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Evaluation of flow regime effect on shell and tube thermal energy storage system

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Abstract — **In this paper, we have studied numerically thermo-convective characteristics between a heat transfer fluid (HTF) and phase change material (PCM) in shell and tube thermal energy storage unit. The paraffin wax is considered as a phase change material (PCM), while the water plays a role of a HTF and flows inside the tube at the moment of charging and discharging cycle. The heat transfer between HTF and PCM is performed by conduction and forced convection, this transfer allows to change the physical state of PCM solid-liquid to obtain a quantity of storable heat in order to create a thermal battery. We used the enthalpy formulation for analyzing this heat transfer during the melting and solidification process. A good agreement was found between our numerical predictions and the results of the literature. On the other hand, we have investigated the effect of Reynolds number on the charging and discharging cycle, where it has shown a too much impact on the HTF outlet temperature and the time and rate of solidification and melting process.**

Keywords — **Heat transfer fluid, Phase change material, Latent heat storage, Shell and tube**

I. INTRODUCTION

The problems of energy shortages have worsened due to the increase of industrial, commercial and residential activities, while the current technological development imposed on us energy consumption abundantly. In such case, there is a huge need to use renewable energy sources because they represent a good solution to such problems, and among the known renewable energies, the thermal solar remains the most exploited type. As it is unstable along the time (day and night) and due to its periodic nature, we must use a thermal energy storage device in order to ensure continuity of this energy during the time. Amongst the types of thermal storage systems, there is the thermal latent heat storage based on the use of phase change materials (PCMs) which have advantages such as high storage density and a short interval in the heat transfer. Many numerical and experimental studies were performed on the latent thermal energy storage systems. An experimental study on the vertical shell and tube LHTS unit has been conducted by Wang et al. [1], where the Erythritol considered as PCM and the air has been chosen as HTF, where it flows downwards during charging and discharging cycle. The effects of some physical parameters, such as mass flow rate, inlet temperature, and inlet air pressure of the HTF on the phase change heat transfer have been conducted, whereas the increase of the HTF mass flow rate and inlet temperature has decreased a charging process time, while the inlet air pressure has a little influence on the heat transfer inside a PCM. Tiari and al [2] have studied numerically a transient three-dimensional model of a high temperature LHTES unit, which assisted by finned heat pipes with different configuration of embedded system. The effect of different heat pipe arrangement and the heat pipe quantities was studied on the thermal behavior of the system, where it has shown that the increase in the melting rate of PCM allows to accelerate the charging process. Tiari and al [3] has studied numerically the same physical model by transient two-dimensional in order to investigate the effects of natural convection heat transfer, heat pipe spacing, fin length, and the number of fins during discharging process, among these influences the heat pipe spacing and number of fins are the most influential on the time and rate of solidification process.

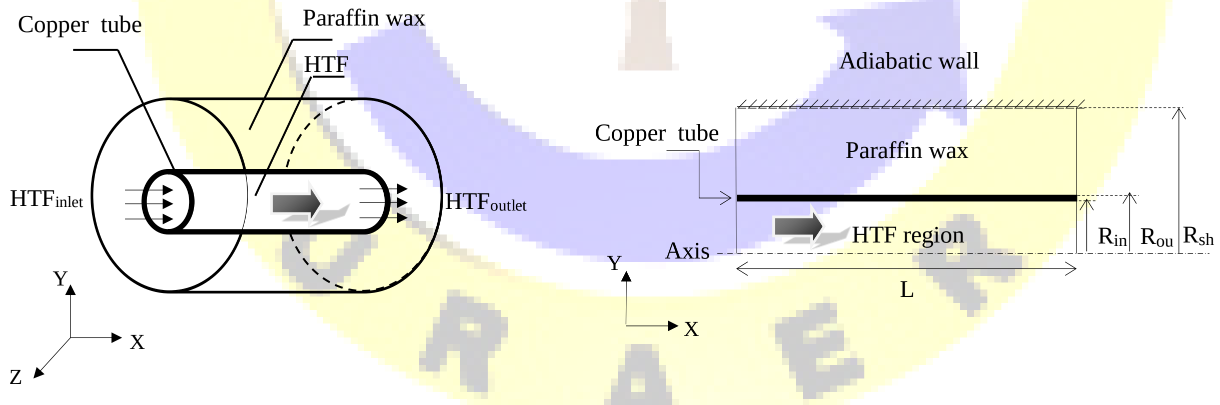
Based on the enthalpy method a numerical study has been carried out by Tao and al. [4] in order to enhance the performance of PCTES unit used in a dish solar thermal power generation system. The effects of the enhanced tubes have been studied on the behavior of PCM melting, where have shown in same working conditions that the melting time is 437.92 min for the smooth tube, 350.75 min for dimpled tube which is reduced about 19.9% and 320.25 min for cone-finned tube which is reduced about 26.9% and 302.75 min for helically-finned tube reduced about 30.7%. A phase change process dominated by heat conduction in a shell and tube TES unit has been studied experimentally and numerically by solving a developed analytical model by Kibria et al. [5] for a medium temperature of melting. In order to evaluate the time of solidification and melting process in terms of HTF outlet temperature, various physical and geometric parameters have been conducted. The results revealed that the inlet temperature of HTF and inner diameter of tube have a strong effect on the heat exchange rate during phase change process compared to the impact of HTF mass flow rate and tube thickness. A numerical investigation using FLUENT software 6.3.26 has been carried out by Darzi and al [6] on the melting process of N-eicosane PCM inside two cylinders in concentric and eccentric arrays, whereas the study focused about the effect of inner cylindrical tube position on the melting process, where the PCM filled in the space which is between the inner and outer cylinder. The results revealed that the natural convection heat transfer was more effective on the increase of the melting rate when the inner cylinder tube moves toward down of the centre. A numerical investigation has been carried out by Shmueli and al [7] on the melting of a phase change material (PCM) in a vertical cylindrical tube, where the comparison between a heat transfer rates from the experiments with the numerical analysis revealed a good matching, also the influence of the pressure–velocity coupling and pressure discretization has been conducted. In the present investigation, we have studied numerically based on the enthalpy formulation the heat transfer by convection mode on a shell and tube thermal energy storage unit (TES), we considered the physical model as 2Dimension and axisymmetric, whereas the Paraffin wax and water have been considered as PCM and HTF respectively, where they were analyzed by an iterative finite-volume method. We performed in this study, a numerical validation with previous numerical and experimental investigation of Kibria et al [5], on the other hand, we performed the effect of Reynolds number to evaluate the evolution of HTF outlet temperature and the time of charging and discharging process.

II. MODELE MATHEMATIQUE

The Phase Change Thermal Energy Storage (PCTES) Unit under investigation is shown in Fig 1. This unit was been used previously by Kibria et al [5]. The inner tube is made of copper. Distilled water flows through the inner tube as HTF. The phase change material « paraffin wax » fills the annular space. The outer surface of the storage unit is well insulated. The geometric parameters of the under configuration are displayed in table 1.

As the problem under examination is axisymmetric, a schematic 2-D computational domain for all investigated cases is presented in Fig 1.b. In our case, we use the same geometry considered by Kibria et al [5]. Therefore, we use the same hypothesis, boundary and initial conditions of the last authors, which are:

(i) The shell and tube system is two dimensional and axisymmetric
(ii) The external walls of the system are adiabatic.
(iii) The thickness of the inner tube wall is considered
(iv) The thermo-physical properties of HTF and PCM are constant with respect to the temperature
(v) The initial temperature of the latent thermal storage unit is uniform.
(vi) HTF flow is laminar
(vii) Natural convection inside the Paraffin wax was not considered
(viii) Forced convection utilized in HTF region.



All view of the system

Axisymetric view of the configuration

Fig.1. Latent heat storage unit

Table.1.The measures of the geometric configuration

The inner radius of tube	(Rin)	[m]	0.0054
The outer radius of tube	(Rou)	[m]	0.006
The radius of the shell	(Rsh)	[m]	0.018
The length of tube	(L)	[m]	1
The thickness of copper tube		[m]	0.0006

During the charging, the HTF flows inside the tube by inlet temperature of 88°C and a mass flow rate of 0.072 kg/min. On the other hand, during the discharging after storage, we took the heat stored using HTF passage by a temperature of 25°C and a mass flow rate of 0.07 kg/min.

The thermo-physical properties of phase change materials with water HTF which used in the present investigation are shown in Table 2. This two-dimensional problem is governed by unsteady energy and Navier-stokes equations:

The.continuity:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \qquad (1)$$

The momentum:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_j u_i) = \mu \frac{\partial^2 u_i}{\partial x_i \partial x_j} - \frac{\partial p}{\partial x_i} + S_i \qquad (2)$$

The energy:

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i}\left(k \frac{\partial T}{\partial x_i}\right) + S_h \qquad (3)$$

Where ρ is the density, k denotes the thermal conductivity, µ is the dynamic viscosity, Si and Sh are the source terms, ui is the velocity component in the i-direction, xi is a cartesian coordinate, and h is the specific enthalpy.

The source terms Si and Sh are given by:

$$S_i = -A(\gamma) u_i \frac{C(1-\gamma)^2}{\gamma^3+\varepsilon} u_i \qquad (4)$$

$$S_h = \rho L \frac{\partial \gamma}{\partial t} \qquad (5)$$

Where A(γ) is defined as the ”porosity function” which governs the momentum equation based on Carman-Kozeny relationship for flow in porous media. The function reduces the velocities gradually from a finite value of 1 in fully liquid to 0 in fully solid state within the computational cells involving phase change. The epsilon ε = 0.001 infinity avoidance constant due to division by zero and C is a constant reflecting the morphology of the melting front where $C = 10^5$.

Table.2.Thermophysical properties of PCM and HTF [A.F. Regin [8], W.R. Da Veiga [9]] in Ld: liquid state and Ls: solide state

PCM	Density [kg/m3]		Specific heat [J/kg K]		Latent heat [J/kg]	Thermal conductivity [W/ m · K]		Dynamic viscosity [N s/m2]		Melting Point [°C]
	Sd	Ld	Sd	Ld		Sd	Ld	Sd	Ld	53~61
Paraffin wax	910	790	2000	2150	190000	0.24	0.22	0.004732	0.004108	61
RT60	880	770	2660	2340	123506		0.2		0.00003705	
HTF										
Water at 25°C	997		4179			0.613		0.000855		0
Water at 88°C	967.1		4203			0.674		0.000324		

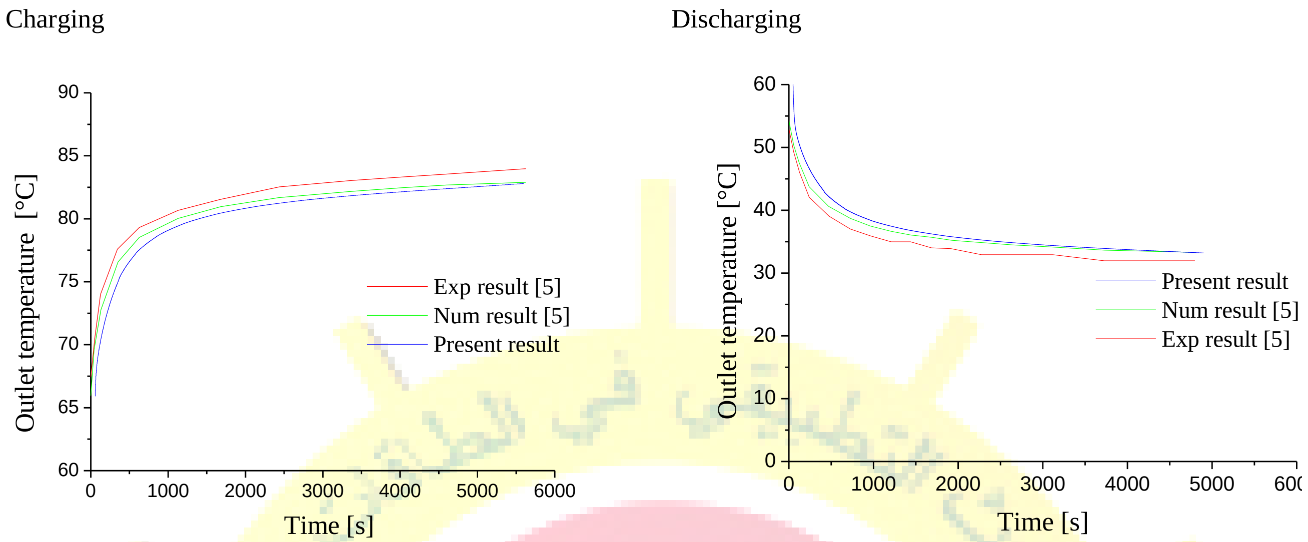


Fig. 2 Effect of tube length in charging and discharging cycle

The governing equations are solved by using the commercial code FLUENT 17 with the first order implicit scheme for the time and the second order upwind scheme for the space. Moreover, the SIMPLE algorithm is used. The local criterion for numerical convergence, i.e. the maximum relative difference between two consecutive iterations is imposed less than 10-6.

III. RESULTATS

A. Validation

The validation was performed on the evolution of HTF outlet temperature at the charging and discharging cycle. The comparison between our numerical results and analytical and experimental results of Kibria et al [5] shows a good agreement in Figure 2.

During the charging process, the system has initialized from the melting point 61°C, where we were interested on the melting process time from the beginning of the change phase. The HTF outlet temperature increase over time but it reduce compared the inlet temperature 88°C, where it came out by a temperature 83°C, this difference due to the heat absorption by melting Paraffin wax, the results show that the outlet temperature of system is close to those obtained analytically and experimentally by Kibria et al [5] where this process took about 6500s to complete the charging cycle. On the other hand, in discharging process the HTF absorbs the heat stored in the Paraffin wax whereas HTF outlet temperature has decreased and came out by a temperature 33°C until the paraffin wax becomes in the solid state at 6500 s. Our predicted temperature behaves as of Kibria et al [5]. The small discrepancy between the numerical result and those obtained experimentally is due to the simplifications considered in the numerical model. During the discharging cycle the water introduce at 25°C. The PCM start to lose the stored heat, Because of this, the heat transfer surface is decrease between the wall of tube and HTF which makes the temperature decreases gradually in different times and axial positions. We found a good agreement with the numerical results of Kibria et al [5] as shown in the figure 2.

B. PARAMETRIC STUDY

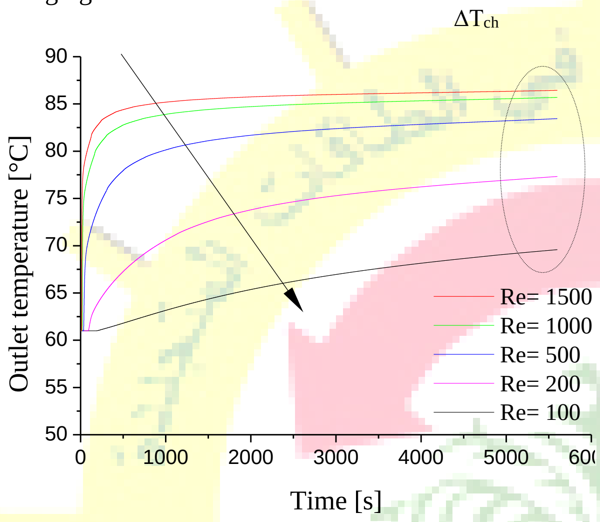
After validating our numerical model with the results of Kibria et al [5], we have made a parametric study based on the grid systems of 35x300 quadratic cells and time step of 0.05s to examine the effect of Reynolds number on the time and rate of charging and discharging process.

Effect of Reynolds number

The regime of the flow depends on the HTF properties as the viscosity and velocity, flow rates of each of the phases, also the size of the conduit. As well known the considered flow of HTF is laminar. Here we have investigated the effect of Reynolds number in the range Re= 100 to 1500.The augmentation of Reynolds number allows to decrease the solidification and melting time, and has showed in the charging cycle that a greatest value of Reynolds number has

HTF outlet temperature of 86.5 °C, while its smallest value has 69.5°C , whereas the temperature difference ΔTdis of HTF outlet temperature in discharging cycle has been about 9.6°C and 17°C of ΔTch in charging cycle as shown in Figure 3. It can be said from the figure that the fluid flow velocity in the diminution of the flow regime has small influence on the heat transfer delivered during charging and discharging cycle. In addition , we noticed that when we increase a regime of the flow, the boundary layer between the HTF flow and tube wall will be decreased, which allows to increase the heat transfer between the tube and PCM, for this the time of solidification and melting has been decreased. Further, the increase of this parameter allows to augment the enthalpy flow in the HTF region and the driving force for heat transfer in the PCM region which is a difference between the temperature levels in the solid and liquid fraction of Paraffin wax.

Charging



Discharging

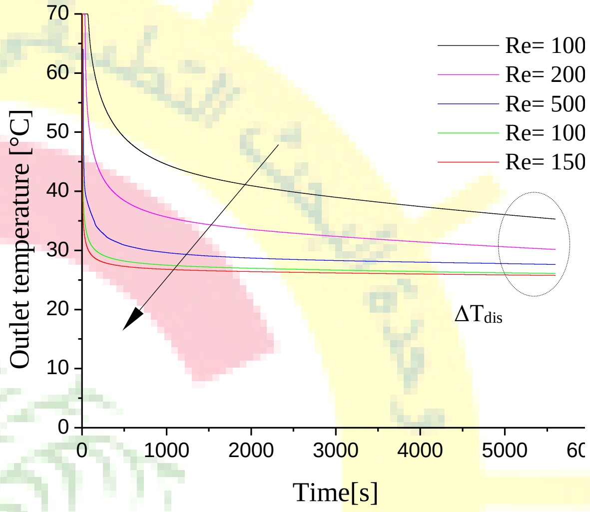


Fig. 3 Effect of Reynolds number in charging and discharging cycle

IV. CONCLUSIONS

In the present investigation we have interested in this study the examination of the physical influence on the shell and tube model in constant work conditions which have been chosen by author Kibria et al [5].

Firstly, we have validated our numerical model against the results of Kibria et al [5] such as the evolution of HTF outlet temperature in charging and discharging cycle, different HTF inlet temperature and heat transfer rate, where we have found a good matching with them. Concerning the results of our parametric study, it has shown that the Reynolds number has too much impact on the behavior of the unit in terms of time and rate storage.

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