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Energy and Exergy Analysis of Latent Heat Thermal Energy Storage System(LHTESS) Using Multiple Phase Changing Materials

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ABSTRACT.
This study presents the results of an experimental investigation into a new thermal energy storage system having multiple PCMs. The system's performance is tested using three PCMs, each with a different melting temperature, arranged in an increasing and decreasing order of melting temperatures, and water is used as the heat transfer fluid. In the experiments, the impact of raising the heat transfer fluid's mass flow rate on the PCM charging and discharging process was examined. The results show that as the mass flow rate is raised from 1 LMP to 5 LMP, exergy efficiency is reduced by 6%. However, energy efficiency rises from 52.7% to 73.4%. Also, melting time in the case of charging is reduced from 500 min to 350 min and discharging time is reduced from 350 min to 250 min for a 5 LMP mass flow rate. Further, it was also found that the exergy stored in multiple PCMs is 820 KJ at 5 LMP, whereas the exergy stored in a single PCM is 500 kJ at 5 LMP, as the exergy represents the maximum useful work possible. It is found that multiple PCM-based energy storage systems are much more efficient than single PCM-based energy storage systems.

KEY WORDS: Phase changing material (PCM), Thermal energy storage (TES), Charging, and Discharging

1. INTRODUCTION:

Energy storage has emerged as a critical issue in recent years due to the challenges of rapidly depleting conventional energy sources, ever-increasing energy demand, and increasing energy consumption across various industries, forcing mankind to rely heavily on energy storage. Thermal energy storage is one of the most powerful techniques of energy storage not only to bridge the gap of demand and supply but also to give a possible solution for energy wastages and Surplus energy Sensible, latent, and thermo-chemical heat or cold storage are the three main types of thermal energy storage. Due to its high energy density, LHTES is more impactful as compared to the other thermal energy storage techniques.[1]–[3]LHTES mainly consist of charging and discharging process energy is stored during the phase change of the charging process(solid to liquid) which is retrieved during the phase change of the discharging process.(liquid to solid) However, due to its high energy storage capacity and isothermal behaviour during the phase change, PCM has become one of the most popular techniques for energy storage. It is also the first choice of many researchers. Researchers and scientists are concerned about the widening gap between supply and demand for energy, as well as the enormous amount of energy [4]–[7]Even though renewable energy can solve these problems, the best solution is to improve thermal energy management practises and store excess energy. However, excess energy can be stored using a PCM-based thermal energy storage system, which can help to reduce costs by bridging the supply-demand gap. For their experiment,[8]used a TES system. In which sodium nitrate with a melting point of 306 °C was used as a PCM and air was used as an HTF.[9]conducted a more in-depth study on the use of PCM in building materials, especially the use of PCM in the roofing of the buildings, as described in detail by.[10]His audit was focused on the type of material used as PCM, its heat transfer properties, and applications. 45 commercially used PCM out of 150 PCM where examined [11].carried out an extensive review of the most recent developments in PCM based LHTESS.[12] publish the comparative study of conventional TESS with the recent PCM based LHTESS. Further PCM based thermal energy storage with little temperature difference have modest and high direct-storage density. PCM's usage in household hot water generation and heating was thoroughly examined by [13], [14]circulated liquid PCM throughout the melting process to enhance heat transmission. It was found that encapsulating PCM with molten salt as HTF improves the workings of the packed-bed storage system. The enthalpy approach was used to look at the phase transition process within the phase-changing material capsule. In the first [15]compared PCM filled TES tanks to tanks filled with water. The result shows that the PCM-filled tank had a 35.5% higher energy storage capacity than the water-filled tank.,[16]and [17]studied the behaviour of real-scale PCM storage and documented their findings. One of the study's primary discoveries was that sub-cooling and hysteresis effects do not behave as expected. [18]used ice-filled rectangular PCM slabs. Based on a one-dimensional approach and taking temperature variations along the flow direction of the heat transfer fluid into account, the model developed was found to be very close to reality. Further researchers also developed new innovative techniques such as use of composite PCM, fins. PV, SWH to enhance the energy storage and other thermophysical properties of the PCMprepared a composite phase changing material by doping magnesium particles in ternary carbonate salt and found that the thermal conductivity of the ternary salt was increased by 46% for 2% wt of magnesium particles..[19]found that the use of fins in the PCM enhances the thermal conductivity of the PCM[20]discovered that PCM helps to enhance the performance of PV[21]reviewed SWH integrated PCM presented the technical and the economical aspect it was found that use of PCM subsidized the energy cost.

Although the literature survey gives various methods to enhance the thermal storage capacity of the thermal energy storage system, the enhancement is still within the limits of what is possible to enhance the storage capacity further. Deeper research is needed.

The present study focuses on the use of multiple phase-changing materials to enhance the energy storage of thermal energy storage systems. The system's performance is tested using three PCMs, each with a different melting temperature, arranged in an increasing and decreasing order of melting temperatures, and water is used as the heat transfer fluid. The result shows that the use of multiple PCM enhances the storage capability of the thermal energy storage system

2.EXPERIMENTAL SETUP

The LHTES system consists of a cylindrical storage tank measuring 450 mm in length and 142 mm in diameter, with a thickness of 2 mm. The shell of the storage tank is made of stainless steel, and the tube is made of copper, with a diameter of 70 mm and a thickness of 2 mm. To avoid leakages, CPVC pipe fittings are done for the complete setup. The shell of the storage tank consists of an inner and outer tube, and the space between them is filled with three different kinds of PCM separated by a thin wall, creating three different zones with distinct melting temperatures. PCMs with decreasing melting temperatures are arranged for the charging cycle along the hot fluid direction, and PCMs with increasing melting temperatures are arranged for the discharging cycle along the cold fluid direction. Four thermocouples are installed to record the temperature of PCM, and two thermocouples are installed at the inlet and outlet of the cylinder in order to record the inlet and outlet temperatures of fluids. Water is used as the HTF. And to maintain the temperature and flow of HTF, electric heaters and centrifugal pumps are used. The PCM tank of the heat exchanger makes use of several PCMs or a group of PCMs together. Except for the existence of PCMs, they are identical to typical single-PCM LHTS systems, as shown in Figure 1 Model of the experimental setup. The major drawback of the single PCM unit is that it takes a longer time for the charging and discharging cycle. This happens because the temperature difference between the HTF and the PCM falls quickly as the melting proceeds. To overcome this issue, more than one phase-changing material is used. Concerning the HTF flow direction, these PCMs are stacked in decreasing melting temperature order. During the charging cycle, the reverse order is taken during the discharging cycle. This arrangement maintains the temperature difference between the HTF and PCM, and faster charging and discharging of the PCM are observed.

Figure 2 Schematic diagram of the PCM Arrangement.

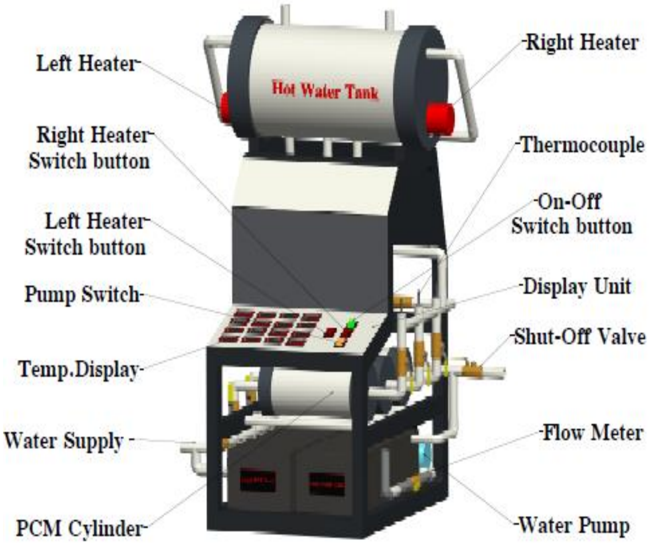

Figure 1 Model of the experimental setup

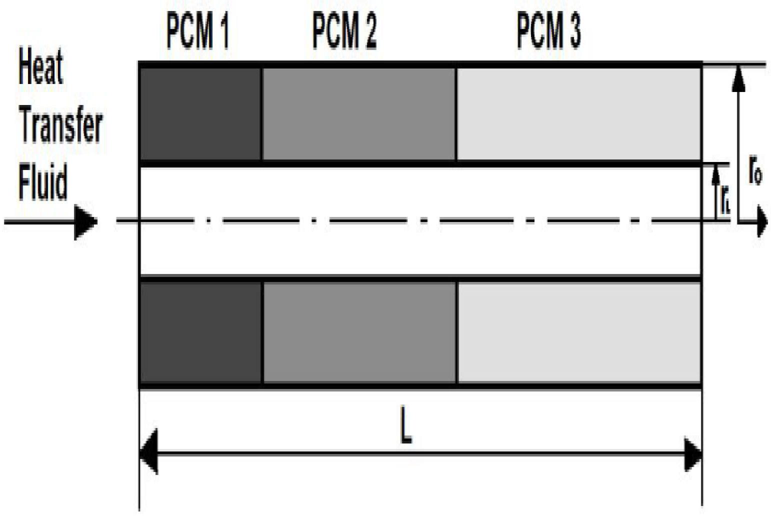

Figure 2 Schematic diagram of the PCM Arrangement.

2.1EXPERIMENTAL PROCEDURE

The experimental procedure begins by heating the water in the HTF tank. Heating continues until the HTF temperature passes the melting temperature of the PCM. Further, with the help of the regulatory valves, the hot HTF is allowed to pass through the heat exchanger or the PCM tank. The mass flow rate of the HTF is controlled by the control unit of the heat exchanger. Figure 3 shows the shell and tube heat exchanger with multiple PCMs. The PCMs are arranged in decreasing order of melting temperature to maintain the temperature difference between the HTF and the PCM. The order is reversed in the case of the discharge process. As the HTF enters the heat exchanger, it transfers the heat energy to the PCM. The temperature of the PCM starts to increase and reaches its melting temperature. Temperatures are recorded by the sensors and thermocouples, which are further recorded and displayed by the control unit. The experiment was performed at a mass flow rate of 1,3,5LMP

2.2 PCM ARRANGEMENT IN THE CYLINDER: -

The arrangement of PCM is the most important aspect of the experiment. The 450mm length of the cylinder is divided into three zone filled with three different PCM having three different temperatures. each zonesis has 2kg of PCM. A total of 6 kg of PCM is loaded into the cylinder. The length of each zone is given as L1=L2=L3=L/3

S.N	Property	RT-55	RT-60	RT-65
1	ρ [Kg/m^3]	775	775	775
2	Specificheat [kJ/Kg·K]	2	2	2
3	Thermal conductivity[W/m·K]	0.23	0.23	0.23
4	Dynamic viscosity[$N\cdot S/m^2$]	0.0268	0.0287	0.04
5	Latent heat[kJ/Kg]	170	160	150
6	Ts[K]	52^0C	56^0C	59^0C
7	T_l [K]	55^0C	60^0C	65^0C

2.3 MATERIAL SELECTION

Rubytherm-55, Rubytherm-60, and Rubytherm-65 are used as PCM-1, PCM-2, and PCM-3 for the multiple PCM arrangement. As shown in Table 1, all the other materials such as PCM tank, HTF tank shell and tubes are made up of high thermal conductivity materials to enhance the thermal performance of the system.

Table 1. Properties of Phase changing Materials

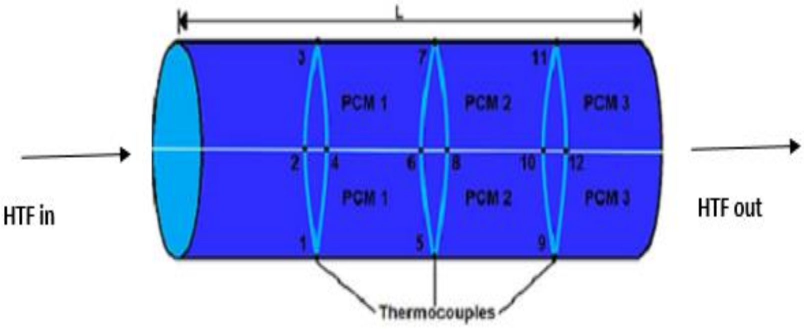

Figure 3: Multiple PCM based heat Exchanger

2.3ENERGY AND EXERGY MATHEMATICAL FORMULATION:

Mathematical calculations during melting and solidification are given as follows

$$\mathbf{E_{in}} = \mathbf{\dot{m}C_{HTF}} \int_0^t [\mathbf{T_{in}} - \mathbf{T_{out}}]\mathbf{dt} \quad (1)$$

$$\mathbf{E_{out}} = \mathbf{\dot{m}C_{HTF}} \int_0^t [\mathbf{T_{out}} - \mathbf{T_{in}}]\mathbf{dt} \quad (2)$$

Whereas E_{in} and E_{out} represent the PCM's absorbed heat and the water's absorbed heat from the surrounding environment, respectively. The mass flow rate is m, and the fluid's specific heat is C_{HTF}

The storage tank's thermal efficiency can be calculated as

$$\boldsymbol{\eta} = \frac{\mathbf{E_{out}}}{\mathbf{E_{in}}} (3)$$

The following equations can be used to calculate the amount of exergy

$\mathbf{X_{in}} = \dot{\mathbf{m}}\mathbf{C_{HTF}} \int_0^t [(\mathbf{T_{in}} - \mathbf{T_{out}}) - \mathbf{T_0} \ln(\frac{T_{in}}{T_{out}})]$ (4) $\mathbf{X_{out}} = \dot{\mathbf{m}}\mathbf{C_{HTF}} \int_0^t [(\mathbf{T_{out}} - \mathbf{T_{in}}) - \mathbf{T_0} \ln(\frac{T_{out}}{T_{in}})]$.(5) $\mathbf{X_{stored}} = \dot{\mathbf{m}}\mathbf{C_{HTF}} \int_0^t [(\mathbf{T_{in}} - \mathbf{T_{out}}) (1 - \frac{T_0}{T_{melt}})] \mathbf{dt}$.(6)

T_{in} and T_{out}, $T_{melt}$and $T_o$are theinput, output, melting and ambient room temperature. Calculation of the TES unit's charging, discharging, and overall efficiencies is given by the equations below:

$\varepsilon_{charging} = \frac{X_{stored}}{X_{in}}$(7).

$\varepsilon_{discharging} = \frac{X_{out}}{X_{stored}}$(8)

3. RESULTS AND DISCUSSION

3.1 CHARGING PROCESS

In the current experimental work, the charging and discharging bed have multiple PCMs with increasing melting and solidification temperatures. Initially, electric heaters heat the water to the required temperature. It is made to pass through the heat exchanger with multiple PCM heat transfer fluids that transfer the heat to the PCM. The temperature of the PCM starts to increase and reaches 75^0C, at which point complete melting of the PCM is achieved and the charging process is completed. The PCM temperature and the HTF temperatures are recorded, with the help of thermocouples placed at various points in the heat exchanger. The mass flow rate of the HTF has a high impact on the charging and discharging rates of the PCM. As the mass flow rate increases, the charging and discharging times are reducedFigure 4-Figure **6**it was found that as the mass flow rate increases from 1LMP to 5LMP the charging time is reduced from 520 min to 382 min

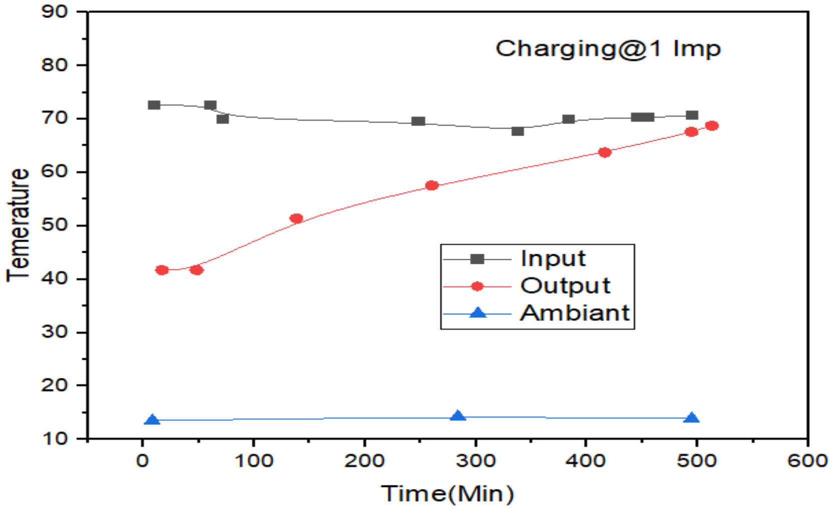

Figure 4. Variation in temperature during 1 LMP charging.

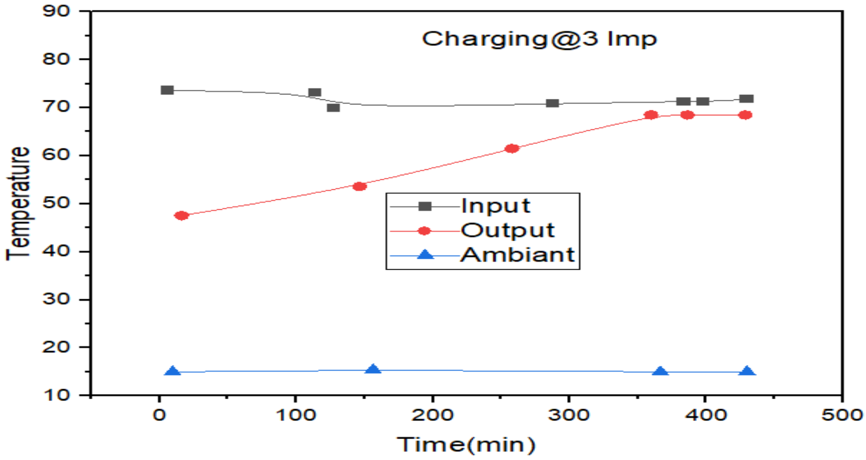

Figure 5: Variation in temperature during 3 LMP charging

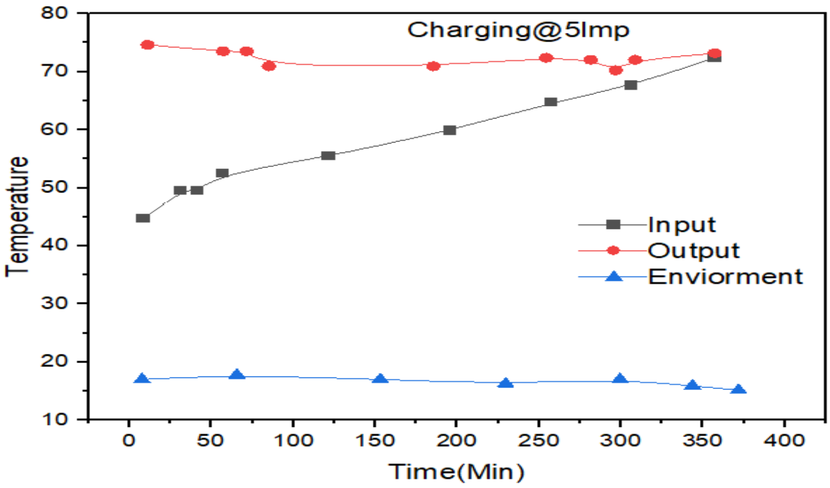

Figure 6: Variation in temperature during 5 LMP charging

3.2 DISCHARGING PROCESS: -

To facilitate heat transfer, the melting process was followed by a solidification process. Cold water is circulated through the tubes of the heat exchanger. HTF extracts heat from melted PCM. PCM releases the latent portion of the heat energy and begins to solidify. The process is repeated several times until equilibrium with the room temperature is attained.Figure 7-Figure 9depicts the discharging cycle of HTF at different mass flow rates at an inlet temperature of 30–32 °C.The outlet temperature is monitored at various stages of the discharging process. It was found that as the mass flow rate increases from 1 LMP to 5 LMP, the discharging time is reduced from 350 minutes to 250 minutes.

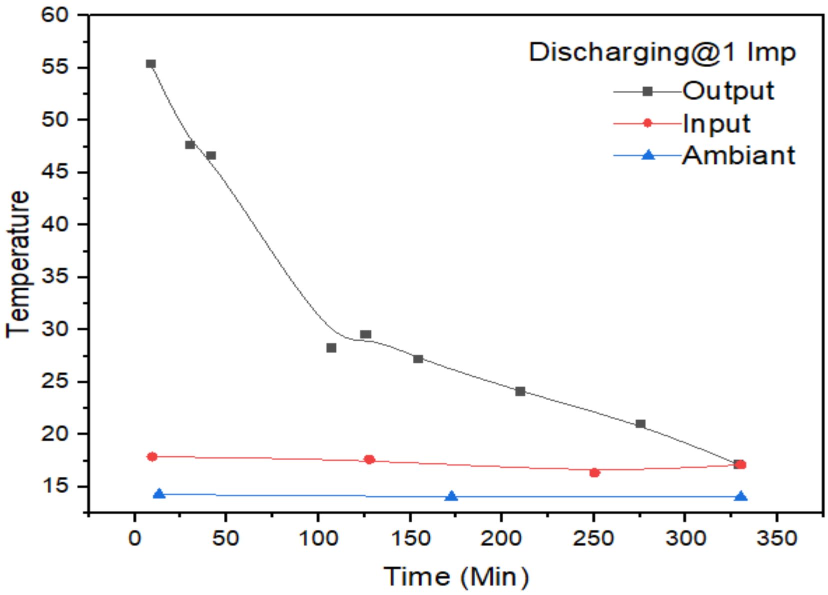

Figure 7: Temperature variation during discharging at 1LMP

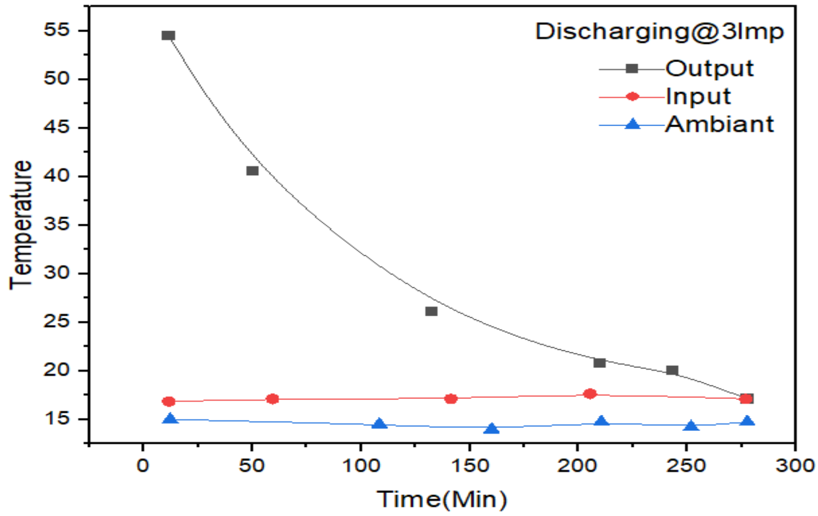

Figure 8: Temperature variation during discharging at 3 LMP

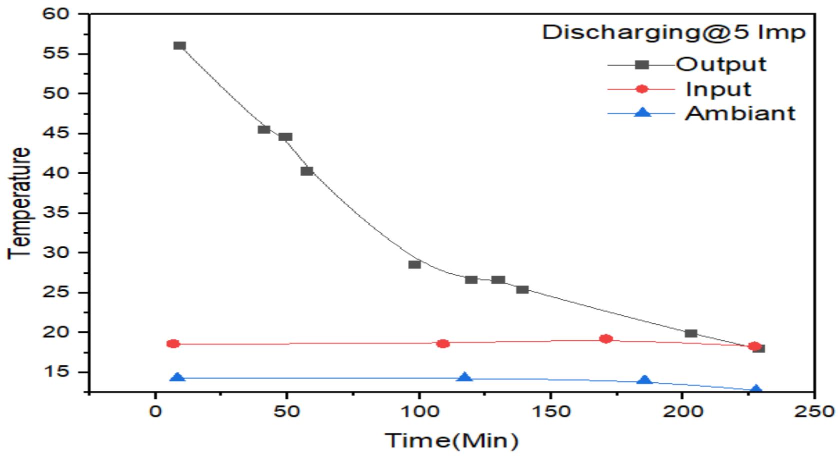

Figure 9: Temperature variation during discharging at 5 LMP

3.3 EFFECT OF THE MASS FLOW RATE ON MULTIPLE PCM

As stated earlier, the heat exchanger used in the study consists of three consecutive layers of PCM having distinct melting and solidification temperatures as $T_{pcm1} > T_{pcm2} > T_{pcm3}$ for the charging cycle and $T_{pcm1}<T_{pcm2}<T_{pcm3}$ for the discharging cycle. Experimentally, the effect of varying mass flow rates on the charging of these PCM layers was experimentally studied, and it was found that as the mass flow rate of HTF increases, it increases the temperature gradient between the PCM and HTF. As a result, more heat is transferred from the HTF to the PCM and the PCM's charging time gets shorter. Since the temperature difference between the HTF and the PCM plays a critical role in the charging process, In the case of a single PCM, as soon as the PCM reaches its melting temperature, charging stops. However, multiple PCM-based heat exchangers facilitate maintaining the proper temperature gradient between the HTF and the PCM. As the HTF enters the exchanger, charging of PCM1 starts. As soon as the PCM1 reaches its melting temperature, charging in zone one stops. Since $T_{pcm2}< T_{pcm1}$ charging of PCM2 continues until it reaches its melting temperature. a similar process is followed for the PCM3 layer also. It is concluded that heat transmission and extraction rates are improved while using multiple PCMs, and the melting time is reduced as compared to the single PCM. Also, energy stored using multiple PCM is much higher as compared to a single PCM, as shown in
Figure 10, Figure 11,and Figure **12**.The comparative melting time at various HTFtemperatures is shown in Figure 13.

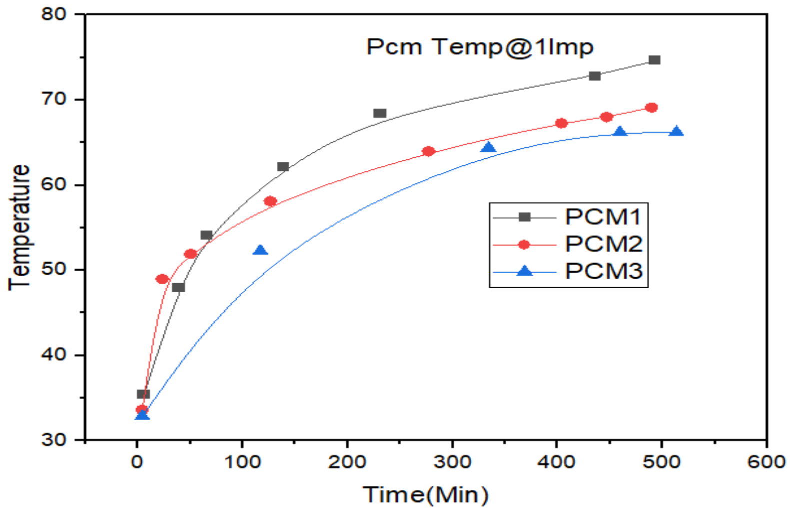

Figure 10. PCM Temperature variation during discharging at 1LMP .

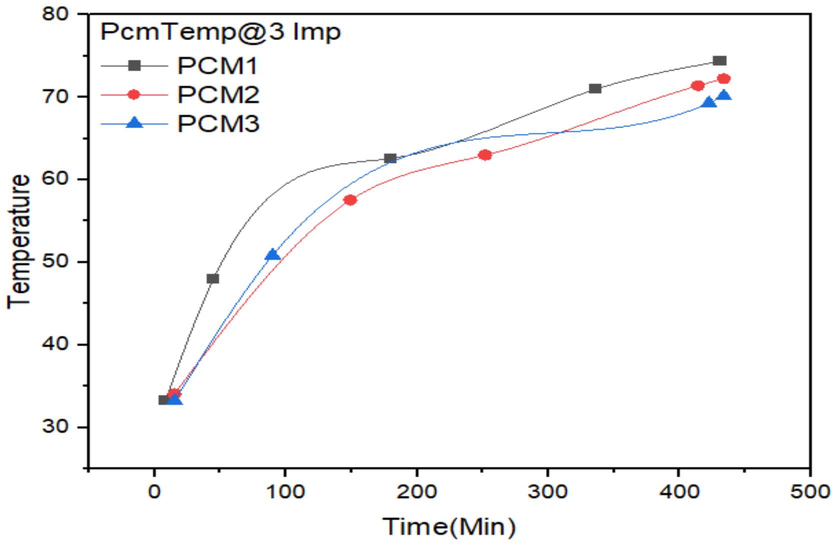

Figure 11: PCM Temperature variation during discharging at 3 LMP.

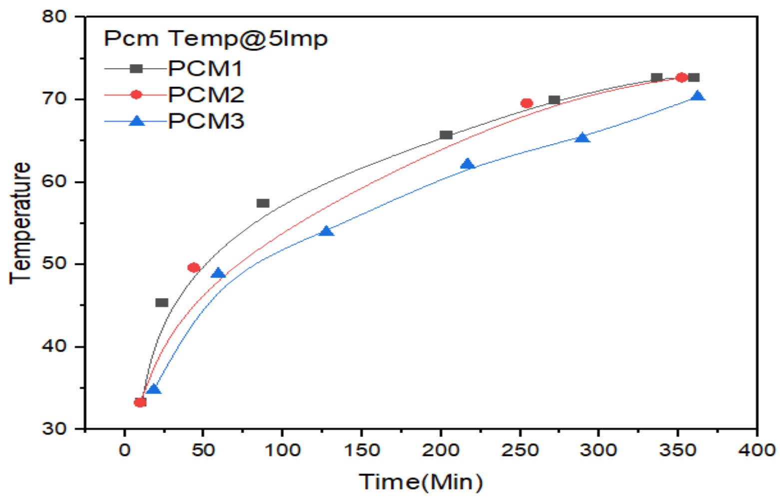

Figure 12: PCM Temperature variation during discharging at 5 LMP

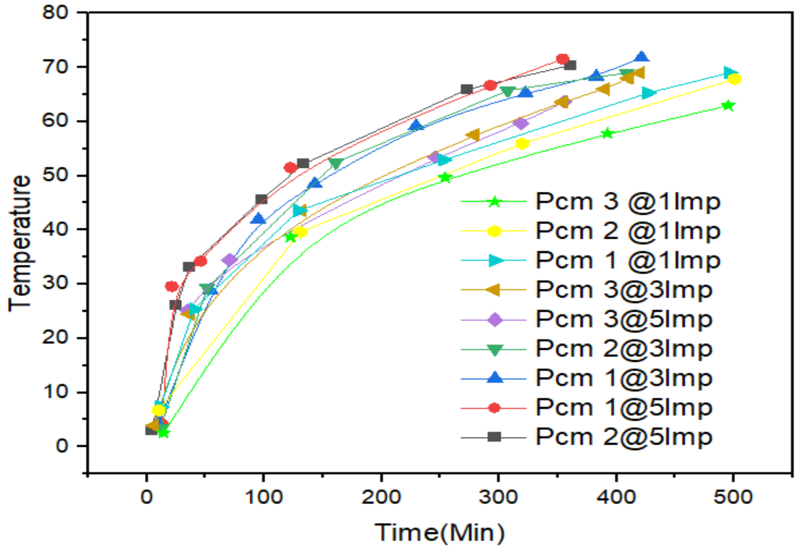

Figure 13: PCMs Variation of temperature distribution with time for multiple PC

3.4. ENERGY AND EXERGY ANALYSIS

Energy stored in PCM and energy extracted by the HTF is calculated using Eq1,Eq2,Eq3 All the output and input energy are tabulated in Table 2, which shows that as the mass flow rate increase, energy loss, and the charging efficiency Increase. However, the discharging and overall efficiency decrease which as shown in

Figure 14.

Table 2. Energy Efficiency

S.no	Flow Rate (LMP)	E_{in} (KJ)	E_{out} (KJ)	E_{lost} (KJ)	Efficiency (%)
1	1	1004.7	530	474	52.7
2	3	1608.3	1089	519	67.7
3	5	2149.5	1578	571.	73.4

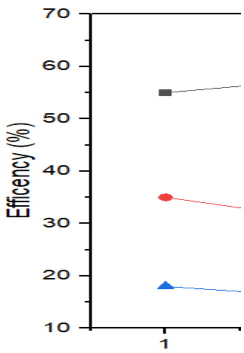

Figure 14: Variation of efficiency vs HTF flow rate

Exergies of the TES system is calculated using the Eq4,Eq5,Eq6 Eq7,Eq8**,** and is tabulated in

Table 3 shows that as the mass flow rate increases, energy stored also increases, but energy efficiency decreases as shown inFigure 15.Results also show that the efficiency of the TES system increases with the increase in the mass flow rate of the system, but the as the mass flow rate of HTF is reduced, the exergy efficiency improves.

S.no	Flow Rate (LMP)	Exergy (KJ) Input	Exergy (KJ) Output	Exergy (KJ) Stored	Energy (KJ) lost	Efficiency (%)

1	1	504.7	108	310.2	396.4	21.4
2	3	988.3	165	570.3	822.4	16.7
3	5	1279.5	195	825.1	1083.	15.3

Table 3. Exergy Efficiency

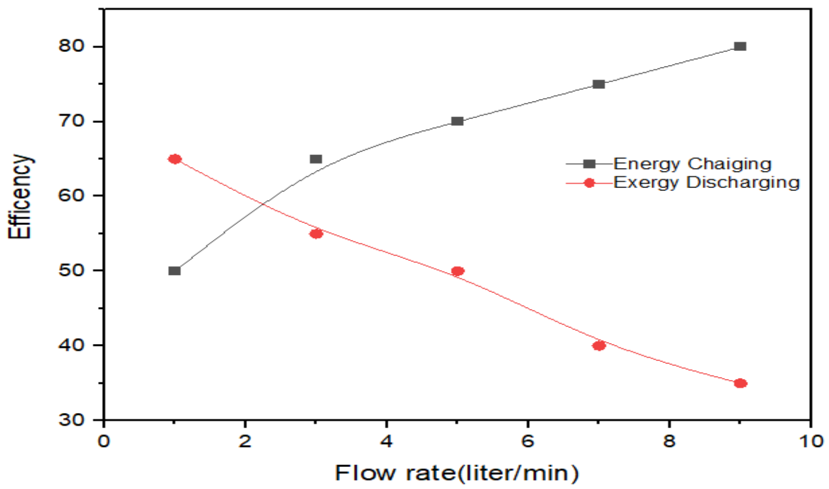

Figure 15: Variation of exergy efficiency and HTF flow rate

3.5. COMPARISON OF SINGLE PCM UNIT WITH MULTIPLE PCM UNITS

The Performance of the multiple PCM units is much higher than the single PCM.This happens only because the multiple PCM units is capable of maintaining the temperature difference between the HTF and PCM, which results in the higher heat transfer and extraction by the HTF enhancing the exergy efficiency of the multiple PCM as compared to the single PCM higher exergy efficiency means the efficiency of the system is improved as shown inFigure 16.

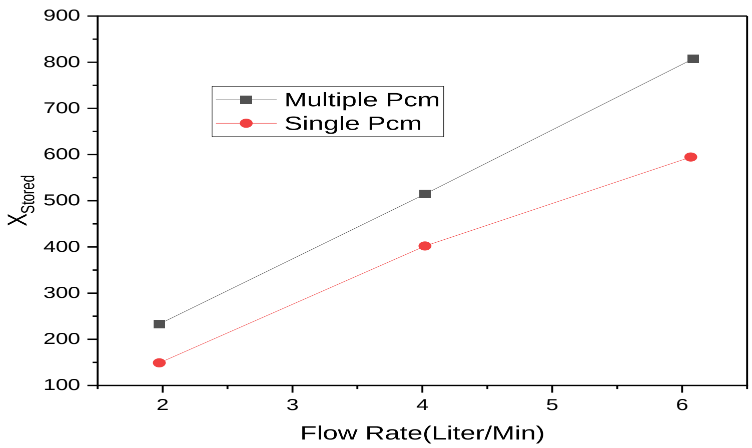

Figure 16: Variation of energy stored vs HTF flow rate

4.CONCLUSION:

Three different PCMs with different melting temperatures were used in an experimental study on a latent heat storage system. Various experiments with various operating parameters were carried out to analyse the impact off mass flow rate on the melting and solidification process. These experiments yielded the important results listed below:

- Energy efficiency increases from 56% to 68% when the rate of HTF (water) is increased from 1 to 5LMP
- According to the data presented above, the heattransfer process is greatly influenced by the mass flow rate of HTF. The charging and discharging processes are significantlybenefitted using a higher flow rate.
- Exergy efficiency decreases by 6% whenthe mass flow rate increases from 1 LMP to 5LMP
- According to the results, the single PCM-based TES unit has less energy storage than the multi-PCM system.

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