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Solar Thermal Energy Storage Using Latent Heat: Discharging Energy from Phase Change Material

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Abstract

The amount of solar thermal energy on the earth is not constant; it depends on weather conditions and location. To resolve the mismatch between energy supply and energy demand in solar thermal systems, the useful solutions is to store this solar thermal energy using phase change materials (latent heat) named PCM. In this paper, we studied numerically the discharging and charged energy from and to PCM. To improve the conjugate heat transfer between the heat transfer fluid (water) and the PCM at liquid state, we simulate the influence of the addition of fins to our storage unit with various configurations including online and staggered fins. Then we studied the effect of the inlet fluid flow and the fluid inlet temperature on the total PCM freezing time and the effect of the natural convection in our storage unit. Furthermore, we valid an experimental work. In addition, we used the computational fluid dynamic ansysFluent 15 based on enthalpy formulation to solve the formulation, where we develop three users define to describe the viscosity, density and the thermal conductivity of the PCM.

1. INTRODUCTION

Heating homes in residential and commercial building and water heated present more than 35.3 % of the total energy consumed [1]. At evening where the peak period of the energy demand, for the solar thermal systems that's become a bad situation where there is no sun. A better solar system who have the best storage system. In this sens, the PCM can be used to store the solar thermal energy because they have significant latent heat. After charging of the PCM (also known as melting) in the day, this energy must be recovered (also named as freezing or solidification of PCM) to be used. Various methods have been proposed, where searchers used fins to increase the heat exchange area [2].

2. PCM INCORPORATION TO SOLAR STORAGE TANK

South Algeria has a strong solar radiation that exceeds 1000 W / m2, where the use of Solar Systems has a greater efficience. The use of PCMs presented a most powerful solution between all other storages methods. At day, use the water in the solar heater and melt the PCM in the storage tank also named the charge of the PCM, and this heat at evening [3]. Many paper experimental and numerical studies are accompanied to involve the performance of the storage unit under different operating conditions and different design to reduce volume and cost of the price of the energy. Among parameters that have influence in thermal stratification founded by searchers are the heat conduction in the storage unit wall, convection and the isolation of the unit storage from the ambient. [4], [5] and [6] study the heat and cold storage. Researchers incorporate PCM into the hot water storage unit to increase the heat capacity of thermal storage.

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Al-Hinti et al. [7] present an experimental work of water- phase change material performance where the PCM is used with the conventional solar water heater. They found that the stored water temperature remained at least 30 °C higher than the ambient temperature. Also the adding of PCM to water storage unit is tested experimentally by Muhsin Mazman et al. [8] where an increase of the temperature in the storage unit was observed. What the adding of the encapsulation salt hydrates to a domestic hot water tank is analyzed by A.Barba et al. [9] where their results were shown include the position of the moving surface, distribution of the temperature, the solid PCM amount, the energy released and time of the complete solidification. López-Navarro et al. [10] experimentally present the versatile latent heat storage unit. The storage unit contains paraffin as PCM. They found that the 78% of the maximum of the capacity is reached.

An exergetic study of a solar thermal collector with a rectangular storage tank contains PCM, and analytical solution of the PCM melting process is presented by F.Aghbalou et al.[11]. They compared their results with previous experimental work. Also, Roberta Padovan et al. [12] present a study of the PCM adding to a domestic water solar heater, where they optimized and analyzed the relation between the geometry of the storage tank, the PCM temperature and the performance of the system. Further Robynne E. Murray et al.[13] found for solar domestic water heater included a latent heat storage unit in the charging period flow rate decrease the melting time but in discharging period this flow rate have no effect by a numerical and experimental study. Abduljalil A. Al-Abidiet et al. [14]. Added internal and external fins to the triplex tube contain RT82 in disication HVAC installation, and they study numerically and experimentally the solidification of a PCM. The Results indicate that the unit geometry with internal and external fins achieved complete solidification in a short time. The influence of the added and the fin structures on the process of melting and solidification of the PCM has been studied by [15], [16], [17], and Velraj et al. [18] Ismail et al. [19] theoretically and experimentally studied the solidification process about a vertical tube with longitudinal fins.

3. PHYSICAL AND NUMERICAL MODEL

Figure.1 represents the physical areas of the thermal energy storage tank studied in this works. The storage unit filled with an RT 25 as PCM with 15 * 25 cm width and length. The heat transfer fluid (water) flows through the U-tube.

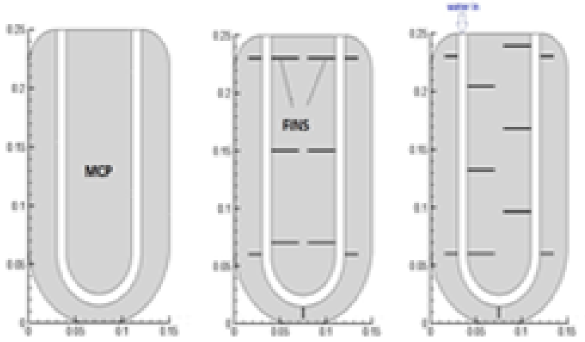

Figure 1. *Schematic representation of physical model a) U-tube, b) U-tube with in-line fins c) U-tube with staggered fins of storage tank*

The dimension of the pipe and fins are presented in Table 1.

Table 1. *The dimension of pipe and fins.*

Parameters	Value mm.
dpipe	10
Inner Fins	30
Horizontal fins	25
Outer vertical fins	

3.1. Governing Equation

The enthalpy method is used in ANSYSFLUENT15 to solve governing equations in the solidification/fusion problem. The governing equations are [14]:

The Conservation of the mass equation: Momentum and energy equations are [14]:

$$\frac{\partial \rho_{pcm}}{\partial t} + \nabla(\rho_{pcm} u\ ) = 0 \tag{1}$$

The equation of the Conservation of momentum:

$$\frac{\partial \rho_{pcm}}{\partial t} + \nabla(\rho_{pcm} u \otimes u) = \nabla \sigma + (\rho_{pcm} g) \tag{2}$$

And the Energy equation:

$$\frac{\partial}{\partial t}(\rho_{pcm} H_{pcm}) + \nabla.(\rho_{pcm} u H_{pcm}) = \nabla.(\lambda \nabla T) \tag{3}$$

ρ_{pcm}, µpcm and Hpcm are the density, the dynamic viscosity and the enthalpy of the PCM respectively, g is the gravity acceleration and λ is the thermal conductivity.

The liquid fraction β is defined as:

$$\Delta H_{pcm} = \beta L \tag{4}$$

And L is the latent fusion heat.

3.1.1. Constitutive equations

The RT25 density, ρpcm, is given by [2]:

$$\rho_{pcm} = \frac{\rho_f}{0.001(T - T_{liqui}) + 1} \tag{5}$$

0.001 is the thermal expansion coefficient defined by Humphries and Griggs (1977) and ρ_f is density of PCM at temperature of melting.

The RT 25 viscosity is given by Reid et al. formula (1987):

$$\mu_{mcp} = 0.001 \exp(-4.25 + 1790 / T) \tag{6}$$

The thermophysical properties of the RT25, copper and water are given in Table 2. [20]

Table 2. *Thermo-physical properties of the PCM, Copper, and water*

Property	RT25	Copper	Water
Density of PCM, solid, ρs (kg/m3)	785	8978	998
Density of PCM, liquid, ρl (kg/m3)	749	-	-
Specific heat of PCM, liquid, Cpl, Cps (J/kg K)	2400, 1800	381	4182
Latent heat of fusion, L (J/kg)	232000	-	-
Melting temperature, Tm (k)	299.6	-	-
Thermal conductivity, solid, liquid (W/mK)	0.19, 0.18	387.6	0.6
Dynamic Viscosity, μ (kg/m s)	1.798×10-3	-	0.001003

3.2. Initial and Boundary Condition

At the initial time, the temperature of all the system is 313K, and the inlet water temperature is 293 K with 0.1 m / s of velocity (rate of flow7.85 * 10-6 m3 / s), the system is regarded as perfectly isolated

3.3. Numerical Modelling

In ANSYS FLUENT 15, the pressure staggering option PRESTO schema is used and the under-relaxation factors for pressure,velocity, energy, and liquid fraction are 0.3, 0.2, 1, and 0.9, respectively , the time steps is 0.1 s The MCP grid sizes, including 14 585+15093 cells. Three User-defined functions (UDF) written in C language to account for the temperature - dependence of the thermo-physical properties of RT 25.

3.4. Experimental and Numerical Work Validation

We validated the work of Abduljalil A. Al-Abidi et al. [14] who studied the adding of RT 82 to disication installation for HVAC system .To reduce the time of the solidification and increase the energy stored by the PCM they added internal and external fin to the triplex cylindrical tube. The Figure 2, shows a comparison of the liquid fraction of our work and the work of A Abduljalil Al-Abidi et al. [14] versus time. We note that MCP to be completely solidified, it is takes 270 minutes (4.5 hours). Also, we observed a good followed between two curves.

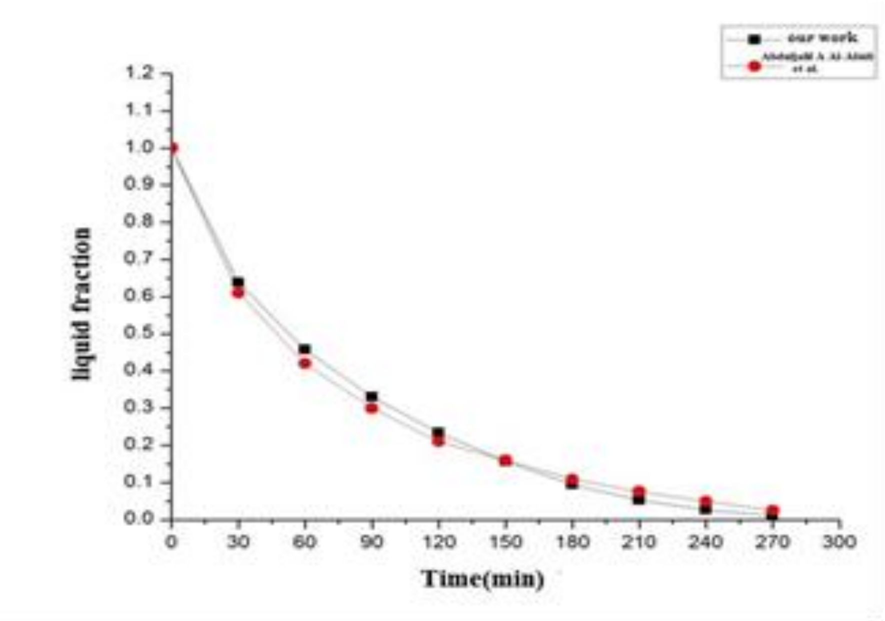

Figure 2. *Comparison of the liquid fraction of our work and the work of A Abduljalil Al-Abidi et al. [14] versus time*

4. RESULTS AND DISCUSSION

4.1. Effect of Geometrical Design

The Figure 3 represent the liquid fraction of RT 25 versus time for three designs. It is found that the storage unit with fins performs better than the unit without fins. Where the addition of fins enhance the surface of heat exchanger between the water and the PCM. Further, more heat transfer rate between a tank with staggered fins and inline fins, where this can explain by the effect of the natural convection and fins arrangement. We also note that between 100% and 2 % of the liquid fraction in PCM, the effect of the fins is remarkable, and for the remaining 2% little difference, it is due to the natural convection effect between the amount and beam of our storage unit. Also in this Figure, we give the total time for the liquid fraction for the three geometries simulating we note that: U-tube without fins: 1669 min to reach the 100% frozen; for U-Tube with inline fins, it take 976 min and U-Tube with staggered fins 996 min.

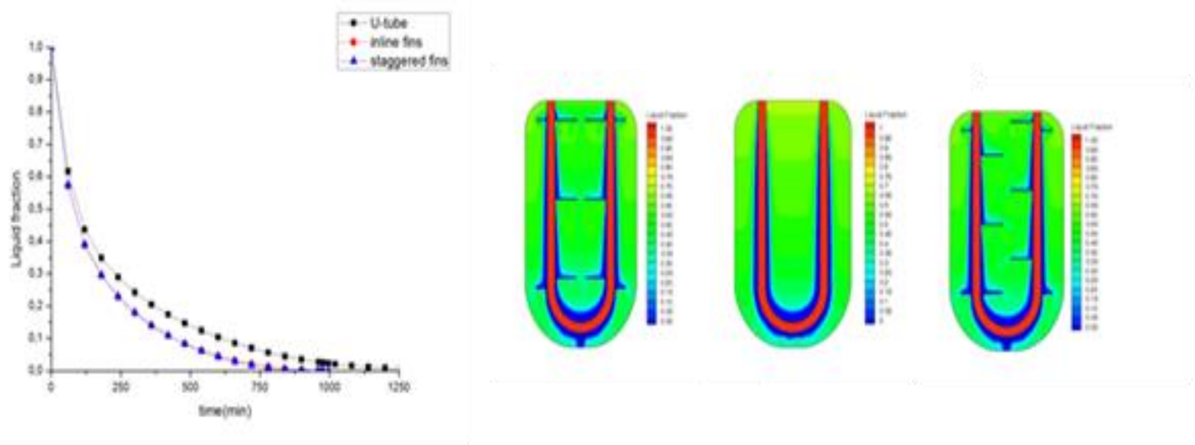

Figure 3. *Liquid fraction average of discharging of the PCM for U-tube design, U-tube with inline fins and U-tube with staggered fins and the contour of liquid fraction distribution at t = 120 min.*

4.2. Effect of Cold Fluid Temperature (Water)

To study the effect of the inlet fluid temperature we tested three temperatures 288, 290 and 293 K, Figure 4 represent the average of the liquid fraction of the MCP where we find for 288 K MCP take 494 min to be totally frozen and 610, 696 min for 290 and 293 K respectively. Looking further the inlet temperature has a significant influence on the liquid fraction that for the range of operating temperature of MCP. What we can explain by a high temperature for the same exchange surface allows providing enough energy (heat exchange) at MCP while increasing convective and conductive effects in PCM Also the contour of the liquid fraction during the freezing of MCP at t= 240 min. Where the MCP contain 20%, 10%, 9% at solid state for 293, 290 and 288 K inlet temperature of the cold fluid flow respectively.

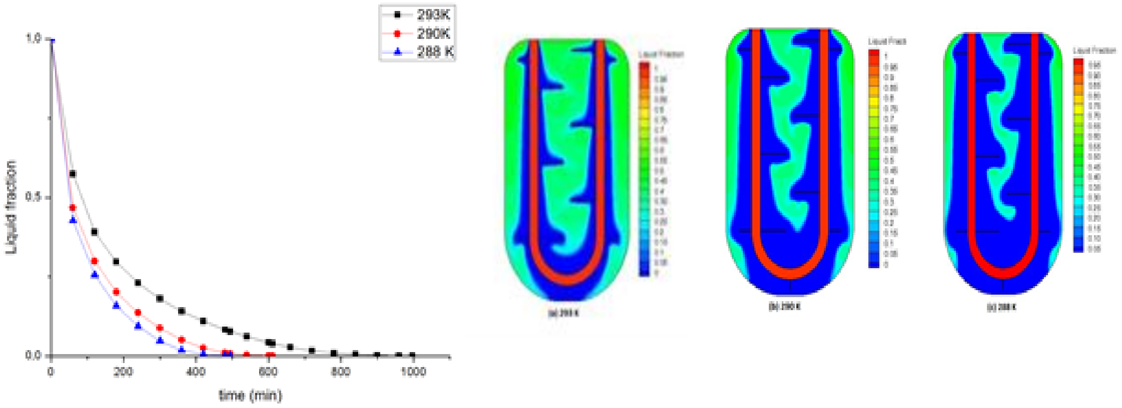

Figure 4. *Liquid fraction average of discharging (solidification) of MCP for three inlet temperature and Liquid fraction distribution for (a) 293 K (b) 290 K (c) 288 K during discharging at t = 240 min.*

4.3. The Effect of Fluid Flow

Before studying the influence of the water flow. We defined the interval to stay in laminar flow (Reynolds number <2000) which gives us a water flow should be less than 10.2 * 10-6 m3/s means the velocity must be less than 1.3 m/s, we used three velocity V1, V2 and V3 where their values are 0.1,0.15 and 0.2 m / s respectively.

Figure.5 shows us the MCP liquid fraction for three velocities (flow). The MCP to complete freezing it takes for V1 996,85 min, 992 min for V2 and 991 for the V3, from which it can see that the inlet flow it have a little effect in the total time of MCP solidification. This effect is clearer from 100% to 10%, bless than the 10 % we have a small change, that can be explained to the natural convection occur during discharging. More, the contour of the liquid fraction during the freezing of the MCP at t= 240 min, Where the MCP contain 23 %, 22.7 %, 22.6 % at solid state for 0.1, 0.15 and 0.2 inlet velocity of cold fluid flow respectively.

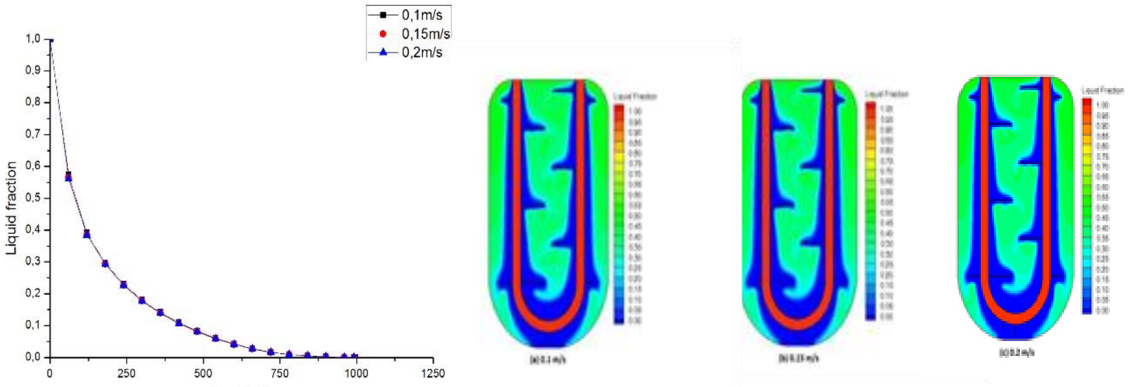

Figure 5. *Liquid fraction distribution in PCM for three vilocity during discharging and the contour of liquid fraction for (a) 0.1 m/s (b) 0.15 m/s (c) 0.2 m/s at t = 240 min.*

4.4. Charging

The Figure 6. represent the liquid fraction during melting of the MCP (charging), where the inlet temperature of the fluid was 303 K and the initial temperature of MCP was 293 K, the total time taken by the MCP to betoltaly liquefied is 285 min, we note that there is a large difference between total freezing and melting time, that can be explained by differences between the bottom and the top in our geometry, in this figure also we represent the contour of the liquid fraction during melting after 30 and 60 min where the fraction liquid is 40 % and 77% respectively .

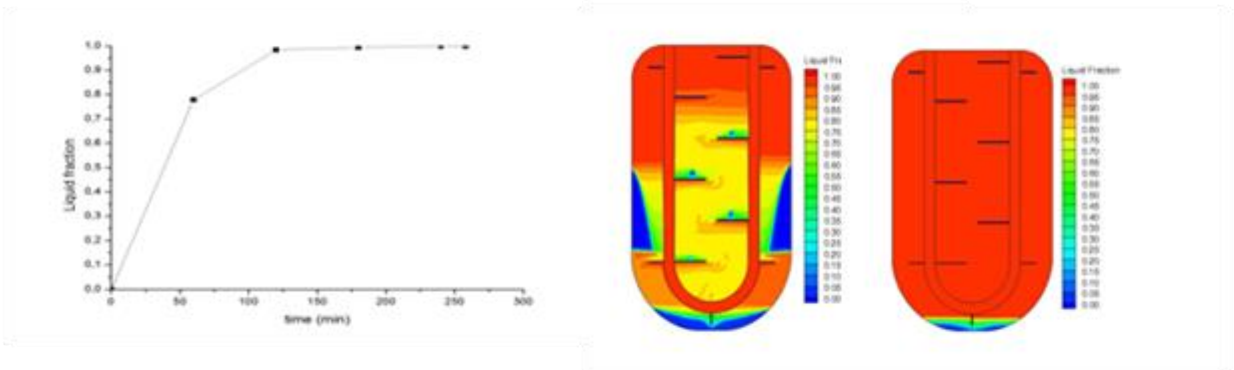

Figure 6. *Distribution and contour after 30 and 60 min of the Liquid fraction during charging*

5. CONCLUSION

In this work, we simulate numerically with ANSYS FLUENT 15 a storage unit in the solar thermal system. At first, we tested the effect of the fins adding in inline and staggered arrangement to our unit means the increase the heat exchange surface between the water and the PCM. We fond that the use of fins decrease the total freezing time of the PCM also the unit with staggered arrangement of fins gives us a better result than in-line fins.

Secondly, the fluid inlet temperature has the biggest effect on the time of PCM freezing; it is due to the increase in convective and conductive heat exchange in the PCM when the water temperature increases. More, the increased of the fluid flow rate a little effect in in total freezing process time of the PCM. Looking further the differences between the bottom and the top in our geometry imposes a large difference between total freezing and melting time. Where the natural convection has a strongly influenced occur during scharging and discharging.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors

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