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Experimental & CFD Analysis for the Solar Heat Pump by Using Phase Change Material



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ABSTRACT

The hot climate in Basra city requires many research to find a solution to reduce heat. The objective of the study is the possibility of building a heat pump using renewable energy. Present work addresses as a renewable energy heat pump by using paraffin wax during daytime. The experimental and the CFD model of solar collector and thermal energy storage (TES) system based on phase change materials (PCM) as a renewable heat pump system were presented. An experimental rig was constructed to conduct a practical analysis by measuring the intensity of solar radiation at different hours of the daytime. Temperatures distribution were measured with 24 type K thermocouples at different sites for the system. A numerical investigation has carried out to predict flow and heat transfer for the solar heat pump. Free convection of turbulent flow with 2-D unsteady state incompressible flow were examined. The numerical work is divided in two parts: the first part present the development of numerical models of the heating collector room while second is the numerical model of paraffin wax room. ANSYS FLUENT code 16 was applied to solve Navier Stock, energy and k- ϵ model equations by using finite volume method. The calculations of the velocity, temperatures distribution, and then the Nusselt number values with different Rayleigh number for air at both heat collector room and paraffin wax room at different daytime were reported. The results of the present work great guarantee future development of this technology for the food or agriculture industry. Maximum cooling temperature of the hot air was reached more than 20 °C. It was found that a PCM led to maximum energy savings and greater peak load at high solar intensity value.

1. INTRODUCTION

In the past years more systems combining solar thermal collectors with heat pumps had been developed and introduced to the market for both domestic hot water and space heating. Usually the thermal pump needs an external energy to ensure its continued operation. Now renewable technologies were considered as clean sources of energy and optimal use of these resource minimize environmental impacts. Also renewable energy products minimum secondary wastes and sustainable based on current and future economic. Clean energy generation becomes more and more crucial day by day due to the growing significance of environmental issues. Renewable energy sources (RES) supply 14% of the total world energy demand. Renewable energy resources will play an important role in the world's future and are also often called alternative sources of classic energy. RES includes biomass, hydropower, geothermal, solar, wind and marine energies. Among the clean energy technologies, solar energy is recognized as one of the most promising choices since it is free and provides clean and environmentally friendly energy[1]. A thermal solar collector is a device which absorbs the incoming solar radiation, converts it into heat, and transfers this heat to fluid (usually air, water, or oil) flowing through the collector. Solar collectors are usually classified into two categories according to concentration ratios: non-concentrating collectors and concentrating collectors. The non-concentrating has area of absorbing equal to the area exposed to the solar radiation, while in the state of concentrating solar collector has concave and reflexive surface to intercept and focus the beam of sun radiation and give it to a small area of reception[2].

Solar energy is available only during the day, and hence, its application requires an efficient thermal energy storage so that the excess heat collected during sunshine hours may be stored for later use during the night. Because of this limitation, researchers are required to treat this problem. This study aims at finding a solution to substitute for this weakness, that's by using the thermal storage systems for storage of energy during the time of the availability of solar energy.

Thermal energy storage (TES) is a promising technology to attenuate energy crunch and environmental problems. The storage of thermal energy is very important to many engineering applications [3]. Thermal energy storage (TES) can take the form of sensible heat storage (SHS) or latent heat storage (LHS).The latent heat thermal energy storage (LHTES) method that is suitable for solar heating and air conditioning can store much more thermal energy for a given volume. When LHS is used to store solar energy it can increase the thermal storage

efficiency. PCMs are latent heat thermal storage materials[4]. Materials that have been studied during the last 40 years are hydrated salts, paraffin waxes, fatty acids and eutectics of organic and non-organic compounds. Depending on the applications, the PCMs should first be selected based on their melting temperature. Materials that melt below 15 ° C are used for storing coolness in air conditioning applications, while materials that melt below 15 ° C are used for storing coolness in air conditioning, while materials that above 90 ° C are used for absorption refrigeration. All other materials that melt between these two temperatures can be applied in solar heating and for heat load leveling applications.

Yuwen Zhang* and Amir Faghri 1995 [5] studied a numerical solution of laminar forced convection heat transfer of a microencapsulated phase change material suspension in a circular tube with constant heat flux. **P.Lamberg and K.sire 2003 [6]** studied analytical model based on a quasi-linear, transient, thin- fin equation for melting in a semi-infinite PCM storage with an internal fin. **Darius Heim 2005 [7]** studied a comparative two solution methods of specific and latent heat transfer in building components e.g. walls, ceilings or floors numerically. This study is a contribution to the integration of latent heat storage materials to the integration of latent heat storage materials with in whole building dynamic simulation using two different approaches. **A.Carbonari et al .2005 [8]** studied numerically and experimental analyses of PCM containing sandwich panels for prefabricated walls. A finite element numerical algorithm used for the simulation of two dimensional problems of heat transfer with phase change is veracious. Four prototypes of PCM containing sandwich panels for prefabricated walls were tested (two of them used validate the numerical finite element method for design purposes) in a test-room capable of simulating several kinds of outdoor and indoor environmental conditions, comparing the numerical results with the experimental ones derived from tests carried out on two different kinds of PCM containing sandwich panels.

Heat pump is a device which pumps heat from one or more low temperature sources to one or more high temperature sinks. Heat pumps are designed to move thermal energy opposite to the direction of spontaneous heat flow by absorbing heat from a cold space and releasing it to a warmer one[9]. Heat pumps are very efficient for heating and cooling systems and the can significantly reduce the energy costs. Until now there is no researchers were interested of solar energy with PCM together into the thermal applications. The aim of this study is to benefit from the changing material phase to build a thermal pump using renewable energy through

combine the benefit of both solar energy as heat source and PCM material as a sustainable heat sink.

2.THEORETICAL ANALYSIS:

This section describes governing equations and numerical solutions by using computational fluid dynamics (CFD). Also description of the turbulence models k- ϵ and boundary condition which are used in this study.

Theoretical analysis includes two main parts only.

i-Solar collector as the source heating room with inclined finned black wall. All fins are rectangular uniform cross section and fixed at equal interval space.

ii-Paraffin wax room as sink of absorb heat .

For above system heat conduction and free convection were analysed into two dimensional at turbulent flow with different solar intensity and daytime.

To solve this problem, the following assumptions are necessary:

- (1) Solar intensity fall on the solar collector as constant heat flux at a fixed time.
- (2) The thermophysical properties of the PCM, solid and HTF (air) are independent of temperature.
- (3) The PCM is homogeneous and isotropic.
- (4) The PCM is initially in solid phase at initial temperature low than melting temperature.
- (5) The heat transfer in the PCM is controlled only by conduction.
- (6) The flow of HTF is two dimensional, incompressible, turbulent flow, no slip and steady state velocities with variable temperature with time only.
- (7) The energy dissipation of HTF is negligible.
- (8) The pressure gradient of HTF flow is in axial direction only.

Now, based on the previous assumption, the system of equations governs the velocity and temperature fields of HTF are written as follows [9]:

Continuity equation

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

Momentum equation (2)

$$\frac{\partial(\rho u_j u_i)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\mu + \mu_t) \frac{\partial u_i}{\partial x_j} \right]$$

Energy equation

$$\frac{\partial T_f}{\partial t} + u \frac{\partial T_f}{\partial x} + v \frac{\partial T_f}{\partial y} = \frac{k_f}{c_f} \left(\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial y^2} \right) \quad (3)$$

Also, the suitable and simplified governing energy equation for two dimensional, unsteady state heat transfer in the solid paraffin without heat generation is shown below:

$$\frac{\partial T_s}{\partial t} = \frac{k_s}{c_s} \left(\frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial y^2} \right) \quad (4)$$

By solving the governing equations, the discretization equations for the velocity, pressure and temperature fields can be obtained. The governing equations are solved numerically using the finite volume method (Upwind scheme) by explicit difference for time and forward difference [10]. All discretization equations, except energy equations, are solved by using the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm method. Numerical model was employed for complete results which solved with help of ANSYS FLUENT code 16.0. From the obtained pressure, velocity and temperature distributions, respectively, one can determine the axial variation of the thermal performance as average Nusselt number.

3.INITIAL &BOUNDARY CONDITIONS:

i -Initial condition: $T=T_i$ at time=0

ii- The solar collector.

Collector is inclined finned wall:

Constant heat flux, no slip wall: $u=v=0$. All fins are insulated tip $t > 0$ at.

iii- All Inlet and outlet pipes are insulated.

iv-Paraffin room:

Walls are insulated and no slip condition.

Paraffin Top surface is coupling boundary; Fluid-solid interfaces at $t > 0$.

$$\left. \begin{aligned} u = v = 0 \\ -k_f \frac{\partial T_f}{\partial y} = -k_p \frac{\partial T_p}{\partial y} \end{aligned} \right\}$$

Paraffin bottom surface is coupling boundary; Solid- fluid interfaces at $t > 0$.

$$\left. \begin{aligned} u = v = 0 \\ -k_f \frac{\partial T_f}{\partial y} = -k_p \frac{\partial T_p}{\partial y} \end{aligned} \right\}$$

THERMO-PHYSICAL PROPERTIES OF TESTED PARAFFIN WAX[10]

Parameters	Values
Density [kg/m ³]	880 (solid)/760 (liquid)
Specific heat [kJ/kg K]	2.9 (solid)/2.2 (liquid)
Thermal conductivity [W/m K]	0.2
Melting temperature [°C]	51
Latent heat [kJ/kg]	140
Thermal expansion [K-1]	0.001

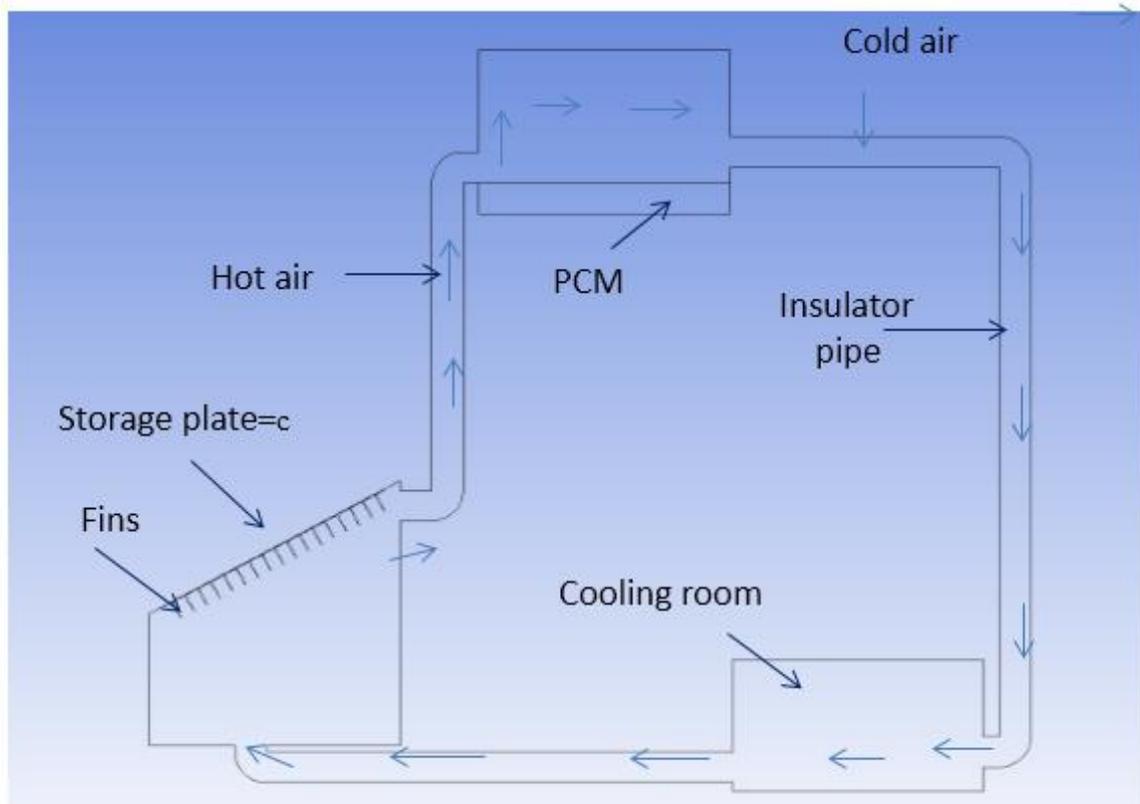


Fig. 1: Schematic diagram for the renewable heat pump.

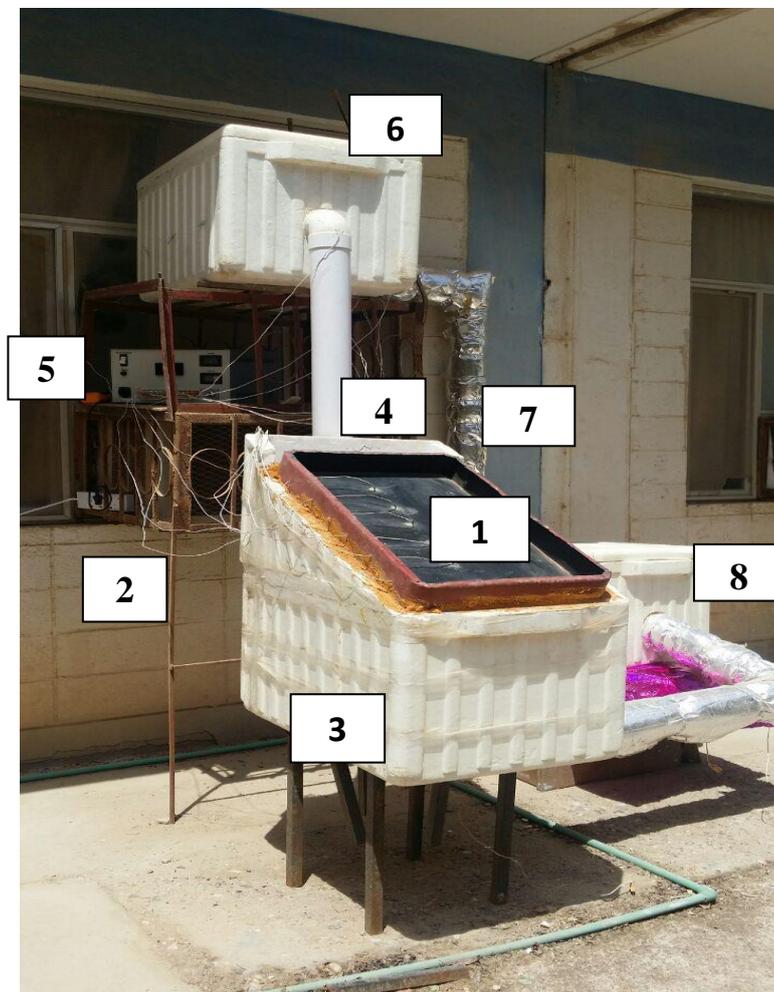
Figure 1 presents the system diagram with boundary conditions to explain the air flow direction through the closed system. Heat absorbs through the top surface of the PCM as a sensible heat and is rejected to the atmosphere from the bottom surface.

4. EXPERIMENTAL SETUP:

Photograph of the experimental setup with the solar collector connected to the PCM room is shown in figure 2. The setup consists of an insulated room which holds 25 kg of the PCM layer and an inclined solar finned flat plate collector. Three cork boxes have a capacity of $(0.79 * 0.43 * 0.5)$ m, one of them is filled with paraffin wax and fixed above the collector room. The solid PCM is encapsulated in the cork room at a height of 100mm. The collector room consists of an inclined black finned wall fixed at the top face of the second cork room with an internal length of (790) mm and a height of (860) mm, it houses the PCM room with an insulated pipe dia (100) mm and allows hot air to flow over the PCM layer, then heat transfer between the PCM and the air occurs. All pipes and rooms are insulated with 50mm of glass wool.

At (150) cm bottom side the third cooling room is placed and the closed circuit system is constructed.

24 K thermocouples are fixed at different positions of the system: nine is fixed a collector room, 9 at paraffin room and others at inlet and outlet ports of each pipe. All thermocouples are controlled by H112 heat transfer service unit as a selector for reading temperature. A pyranometer is used to measure total hemispherical radiation- beam plus diffuse- on a horizontal and inclined surfaces. This a type of actionometer is used for measuring solar irradiance and the solar radiation flux density (w/m^2) from the hemisphere above within a wavelength range $0.3 \mu m$ to $3 \mu m$.



1-Storage plate. 2-Thermocouple "K".3-sollar collector.4-pipe . 5-H112 .Heat transfer service unite (HTSU). 6-Paraffin room . 7-Insulation. 8-Cooling room.

Fig 2: Photograph view of solar heat pump with PCM.

5. RESULTS & DISCUSSION:

This section presents the results obtained from the theoretical and experimental analysis. The first part of the analysis was a convergence study for the proposed numerical code. The second part present is the experimentally results from the measured data. Then the final is the comparison between numerical and experimental results.

I-Theoretical results: Figure. 3 presents the numerical results of the air stream function through the heat pump system at $Ra=15 \times 10^{11}$. The effect of free convection is clearly appeared along the system. The variation of stream function means that there is a change in power between the intensity of radiation as a source of heat absorbed by PCM. Also figure 4 shows the same conture but for velocity magnitude of air inside heat pump. Maximum velocity is reached about 0.17 m/s through the inlet port of the paraffin room due the difference in cross area, where the pipe dia is 10 cm.

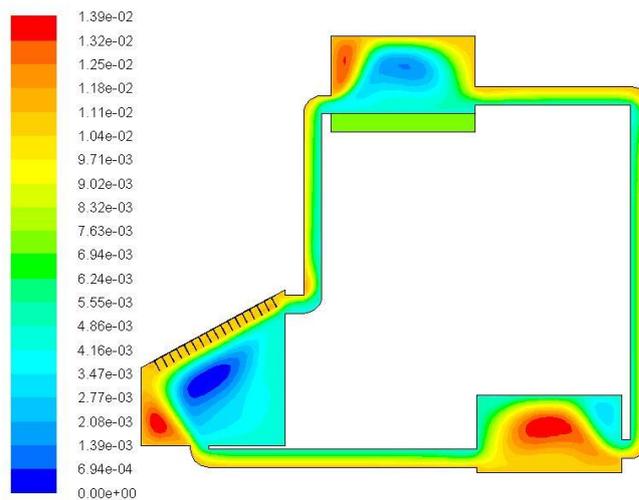


Figure 3: Conture of stream function for system during 21 May 2018 $Ra=15 \times 10^{11}$

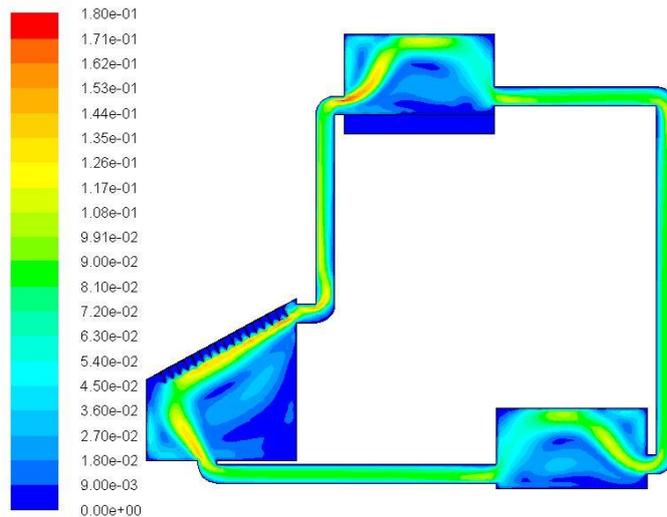


Figure 4: Contour of velocity magnitude for system during 21 May 2018 $Ra=15 \times 10^{11}$

Figure .5 shows the thermal numerical results for the inclined finned wall collector with time. Results present temperature distribution along the wall through one hour with 10 min time step. Highest values for temperature are recorded at time 12.0 AM. Theoretical prediction for solar intensity with different day in March 2018 at the climate of Basra city is presented at figure 6. In all days the highest solar intensity recorded at 12 hours, and maximum value at BASRAH during March reached to 900 w/m^2 . From the energy equation and the numerical solution the average Nusselt number of the fluid is presented at figure 7 with different inclination angle of the collector wall. At constant heat flux, high Nusselt number means low temperature difference. So at angle $\theta = 30^\circ$. low value of Nu_{avg} than angle 28° . At initial value maximum Nu_{avg} is occurred then decreased at the end time. This result is agree with the climate of Basra weather forecast.

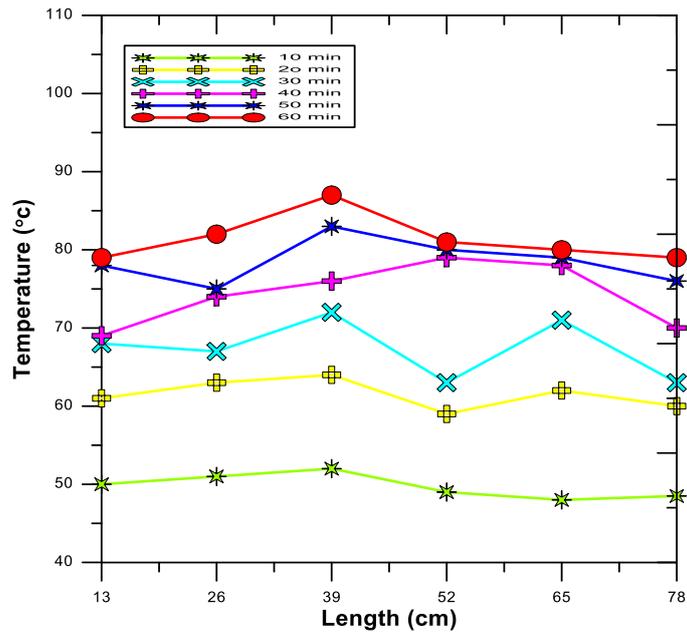


Figure 5: Variation of theoretical temperature along the collector wall with time at $\theta=30^\circ$ and $Ra=14 \times 10^{11}$, (15 March 11.0 \rightarrow 12.0 AM).

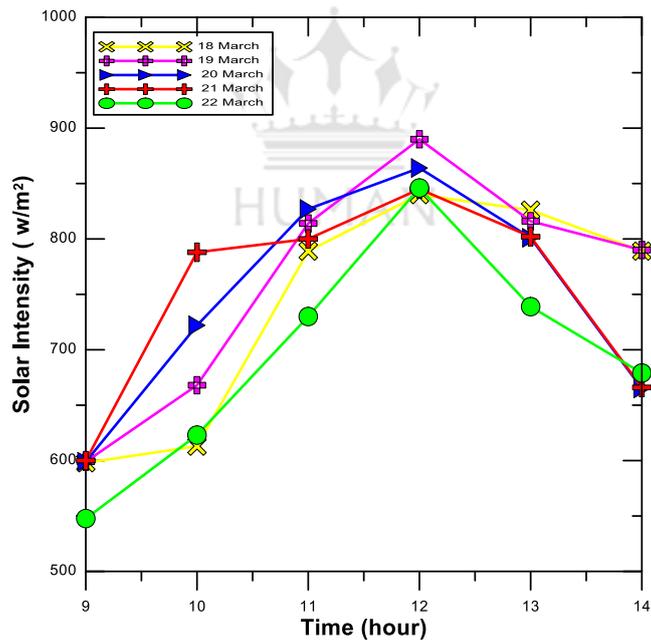


Figure 6: Theoretical Solar intensity variation at different days with time at $\theta=30^\circ$ (March 2018).

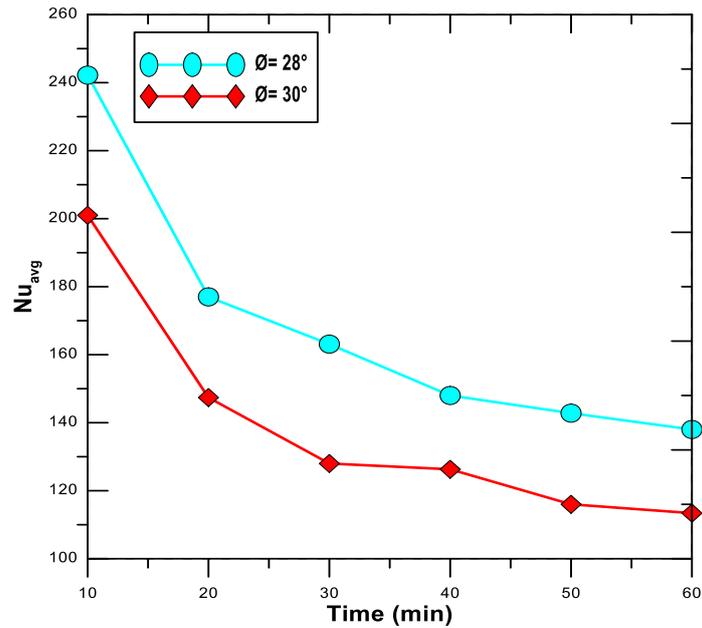


Figure 7: Theoretical average nusselt number of air inside Solar collector with different collector inclination angle (15 May 11.0→12.0 AM)

ii-Experimental results: The experimental results include the both solar intensity and local temperature reading and then calculate the fluid average Nusselt Number. Figure 8 presents the actual average solar intensity value at march and May months with different times respectively. High solar intensity was recorded at May 2018 and maximum value at time 12.0 hour with collector angle $\theta=30^\circ$. Experimentally the temperature distribution is recorded along the collector wall at $\theta=30^\circ$ and $Ra=14 \times 10^{11}$.with different time along one hour. High level of the temperatures were indicated at hour 13.0 PM as shown in figure 9.

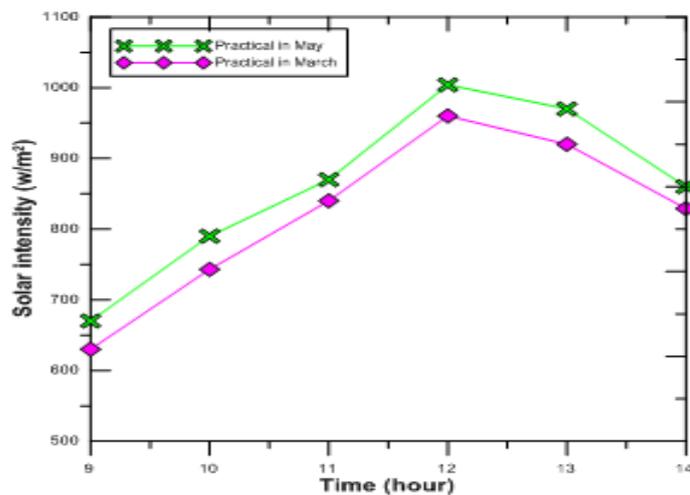


Figure 8: Practical solar intensity comparison at March and May months 2018 during daytime

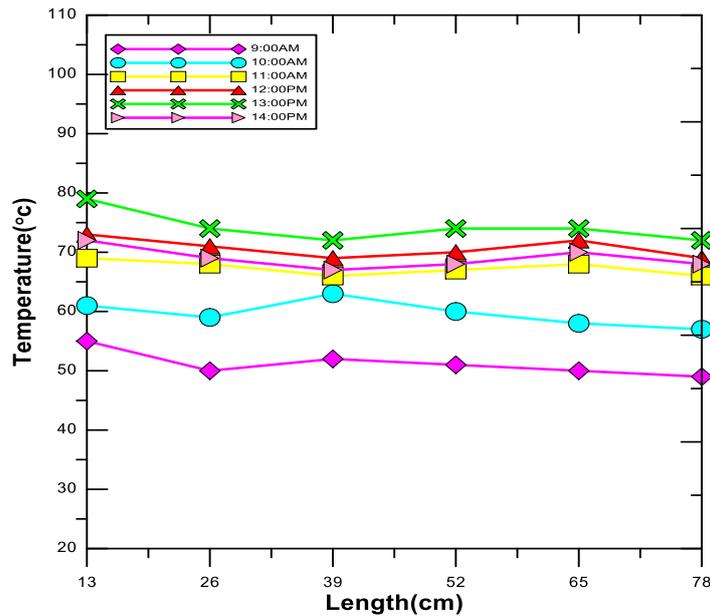


Figure 9: Variation experimental temperatures along the collector plate at $\theta=30^\circ$ and $Ra=14 \times 10^{11}$ (15 March).

Thermal analysis for the paraffin room is examined experimentally as explained in figure 10 at 10 Min interval time. Temperatures distribution along the Paraffin wall at $\theta=30^\circ$, melting point 53°C and $Ra=14 \times 10^{11}$ are recorded. For all times the paraffin wall temperature is decreased with increased length due to the heat transfer between hot air and solid paraffin. Also the sensible storage heat is absorbed by the temperature gradient and wall temperature increased with increased time. Figure .11 shows the variation of the Nu_{avg} of the fluid near Paraffin wall at $\theta=$ during 15 March with interval time equal to 10 min. Maximum heat transfer coefficient is accrued when the temperature difference decreased and heat flux variation during the day.

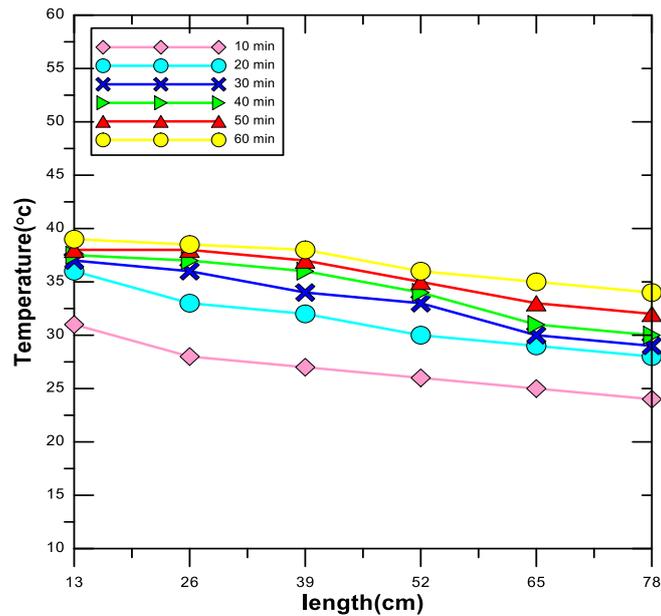


Figure10: Variation of experimental temperature along the Paraffin wall at $\theta=30^\circ$ and $Ra=14 \times 10^{11}$ (15 March 11→12 AM).

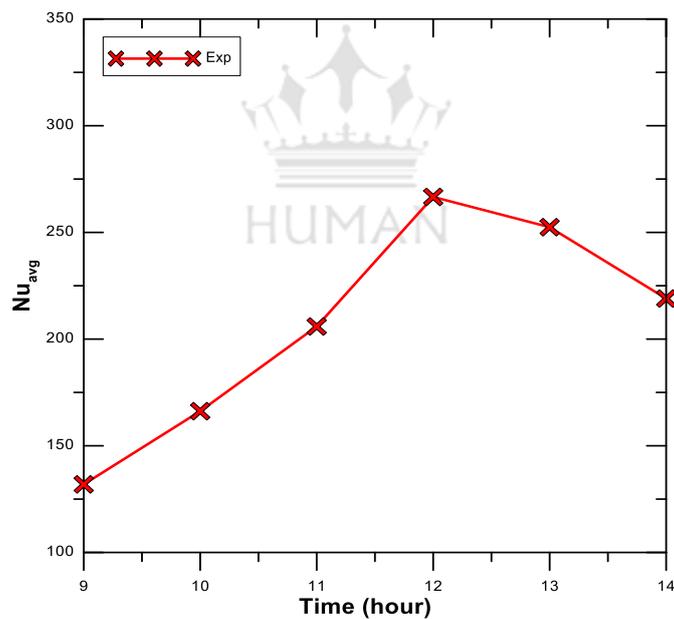


Figure 11: Experimental average nusselt variation with time into the Paraffin room at $\theta=30^\circ$, 15March

iii- Comparison results: Figure 12 presents the comparison of the Paraffin wall temperature at $\theta=30^\circ$ during 15 May (11→12 AM). The results show an increased of the average wall temperature when increasing time due to charging energy by PCM. Also it illustrates a good agreement between theoretical and experimental results. The average temperatures for collector

will explain at figure 13 during months March and May respectively. Also the average wall temperature is increased with time as explained at figure 7. The comparison show good agreement at all times. Finally the important result is presented at figure 14. Results show good performance for the heat pump by using PCM together with solar energy. The difference between the exit hot air from the collector and the exit the cold air from the cooling room more than 20 °C at the climate of Basra city. Also good agreement between CFD and experimental results.

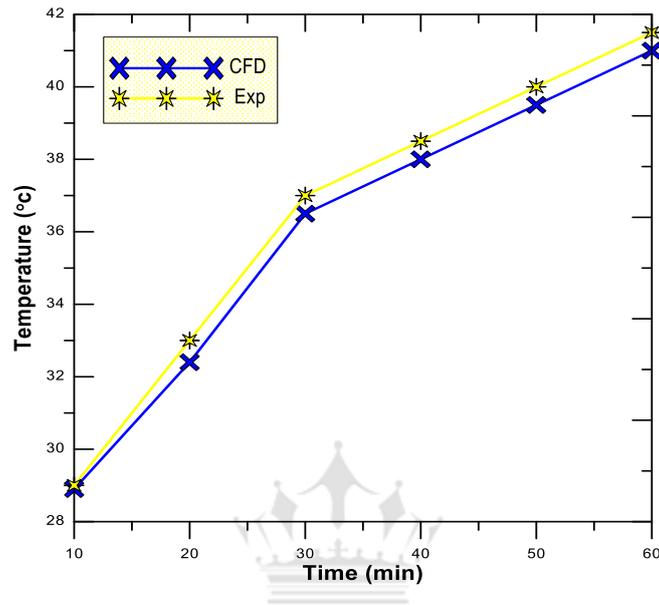


Figure 12: Comparison of the Paraffin wall temperature at $\theta = 30^\circ$, and 15 May (11→12 AM)

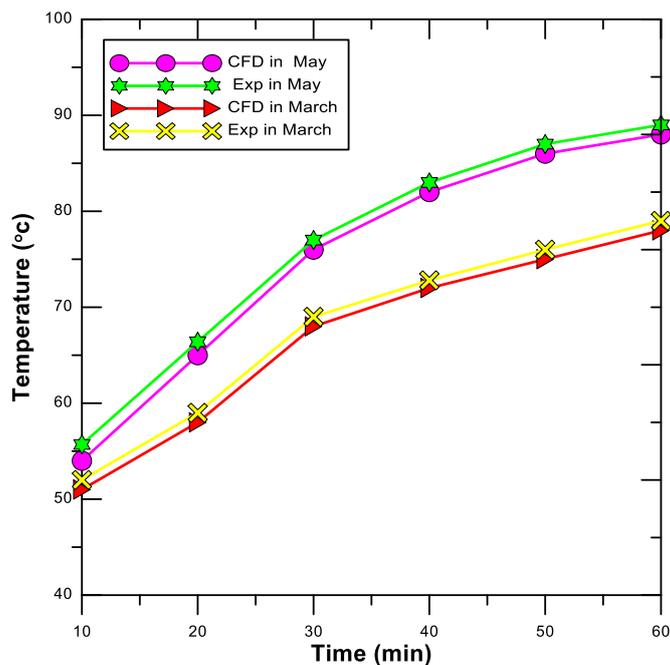


Figure 13: Comparison of the collector wall temperature at $\theta = 30^\circ$ and 11.0→12.0 AM.

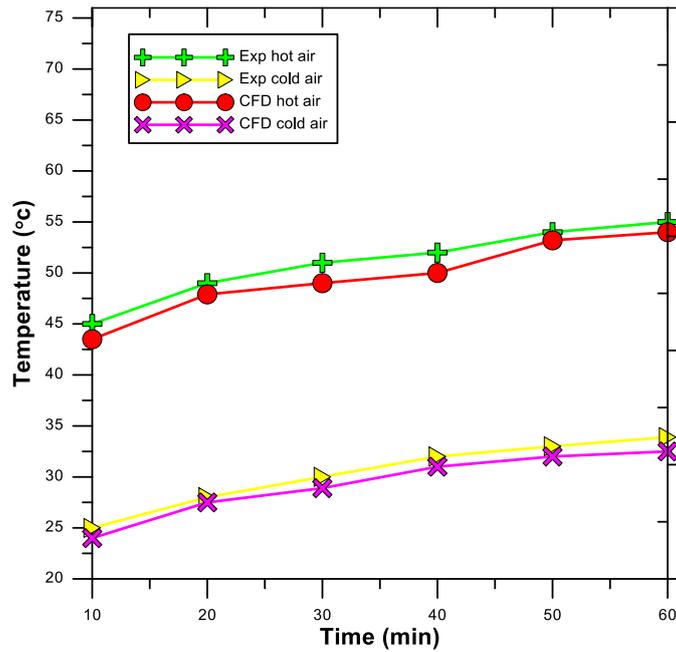


Figure 14: Comparison for hot air exit and cold air exit temperature at March, $\theta=30^\circ$, 11.0→12.0AM .

6. CONCLUSION:

Energy storage plays an important roles in conserving available energy and improving the solar energy applications. This work is based on two parts: the first part concerns the development of numerical models for simulating the transient behavior of the –Solar-PCM energy, to predict the energy balance in space and time and the overall performances and their application to several test cases. The second part concerns the design and the implementation of a test rig specifically built for experimental investigation of heat storage devices. The renewable heat pump will be used in many fields such as protected agriculture, poultry fields and birds that need large cooling areas. This work will be the beginning of the development of incubators and protected areas that require special climatic conditions.

NOMENCLATURE

ρ	Density	k	Turbulent energy.
β	Thermal expansion	ϵ	Turbulent dissipation energy.
T_m	Melting temperature	u,v	Average Fluid velocity.
T_p	PCM temperature	\emptyset	Collector inclination angle.
T_f	fluid temperature.	CFD	Computation fluid dynamics
PCM	Phase change material.	C	Specific heat
T_s	Solid temperature	k	Thermal conductivity
g	Gravity	μ_t	Turbulent dynamic viscosity
t	Time	Exp	Experiment
P	Phase change	f	Fluid

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