PERFORMANCE ENHANCEMENTS OF PHASE CHANGE MATERIAL (PCM) CASCADE THERMAL ENERGY STORAGE SYSTEM BY USING METAL FOAM

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Abstract:
A numerical simulation is proposed for the thermal performance enhancement of Cascade Thermal Energy Storage System (CTESS) of paraffin wax Phase Change Materials (PCMs), by using Metal Foam (MF). Both melting and solidification processes were investigated. Copper foam with different porosities was used as MF and air as Heat Transfer Fluid (HTF). The numerical study includes charging and discharging processes at different velocities of (HTF) for three systems: CTESS with MF in the PCM side (MF-CTES), CTESS with MF in the fluid side (MF-AIR) and CTESS with MF in both PCM and fluid sides (MF-ALL). A numerical simulation by using CFD ANSYS FLUENT software package (Version 19) was done for the problem. The main results showed that by using metal foam in both sides (MF-ALL), the heat transfer enhanced greatly; it was between (53% - 84%) in charging process and between (60% - 86%) in discharging process, compared to the improvement obtained by previous work (Hiba and Ihsan [VI-IX]) which ranged between (20.96 % to 42.04%) and (25.31% to 54.92%) for charging and discharging process respectively. This enhancement increases with increasing velocity and also the time of melting and solidification process reduced compared with (MF-CTES) and (MF- AIR).

Keywords: Cascade Thermal Energy Storage, Metal Foam, Charging and Discharging Process, Numerical Simulation

I. Introduction
The environmental protection at the present time put a new confrontation in front of researchers. It is needful to create a system that can be charged or discharged itself [III]. Thermal Energy Storage System (TESS) is an effective technology which stores thermal energy by increase or decrease the temperature of storage medium (heating or cooling), and can use the energy that is stored for heating, cooling application and power generation[X]. TESS can be classified into three categories:
sensible heat storage, latent heat storage and thermo-chemical according to mechanisms of storage. Energy stored in sensible heat storage (SHS) is by increasing the temperature of material, and there is no phase change in the material used to store heat but in Latent Heat Storage it is based on phase change of storage material from state to state when the heat is absorbed or released. The base material used in LTESS (Latent Thermal Energy Storage System) is called Phase Change Material (PCM) [I]. PCMs are used in many applications in TESS such as: building energy saving, solar cooker, solar power plant, industrial (cooling of heat and electrical engines … etc.) and medical applications (transportation of blood) [XIII]. PCM have many desirable characteristics such as; availability and low cost but, they also have undesirable characteristic which is very low thermal conductivity, and for this reason; various techniques have been used to improve the low thermal conductivity of paraffin wax among these techniques used MF [II].Metal foam (MF) is a cellular structure solid matrix of metal, consisting of a lot of pores which is filled with gas [IV].

Chen et al. [XII] investigated numerically the enhancement of the energy transport inside PCM in TESS using metal foam. Both heat transfer fluid (HTF) and PCM sides filled with MF in TES unit. The results showed that when the metal foam was inserted in both HTF and PCM sides the performance was improved greatly. Zhao and Zhou [V][experimental investigation on heat transfer features of PCMs; the results showed that the addition of porous material will enhance the heat transfer rate of (PCM). Marwah and Ihsan [XI] proposed experimental and theoretical study of thermal conductivity enhancement of PCM by using metal foam. The obtained experimental results showed that, the thermal conductivity of PCM with MF raised by (37-39 %) compared with pure PCM. Hiba and Ihsan [VI, VII, VIII and IX] investigated numerically and experimentally the performance enhancement of CTESS. The results showed that the addition of metal foam in both cases STES and CTES decreased the time of melting and solidification than pure PCM.

The previous researchers carried out theoretical and experimental studies to improve thermal properties of PCM, However, it has been shown that the addition of metal foam is more effective and has better results for charging and discharging process of TESS. Accordingly, CTESS with MF in both sides need more numerical and experimental studies to show its effect on performance enhancement of PCM. In the present work, CTESS with MF in both sides (wax and fluid sides) will be studied numerically for charging and discharging process. The present work is extension to the work of Hiba and Ihsan 2018 [VI-IX], and is part of M.Sc. thesis research for the 1st author supervised by the 2nd author.

II. Physical problem

In the present work, a numerical study is proposed for three cases of CTES system: (MF-CTES), (MF-AIR) and (MF-ALL), see Figure 1. The study was numerically done by using CFD ANSYS FLUENT (Version 19) software program. Paraffin wax with different melting temperatures was used as PCM, copper foam with different porosities (0.85, 0.9 and 0.95), 30 PPI was used as MF and Air is HTF. The properties of PCM, MF and air are shown in Table 1[V1 - IX]. The study includes charging and discharging process. In charging process, inlet temperature was 373K and PCM with lowest melting temperature placed at the end of storage to ensure that all PCM melting by enough temperature difference that was obtained from this
arrangement, in discharging process, inlet temperature was 294K and this arrangement of PCM was inversed, see figure 2. The present work and present results are compared with results of Hiba and Ihsan [VI - IX].

**Figure (1):** (a) MF-CTES (MF in PCM side, (b) MF-CTES (MF fluid in side), (c) MF-CTES (MF in both sides)

**Figure (2):** PCM arrangement
Table (1): Properties of PCM, HTF and MF [VI - IX]

| Properties                        | Materials          | PCM1 (Paraffin wax) | PCM2 (Paraffin wax) | PCM3 (Paraffin wax) | Air  | Copper |
|-----------------------------------|--------------------|---------------------|---------------------|---------------------|------|--------|
| Melting temperature [K]           |                    | 330                 | 334                 | 338                 | -    | -      |
| Solidus density [kg/m³]           |                    | 841.32              | 852.14              | 860.77              | -    | 8978   |
| Liquidus density [kg/m³]          |                    | 757.25              | 766.11              | 770.53              | 1.225| -      |
| Specific heat [J/kg K]            |                    | 2891                | 2900                | 2952                | 1006.43| 381 |
| Thermal conductivity [W / m K]    |                    | 0.241               | 0.265               | 0.322               | 0.0242| 387.6 |
| Dynamic viscosity [kg/m s]        |                    | 0.0155              | 0.0121              | 0.0125              | 1.78*10⁻⁵| -  |
| Thermal expansion coefficient [1/K] |                   | 0.00031             | 0.000305            | 0.0003              | -    | -      |
| Latent heat [J / kg]              |                    | 267670              | 270715              | 273760              | -    | -      |
| Solidus temperature [K]           |                    | 320                 | 324                 | 328                 | -    | -      |
| Liquidus temperature [K]          |                    | 334                 | 338                 | 342                 | -    | -      |

III. Numerical simulation

The present work was numerically simulated by using CFD ANSYS FLUENT (Version 19) software program. The simulation was done by using two computers, the first one: MSI Laptop with windows 10 Home 64-bit, Ram 16 GB, NVIDIA GeForce GTX 1070 (Total memory 16GB) and processor Intel (R) core (TM) i7-7920 HQ CPU@3.1GHZ (8 CPUs). The second computer: MSI Desktop with windows 10 pro 64-bit, Ram 16 GB, Radem RX580 (Total memory 16 GB), Processor AMD Ryzen 7 2700 x eight core (16 CPUs) 3.7 GHZ. The computing time for one case was about 5 hr.
IV. Result and discussion

❖ Effect of velocity and porosity

Figure (3) shows the effect of HTF velocity for charging and discharging process. During the process of charging with increasing HTF velocity, the time for this process decreases because of the increase in velocity, the difference in temperature between inlet and outlet decreases and this decrease makes air flow with less time over PCM and enable better heat exchange, and the same thing for discharging process. The effect of porosity is shown in figure (3). For both cases of MF-AIR and MF-ALL it was noted that with decreasing porosity with fixed pore density for same velocity, the time of charging process increases because larger porosity has lower heat transfer rate, and the change in temperature occurs quickly and with increasing porosity the time of discharging process increase.

❖ Effect of Metal Foam

Metal Foam was used to improve the thermal conductivity of PCM. MF-CTES was studied by Hiba and Ihsan [VI-IX], while the present work studied MF-AIR and MF-ALL and compared among the three cases which studied to conclude the best improvement. The results showed that when MF was used in all sides (MF-ALL) the time is reduced greatly compared to MF-CTES. During MF-ALL, paraffin wax needs about (3200-380) seconds to melt completely depend on velocity, and needs about (2500-220) seconds to solidify completely, while in MF-CTES[VI-IX] paraffin wax melts through (7600-2300) seconds and solidify through(6300-1600) seconds which means that time with velocity 1m/s in MF-ALL is equivalent to time of velocity 10m/s and during MF- AIR paraffin wax needs about (6200-1600) seconds to melt completely, and needs about (3100-1600) seconds to solidify completely. Figure (5) shows this comparison and figure (14) shows the effect of adding MF on the fluid passage side in the present work and comparing it with the result of Hiba and Ihsan [VI-IX], and this comparison was taken at the same time (500 s) and velocity (7m/s) for discharging process.

Figure (4) shows the percentage thermal enhancement depending on the completion time of the melting and solidification processes. It is noted that the enhancement in case of MF-ALL is large, it was between (53% -84%) in charging process and between (60%-86%) in discharging process, and in the case of MF-AIR the enhancement between (9% - 37%) for charging and between (12% -50%) for discharging process, while the improvement by previous work (Hiba and Ihsan [VI-IX]) ranged between (20.96 % to 42.04%) and (25.31% to 54.92%)for charging and discharging process respectively. These enhancement percentages were calculated by comparing the result of MF-ALL and MF-AIR with the results of MF-CTES that obtained by (Hiba and Ihsan [VI-IX]), while (Hiba and Ihsan [VI-IX]) enhancement percentages were calculated by comparing MF-CTES with CTES.

The enhancement in MF-AIR is decreased with the increase in velocity for discharging process because PCM was bad conductor of heat whereas thermal conductivity is low and in this state there is no MF with PCM to improve it and the MF in the air side it impedes airflow and causes heat exchange with PCM surface, because thermal conductivity of PCM is low so, heat needs more time to reach to the middle and complete solidification process, while in the charging process the
enhancement percentages are close when velocities varies for the same porosity and the enhancement percentages increase when the porosity increases. The reason for the enhancement percentages is convergent because of the high temperature difference contrary of discharging the effect of temperature difference will decrease and dominance of the effect of MF, and will be one factor affecting it in the present work, which is the porosity. And the reason for increasing the enhancement percentages when increasing the porosity is that increasing the porosity means that the amount of the metal is less, so the time needed to raise the temperature from the initial value to the PCMs melting temperature will decrease, but when the porosity is low, the amount of metal increases, so it takes more time to transfer heat from the air to the PCMs. But in MF-ALL case the thermal conductivity of PCM improved and the heat transfer to the air side is better, since there is MF works to transfer heat, therefore, it was found that the enhancement percentages are high.

Temperature distribution
The process of charging and discharging was complete when heat transfer stopped from air to PCM and vice versa, and because that the outlet temperature of air (T4) in figure (6) shows the location of points of temperature (T1, T2, T3, T4). From the figure (7) in the state of MF-ALL the time to complete the process is lower; that means the process was very faster than MF- AIR. The time of charging process is finished when the curve reaches 371K and 300K in discharging process. Figure (8) shows temperature distribution of T1, T2, and T3. It shows also the quick heat exchange in the case MF-ALL and shows the melting temperature of PCM in charging and discharging. It is clear the difference between MF-All and MF- AIR, so was noted that in MF-AIR the path of melting process is evident in every part of the paraffin wax (PCM1, PCM2 and PCM3) where the temperature has increased in the charging process and decreased in discharging process gradually until it reached the separating temperature between melting and solidification point and so that the curve in this region is almost constant at either temperature in MF-ALL, not noticed this region because the process of melting and solidification was done quickly and the figure (8) showed a rapid change in temperature.

Mass Fraction
Figure (9) shows the average mass fraction. For charging process it was noted that PCM melted quickly with lower time in MF-ALL than MF-AIR, and also noted that increasing the velocity decreases the time to complete melting process, the same thing for discharging process. Increasing velocity decreases the time required to complete solidification process. See figures (12, 13).

V. Conclusions
Numerical investigation was made for charging and discharging process of CTESS, by using MF with different porosities (0.85, 0.9 and 0.95) in PCM side (MF-CTESS), in air side (MF-AIR) and in both PCM and air sides (MF-ALL), and comparison between them. The results show that the case MF-ALL gives the best enhancement, it was between (53% -84%) in charging process and between (60% - 86%) in discharging process. This enhancement increases with increasing velocity. Also, with increasing the velocity of HTF the time to complete the process decreases.
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Figure (3): The effect of velocity and porosity for (a) Charging process, (b) Discharging process

Figure (4): The percentage enhancement for (a) Charging process, (b) Discharging process
Figure (5): (a) Comparison of time for charging process (b) Comparison of time for discharging process

- T4
- T1
- T2
- T3

Figure (6): Location of temperature points selected in the middle

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Figure (7): Outlet temperature (T4) for (a) Charging (b) Discharging

Figure (8): Temperature distribution at different location (T1, T2 and T3) for (a) Charging (b) Discharging

Figure (9): Average mass Fraction for (a) Charging (b) Discharging
Figure (10): Temperature contour of MF-ALL, porosity 0.85 for (a) Charging, (b) Discharging
Figure (11): Temperature contour of MF-AIR, porosity 0.85 for (a) Charging, (b) Discharging
Figure (12): Mass fraction contour of MF-ALL, porosity 0.85 for (a) Charging, (b) Discharging
Figure (13): Mass fraction contour of MF-AIR, porosity 0.85 for (a) Charging, (b) Discharging
Figure (14): Comparison between Hiba and Ihsan [VI - IX] (MF-CTES) and the present work for discharging

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