Energy Storage Using Sensible Heat Storage Media: Thermal and Economic Considerations

Laxman Mishra, Abhijit Sinha, Prasanta Majumder, and Rajat Gupta

Abstract Storage of energy is an important technology to bridge the time and space gap between the source/supply and sink/utilization of energy. Thermal energy storage has emerged as a means to capture heat from both low- and high-temperature sources. Storage of waste heat and solar thermal energy is easier and cheaper with the application of sensible heat storage materials. However, the knowledge of thermal and physical properties of sensible heat storage materials is important for economical and effective heat storage. Therefore, this paper presents the thermal and economic aspects of liquid and solid-state sensible heat storage materials. Thermal aspects are important for designing of the energy storage systems, while economic considerations are important in material selection and payback calculations. From the thermo-economic studies, it is found that water and rocks have great potential as liquid and solid sensible heat storage materials, respectively, primarily due to their low cost. Water also has impressive thermal properties which makes its storage density higher as compared to other liquids. Also, cast iron and steel present good potential as heat storage materials due to their high thermal capacity.

Keywords Cost · Sensible energy storage · Thermal capacity · Thermal conductivity

1 Introduction

With rapid development and improvement in standard of living, demand for energy has been increasing at an accelerated rate. Increased use of fossil-based energy sources has led to environmental concerns in the international society [1]. Also, the demand for energy varies depending on time of the day and month of the year. For example, demand of energy is higher during evenings as compared to mid-day. Thermal energy is in higher demand during winter months than those of summer.

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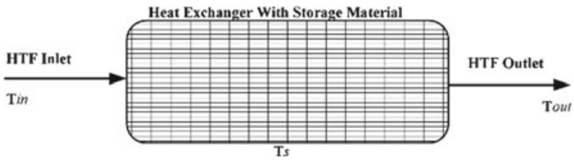

Fig. 1 Sensible heat storage system

Similarly, sources of energy like solar and wind are intermittent in nature. The existence of discrepancy in demand and supply makes it important to store energy when it is in surplus so that it may be utilized during instances of high demand [2]. Storage of energy is also important as it can be collected from place of availability, stored, and supplied where and when it is required [3].

Various means and media have been used for storage of different forms of energy. Thermal energy is one of the important forms of energy essential for both household and industrial applications. It can be stored in three forms, viz. sensible heat, latent heat, and thermo-chemical energy [4]. Schematic of sensible heat storage system is shown in Fig. 1. The system is said to be charging when the material absorbs heat from the heat transfer fluid (HTF). This happens when the inlet temperature (T_{in}) of HTF is greater than storage temperature (T_{s}) of the storage material. Discharging occurs when T_{in} is lesser than T_{s}. In this condition, the HTF gains heat from the storage material and its outlet temperature (T_{out}) is greater than T_{in}.

Each method of energy storage holds some basic advantage over others and is also associated with some drawbacks. Storing energy as sensible heat or latent heat is simple and relatively cheaper [5]; however, it cannot be stored for longer periods in these forms [1]. It has to be used within certain period of time after storage since it is lost to the ambient once the source of energy supply has been removed. Hence, they are mostly used for heating applications during intermittent cloudy hours or during the night hours of the same day. However, thermo-chemical storage overcomes this drawback. In such systems, thermal energy is stored in the form of chemical reactions, usually by removing the water of hydration from hydrated salts. The stored energy can be stored for months and recovered by mixing the separated chemical species back to get the original product along with release of stored heat. In sensible and latent mode of heat storage, there is loss of heat during storage. However, in thermo-chemical storage, since the salt and water are stored separately there is no loss of heat [6]. Also, the storage capacity or storage density of thermo-chemical storage is much higher than sensible and latent heat storage. However, this technology is not well developed yet which limits its practical application.

Effective methods of heat storage are also important for efficient use of solar energy which is a free source of energy [7, 8]. Application of sensible heat storage media enhances the absorption of solar flux and thus improves the daily output of a solar energy-based system [9]. Storage of thermal energy is necessary for an uninterrupted supply of power from solar thermal plants [10]. The heat storage materials are also useful for recovery of waste heat from thermal systems. Hence, this paper presents the thermal and economic aspects of sensible heat storage materials. The thermal properties of these materials are important for design of the energy storage system. While the economic aspects are important considerations that affect the choice of materials for energy storage.

2 Methodology

The thermal capacity has been obtained as the product of the density of the material and its specific heat capacity as shown in Eq. (1).

$$\text{Thermal Capacity} = \text{Specific Heat Capacity} \times \text{Density} \quad (1)$$

The thermal conductivities of the materials have been obtained from the literature. It is also important for faster and uniform distribution of heat within the bulk of the material which enhances its overall performance as energy storage material. The cost price of the materials has been obtained from online store [11]. The minimum price for a reasonable purity of the materials has been reported. The price is expressed as US dollars per ton of material.

3 Results and Discussion

Thermal and physical properties of materials are of important consideration while selecting a material for sensible heat storage. The amount of heat stored depends on thermo-physical properties of the material, viz. heat capacity and density. The rate of storage and retrieval depends on the thermal conductivity of the materials. Sensible heat storage materials have been divided into liquid materials and solids for the sake of convenience.

3.1 Liquid Sensible Heat Storage Materials

Liquids like water, thermal oil, etc., have been widely used as thermal storage materials. A list of common liquid sensible heat storage materials and their thermo-physical properties are shown in Table 1. Water is abundantly available and is free natural resource. It also has high heat capacity which makes it popular among several applications.

Figure 2 shows the thermal capacity of some common liquid materials and liquid mixtures. Water has the highest thermal capacity of 4186 kJ/m^{3}K followed by water–ethylene glycol mixture in 50–50 fraction. Although engine oil has relatively lower thermal capacity of 1669 kJ/m^{3}K, it has been used by several researchers due to its stability in the temperature interval of its application and relatively lower price.

Table 1 Thermo-physical properties of some common liquid sensible heat storage materials

Material	Density (kg/m^3)	C_p	References
Water	1000	4.186	[12]
Water–ethylene glycol (50:50)	1050	3.47	[13, 14]
Draw salt	1733	1.55	[13, 14]
Ethylene glycol	1116	2.382	[13, 14]
Molten salts	500–2600	1.5	[12]
Isobutanol	808	3	[13, 14]
Lithium	510	4.19	[13, 14]
Mineral oil	800	2.6	[12]
Propanol	800	2.5	[13, 14]
Synthetic oil	900	2.1–2.3	[12]
Butanol	809	2.4	[13, 14]
Dowtherms	867	2.2	[13, 14]
Ethanol	790	2.4	[13, 14]
Isopentanol	831	2.2	[13, 14]
Octane	704	2.4	[13, 14]
Engine oil	888	1.88	[13, 14]
Therminol 66	750	2.1	[13, 14]
Sodium	960	1.3	[12]

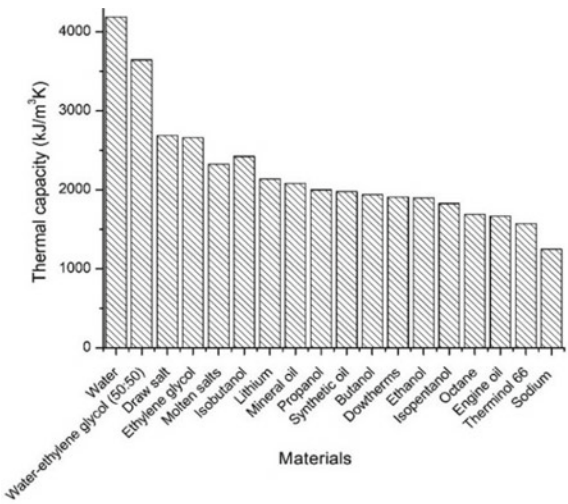

Fig. 2 Thermal capacities of some common liquid sensible heat storage materials

3.2 Solid Sensible Heat Storage Materials

Several solids have been adopted for sensible heat storage. One major advantage of using solids is that they do not need any specialized mechanism for heat exchange between the material and charging/discharging medium (heat transfer fluid). Liquids, on the other hand, need better sealed heat exchangers to avoid leakage. Also, most solids are stable and do not undergo any major changes under repeated cycles of charging and discharging. Use of solids as sensible heat storage materials has several advantages including lower cost, wider range of temperature application, absence of leakage and corrosion, no requirement for freeze protection, and ability to use locally available materials for energy storage [15]. Solids are also easy to handle, and there is no loss of material with time (other than corrosion which is usually slow). Figure 3 shows thermal conductivity and thermal capacity of some solid sensible heat storage materials.

Table 2 shows the thermal capacity and thermo-physical properties of some solid sensible heat storage materials. These solid-state sensible heat storage materials have a vast range of thermal capacities ranging from cast iron (4980 kJ/m^{3}K) to sandstone (2000 kJ/m^{3}K). Materials below 2000 kJ/m^{3}K are usually not preferred as heat storage materials. They are used in some cases due to their lower price or some other specific requirements. Compounds of iron, viz. cast iron, steel, and magnetite, have highest thermal capacities. These are followed by gravely soil and wet earth

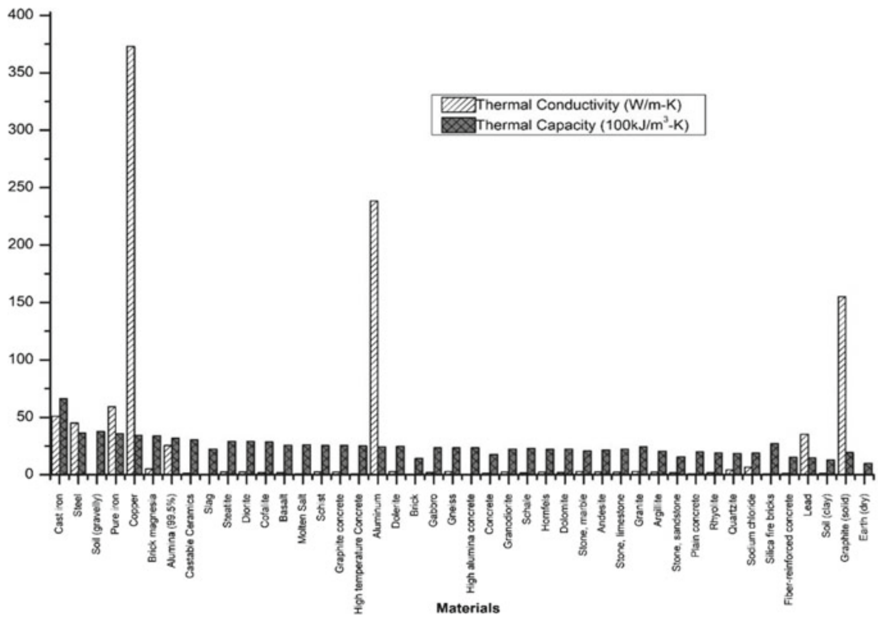

Fig. 3 Comparison of thermal conductivity and thermal capacity of solid sensible heat storage materials

Table 2 Thermal capacity and thermo-physical properties of solid sensible heat storage materials

Material	Density (kg/m^3)	Thermal conductivity (W/m K)	Specific heat (kJ/kg K)	Thermal capacity (× 100 kJ/m^3 K)	References
Cast iron	7900	51.15	0.837	66.12	[10, 12–14, 16, 17]
Steel	7840	45	0.465	36.46	[12–14, 17]
Soil (gravelly)	2040	0.5	1.84	37.54	[12–14, 17]
Pure iron	7897	59.3	0.452	35.69	[13, 14, 17]
Copper	8954	373	0.383	34.29	[12–14, 17]
Brick magnesia	3000	5	1.13	33.90	[12–14, 17]
Alumina (99.5%)	3960	25.5	0.8	31.68	[10, 12]
Castable Ceramics	3500	1.35	0.866	30.31	[12, 18–21]
Slag	2700	0.6	0.836	22.57	[10, 12]
Steatite	2850	2.5	1.024	29.18	[12]
Diorite	2900	2.5	1	29.00	[12]
Cofalite	3120	1.75	0.917	28.61	[10, 12, 18, 19]
Basalt	2650	1.75	0.965	25.57	[12]
Molten Salt	1750	1.075	1.5	26.25	[18, 19]
Schist	2700	2.55	0.945	25.52	[12]
Graphite concrete	2680	2.43	0.95	25.46	[2, 21]
High temperature concrete	2750	1	0.916	25.19	[12, 14, 19, 20]
Aluminum	2707	238.4	0.896	24.25	[12–14, 17]
Dolerite	2800	2.6	0.885	24.78	[12]
Brick	1698	0.5	0.84	14.26	[12–14, 17]
Gabbro	2950	2.05	0.8	23.60	[12]
Gneiss	2700	2.9	0.8745	23.61	[12]
High alumina concrete	2400	0.2	0.98	23.52	[10, 12]
Concrete	2000	1.279	0.88	17.60	[12–14, 17]
Granodiorite	2700	2.35	0.835	22.55	[12]
Schale	2800	1.6	0.82	22.96	[12]
Hornfels	2700	2.25	0.82	22.14	[12]
Dolomite	2800	2.1	0.802	22.46	[12]
Stone, marble	2600	2.75	0.8	20.80	[12–14, 17]
Andesite	2650	2.55	0.815	21.60	[12]
Stone, limestone	2500	2.2	0.9	22.50	[12–14, 17]
Granite	2750	2.9	0.892	24.53	[12, 13, 16, 17]

(continued)

Table 2 (continued)

Material	Density (kg/m^3)	Thermal conductivity (W/m K)	Specific heat (kJ/kg K)	Thermal capacity (× 100 kJ/m^3 K)	References
Argillite	2450	2.2	0.838	20.53	[12]
Stone, sandstone	2200	1.8	0.71	15.62	[12–14, 17]
Plain concrete	2451	1.02	0.81	19.85	[2, 14]
Rhyolite	2450	1.95	0.785	19.23	[12]
Quartzite	2550	4.3	0.7265	18.53	[12]
Sodium chloride	2200	6.75	0.855	18.81	[12]
Silica fire bricks	1800	1	1.5	27.00	[12]
Fiber-reinforced concrete	2440	1.16	0.63	15.37	[2, 14]
Lead	11,340	35.25	0.131	14.86	[12–14, 17]
Soil (clay)	1450	1.3	0.88	12.76	[12–14, 17]
Graphite (solid)	2200	155	0.879	19.34	[10, 12]

with thermal capacities of 3772 kJ/m^3K and 3680 kJ/m^3K, respectively. Both iron compounds and soil are very stable materials which can be used for several cycles of heating and cooling without causing major changes in their thermal properties. This contributes to their wide acceptance as sensible heat storage materials.

3.3 Thermal Conductivity

Thermal conductivity of energy storage materials is an important factor while making selection of materials. This is because the rate of storage and retrieval of heat to and from the material depends largely on its thermal conductivity. A material with higher thermal conductivity is more effective in storing energy and is preferred over other materials with lower conductivities. Thermal capacity, on the other hand, determines how much of heat energy can be stored by a given material. From Fig. 3, it can be seen that copper has the highest thermal conductivity and also thermal capacity which is desired from a sensible heat storage material. While pure iron, steel, and cast iron have lower thermal conductivities and appreciably high thermal capacities. Aluminum and graphite have high thermal conductivities and good thermal capacities. Rocks and pebbles have average thermal capacity and low thermal conductivity. However, they are widely used due to their economic aspects, easy availability, and thermal stability. Copper, aluminum, and graphite are less popular in spite of their good thermal properties. This is because of the economic considerations which is discussed in the following section.

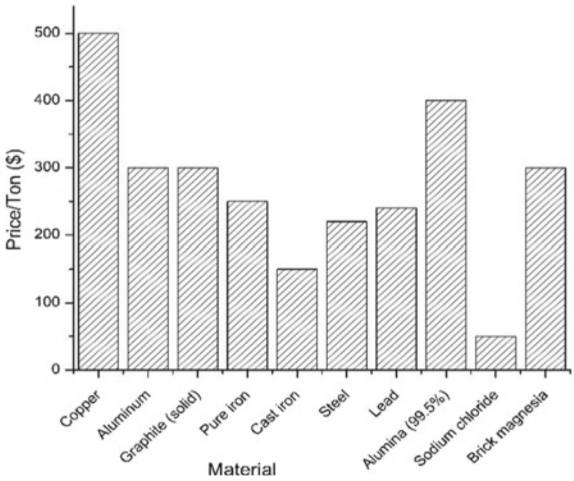

Fig. 4 Cost of some common solid sensible heat storage materials

3.4 Economic Aspects

Cost of the energy storage material is one of the most important factors which often dominates over thermo-physical properties. Materials with lower cost are preferred over others since it leads to lower initial investment and return on investment is faster. Some materials may not be used for energy storage in spite of having high thermal capacity and thermal conductivity because of its high cost. Figure 4 shows the cost price of some common sensible heat storage materials in US dollars per ton. It can be observed from the figure that copper has the highest price which makes it less popular as energy storage materials even though it has high thermal conductivity and thermal capacity as seen from Fig. 3. On the other hand, iron derivatives like steel and cast iron have been in wide use due to their low cost and high thermal capacity.

4 Conclusion

The thermal capacities of some solid and liquid sensible heat storage materials have been presented. Thermal conductivities and cost of some common solid materials have also been discussed. Based on thermo-physical properties, thermal conductivity, and cost of materials, it is found that certain materials having average thermal properties are more popularly used than others with better thermal properties due to their low cost and availability. Among liquids, water is widely used due to its high thermal capacity of 41.9 MJ/m^3K and low cost. Among solids, rocks and pebbles find application in several systems due to their low cost and easy availability. Iron derivatives like steel (36.4 MJ/m^3K) and cast iron (66.12 MJ/m^3K) have good thermal capacities, average thermal conductivities of 45 W/m K and 51.15 W/m K, respectively, and relatively low price. Hence, they are more popular than copper or aluminum which have excellent thermal properties but are costly.

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