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Evolution of Thermal Energy Storage Systems

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Abstract. A world with constant and unhindered supply of power from thermal sources is a feasible possibility. It is left to us researcher to find out the most optimal way to collect and store energy in this form. This review work seeks for thermal storage materials and methods to promote harnessing the thermal component of renewable and abundant solar energy at Covenant University, Ogun state, in Nigeria. The efficient implementation of thermal renewable energy sources is still being faced by a few challenges such as storage and efficiency. The review seeks methods of incorporating cost effective and efficient thermal energy storage techniques into the University campus energy system. Such techniques can be in form of thermal energy storage materials such as $\text{LiNO}_3\text{-NaCl}$ containing 87 wt% of LiNO_3 and 13 wt% of NaCl with latent heat capacity of 300 kJ/kg and melting temperature of 220 °C. This paper reviews the evolution as well as trends of thermal energy storage systems considering the sensible and latent heat storage materials. Results of previous researches are discussed and these include the thermal properties of various proposed heat storage and heat transfer materials such as the heat capacity, latent heat capacity, melting point, thermal conductivity and maximum temperature of stability. These results were reviewed for the two categories of storage materials considered namely: latent and sensible heat materials.

Keywords: Thermal energy, thermal storage materials, sensible heat

1. Introduction

Over the years, production of energy from non-conventional energy sources have faced the following major challenges such as efficiency and storage. Industrial heat energy waste can be optimally utilized if proper energy storage technologies are employed. Exhaust heat energy from industries and power plants can be reused for domestic as well as the production of electricity at a small to medium scale. Another reason for energy storage is to compensate for the intermittent nature of renewable energy sources [1].

For the past few decades, researchers have come up with different technologies and methods of constructing a viable thermal storage system. The ideal thermal storage system consists of heat transfer fluid as well as heat storage material with both high thermal conductivity and thermal capacity and durability as well. In addition to these properties, this system will be cheap and portable [2,3]. According to [1], there are three (3) major key points to be considered as regards an efficient thermal storage system. These are: the environmental impact, technical properties of the system and cost. The technical properties are: storage capacity, thermal conductivity, thermal stability over time, compatibility and thermal loss [1].



Researchers have identified three main modes of thermal energy storage. These are sensible heat storage, latent heat storage and chemical heat storage. When a material stores or releases heat by the rise and fall of its temperature, the material can be said to be a sensible heat storage material. This material can either be in the solid or liquid phase. Examples of solid sensible heat materials are iron, steel and concrete. Their known working temperature is between 200 °C to 1200 °C. these materials have high thermal conductivity. Examples of liquid state sensible heat storage materials are nitrate salts, carbonate salts and synthetic oil. Molten salts are the most viable for use in thermal systems as a result of the following properties they possess: high thermal conductivity, low viscosity, low vapour pressure, thermal stability, non-toxic and non-flammable [4,5,6]. Sensible heat materials are relatively low cost compared to the other two class of materials. As cheap as these materials are, they have very low thermal capacity and this puts them at a disadvantage. Thermal systems built with these materials will be large compared to the amount of heat energy they store [1].

For the second category, latent heat storage materials store and release thermal energy when they change phase. They are also called phase change materials (PCM). Their thermal capacity is far greater than those of sensible heat storage materials [1]. Paraffin is an example of a phase change material. They absorb and release heat almost isothermally. There is no significant change in temperature during thermal absorption and dissipation. The major disadvantage of these materials are they have very low thermal conductivity. Their thermal conductivities in watts per meter-kelvin vary between 0.2 W/(mk) – 0.7 W/(mk) [5].

Solar energy is the most abundant source of energy today and every day the earth receives a huge dose of this energy. Most of it goes to waste. Another source of waste energy is industrial thermal waste. This wasted energy from the sources listed above can be put to good use through proper storage. This study is a review article on the evolution of thermal energy storage systems. The approaches as well as results of past and current researchers will be looked into.

2. Evolution of Thermal Storage Systems

Various improvements on the technology for thermal storage have been proposed over the years. From the time of sensible heat storage materials being the dominant storage media to the discovery of phase change materials and then to the use of highly reversible chemical reactions that absorb and discharge heat. This section is a review of some of the methods employed for optimal and cost effective thermal storage.

2.1. Sensible Heat Storage Materials

This section focuses on past work done on analyzing materials that fall under the first two categories which are the sensible heat storage and the latent heat storage materials. As regards sensible heat storage systems, [6] experimented on the most effective mixture of molten salts that will possess the following properties: low vapour pressure, low freezing point, good chemical stability at high temperatures and good thermal properties. They tested the melting temperatures of the following salts: 50-80 wt% of KNO₃, 0-25 wt% LiNO₃, and 10-45 wt% Ca(NO₃)₂. Their salt mixtures had the maximum melting temperature to be 450 °C. their viscosities were found to be lower than 10cP when within the range of operating temperature. The salts were stable and cost effective as well.

The study of sunflower oil as a viable sensible thermal storage material was the aim of [7]. Data was recorded on its performance under different conditions during charging, retention for 24 hours and discharging.

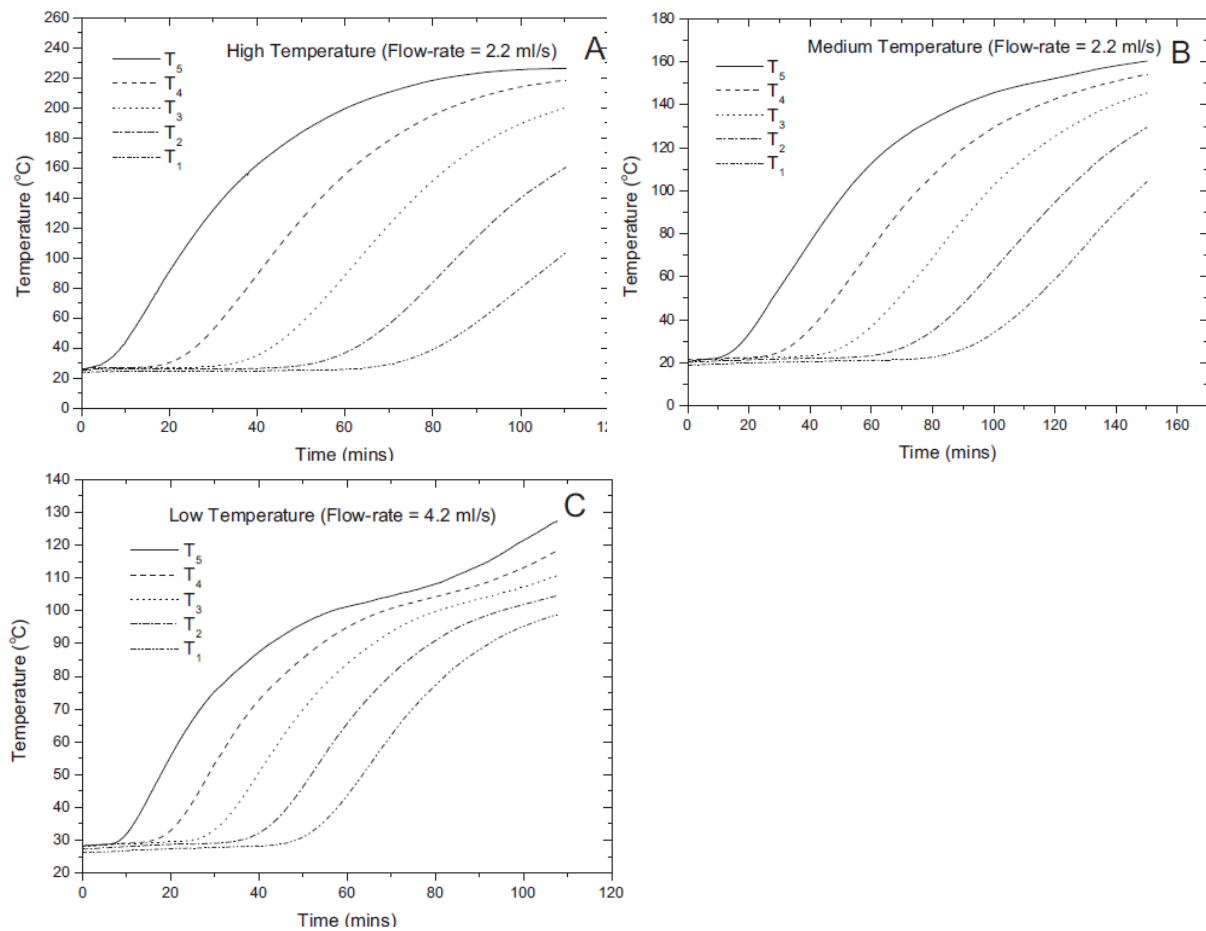


Fig. 1. Results of low, medium and high temperature charging conditions of sunflower oil [7]

From figure 1, as a result of the top of the tank having higher temperatures, thermal stratification was observed. Due to higher flow rates used in low temperature charging, the thermal stratification observed was significantly reduced. Higher flow rates resulted in faster heat transfer rate. In the case of the high temperature charging, the low flow rate enhanced thermal stratification. This served as a major factor that determined the performance of the system. For high, medium and low temperature charging, 230, 160 and 160 °C were recorded respectively at the top of the tank.

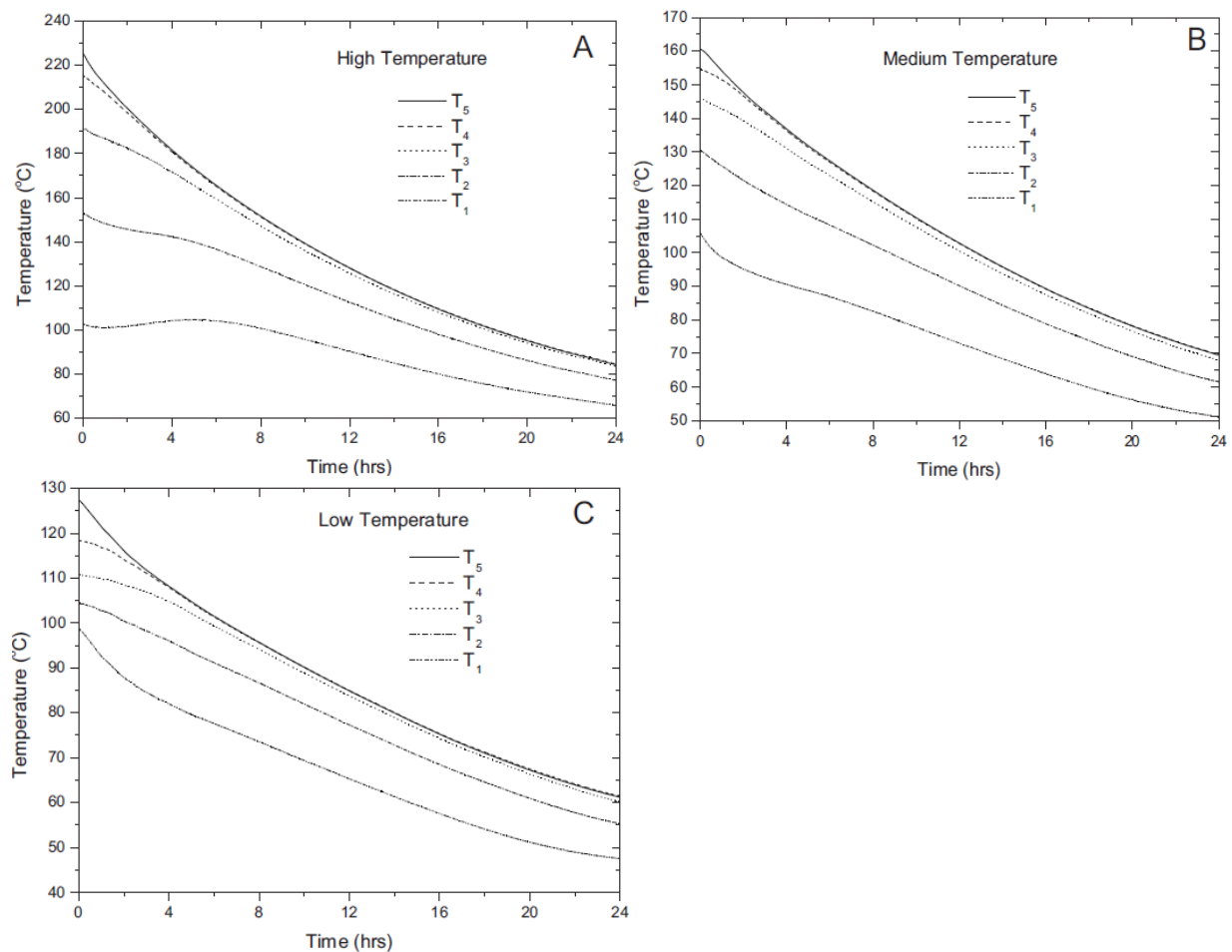


Fig. 2. Heat retention for a 24 hour period [7]

Figure 2 shows data from the system during a 24 hour heat retention for three categories studied. There was a higher rate of heat loss at the top 3 levels. This was attributed to heat loss due to convection. Another possibility for this was that the lower levels (level 1 and 2) had higher densities and therefore increasing their thermal density with time. Thermal loss was more at higher temperatures than at lower temperature during retention. This was as a result of different thermal masses along the height of the storage tank.

Concrete and sand are known to be low cost sensible thermal storage materials. However, the cracks associated with repeated expansion and contraction reduces the thermal conductivity of the system with time. This has led to the damage of the pipes that convey the heat transfer fluid as well. Sand is a good alternative but the pores present in it also limits thermal conductivity since they are basically filled with air [8]. They [8] made a comparison between concrete without cracks, concrete with cracks and sand saturated with heat transfer fluid (Hitec^(R)). Hitec^(R) is a commercially available heat transfer fluid.

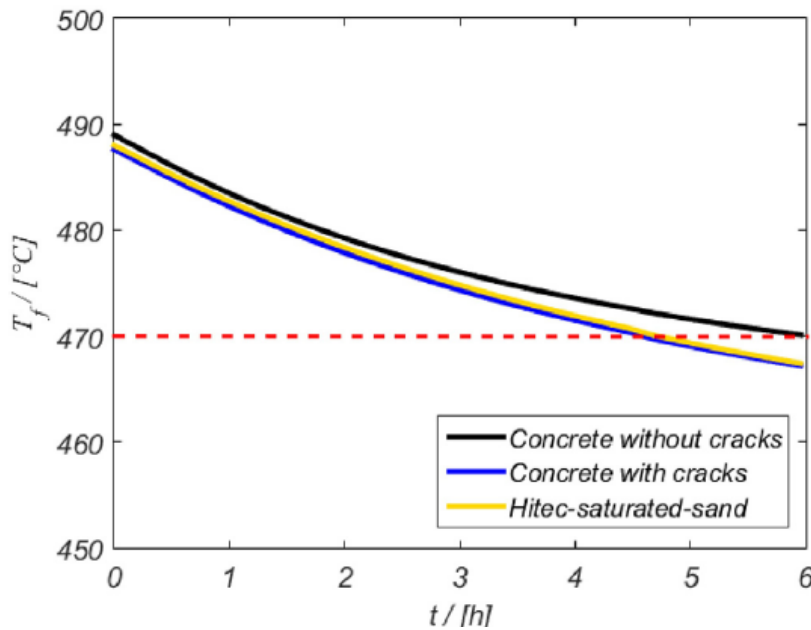


Fig. 3. Temperature at the exit point of heat transfer fluid within a 6 hour period [8]

In figure 3, the system containing concrete without crack maintained a heat transfer fluid temperature above the cut-off temperature indicated with the red dashed line throughout the six hour period. However, the system containing concrete with cracks had a 3 °C drop below the cut-off temperature in the last 1.5 hour of the six hour period. For sand saturated with Hitec®, there was a slight improvement over the performance of cracked concrete. They concluded that sand saturated with Hitec® was 4.5 % more efficient compared to cracked concrete.

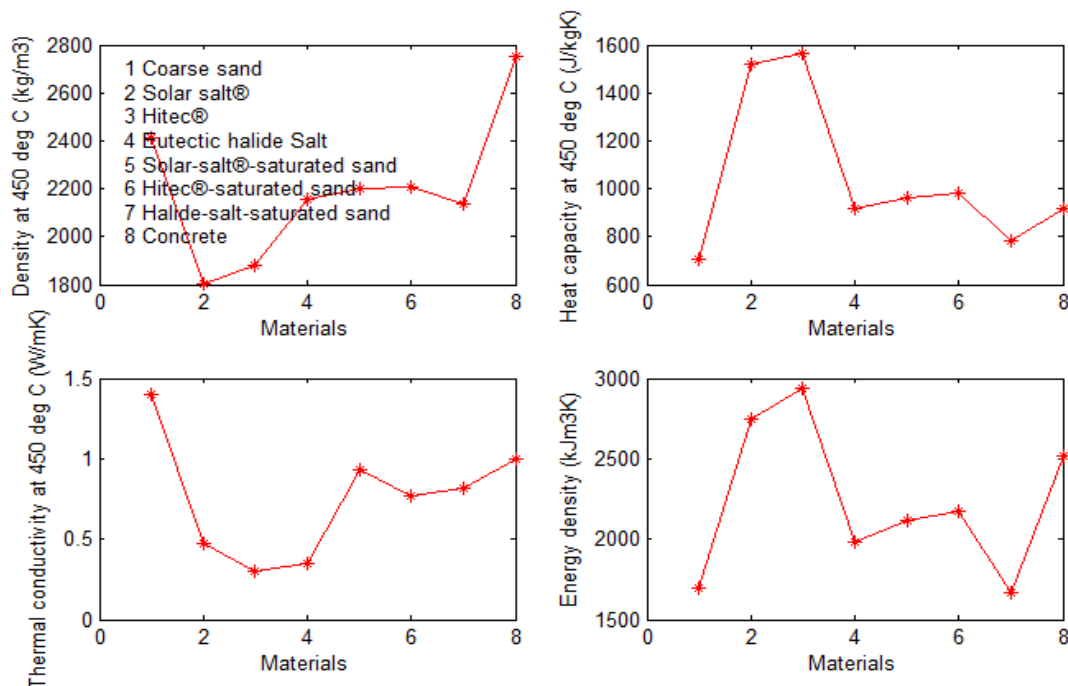


Fig. 4. Graphical illustration of properties of materials at 450 °C

Figure 4 was plotted from the data in [8]. Figure 4 shows a direct correlation between energy density and heat capacity for all the materials at 450 °C. This correlation is also observed between coarse sand and concrete. From the data presented in figure 4, the material with the highest thermal conductivity and lowest thermal capacity is coarse sand. Its thermal conductivity reduces while its thermal capacity increases significantly when mixed with solar-salt[®] (solar-salt[®] is a commercially available heat transfer fluid). This same effect is true when sand is mixed with Hitec[®] as well as Halide-salt. When mixing sand with any of these fluids, one has to consider the reduction of thermal conductivity for the increase in thermal capacity. The material with the second highest thermal conductivity is concrete. It has the third lowest thermal capacity.

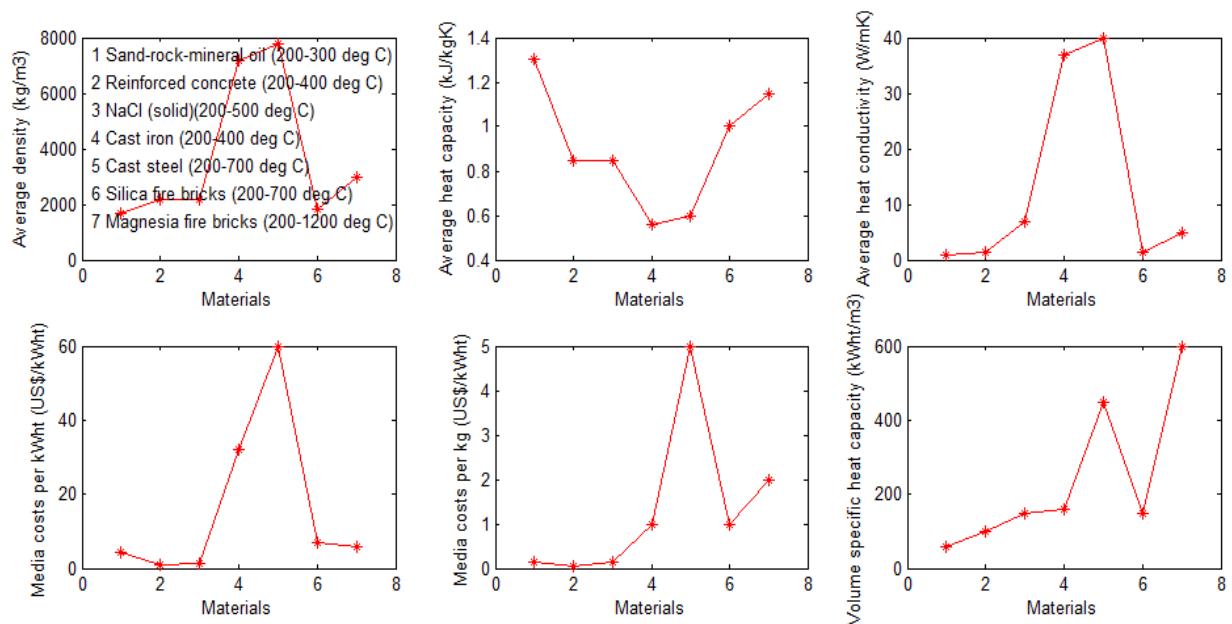


Fig. 5. Comparison of material properties and their costs

Figure 5 was plotted from the data in [13]. From figure 5, materials with the highest average thermal conductivity have the lowest thermal capacity and vice versa. Cast steel has the highest thermal conductivity and has the second largest value for volume specific heat capacity. The drawback with cast iron is that it is the costliest. Cast iron and cast steel have considerably good thermal conductivity and their thermal capacity can be enhanced by incorporating other materials that will enhance thermal capacity. The drawback is cost. Enhancement techniques employing the use of sand-rock-mineral oil which has the highest average thermal capacity in the list as well as its relatively low cost and cast iron having a very high average thermal conductivity with a good price compared to others will yield optimal results.

2.2. Latent Heat Storage Materials

Latent heat storage materials are more efficient when it comes to heat capacity. Within a very small temperature range, a very large amount of heat can be stored within the material. In latent heat storage, there are three (3) ranges of temperature: low temperature thermal storage (<120 °C), medium temperature thermal storage (120-300 °C) and high temperature thermal storage (>300 °C) [9].

Industrial heat energy waste is a good source for medium thermal energy storage for phase change materials with melting temperature in the range of 120 °C to 300 °C [10]. LiNO₃-NaCl with 87-13% mix proportion was worked on by [10]. A melting temperature of 220 °C was recorded. A latent heat capacity of 300 kJ/kg was recorded as well. The temperature at which the salt is stable is within the range of 400 °C and 450 °C.

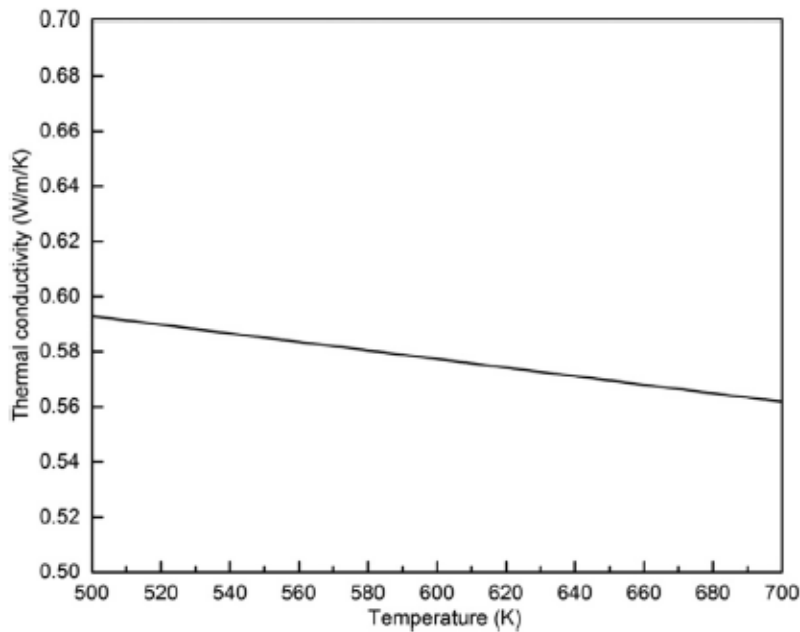


Fig. 6. Thermal conductivity of $\text{LiNO}_3\text{-NaCl}$ (87-13%) as it varies with temperature [10]

From figure 6, they plotted the predicted thermal conductivity of $\text{LiNO}_3\text{-NaCl}$ (87-13%). Its thermal conductivity as it melts reduces as temperature increases. Below 400 °C, the predicted thermal conductivity is between 0.57 W/m/K and 0.6 W/m/K. they reported the thermal conductivity to be higher than that of many other organic phase change materials as well as a few nitrate mixtures.

The use of metal foam as well as microencapsulation of phase change materials as a medium to increase thermal conductivity of a latent heat storage based system was made by [11]. They had three (3) sets of storage systems for comparison. Figure 7 shows details on the setup of the system before and after adding the microencapsulated and pure phase change material. The first was the phase change material (paraffin) without microencapsulation. The second was phase change material without encapsulation but with metal foam included. The last was microencapsulated phase change material with metal foam enhancement.

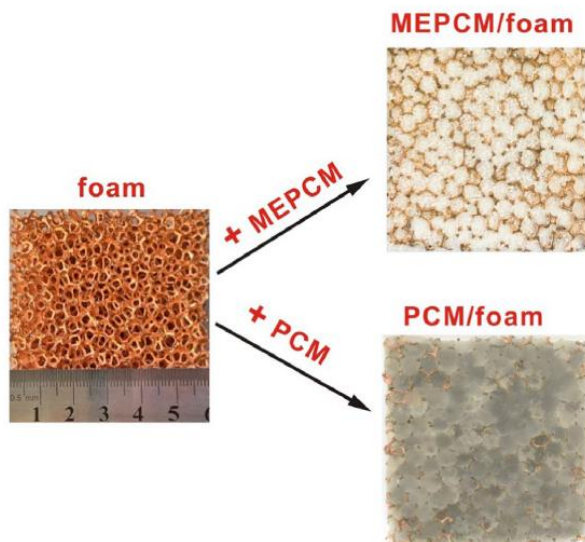


Fig. 7. Appearance of the metal foam before and after injecting the phase change material [11]

The porosity and thickness of the metal foams affects the thermal properties of the system. They also found that the metal foam enhanced the thermal conductivity of the system.

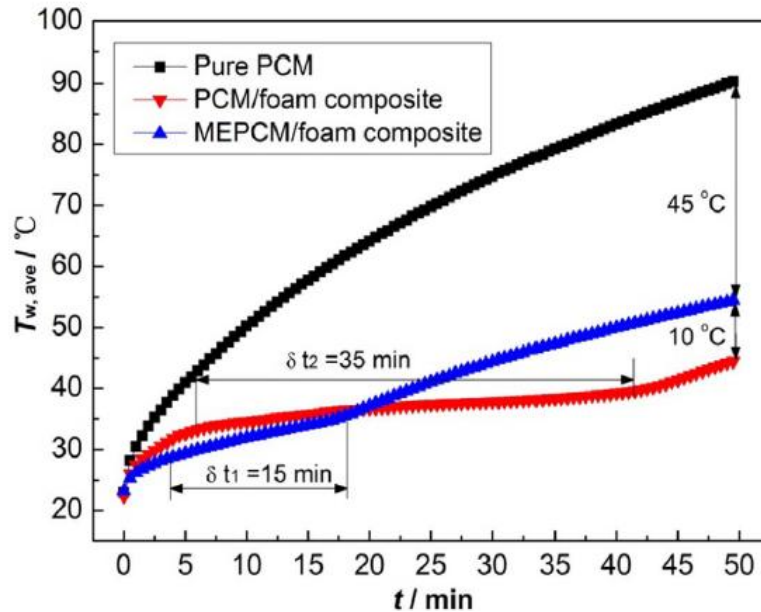


Fig. 8. Reaction of the surface temperature for the different phase change material setups [11]

The time-related arithmetic-averaged temperatures of the top side of each setup were measured from five (5) different points. Figure 8 shows the results for the three setups. In figure 8, a very large amount of temperature reduction was recorded for the setup containing microencapsulated phase change material/foam system as well as for that containing the phase change material/foam system when compared to the setup containing only phase change material. There is a temperature reduction of 45 °C for the microencapsulated phase change material/foam setup and a 55 °C reduction for the phase change material/foam setup as compared to the pure phase change material setup at the fiftieth minute. This is because the thermal conductivity of these two setups have been enhanced by the metal foam contained in it.

3. Conclusion

From the information provided in this review, we can merge the strengths of the thermophysical properties of both sensible and latent heat storage materials together utilizing enhancements [8,11,12] employed in these articles. Sensible heat storage materials are good for thermal fluids because they are cheap and also have considerably high thermal conductivity. Their cost advantage is also important because a significant volume of heat transfer media will be required for an average system. Thermal conductivity is important for a heat transfer fluid so as to enhance efficient thermal charging and discharging. On the other hand, latent heat storage materials are ideal as the storage material because of their high latent thermal capacity. The issue with these materials is their low thermal conductivity. This according to literature can be enhanced by microencapsulation and/or the use of metal foams [8,11,12]. This has enhanced the thermal conductivity of the systems they worked on. It is believed that further enhancement of thermal conductivity of latent heat storage materials as well as enhancement of heat capacity of sensible heat materials can be done in order to further enhance the efficiency of thermal storage systems.

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