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Thermal performance comparison of three sensible heat thermal energy storage systems during charging cycles

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ABSTRACT

Experimental results evaluating and comparing three sensible heat storage systems are presented during charging cycles with three different flow-rates of 4 ml/s, 8 ml/s and 12 ml/s respectively. Two packed storage systems using Sunflower Oil as the heat transfer fluid with two particle diameters (10.5 mm and 31.9 mm) are compared with an oil only storage tank. The oil storage system charges up fastest, followed by the small pebbles thermal energy storage (TES) and lastly by the large pebbles TES due its lower thermal mass. The small pebbles TES has a faster rate of temperature rise because the small pebbles reach thermal equilibrium more easily than the big pebbles which normally experience temperature drops. The purpose of this work is to determine the thermal performance of pebble packed beds using Sunflower Oil as the heat transfer fluid (HTF) in the medium temperature ranges suitable for cooking applications. Three thermal performance parameters are evaluated during charging cycles which are the energy rate, exergy rate and stratification number. Higher charging energy and exergy rates are obtained with small pebbles TES system making it the best storage system in terms of energy and exergy rates. Exergy rates are found to be dependent on temperature differences between the top and the bottom of the storages and on average storage temperatures. Charging flow-rates have no clear relationship with exergy rates. Thermal stratification in TES systems that employ the use of liquid media as storage materials improve the energy efficiency of such thermal storages. Stratification occurs when the lower density hot liquid rises to the top of the storage tank while the higher density cold liquid sinks to the bottom. Stratification number profiles of the experiments conducted are seen to rise and drop during charging cycles for all thermal storage systems. The oil TES system shows the fastest rise and drop of the stratification number due to its lower thermal mass. Generally, the slowest rate of drop in the stratification number profiles is seen with the large pebbles TES system for all flow-rates. This suggests that more quality useful energy is stored in this system of large pebbles inspite of the fact that it charges up with a lower initial rate. The small pebbles TES performed better in terms of the thermal performance parameters evaluated in this study.

Introduction

Thermal energy storage (TES) is an emerging advanced technology for storing thermal energy that can enable more efficient and clean energy systems. TES is important in overcoming the mismatch between energy supply and demand in a wide range of applications such as in solar energy utilization, compressed air energy storage, power plants, waste heat utilization, heating and cooling and in air conditioning. In solar TES systems, energy can be stored during sunny hours for usage at a later time when the sun is not available. TES systems are also becoming useful in food preparation where solar heat is stored during low energy demand hours, and this heat is used during peak demand periods [1]. Herrmann and Kearney [2] noted that TES generally has lower capital costs and their operating efficiencies can be compared to other storage technologies such as a battery. The operating efficiency of a battery is relatively higher than that of the packed pebble storage system. However, the battery thermal storage is more expensive than the storage of a packed bed of pebbles. This is because rocks are common and widely available. Ryan et al. [3] indicated that TES systems should have high energy storage densities, good heat transfer between the heat transfer fluid (HTF) and the solid storage medium, good stability (mechanical and chemical), low thermal losses and low cost regardless of type. Ryan et al. [3] also found out that when a small amount of energy is required, low density and cheap materials such as pebbles can be used for thermal energy storage. In cases where a large amount of energy is required, then high density materials can be used

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Nomenclature

Abbreviations

TES	thermal energy storage
SHTES	sensible heat thermal energy storage
HTF	heat transfer fluid
PCM	phase change material
LHTES	latent heat thermal energy storage

Roman symbols

m	mass (kg)
T	temperature (°C and K)
V	volume (m^3)
c	specific heat capacity ($Jkg^{-1}K^{-1}$)
$\dot{V}$	volumetric flow-rate (ml/s)
y	axial position (m)
n	integer (–)
$\dot{Q}$	charging energy/exergy rate (W)
$Strn$	stratification number (–)

Greek symbols

ρ	average density (kgm^{-3})
ε	porosity (–)

Subscripts

i	initial
out	outlet
in	inlet
f	final
T	tank
s	Sunflower Oil
w	water
c	calorimeter
r	rock
ce	charging energy rate
cx	charging exergy rate
xf	exergy factor

for thermal energy storage. TES systems are categorized as sensible heat storage (SHS), latent heat storage (LHS), thermochemical reactions or a combination of any of them. Out of the three major categories of TES systems, most installed TES systems apply sensible heat storage for domestic scale TES applications. This is because sensible heat materials (SHMs) usually have larger thermal conductivities as compared to phase change materials (PCMs) for solar energy applications. The large thermal conductivity of sensible heat materials is important for easy heat transfer during charging and cooking. PCMs usually have low thermal conductivity and require a longer time to absorb and release the same energy for any domestic applications such as cooking. According to Foong et al. [4], SHMs are cheaper than PCMs and thermochemical reactions. Therefore, small sensible heat TES (SHTES) systems for TES are more appropriate in many countries in the developing world. This is mainly because they are easy to fabricate and maintain. SHTES systems can apply media such as sand, rocks and concrete charged using air, water and thermal oils as HTFs.

Several studies have been performed both numerically and experimentally on the use of air/rock packed bed TES systems [5–9]. Air generally has low thermal conductivity. Air requires a bigger volume to store enough energy for any TES operation because it expands considerably and has low thermal capacity. Similarly, air TES systems require a high pumping power to store a large amount of heat. To cater for the shortfalls of air, water TES systems have been studied [10–14]. Water does not stratify properly in simple storage tanks without suitable stratification devices. The stratification devices automatically add more costs to the storage systems. Furthermore, water has a challenge of vapourising at 100 °C. This necessitates the use of pressurizing equipment for water to operate at higher temperatures than its low boiling point. Operating above the boiling point of water increases the cost of the heat exchangers and the engineering mechanisms involved.

Due to the low thermal conductivity of air and low boiling point of water, thermal oils have been used to store thermal energy in storage systems [15–22]. Winter et al. [15] studied thermal, synthetic and silicone oils for operating temperatures exceeding 300 °C. The study was limited to temperatures less than 350 °C due to stability and safety reasons. A review on solar collectors and TES by Tian and Zhao [16] found out that two tank thermal oil systems are the most commonly used storages. Turchi et al. [17] recommended that single tank systems could reduce the cost of TES systems. Bob and Benjamin [18] conducted an experiment on storage of thermal heat using a sand bed. They discovered that the sand bed was slow to collect heat during charging. Ben et al. [19] tested an experiment of sand saturated with Xceltherm 600 heat transfer oil in a temperature range of 27 °C–55 °C. The results obtained were used to validate an 1D transient enthalpy-based model for simulation of thermal storage. The model was then applied to study and compare the thermal storage performance of sand saturated by Hitec as the heat transfer fluid and concrete in a 600 MW power plant for temperatures ranging from 400 °C to 500 °C. They found out that more energy was stored and extracted when Hitec-saturated sand was used as storage media than using the concrete thermal storage system. Concrete particularly undergoes degradation associated with the mismatch of its thermal expansion. The cooking experiments by Nahar [20] indicated that a cooker filled with engine oil out performed a similar solar cooker without oil. He also noted with concern that engine oil was quite expensive. Herrmann et al. [21] reviewed a solar electric generating system in California using a mineral oil (caloria). They discovered that this oil alone represented 42% of the TES investment cost and the oil was very flammable. Kuravi et al. [22] evaluated characteristics of therminol and it required well-regulated conditions for the solar thermal system to operate well. Therefore, thermal (mineral) oils are mainly suitable for power plant heat storages. They are not recommended for domestic applications since they are highly degradable, flammable, expensive and release dangerous fumes especially at high temperatures.

Because of the expensive and harmful nature of commercial thermal oils, there is a necessity to use the locally available vegetable oils [23–33]. Urbicain and Lozano [23], Rao [24] and Bhatnagar et al. [25] conducted studies on temperature-dependent thermal properties of various vegetable oils. In all their findings, it was clear that Sunflower Oil had a high specific heat capacity value and a wide temperature range of operation. They further acknowledged that the viscosity of Sunflower Oil remained low at extreme temperatures. This property allows easy circulation at high temperatures. Mawire et al. [26] conducted a study on thermal oils with reasonably low viscosities for medium temperature applications. The three oils were Sunflower Oil, Shell Thermia B and Shell Thermia C. They recommended that Sunflower Oil was the best option because of its price of about USD 1.2 per litre which makes it cheaper than the other oils. It is also readily available for wide usage in most developing countries. The cost of Shell Thermia B and Shell Thermia C is approximately USD 1.52 per litre. They further noted that domestic cooking required the temperature range of the storage medium to be around 100 °C and 250 °C. When the thermal properties of the different oils as a function of the temperature