Thermal Energy Storage Systems

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I. Introduction and Objectives

Phase Change Materials (PCMs) are known for their ability to efficiently store and release thermal energy, making them highly useful in various thermal management applications. These materials can absorb and release significant amounts of latent heat during phase transitions, typically between solid and liquid states. This experiment, focused on thermal energy storage systems, investigates the thermal behavior of PCMs during the process of sensible heating, where the temperature of the material increases without a phase change.

The main objectives of this experiment are as follows:

- Measure the temperature of different PCMs during sensible heating.
- Calculate the specific heat capacity of each PCM tested.
- Plot the curve of specific heat versus temperature for each PCM to analyze energy storage characteristics under various thermal conditions.

II. Essential Background

A. *What do you understand by the heat capacity of a substance? Do different phases of a substance have different heat capacities? Explain.*

Heat capacity is the amount of heat energy required to raise the temperature of a substance by 1°C (or 1 K). It shows how much energy a material can absorb before its temperature changes.

This property varies based on the material's composition and phase. For example, in experiments, substances like water and paraffin wax were found to need different energy amounts to reach the same temperature. This variation is due to differences in molecular structure and bonding. The heat capacity changes across different phases (solid, liquid, gas) because the energy required to increase temperature depends on the degree of molecular motion in each phase.

B. *What do you understand by sensible heat and latent heat?*

Sensible heat is the heat that changes the temperature of a substance without altering its phase, directly linked to the substance's heat capacity. Latent heat, however, is the heat absorbed or released during a phase change (e.g., melting or evaporation) while the temperature remains constant. This heat helps overcome the forces between molecules to facilitate the phase change.

C. *What are phase change materials (PCMs), what are some applications of thermal storage with PCMs. Give some examples of commonly used PCMs.*

Phase Change Materials (PCMs) absorb or release significant amounts of latent heat during phase changes, commonly from solid to liquid and vice versa. In an experiment, paraffin wax was used as an example of a PCM. These materials are highly effective for thermal energy storage as they can store energy when melting and release it when solidifying. PCMs are applied in areas like solar thermal systems, building insulation, and cooling of electronic devices. Common PCMs include paraffin wax, salt hydrates, and fatty acids.

D. *Quantify the heat capactiy of latent heat storage systems(LHS), Explain all terms.*

The heat capacity of a latent heat storage system can be represented by the equation:

$$\boxed{Q = mC_s\Delta T + mL + mC_s\Delta T(s)}$$

The terms in the equation can be explained as follows:

- m: The mass of the phase change material (PCM) in kilograms (kg).

- C_s: The specific heat capacity of the PCM in J/(kg°C), representing the amount of energy needed to raise the temperature of 1 kg of the substance by 1°C.
- L: The enthalpy of fusion (or latent heat of fusion) in J/kg. This is the energy needed to change the phase of 1 kg of the material from solid to liquid (or vice versa) at a constant temperature.
- ΔT: The temperature difference (in °C or K), representing the change in temperature either before the phase change (ΔT) or after the phase change ($\Delta T(s)$).

This formula accounts for:

- **Sensible heat before the phase change** ($mC_s\Delta T$): Energy needed to raise the temperature to the phase change point.
- **Latent heat** (mL): Energy needed for the phase change itself (e.g., melting or boiling).
- **Sensible heat after the phase change** ($mC_s\Delta T(s)$): Energy needed to increase the temperature after the phase change.

E. Define efficiency of thermal energy storage system.

The efficiency of a thermal energy storage system is the ratio of the energy retrieved from the system to the energy initially stored in it. It can be expressed as:

$$\boxed{\text{Efficiency} = \frac{\text{Energy recovered}}{\text{Energy stored}} \times 100\%}$$

III. Experimental Setup

The setup consists of a heat transfer fluid (HTF) system with separate tanks for cold and used HTF storage, a main hot/cold source tank with electric heaters, pumps, temperature sensors ($T_{b1}, T_{b2}, T_{b3}, T_{b4}$), flow sensors, and multiple valves for controlling the flow of the HTF. The PCM used in this experiment is paraffin wax, which is placed within a heat exchanger.

IV. Experimental Procedure

1. Filling the HTF Storage Tanks

1) Open valve V6 to fill the cold HTF storage tank to full capacity.
2) Open valves V2 and V3, and start the pump to transfer HTF to the main hot/cold source tank.
3) Stop the pump and close all valves when the source tank overflows and returns HTF to the storage tank.

2. Heating the HTF

1) Turn on the electric heaters and monitor the temperature using the temperature sensors.
2) Turn off the heaters when the HTF in the source tank reaches the target temperature.
3) Record temperature readings from sensors T_{b2} and T_{b3}.

Fig. 1. Experimental Setup

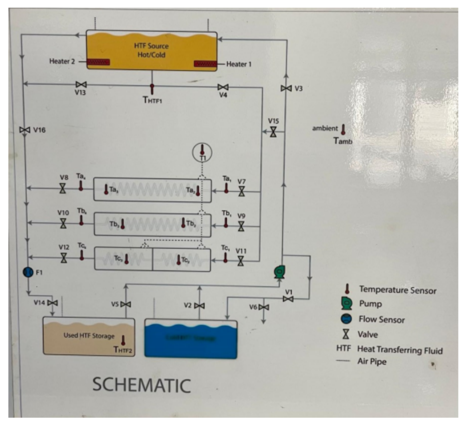

Fig. 2. Schematic of the Setup

3. Circulating the HTF

1) Open valves V4, V9, and V10 to circulate the hot HTF through the heat exchanger. Use valve V10 to adjust the flow rate.
2) Periodically take temperature readings from T_{b2} and T_{b3}. Continue until the paraffin wax reaches its melting point.

4. Shutting Down the System

1) Close valves V4, V9, and V10 to stop the process once the PCM has melted.
2) Open valves V13 and V14 to drain the HTF from the hot/cold source tank.

V. Calculation and Results

Calculating the specific heat stored of PCM (Phase change Material):

In this experiment, we used Paraffin wax as the Phase Change Material (PCM). The specific heat stored during heating can be calculated as follows:

$$\boxed{c_{\text{stored}} = \frac{\text{Heat Transferred to the PCM } (Q)}{\text{Mass of the PCM } (m)}}$$

Where:

$$\boxed{Q = mC_s\Delta T(s) + mL + mC_s\Delta T}$$

The first term represents the heat absorbed before the phase change, the second term represents the heat absorbed during the phase change, and the third term represents the heat absorbed after the phase change. Since we did not reach the boiling point of Paraffin wax, we ignore the second term and third term, yielding:

$$\boxed{\frac{Q}{m} = C_s\Delta T_{\text{avg}}}$$

Given the flow rate of 0.3555 L/min and a mass flow rate of 0.31995 Kg/min, with a specific heat capacity $C_s = 2.9$ KJ/Kg-K for the solid state, we calculate T_{avg} as:

$$\boxed{T_{\text{avg}} = \frac{T_{b2} + T_{b3}}{2}}$$

The initial temperature is taken as $24.75°$C.
Now, we can calculate

$$\boxed{C_{stored} = \frac{Q}{m} = C_s\Delta T_{\text{avg}}}$$

T_{b2} (°C)	T_{b3} (°C)	T_{avg} (°C)	ΔT_{avg} (°C)	c_{stored} (KJ/Kg)
25.9	24.3	25.1	1.1	3.19
26.3	24.7	25.5	1.5	4.35
26.6	25.0	25.8	1.8	5.22
26.9	25.3	26.1	2.1	6.09
27.5	25.7	26.6	2.6	7.54
27.9	26.4	27.15	3.15	9.135
28.5	26.9	27.7	3.7	10.73
29.1	27.4	28.25	4.25	12.325
29.7	27.9	28.8	4.8	13.92
30.4	28.5	29.45	5.45	15.805
31.1	29	30.05	6.05	17.545
31.9	29.6	30.75	6.75	19.575
32.7	30.2	31.45	7.45	21.605
33.6	31.2	32.4	8.4	24.36
34	31.5	32.75	8.75	25.375
34.4	31.8	33.1	9.1	26.39
34.8	32.1	33.45	9.45	27.405
35.2	32.4	33.8	9.8	28.42

TABLE I
TEMPERATURE MEASUREMENTS AND CALCULATED SPECIFIC HEAT STORED FOR PARAFFIN WAX

The Figure 3 graph represents the relationship between specific heat storage and average temperature for paraffin wax.

In this graph, the dark blue line represents the actual data points collected for the specific heat stored versus the average

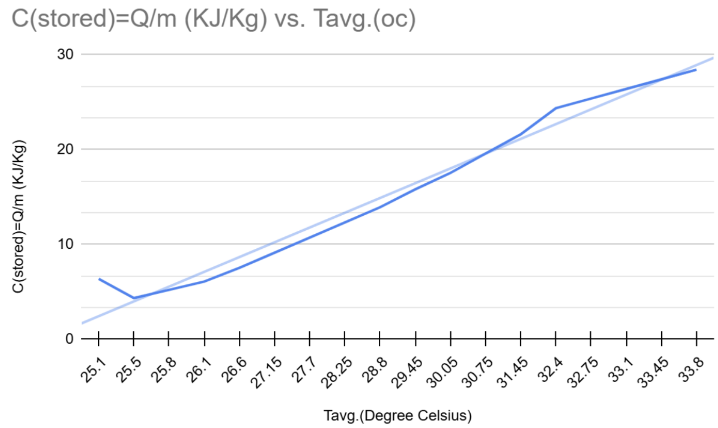

Fig. 3. Variation of the specific heat stored with average temperature for Paraffin wax

temperature. The light blue line, on the other hand, represents a fitted line that approximates the trend of the data.

With a mass flow rate of 0.31995 Kg/min and a flow rate of 0.3555 L/min, various temperature measurements were taken to calculate C_{stored} for different average temperatures. The temperature differences and corresponding specific heat stored values were calculated and plotted, showing an increasing trend in stored heat as the temperature rises.

The resulting graph indicates a positive correlation between the average temperature and the specific heat stored, suggesting that as the PCM approaches its phase transition, the material stores more heat efficiently. The data table provides detailed temperature values and their respective calculated specific heat stored values, allowing for a comprehensive analysis of the PCM's thermal storage properties.

The Figure 4 graph represents the relationship between specific heat storage and average temperature for fatty acids.

This graph illustrates the relationship between specific heat stored and temperature for fatty acids. As shown, the specific heat stored (in kJ/kg) increases linearly with temperature within the observed range. This trend indicates that as the temperature of the fatty acids rises, they absorb more heat, which is stored within the material. The linear pattern suggests a consistent rate of heat storage increase per degree Celsius, reflecting the thermal properties of fatty acids.

Fatty acids are known for their ability to store thermal energy, making them suitable for applications in thermal energy storage systems. This characteristic is particularly valuable in systems that rely on phase change materials (PCMs) or latent heat storage, where fatty acids can serve as efficient heat storage mediums due to their thermal stability and capacity to absorb and release heat gradually.

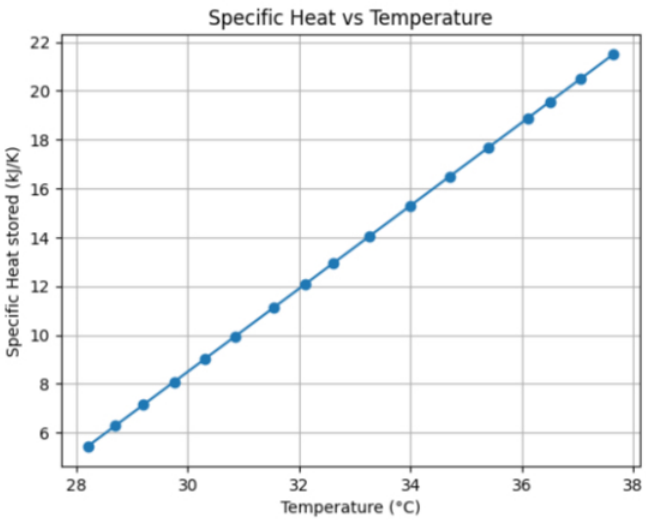

Fig. 4. Variation of the specific heat stored with average temperature for Fatty acids.

Note: We were unable to gather data for Fatty Acids, so we took it from the group which performed earlier.

VI. Errors

- **Sensor Calibration Errors**: If temperature sensors aren't calibrated correctly, they may show incorrect temperatures. Regular checks help maintain accuracy.
- **Uneven Heating**: The heat transfer fluid (HTF) might not heat the phase change material (PCM) evenly, leading to temperature differences within the PCM. This can cause uneven melting, making it hard to measure heat capacity accurately.
- **Leaks**: Leaks in the system, like from valves or connections, can cause HTF to escape, lowering pressure and flow rate. This might prevent the PCM from heating fully.
- **Flow Rate Inconsistencies**: Adjusting valves unevenly can cause flow rate fluctuations, affecting the speed and efficiency of heat transfer.
- **Heat Loss to Environment**: Some heat may escape from the system into the surrounding environment, reducing the effectiveness of heating. Proper insulation can help reduce this loss.
- **Measurement Errors**: Incorrect measurements of the PCM or HTF mass can lead to errors in heat capacity calculations. The positioning of sensors also matters for getting accurate readings.
- **Equipment Malfunctions**: If pumps or heaters fail, the heating process may be disrupted, causing poor flow or insufficient heating.
- **Human Error**: Mistakes in operating valves, recording data, or adjusting settings can introduce inconsistencies.
- **PCM Material Quality**: Variations or impurities in the PCM material can change its melting behavior, which may lead to unexpected results.

VII. Conclusion

The experiment conducted on paraffin wax as a Phase Change Material (PCM) provided insights into its heat storage characteristics during the heating phase. Using data from our group, we measured the specific heat stored by the paraffin wax and calculated the energy absorbed during the temperature increase. The experiment indicated that as the average temperature rose, the specific heat stored in the PCM also increased, demonstrating the wax's efficiency in thermal energy storage near its phase transition.

Comparing the results with data from another group that used fatty acids as PCM, we observed that both materials are effective for thermal storage, they showed a significant and steady heat absorption profile. This implies their potential for applications that require efficient thermal energy management.

VIII. References

1) F. Incropera and D. DeWitt, *Fundamentals of Heat and Mass Transfer*, 6th ed., Wiley, 2006.
2) Y. A. Cengel, *Heat and Mass Transfer: A Practical Approach*, 5th ed., McGraw-Hill, 2014.