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Research paper

Liquid-sensible heat storage units for short-term low-temperature applications: configurations and thermal analysis

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ABSTRACT

Two configurations of liquid-sensible heat storage systems are proposed for low-temperature solar applications. The first is an air-based system, where the storage element is water, while the charging and distributing heat transfer fluids are air. The second is a water-based system, where the storage element is thermal oil, while the heat transfer fluid is water. Regarding the second configuration, sunflower oil, and engine oil are tested for heat storage. The inlet temperatures of hot heat transfer fluids have been measured experimentally using air and water flat-plate solar collectors. Using the existing mathematical equations, the duration of a complete charge-discharge cycle for each storage element was calculated. The temperature variation of the storage element during the entire storage cycle was also examined. During the storage process, we noted that the temperature of the storage media increases with the rise of inlet temperature of the hot transfer fluid. It has been proven that water-based configuration using thermal oils is more efficient than air-based configuration. However, the discharge duration is longer for the air-based system than the water-based system. Moreover, we investigated and discussed the effect of both storage media volume (mass) and cooled transfer fluid's flow rate on the storage material temperature during the whole charge-discharge cycle.

1. INTRODUCTION

Unlimited use of traditional energy sources can cause serious economic and environmental problems in the short and long term. Research and experiments related to energy use have proven that conventional energy consumption can be reduced by using renewable energy sources such as solar thermal energy. Compared to conventional energy sources, solar thermal energy is a more reliable solution for health

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and the environment. Unfortunately, using solar thermal energy requires sunlight, which is not available at night or on cloudy and rainy days. To avoid this problem and improve the performance of solar energy systems, additional auxiliary systems, such as thermal energy storage systems, must be integrated (Kilkis and Kakaç, 1989; Tian and Zhao, 2013). Therefore, the future progress of solar energy devices will depend mainly on thermal energy storage systems (Alva et al., 2018; Barrasso et al., 2023).

The development of a thermal energy storage technology is usually classified according to the following three main criteria: (1) the state of thermal storage material, (2) thermal storage duration, and (3) the thermal energy storage's temperature (Bouraba et al., 2025).

Among thermal heat storage methods (sensible, latent and thermochemical), sensible heat storage method was considered because of its simplicity and practical methods for thermodynamic behavior simulation and design of high, intermediate, and low-temperature applications (Schmidt and Szego, 1976; Schmidt et al., 1977; Bejan, 1978; Garg et al., 1985; Paykoç and Kakaç, 1987; Krane, 1987; 1989). In these systems, thermal energy is stored by sensible heat in solid or liquid materials. Solid materials with low price and high thermal conductivity can be considered as a good choice for use. Water remains the most widely used material in liquid-sensible heat storage systems for storage temperatures between 0 and 100°C. Good selection of storage materials generally depends on several criteria such as material availability and cost, heat storage capacity, and thermodynamic properties, including thermodynamic and transport properties. Concerning latent heat storage systems, the heat can be stored as heat of fusion in molten materials. In these systems, heat can be stored in the phase change material with small temperature changes (Michaels, 1981; De Jong and Hoogendoorn, 1981; Abhat et al., 1981; Agyenim et al., 2010).

Thermal energy storage can be based on criteria of how long the heat is stored and how long it is used. Therefore, its efficiency depends strongly on the charging, storing, and discharging periods. This means that the energy stored for any application must be consumed within a specific period. This period ranges from very short durations to annual cycle time scales (Abhat, 1980; Hahne et al., 1989; Dincer and Dost, 1996; Zhao and Wang, 2019). Thermal energy storage is also often classified according to the temperature level criterion. In this case, thermal energy storage applications are divided into three, according to the temperature level of the storage material. These are low, medium, and high-temperature levels (Wyman et al., 1980; West, 1987; Hasnain, 1998a; 1998b; Laing et al., 2007; Gautam and Saini, 2020). Table 1 summarizes some of the key features of various heat storage systems. A comparison of these technologies has shown that they have all some advantages and disadvantages. Among the several thermal energy storage types, sensible heat storage is the most widely employed since it is the least expensive technology. Nowadays, it is mostly utilized for space heating, household hot water tanks, and heat storage systems (molten salt) for solar thermal power plants (IRENA, 2020). Current state of art, revealed that plenty research results on sensible heat storage method were published recently attesting the interest of this storage method even though its lowest energy density compared to latent and thermochemical storage systems.

In addition, experimental and numerical investigations, including various methods and modeling techniques for domestic and industrial solar applications, have been proposed for the design and rating of thermal energy storage equipment (Taylor et al., 1991; Krane and Krane, 1992a; 1992b; Dinçer et al., 1997; Dinçer and Zamfirescu, 2011; Dinçer and Rosen, 2011; Kalaiarasi et al., 2016). For instance, Hill et al. (1977) proposed a standard procedure for determining the performance of thermal energy storage systems. This standard considered both sensible heat and latent heat storage methods and is related to heat transfer loss and the effective capacity calculation of the entire charge process-discharge process cycle. Their concept was experimentally demonstrated where a liquid or air could be used as a heat transfer fluid. Klein and Beckman (1979) proposed a design approach for a long-term-sensible energy storage system. Correlations between system performance and system design parameters have been presented. Over the past 20 years, many methods have been developed to improve the performance of a new type of sensible heat storage unit, which combines flat-plate solar air collectors with integrated sensible heat storage (Kalogirou, 1997; 1999; Smyth et al., 2006; Kumar and Rosen, 2011; Kalaiarasi et al., 2016; 2020; Lakshmi et al., 2017). A numerical study of a flat-plate air solar collector integrated with solid-sensible thermal energy storage for short-term low-temperature applications was carried out by Boulemtafes et al. (2023). The obtained results have shown the effect of using storage media on the enhancement of outlet air temperature, for hours above sunrise, which is beneficial for solar heating or drying applications.

Table 1. Performance of heat storage technology and their projections (IRENA, 2020)

Attribute	Sensible			Latent			Thermochemical		
	2018	2030	2050	2018	2030	2050	2018	2030	2050
Cost (USD/kWh)	0.1-35	0.1-25	0.1-15	60-120	60-95	60-80	Research level (1)	Pilot scale, 80-160	Demonstration, <80
Efficiency (%)	50-90	60-90	70-90	>90	>92	>95	40-50		(2)
Energy density (kWh/m^3)		0.4-0.9 kW/m^3K (heat capacity)			50-80			800-1200	
Lifetime (years or cycle	1000-3000	3000-5000	5000-7500	1000-3000	3000-5000	5000-7500	<100	500-1000	>1000-3000
Working temperature (°C)		-150-1000		-40-700	-50-950		500-900		500-1000

Notes: (1) Research level: still at an early stage, material development; (2) Value not available due to low technology readiness level.

Among various sensible storage materials, many research papers have been published on the use of liquid storage materials. Typically, the liquid sensible heat storage system consists of a liquid tank containing water or other liquid storage media, the solar collector circuit that supplies energy to the system, and the distribution circuit or cooled heat transfer fluid circuit, which transfers the stored heat for later use in another process. However, this system can be presented in different configurations depending on the presence or absence of a heat exchanger in the system (Garg et al. 1985). In fact, the heat exchanger can be inside or outside the storage tank. When the heat transfer fluid and the liquid storage element are the same, it is advised to use a storage tank without a heat exchanger. However, the use of a heat exchanger inside or outside the storage tank is important when the storage fluid and the heat transfer fluid are not the same. In the work of Bouraba et al. (2024), heat is transferred from the hot water to the storage element via a heat exchanger immersed in the liquid bath. Their results showed a rise in the liquid storage temperature and a drop in the discharge duration when heat exchanger tube length is increased. Meanwhile, the influence of the tube length on the liquid temperature during the complete charge-discharge cycle and on the outlet temperature of the heat transfer fluids becomes negligible when the tube length is greater than 3m.

Thermal oils can be used as a sensible heat storage material due to their high heat transfer coefficient, high density, high specific heat and relatively high thermal conductivity. The results from Mehla and

Kumar (2021) showed that the maximum average energy efficiency of 27.15% and exergy efficiency of 24.8% are achieved for thermal oil storage tank at a high air-flow rate of 159 kg/h using circular fin configuration exposed to a parallel air-flow flowing inside a hollow pipe. For the same arrangement, the maximum average power gain (538.7 W) was attained at high air flow rate (159 kg/h). From the literature, it can be seen that some research has been conducted on the use of engine oil as a sensible heat storage material using an evacuated tube collector (Mehla and Kumar, 2021). Mawire (2016) studied sunflower oil as sensible heat storage material for low, medium and high temperature applications using solar concentrating system.

Based on the in-depth study of the literature summarized in the previous paragraphs, it is found that there are very few reported research activities on the use of thermal oils as sensible heat storage materials for low-temperature applications.

Hence, the main objective of this paper is to study thermal oils as a liquid sensible heat storage medium for low-temperature applications using flat plate solar collector. Two configurations of liquid-sensible heat storage systems are investigated, in which water, sunflower oil, and engine oil are selected and tested. Using a water-based configuration with thermal oils as sensible heat storage material certainly reduces the system size compared to an air-based system. For this purpose, the influence of the storage element mass on the entire charge-discharge cycle and on the heat transfer fluids will be examined and discussed.

It should be noted that in the previous studies such as Krane (1987) and Zubair and Al-Naglah (1999), the ambient temperature and the hot gas source temperature were kept constant. However, in the present study, real experimental data measured on the site of Bouzareah (Algeirs), including ambient temperature and solar collector outlet temperature, were used as heat exchanger inlet conditions. These data are time-dependent and vary during the day with solar radiation.

Environmentally, using non-edible vegetable oils and non-usable synthetic oils, which are second-generation feedstocks, contributes significantly to reducing deforestation and the destruction of wildlife. Noting that edible or non-edible vegetable oils, including sunflower, are (Atabani, 2013) :

- available, renewable and biodegradable,
- with high heat density,
- have lower sulfuric and aromatic contents.

In addition, aliphatic petroleum-based oils, including engine oil, have relatively high density and heat capacity.

2. PROPOSED CONFIGURATIONS

The heat storage system shown in Fig. (1) is an air-based liquid-sensible heat storage system. It consists of a flat-plate air solar collector and a water storage tank. As reported by Krane (1987; 1989), Badar and Zubair (1995) and, Zubair and Al-Naglah (1999), the system operates in a thermodynamic cycle with a single cycle being composed of a storage process followed by a discharge process. During the storage cycle, in the solar collector loop, the valves numbered 1 and 2 are open. Meanwhile, the valves numbered 3 and 4 are closed. Accordingly, hot air with mass flow rate $\dot{m}_s$ leaves the solar collector at temperature T_{is}, and enters the storage system through a heat exchanger immersed in the bath of mass M_l and specific heat c_{pl}. The outlet temperature of air T_{os} and the temperature of the bath T_l progressively approach the hot gas temperature at the inlet of the heat exchanger T_{is}. The hot air valves close and the cold air valves open after the completion of the charging phase, signifying the beginning of the discharging process. In this process, cold air of mass flow rate $\dot{m}_d$ enters the bath at temperatureT_{id}. After passing through the same heat exchanger and receiving the heat from the liquid bath, it exits the system at T_{od}. The operating principle of the second configuration shown in Fig. 2 is quite similar to the previous configuration. A solar water collector is now used instead of the air collector, while the storage elements are other liquids such as thermal oils. This configuration is preferred when fluids in the collector and the distributing circuit are water, while the storage elements are other liquids.

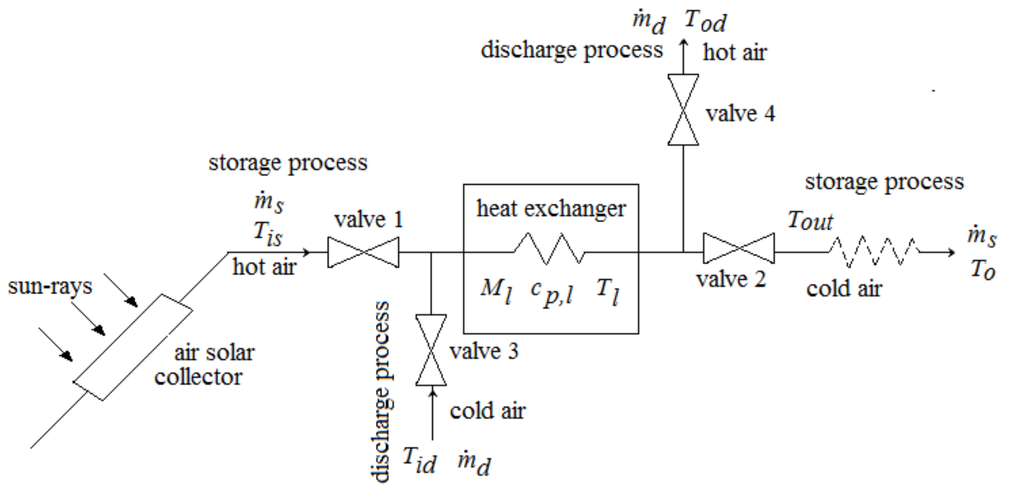

Fig 1. Schematic of an air-based liquid-sensible heat storage system

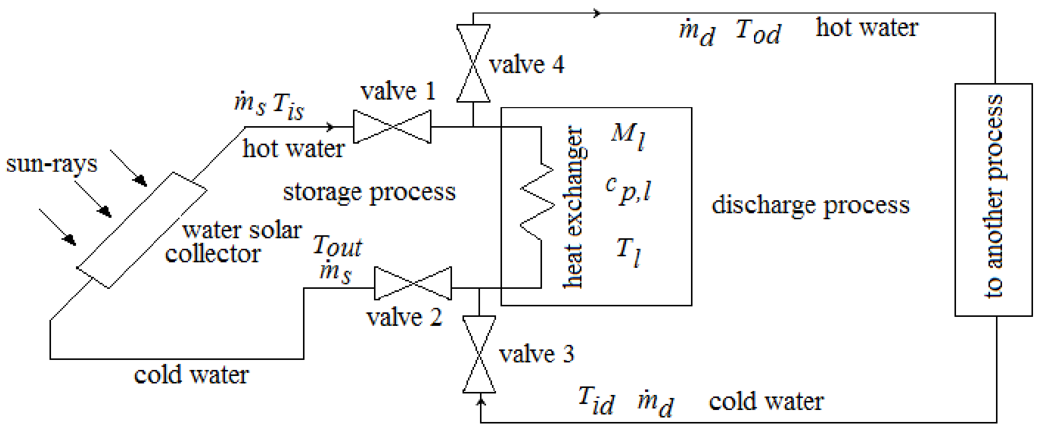

Fig 2. Schematic of a water-based liquid-sensible heat storage

Table 2. Typical composition (%) of sunflower oil and engine oil

Sunflower oil (Nunes, 2013)					
Base oil	Palmitic C16:0	Estearic C18:0	Oleic C18:1	Linoleic C18:2	Others
35-45	6	5	20	60	9
Engine oil (Moricová et al., 2019)					
Base oil	Viscosity improvement additive	Detergent	dispersant	Wear protection	Others
78	10	3	5	1	3

Moreover, sunflower oil and engine oil, as second-generation feedstocks, are selected as storage materials. The compositions of these oils are illustrated in Table 2 (Nunes, 2013; Moricová et al. 2019). In addition, thermophysical properties for sunflower oil and unused engine oil are derived from Rojas et al., (2013) and Bejan (2013), respectively. However, the fundamental thermodynamic properties of water liquid, including thermodynamic properties and transport properties, are derived from Reference Fluid Thermodynamic and Transport Properties REFPROP.8 (Lemmon et al. 2007).

3. MATHEMATICAL PROCEDURE

3.1 Temperature Variations of the Storage element and Heat Transfer Fluids

A schematic diagram of the complete charging-discharging cycle is shown in Fig. (3) (Krane, 1987). The storage process begins when the temperature of the liquid bath T_{Is} becomes higher than the temperature of cold heat transfer fluid T_{id}, which comes from the application, by an amount of εT_{id}, so that (Krane, 1987; Zubair and Al-Naglah, 1999).

$$T_{Is} = (1+\varepsilon)T_{id} \tag{1}$$

Where, $\varepsilon > 0$ is the parameter that characterizes the "tare capacity" of the system in order to deliver thermal energy to load (Zubair and Al-Naglah, 1999). In Fig. (3), subscripts, amb, d, F, I, i, and s, indicate ambient, discharging, end of the process, start of the process, inlet of heat exchanger, and storage process, respectively. Other terminologies are mentioned in Figs. (1) and (2).

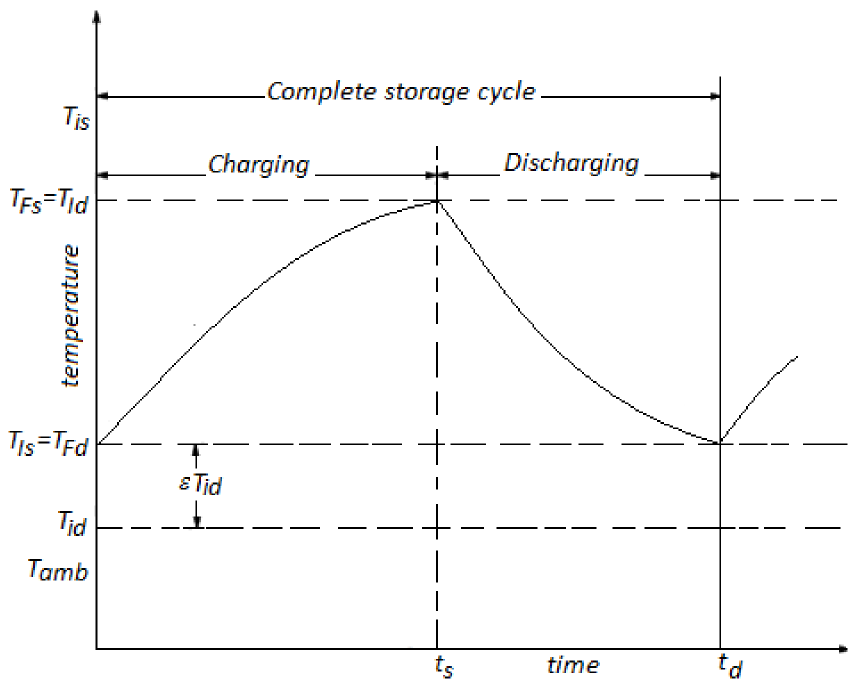

Fig 3. Temperature variation of the storage element for a complete sensible storage cycle (Krane, 1987)

An energy balance on the heat exchanger results in:

$$\dot{m}_s c_{p,f} dT_f = -h_s p dx \left(T_f - T_l\right) \tag{2}$$

c_p : specific heat at constant pressure

h_s : the coefficient of convective heat transfer during the storage process

p : the heated perimeter

x : the axial coordinate

Subscript f refers to heat transfer fluid.

Integrating Eq. (2) along the flow, from $x = 0$ to $x = L_t$ and $from\, T_f = T_{os}$ to $T_f = T_{is}$

L_t refers to the length of the tube:

$$\frac{T_{os}}{T_{is}} = 1 + y_s\left(\frac{T_l}{T_{is}} - 1\right) \quad (3)$$

$y_s = 1 - e^{-Ntu_s}$, and $Ntu_s = h_s p L_t/(\dot{m}_s c_{p,f})$ is the number of transfer units.

For the storage element:

$$M_l c_{p,l}\frac{dT_l}{dt} = \dot{m}_s c_{p,f}(T_{is} - T_{os}) \quad (4)$$

Introducing Eq. (3) into Eq. (4) and integrating from $t = 0$ where $T_l = T_{Is}$ to any time t:

$$T_l = T_{is} + (T_{Is} - T_{is})exp(-y_s\theta) \quad (5)$$

Where, $\theta = \dot{m}_s c_{p,f} t/(M_l c_{p,l})$ is the storage dimensionless time.

For the period of the discharging process, the outlet temperature of the cold transfer fluid T_{od} is expressed by:

$$T_{od} = T_{id}\left(1 + y_d\left(\frac{T_l}{T_{id}} - 1\right)\right) \quad (6)$$

$with\, y_d = 1 - e^{-Ntu_d}$.

$Ntu_d = h_d p L_t/(\dot{m}_d c_{p,f})$ is the number of heat transfer units, where h_d is the heat transfer coefficient calculated during the discharge process. Similar to Eq. (5), the liquid bath temperature during the discharge process is given as:

$$T_l = T_{id} + (T_{Id} - T_{id})exp\left(-y_d\left(\theta - \frac{\dot{m}_d}{\dot{m}_s}\theta_s\right)\right) \quad (7)$$

Where the dimensionless discharging time, over time $(t - t_s)$, is given as:

$$\frac{\dot{m}_d c_{p,f}(t - t_s)}{M_l c_{p,l}} = \theta - \frac{\dot{m}_d}{\dot{m}_s}\theta_s \quad (8)$$

Where $\theta_s = \dot{m}_s c_{p,f} t_s/(M_l c_{p,l})$ is the dimensionless storage time and $t_s < t$ is the total storage period. Furthermore, Ntu_d can be related to Ntu_s as follows:

$$\frac{Ntu_d}{Ntu_s} = \frac{h_d}{h_s}\frac{\dot{m}_s}{\dot{m}_d} \tag{9}$$

3.2 Convective Heat Transfer Coefficients

In the work from Krane (1987) and Zubair and Al-Naglah (1999) the convective heat transfer coefficients for turbulent flow inside a smooth circular tube, h_s and h_d, were calculated by the following universal equation:

$$Nu_{d_h} = \frac{hd_h}{k} = 0.023Re_{d_h}^{0.8}Pr^{0.3} \tag{10}$$

Which is a Colburn equation, for heating or cooling in tubes, as introduced by McAdams et al. (1949).

Nu_{d_h} : Nusselt number calculated on the basis of hydraulic diameter d_h,

Re_{d_h}: Reynolds number,

Pr : Prandtl number of the fluid.

In Eq. (10), $h \rightarrow h_s$ for the charging process and $h \rightarrow h_d$ for the removal process. It should be that Eq. (10) is valide for a Prandtl number between 0.6 and 160 and a Reynolds number greater than 10000 (Incropera et al. 2007).

Substituting Eq. (10) into Eq. (9) results in:

$$\frac{Ntu_d}{Ntu_s} = \left(\frac{\dot{m}_d}{\dot{m}_s}\right)^{0.8}\frac{\dot{m}_s}{\dot{m}_d} = \left(\frac{\dot{m}_d}{\dot{m}_s}\right)^{-0.2} \tag{11}$$

In the present work, the convective heat transfer of water flowing inside a circular tube is calculated using the Dittus-Boelter correlation (1985). After converting to basis SI units, the following equations can be obtained (Winterton, 1998):

For cooling in tube (charging process):

$$\left(Nu_{d_h}\right)_s = \frac{h_s d_h}{k} = 0.0264\left(Re_{d_h}^{0.8}\right)_s Pr^{0.3} \tag{12}$$

For heating in tube (removal process):

$$\left(Nu_{d_h}\right)_d = \frac{h_d d_h}{k} = 0.0241\left(Re_{d_h}^{0.8}\right)_d Pr^{0.4} \tag{13}$$

The dittus-Boelter equation is valid for Prandtl numbers ranged from 0.7 to 120 and a wide range of Reynolds number ($2500 < Re_{d_h} < 1.24 \times 10^5$). Substituting Eqs. (12) and (13) into Eq. (9) gives:

$$\frac{Ntu_d}{Ntu_s} = 0.913 \times \left(\frac{\dot{m}_d}{\dot{m}_s}\right)^{-0.2} Pr^{0.1} \tag{14}$$

3.3 System Efficiency

According to the thermodynamics first rule of, the ratio of the energy that was actually stored during the storage time to the greatest amount that could have been stored during the same period is the called the heat storage system's efficiency during the charging process (Krane, 1987; Krane, 1989):

$$\eta = 1 - exp(-y_s \theta_s) \tag{15}$$

4. RESULTS AND DISCUSSION

Fig. (4*a*) shows the changes in the temperatures of hot water and hot air at the outlets of flat-plate solar collectors and the ambient temperature on January 4, 2022, from 9 am to 4 pm. The solar intensity during the same period is shown in Fig. (4*b*). These experimental values will serve as input conditions for storage systems while studying their performance.

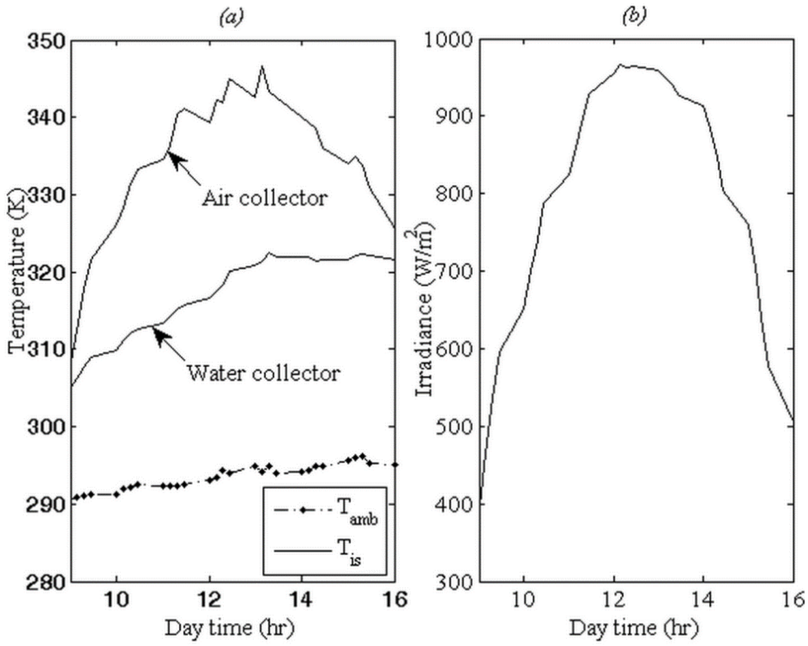

Fig 4. (*a*) Variation of the collector outlet temperature and ambient temperature, (*b*) Solar intensity

The complete storage cycle for an air-based system is illustrated in Fig. (5) for different values of liquid bath mass. As can be seen, liquid temperature decreases as the mass of liquid increases. A liquid with more mass undergoes a smaller temperature change.

A substance's temperature is the measure of the thermal energy stored in it. More specifically, it is the measurement of the particles' kinetic energy level within a substance.

Thus, the temperature of a given substance is strongly dependent on the total energy content of a substance, which is proportional to its mass. This means that a larger mass of the same material will contain more total energy than a smaller mass. However, for a fixed amount of heat, the temperature change diminishes as the liquid mass increases.

It should be noted that increasing the mass of the liquid bath may affect the time it takes to change its temperature. During the removal process, larger masses take longer to cool down than smaller masses. Mass affects the time it takes for water to reach a new temperature when energy is added or removed.

This configuration is typically used to store energy in large quantities of water using a large liquid bath with a large tube-diameter heat exchanger. In this case, the energy source temperature should be higher than what requires the use of a concentrating collector. Badar and Zubair (1995) used an energy source with a constant hot gas inlet temperature of $900K$ and a constant ambient temperature of $300k$ to store heat in a large liquid bath containing water, $M_l = 1000kg$.

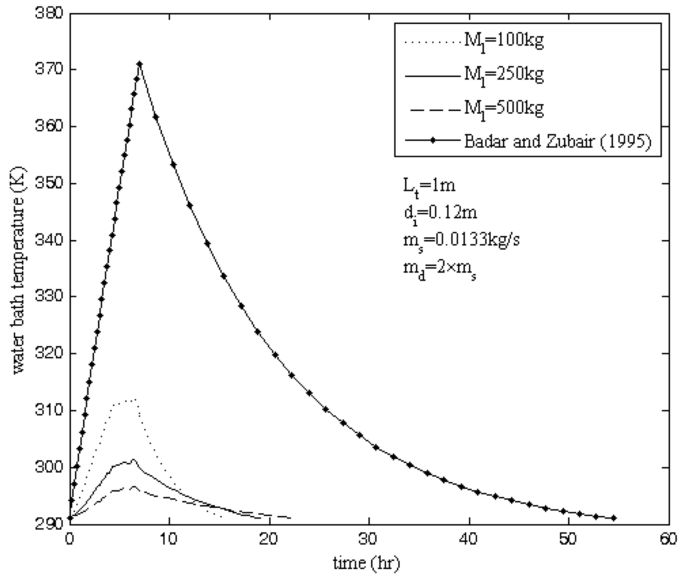

Fig 5. Air-based water heat storage system (for Badar and Zubair (1995): $M_l = 1000kg$, $T_{is} = 627°C$, $T_{amb} = 27°C$, hot air velocity $= 3m/s$, $L_t = 1m$, $d_i = 0.1m$)

For the water-based configuration, the duration of the complete charge-discharge cycle of sunflower oil and engine oil is calculated and plotted in Fig. (6). Under the same operating condition, a comparison with the air-based system is also shown in this figure. During storage period, the temperature of the heat transfer fluid obviously rises. This means that the liquid in the bath absorbs more heat, which increases its temperature. When the storage element's temperature rises by a certain amount $\varepsilon \times T_{id} \approx 3°C$ over the cold heat transfer fluid's intake temperature, the charging process begins. This value changes by changing T_{id}. It can also be observed that the temperatures of sunflower oil and engine oil in the water-based storage system rise more rapidly than that of water in the air-based storage system. Although the hot air inlet temperature of an air-based storage unit is much higher than that of the hot water inlet temperature of a water-based storage unit, the liquid bath temperature of the air-based system remains very far from the hot air inlet temperature. The bath temperature in this configuration, does not range the inlet temperature of the hot air T_{is}. In fact, the temperature at the inlet of the heat exchanger varies during the day. In the evening, when solar irradiation begins to decrease, the hot air temperature decreases rapidly, and the water bath temperature remains almost constant. On the other hand, the discharge period of the air-based storage system is longer than that of the water-based system, while the discharge periods of thermal oils are comparable. These can be related to the lower thermophysical properties of the air flowing through the heat exchanger. Compared to water-based heat transfer fluid, air absorbs and releases heat very slowly due to its low thermal conductivity. In addition, sunflower and engine oils as storage materials have lower heat capacities in comparison with water, requiring relatively small amount of heat to raise the temperature.

Fig. (7) depicts the systems efficiency based on the first law of thermodynamics. It can be observed that the system with engine oil is the best in terms of thermal energy storage efficiency, while water is the worst. This means that thermal oil systems have the capability to store a larger amount of energy than water systems. From previous discussion, this can be attributed to the lower thermodynamic properties of air when an air-based system is used. Furthermore, the temperature changes, the rate of losing heat, and the amount of gaining heat also affect the system storage efficiency. Additionally, the inherent thermophysical properties of thermal storage elements determine how effectively thermal energy is stored.

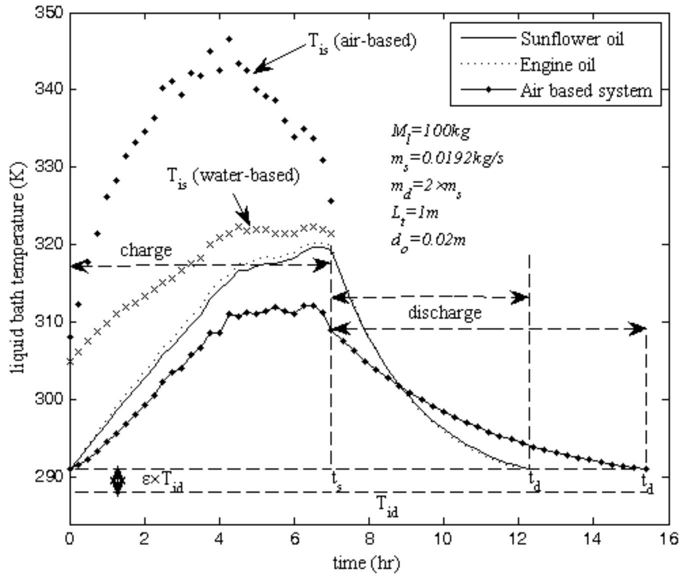

Fig 6. Temperature history for different storage element during complete cycle charging-discharging processes

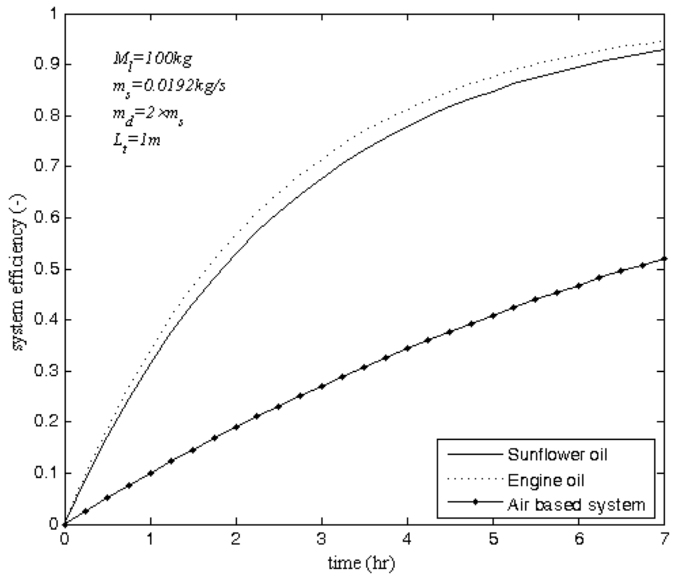

Fig 7. Heat storage efficiency

M_l and $\dot{m}_d$ influence on the storage element temperature are depicted in Figs. (8) and (9), respectively. As can be shown, the mass of the storage medium is strongly affecting the charging process, whereas the mass flow rate in the distribution circuit impacts the discharge process. During the storage period, the liquid bath temperature rises as M_l decreases. The temperature differential between the heat transfer fluid and the bath liquid increases with the mass of the liquid.

The difference becomes negligible as T_l approaches the charging fluid T_{is}. This indicates that the storage element's maximum temperature occurs at a minimal value of M_l. Beyond this point, the storage element's temperature rises more quickly without surpassing the charging fluid's input temperature. Meanwhile, there is no such influence during the discharge process.

When the cold transfer mass flow rate increases, it shortens the discharge period significantly as noted. But its effect on the liquid bath temperature becomes more negligible. Increasing the flow rate of the distribution fluid certainly reduces the amount of heat absorbed by that fluid, causing the quantity of heat stored in the storage medium to quickly decrease.

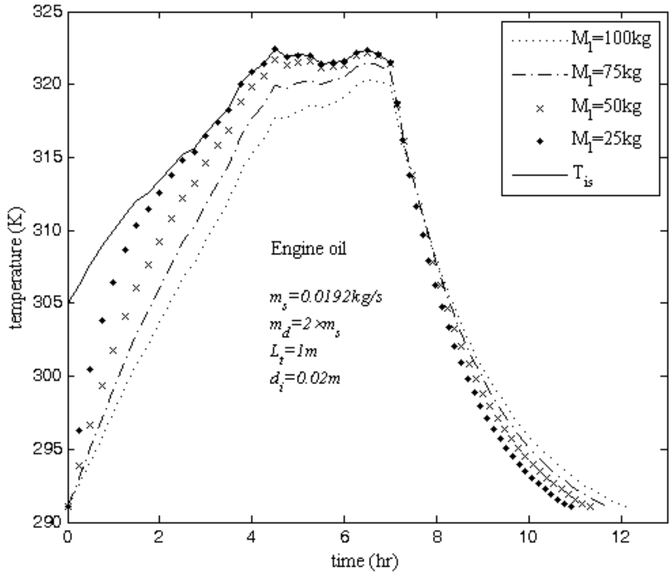

Fig 8. Effect of M_l on the liquid bath temperature

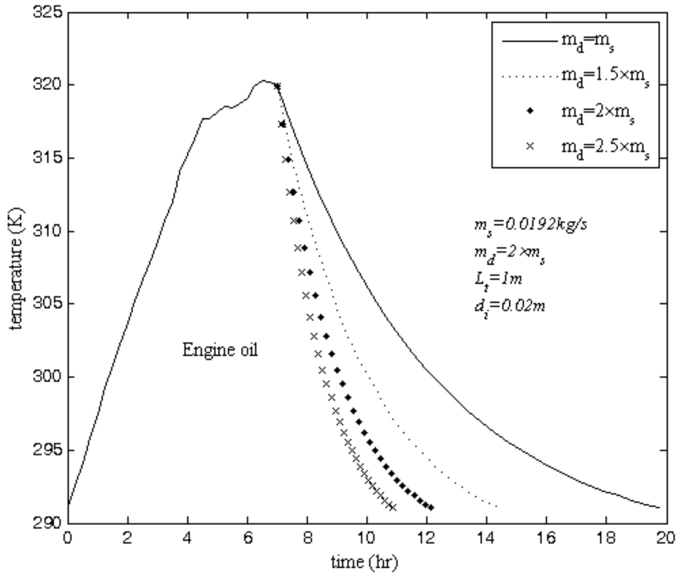

Fig 9. Effect of $\dot{m}_d$ on the liquid bath temperature

5. CONCLUSION

The performance of the liquid-sensible heat storage system is examined in this study as an attempt to improve the solar energy system's efficiency. Two system configurations have been proposed for low-temperature solar applications. In the air-based system, the storage material is water, while air is used in the collector and in the distributing circuit. For the water-based system, the charging and distributing fluids are water, while sunflower oil and engine oil are used as thermal energy storage material. The duration of the complete cycle charging-discharging process was calculated by applying the energy balance on the storage element and the heat exchanger immersed in the bath. For the period of the charging process, the bath temperature is observed to increase, approaching the inlet temperature of the heat exchanger.

Additionally, it was observed that the mass of the liquid in the bath affects the charging process, whereas the mass flow rate of the distributing fluid has an influence on the discharge process duration.

Moreover, the water-based storage system stores more energy than the air-based storage system due to the lower thermophysical properties of the air flowing inside the immersed heat exchanger.

These interesting results could be very helpful before designing and dimensioning sensible storage units for solar low-temperature applications such as heating and drying applications.

NOMENCLATURE

c_p	Isobaric heat capacity [J/kg·K]	T	Temperature [K]
d_i	Tube inner diameter [m]	t	Times [s]
d_o	Tube outer diameter [m]	η	System efficiency
h	Heat transfer coefficient [W/m^2·K]	θ	Dimensionless time
k	Thermal conductivity [W/m·K]	Subscripts	
L_t	Tube length [m]	d	Discharge process
$\dot{m}$	Mass flow rate [kg/s]	F	Final (end of the process)
M	Mass [kg]	i	Inlet of the heat exchanger
Ntu	Number of heat transfer units	I	Start of the process
Nu	Nusselt number	l	Liquid
Pr	Prandtl number	o	Outlet
Re	Reynolds number	s	Storage process

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