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Effect of Porous Medium and Nano Particles Presences in a Counter-Present Day Triple-Tube Composite System

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ABSTRACT To solve the problem of low thermal conductivity of phase change materials (PCMs), three different methods including geometry modification, adding nanoparticles and metal foam are studied in a triple-tube latent heat storage system (LHS). PCM is enclosed in the middle tube while water passes through the inner and outer tubes as the heat transfer fluid (HTF). Different nanoparticles concentrations and metal foam porosities are examined. Different HTF flow directions in the inner and outer tubes related to the gravity direction are assessed. The results show the advantage of the system with counter-current flow of the HTF when the HTF flow in the outer tube is in the gravity direction. By adding 5% copper nanoparticles, the melting/solidification time reduces by 25.9 to 28.2%. By adding 95% porous metal foam, the melting/solidification time reduces by 83.7/88.2% showing the advantage of adding metal foam compared with adding nanoparticles.

Keywords: Phase change material, Latent heat storage; Nano-PCM; Metal foam; Melting; Solidification.

1. Introduction

Energy storage plays a crucial role in saving the excess energy and balance the mismatch between energy supply and energy demand. The high rate of energy waste to the environment in the form of thermal energy can be stored and used efficient which is the major challenge for fossil-fuel usage. Energy storage has been widely used in buildings, power plants and industries recently to provide a more efficient way of energy usage. In buildings, as the most energy consumer in the world which accounts for 36 % of the global final energy consumption, energy storage allows peak-shaving and energy saving during the day [1, 2]. For renewable energies such as solar and geothermal, energy storage helps to store a huge amount of energy which is otherwise can be lost [3]. In industries as well as steam and gas power plants, energy storage can save excess energy to produce more power. By saving energy through the use of energy storage, a huge amount of CO_2 production can be reduced in the buildings and industries as well as saving more renewable energies **[4]**. To achieve efficient thermal processes and remarkable energy-saving benefits, novel technologies for energy storage are of great practical importance.

Thermal energy storage (TES) has the advantages of peak-shaving, high - efficiency use of energy, heat waste recovery, as well as a higher amount of renewable energy saving **[5].** Among different types of TES, latent heat storage (LHS) systems have great potential to provide a cost - effective solution for this problem. Phase change materials (PCMs) are used in LHS systems to store and recover heat. PCMs are also capable to compete with sensible heat storage materials such as MgO in terms of cost per unit kWh, and are far more compact and also cheaper than electrochemical thermal storage. They have an energy density typically 5 to 14 times higher than any rival heat storage systems and the added advantage of almost constant temperature during the phase changing process [6]. The main challenge for efficient use of PCM based technologies is the long melting/solidification time as well as not efficient storing/releasing heat due to low thermal conductivity and low thermal diffusivity within the bulk PCM [7]. These disadvantages lead to limited use of LHS systems.

The Pipe heat exchangers are widely used in industries and power plants for heat transfer in the forms of double-tube, triple-tube and multiple-tube. In solar parabolic power plants, they have been used to transfer the solar radiation to a secondary fluid. For the PCM based pipe heat exchangers, the PCM is kept in one side of the pipe while the heat transfer fluid (HTF) stores/recovers heat to/from it. There has been a lot of studies in the literature working on the performance of double-tube LHTES heat exchangers. Due to the limitation of PCMs, they have tried to modify the double-tube geometry by using fins, eccentric pipes, and wavy channels or using an additive such as nanoparticles and metal foams. [8] assessed the performance of a double-tube LHS unit employing different numbers of tubes. They presented that the PCM temperature increases using a higher number of tubes [9]. Assessed the charging of PCM in concentric and eccentric cylindrical tubes to analyse the effect of the eccentricity of the inner tube using constant temperature for the inner tube's wall. They showed that due to the natural convection in the domain, the location of the inner tube affects the charging time. They presented that the eccentric annulus has less charging time than the concentric annulus and charging time decreases by increasing the eccentricity of the cylinders. One of the methods to improve the rate of charging/discharging in double-tube heat exchangers is increasing the number of pipes results in a triple-tube and multiple-tube heat exchangers. It can enhance the heat transfer area resulting in a higher heat transfer/release rate [IS]. It can be combined with different methods such as fins, Nano-PCMs and composite porous-PCM [10, 11]. Studied a multi-tube PCM based heat exchanger and showed that considering the same mass, the PCM melts 29% faster by using four inner tubes compared to a double-tube unit [12]. Investigated the effect of longitudinal fin arrangement in a triple-tube cylindrical LHS system on the charging time reduction. They performed an experiment for the case of internal-external fins and conducted numerical simulations for various combinations of fins including internal, external and internal-external as well as fin length and fin thickness. They showed 34.7% reduction in the melting time for the best case [13]. Examined different designs of the LHS heat exchanger including one tube with and without longitudinal and circular fins, and multi-tube configurations. They showed the advantage of multi-tube compared with the single tube heat exchanger.

Nanoparticles are widely used to enhance the thermal conductivity of fluids recently. They have been used in LHS systems to solve the problem of low thermal conductivity of PCMs. The use of nanoparticles leads to changes in PCM properties. It generally decreases the fusion latent heat, as well as specific heat transfer coefficient of the PCM, results in the reduction of heat storage capacity and therefore higher amount of PCM mass is required to have an equal heat storage capacity. There has been lots of research in the literature working on the performance of Nano-PCM systems [14].

Employed two different configurations of channel waviness including divergent-convergent and convergent-divergent walls using Cu-water nano-fluid in the discharging process. They presented the negative effect of nanoparticles due to the lower latent heat of the nano PCM and also positive effect of channel waviness. [15] Studied the effect of CuO nanoparticles on the performance of the LHS system using N-Octadecene paraffin as the PCM. They showed the advantage of nanoparticles on the reduction of melting time which is more effective by increasing the volume fraction of nanoparticles. [16] Studied on simultaneous charging and discharging from a fined triple-tube LHS system using Al_2O_3 to enhance the thermal conductivity of PCM. They showed that the effect of adding fins on modifying the performance of the system is much more than that of the nanoparticles. In the composite porous/PCM, the heat is transferred by conduction through the high conductivity porous foam rather than PCM which increases the rate of thermal diffusion [17]. It is shown that the effect of conduction heat transfer by the porous foam is significantly effective on the performance of the charging/discharging process [18].

Based on the literature review, the lack of comprehensive paper on the effect of nanoparticles in the presence of a porous medium can be seen for the PEM based energy storage systems. Therefore, this study aims to study the combination of porous medium and nanoparticles in a PEM based vertical triple-tube LHS system. The triple-tube latent heat storage system is employed as a more efficient system compared with a double-tube unit. In the triple-tube system, composite PEM is located in the middle tube while water passes in the inner and outer tubes as the heat transfer fluid. Different directions of water flow in the inner and outer tubes including the co-current and counter-current flows are studied which has not been studied previously. The effect of copper nanoparticles, copper foam and simultaneous use of nanoparticles and porous medium are studied comprehensively. The system is analysed in both melting/solidification process based on the melting/solidification time, temperature and rate of heat storage/retrieval. Different volume fractions of nanoparticles, as well as different porosities of metal foam, are also investigated. The results of this paper provide guidelines for comprehensive usage of different heat transfer enhancement methods in LHS systems including geometry modification, nanoparticles addition and porous medium addition.

2. Mathematical modelling

In this study, four different cases are studied including the pure PCM, nano-PCM, porous-PCM and porous/nano-PCM. Without the presence of the porous medium, in the solid estate, heat is transferred by conduction and then after generating liquid phase, heat is transferred by both conduction and natural convection. In the presence of a porous medium, heat is more transferred by conduction through the metal foam inside the PCM rather than low conductivity pure PCM [19]. By adding a porous medium, a part of LHS volume is filled with the porous structure and therefore a higher volume of PCM should be employed to have a similar PCM mass. Furthermore, due to the flow resistance made by the porous structure, the effect of natural convection is negligible in the porous-PCM case [20]. In the presence of nanoparticles inside the pure PCM, the properties of PCM are changed. The purpose of adding nanoparticles is modifying the thermal conductivity of pure PCM; however, the latent heat of fusion and specific heat transfer coefficient reduce while the effective density increases.

In numerical modelling, the enthalpy-porosity model is employed for modelling the effect of phase change. The viscous and inertial losses due to the effect of the porous medium should also be considered in the momentum equation [21]. By adding nanoparticles, all the effective properties of pure PCM are determined and employed instead of pure PCM properties in the model.

Two different thermal equilibrium and non-equilibrium can be employed to solve the energy equation for the PEM in the presence of a porous medium. It is true that employing the thermal non-equilibrium model provides a more accurate results compared with the equilibrium model due to considering the local convection heat transfer inside the pores of the porous medium between the metal foam and the PEM; however, the assumption of thermal equilibrium model saves computational resources by maintaining good accuracy as shown in the literature [22]. Furthermore, the difference between the non-equilibrium and equilibrium models depends on the boundary and initial conditions which are significant in the sensible heat domain rather than that during the phase change process due to having an almost constant temperature [23] Furthermore, it is noteworthy that, the non-equilibrium model cannot be used regularly in the 2-D and axisymmetric models, due to generated porous boundaries at the walls between the HTF and the PEM and the limitation of coupled boundary condition for it in FLUENT software. [24]

3. System description

The studied LHS unit shown in Fig. 1 is a vertical triple-tube heat storage system with the length of 500 mm, the inner diameter of 4 cm, the middle diameter of 8 cm and the outer diameter of 12 crn. Due to the nature of the geometry and conditions of the problem, the axisymmetric model is employed (shown in Fig. l (a) and (b)) where a rectangular geometry is considered as the computational domain with the left line as the axis of the problem. **In the** PEM zone, different cases of pure PEM, nano-PEM, porous-PEM and porous/nano-PEM are evaluated. Note that, for different cases, the volume of the unit increases based on the foam porosity and volume fraction of nanoparticles to have a similar PEM mass.

Water passes through the inner and outer tubes of the mritwhile the PCM encloses in the middle tube in the presence of copper foam and copper nanoparticles. The water flow is laminar with the assumption of inlet constant velocity and temperature and outflow outlet. No-slip boundary condition is defined for the walls where the adiabatic condition is assumed except for the middle walls for heat transfer between the water and PCM.

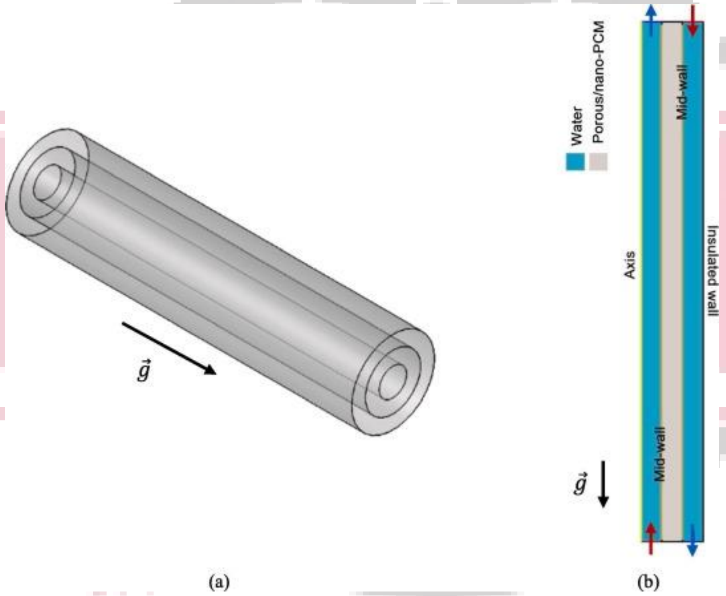


Fig. 1 Effect of porous medium and Nano Practicals

The initial temperature of the PEM is 285 K in the melting process and 323 K in the solidification process. The temperature of water at the inlet is also considered equal to 323 K and 285 K, respectively, in the melting and solidification processes. The PEM is considered RT-35 (RUBITHERM) and the properties are presented in Table 1. Note that the reference density used in the momentum equation is considered equal to the mean densities of the PEM in the solid and liquid estates (815 kg/m) at the reference temperature equal to the average temperature between the solidus and liquids temperatures (305.5 K). The properties of copper as the material of the foam and nanoparticles are also presented in Table 1.

Table 1. Properties of RT 35 [25] and copper

Property	**RT35**
Solidus / Liquids temperature (^{0}c)	302 / 309
Latent heat of fusion (kJ/kg)	170
Specific heat (kJ/kg.K)	2.0
Solid Liquid Density (kg/m)	850 / 780
Thermal conductivity (W/m.K)	0.2
Viscosity (Pa.s)	0.023
Thermal expansion coefficient (l/K)	0.0006
Property	**Copper**
Density (kg/m')	8978
Thermal conductivity (W/m.K)	387.6
Specific heat (J/kg.K)	381

For the HTF, the properties are determined based on the inlet temperature of the water as Presented in Table 2.

Table 2. Properties of Water at different temperatures

Property	285K	323K
Specific heat (kJ/kgK)	4190	4180
Density (kg/rn')	999.5	988

Thermal conductivity (W/mK)	0.583	0.641
Viscosity (Pa.s)	0.0012401	0.0005488

4. Numerical model and validation

ANSYS-FLUENT software is utilized to discrete the governing equations using the SIMPLE algorithm with double-precision solver. The QUICK scheme is used to calculate the diffusion fluxes and convection for the momentum and energy equations while PRESTO scheme is used for the pressure correction equation [32]. The values for under-relaxation factors are set to 0.3, 0.6, I and 0.9 for the pressure, velocity, energy, and liquid fraction, respectively, considering the convergence criteria of 10^{-6} for all the equations. For the grid independency analysis, three different sizes of the mesh including 72000, 120000 and 180000 elements are studied for the pure PCM case. Table 3 presents the results of melting time and average heat storage rate for different meshes. The maximum difference in the melting

Time is less than 0.3% between 120000 and 180000 elements. Therefore, 120000 are chosen as the element's number. Different time step sizes of 0.05, 0.1 and 0.2 s for the case of 120000 cells are also assessed and no considerable change is shown.

Table 3. Grid independency analysis

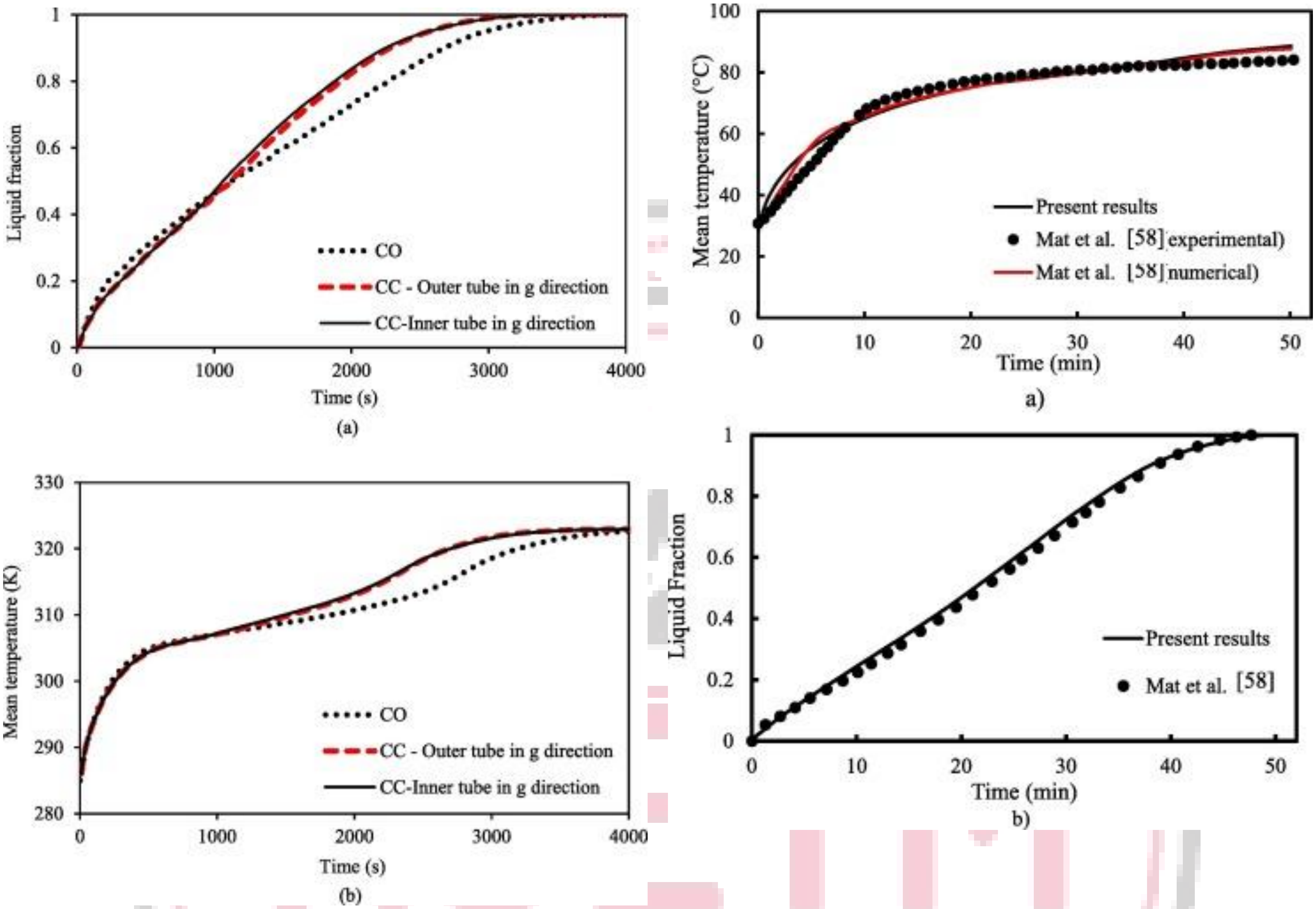
Number of elements	Melting time (s)	Rate of heat storage (W)
72000	3385	110.2
120000	3440	108.4
180000	3450	108.1

5. Results and discussion

In the following, first, the effect of water flow direction in the triple-tube heat exchanger is studied in the melting process related to the direction of gravity. After finding the best condition, due effect of the presence of the porous medium, nanoparticles and simultaneous porous medium and nanoparticles are studied during the melting and solidification processes.

5.1. Effect of water flow direclion

Three different cases are existed according to the directions of the water flow and gravity in the triple-tube heat storage system. The cases include the co-current flow, counter-current flow where the inner tube is in the gravity direction and the counter-current flow where the outer tube is in the gravity direction. Display the variation of liquid fraction and volume average temperature as a function of time for different cases, respectively. It is worth noting that the volume average temperature is useful to demonstrate the liquid fraction variation in the domain. When the average temperature rises from the solidus temperature, all the PCM places in the phase change process and when the average temperature passes the liquidus temperature, all the PCM melts. The counter-current cases show a higher performance according to the melting time. As shown, in the almost first 1000 s, a higher liquid fraction is achieved for the co-current case. During this time, the mean temperature of the PCM is a little higher for the CO case compared with the CC cases and as a result, a higher liquid fraction is achieved. However, after that, the mean temperature of PCM is higher for the CC cases results in a higher rate of liquid fraction enhancement at the same time compared with the CO case. The reason is that at the beginning of the melting process, the heat is transferred only by conduction. In the CC condition, since the gravity is in the direction of the water flow in one of the tubes, it causes a little less heat transfer from the water to the PCM. Then, after some time when convection is gradually generated in the PCM, the effect of counter-current flow starts helping the domination of convection in the PCM domain results in a higher mean temperature of the PCM and therefore shorter melting time.



(a) a) (b) b)

Fig. 2 Effect of porous medium and Nanoparticle's of water flow

5. Conclusions

A triple concentric pipe heat exchanger is fabricated and exper- iments are carried out using it to investigate the heat exchange behavior between three fluids under different operating conditions. The results are presented in terms of temperature distribution of the three fluids along the length of the heat exchanger under co-current parallel flow, both insulated as well as non-insulated conditions, and for different fluid flow rates. The three fluids considered are hot water flowing in the inner annulus, normal tap water flowing in the innermost pipe, and cold water flowing in the outer annulus. This arrangement of fluid flow is called N-H-C arrangement. Another arrangement called as C-H-N is also considered for experiments where the normal and cold water flow passages are interchanged while that for hot water remains unchanged. The heat transfer between the three fluids considered is more effective in N-H-C arrangement of the heat exchanger as compared to that in C-H-N arrangement. Further, normal water is heated more in N-H-C arrangement than in C-H-N arrangement. It is observed that the crossover point occurs between hot and normal water for insulated as well as non-insulated conditions.

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