad \text{(eq.5)}$$

where V_{HTF}.is volume of heat transfer fluid in storage tank, and V_{tank} is the volume of storage tank. Also, maintaining stratification with regular flow of heat transfer fluid is an important criterion for better performance. Therefore, filters should be used in the system to prevent clogging caused by storage materials and provide homogeneous distribution of HTF in the bed (Oro et al, 2013). In this system, two filters with 0.8 mm diameter openings are placed at the bottom and top of the tank.

The packed bed TES system will be investigated both experimentally and numerically under different operating conditions. The numerical model will be developed based on the packed bed column filled with STESM illustration shown in Fig. 5. In Fig b and c the enlarged portion of the packed bed for use in numerical modeling are given. Fig 5 c shows the PEX-Pipe pieces packed aligned in the same orientation. Random packing with PEX-Pipe pieces will also be analyzed.



a) Packed-bed b)Demolition waste as STESM c)PEX-pipe as STESM

Fig.5: Sketch of a sensible heat storage system in packed-bed

Bruch et al. (2014) developed a one-dimensional model for rock bed used for thermal energy storage with thermal oil. Their results showed this model can be used in different dual media and liquid HTF in a wide range of operating conditions (Bruch et al., 2014). This model will be adapted to determine pressure and temperature changes along the packed bed using the new packing materials developed here. The result from the model will be validated with experimental results.

4. Conclusions and Outlook

A laboratory scale TES system with a packed-bed column is designed and built for solar energy storage in industrial applications.. The lab-scale packed bed column TES system will be numerically and experimentally studied. In this system, two types of STESM developed from waste materials demolition waste and PEX-pipe leftovers will be used. Inertiazing such waste materials is expected provide low-cost and sustainable sensible heat storage systems for industrial solar applications. To evaluate thermodynamic behavior of TES system, in further studies, the performance of the system will be tested at different operating conditions and life cycle assessment will be made.

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