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MATHEMATİCAL MODELING OF A FLAT PLATE SOLAR COLLECTOR WİTH PHASE CHANGE MATERİAL

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Abstract: Solar energy is the most promising heat sources for meeting energy demand without having negative impact on the environment. Hence the role it plays in sustainable development cannot be quantified. Solar energy is however intermittent in nature and time dependent energy source. The objective of this work was to develop a mathematical model to evaluate the thermal behavior of a flat plate solar collector integrated with a phase change material (PCM).This PCM acts as a heat source for the solar heating system when the intensity of the solar radiation is low or no longer active. The energy balance equations for the flat-plate heating components of the collector and PCM were formulated numerically. The model was used to investigate the effect of inlet water temperature, water mass flow rate, outlet water temperature and the melt fraction during charging and discharging modes at each of the respective nodes. A comparison was made with a collector with and without PCM. The mathematical model developed for the flat-plate with PCM was based upon the conservation and heat transfer equations to predict the thermal behavior of integrated phase change material in solar collector during thermal storage.
Keywords: Heat storage; Flat plate collector; Mathematical model; phase change material; experimental validation

1. INTRODUCTION
The problems emanating with the world's dependence on fossil fuels continues to foster the public's desire to pursue clean, renewable sources of energy. In both advanced countries and developing countries Due to environmental issues and limited fossil fuel resources, more priority is being given to renewable energy sources [1]. The energy from the sun is one form of renewable energy source. It can be used for water heating in hot water systems, swimming pools as well as a supporting energy sources for central heating installations.

The energy of the solar radiation is in this case converted to heat with the use of solar panel. At present the most often used solar collectors are liquid flat-plate collectors working either in parallel or serpentine tube arrangement as well as the vacuum based structures. The flat plate collector's supplies heating below 80⁰C when not integrated with phase change materials for energy storage and conservation [2], in reality indicative temperature range of operating fluid in flat plate collectors is between the ranges of 30-65⁰C [3].The efficiency index higher than 0.5 is typical for recently available flat plate collectors [4]. However, [5] carried out studies on a solar water heater storage collector system. This system consist of a flat plate collector made of galvanized steel tubes attached to an aluminum plate with MAXORB selective surface and a double walled 100 litres capacity galvanized steel storage tank. Glass wool insulation was however used to insulate the storage tank. The storage tank was located up gradient from the collector. This system solely relies on natural circulation to drive the hot water into the overhead storage tank and allows for cold water to re-circulate to the collector just as the normal return and supply pipes. This researcher discovered that the system can generate about 50.6⁰C water at 4:00pm and 41.6⁰C water the next morning. The overall efficiency of this system was calculated to be about 47%. [6] Also, worked on a solar storage collector system in Algeria. This system employed a copper plate absorber with steel connector pipes and storage tank, and a header-riser flat collector.

This system relied on natural circulation to store hot water in a tank located up gradient from the collector. The maximum temperature was observed to be 53⁰C with an initial temperature of 17⁰C around 7:00am. A maximum flow rate occurred around 1:00pm. [7] Investigated a technique to enhance the thermal performance of a flat-plate solar collector by installing two storage parts within the collector's frame. The two storage parts were made of galvanized steel sheet and filled by paraffin wax and water in the upper and lower parts, respectively. The experiments were conducted in December in Turkey. It was found that the proposed design significantly improved the collector heat transfer characteristics in terms of absorptivity and heat transfer coefficient. The system reduces the cost by almost 41.6% as compared with the conventional solar collector. [8] Developed a mathematical and experimental model for the charging process of a solar collector storage system integrated with salt hydrate as a PCM. They performed their experimental trials under the winter weather of Israel. The heat energy stored was discharged to cold water flowing in a finned heat exchanger (HX) located inside a layer of stationary heat transfer fluid (HTF).In the mathematical model, the researchers used the enthalpy-based finite difference method and ignored the effect of convection. They assumed one-dimensional transient heat conduction in the PCM and stationary heat transfer layer. The proposed model showed high accurate validation with the experimental PCM temperature measurements. However, the neglect of the convection heats transfer in the stationary heat transfer reduced the accuracy of their mathematical predictions. [9] Proposed a comparative experimental study, under a typical sunny day in Malaysia, to investigate the possibility of enhancing the performance of a flat-plate solar collector by integrating paraffin wax with a melting temperature of 60.45⁰C directly in contact with the collector's absorber plate. The proposed system was studied and compared with the conventional collector at three different inclination angles including 10°, 20°, and 30° and constant water mass flow rate of 0.5 kg/min. The results showed that the integration of PCM increased the thermal absorption to 71.15% and reduced the thermal heat losses to be lower than 4.34 W/m² K. The proposed collector achieved an efficiency of 52% at an inclination angle of 10°, which was better by 23% over the conventional collector.[10] proposed a theoretical model based on a one phase Stefan problem to investigate the thermal performance of integrating PCM to the manifold of an evacuated tube heat pipe solar collector system. By comparing the results with the baseline system of the evacuated tube heat pipe solar collector, it was revealed that the usable hot water volume and thermal efficiency of the baseline system significantly decrease with the increment in the water volume flow rate from 50 to 80 litres per hour. The usable volume and the thermal efficiency almost remain the same in the innovative system. This shows the ability of proposed system to provide abundant energy with independence on the operation conditions owing to the stored energy in the PCM.

2. MATERIALS AND METHODS

— Materials and description of the flat plate collector system

A flat plate collector in general, consists of a transparent cover, fluid, heat insulation, phase change materials, absorber plate, and collector casing, Figure 1 shows how the flat plate collector look likes. In line with the principle of operation, the sunlight passing through the glazing cover strikes the absorber plate and the solar radiation in this case is converted into usable heat and transferred via its inner surface to the fluid passing through the respective nodes of the collector.
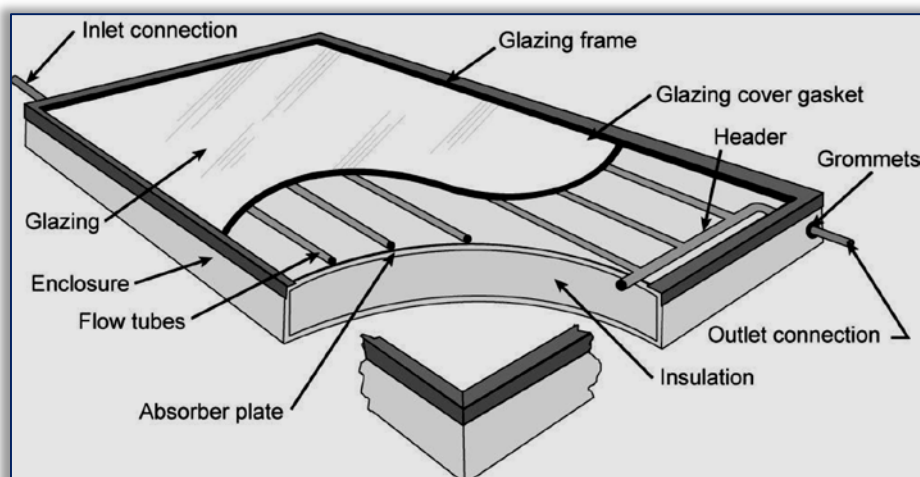

Figure 1. Cross sections of a flat plate collector [11]

Subsequently, the fluid carries the energy away from the collector for a direct use or storage. The absorber plate is made from a thin (flat or grooved) high thermal conductivity metal sheet which could be steel, aluminum or cooper. In order to maximize efficiency of a solar collector, the surface of the absorber plate is painted with black colour pigment because of it high absorptivity property it processes. The flow tubes in the collector are an integral part of the absorber plate; these tubes are connected to the header tubes at both ends and either of which could serve as a supply or return pipe (inlet, outlet). Some of the thermal energy is transferred via convection to the transfer fluid and the other is transferred by both conduction and convection to the phase change material incorporating below the absorber. When the absorbed temperature by the flat plate collector becomes higher than that of the PCM, the heat is first stored as a sensible heat until the PCM reaches its melting temperature. At this point, the PCM starts to melt and after complete melting, the released heat is stored back in the molten PCM as a sensible heat. When the sun is no longer active, all the solar components starts to cool down and the PCM at this point will serve as the main heat source for the flat plate solar system. The PCM releases energy to the absorber and from the latter to the transfer fluid until the PCM completely return back to its initial solid state. The transparent cover made used of in this system is a transparent glass material which helps in reducing convection heat losses from the absorber plate. The conduction heat losses are on the other hand minimised by properly insulating layer the upper, bottom and sides of the collector respectively. A wooden collector casing is used for housing the collector. The whole structure of the collector was sealed using silicon gun and body filler in order to bring about a total reduction in heat losses and also serving as a shield against dirt or moisture.

— **Mathematical model of a flat plate collector with PCM**

A schematic system under study is depicted in Figure 2.The system consists of a thermal solar panel, thermal tank, eutectic phase change materials, piping as well as control valves. The eutectic salt mixture has a good thermal energy storage density and low thermal conductivity.
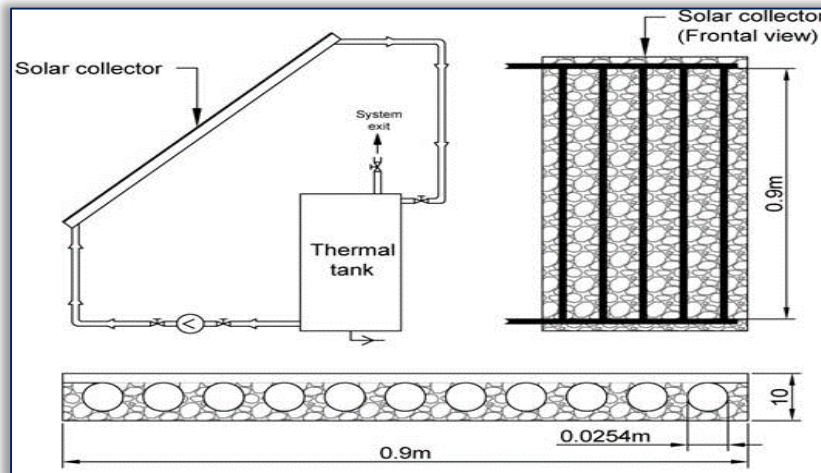

Figure 2. Schematic of a solar thermal system [4]

The PCM was then embedded in the black colour pigment and the pigment was used applied to the solar panel and as well integrated into the heat exchanger in the solar panel as shown in Figure 3.
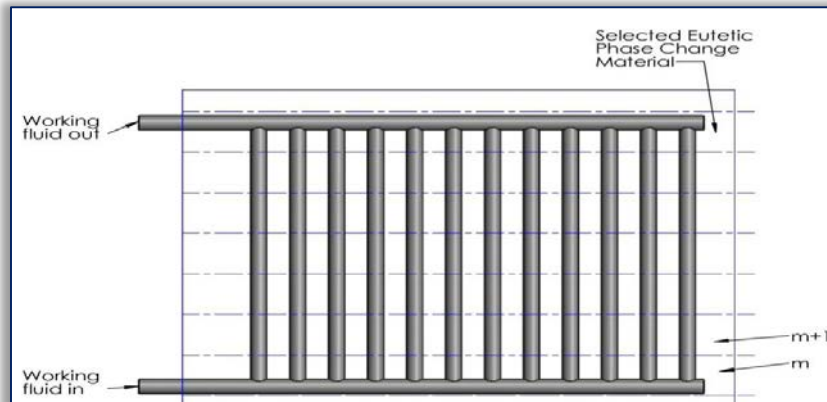

Figure 3. Solar tube heat exchanger finite-difference formulation

In order to write the energy conservation and heat transfer equations of the eutectic salt, the heat exchanger should be considered at each of the respective node because of the non-uniformly temperature distribution across each section. However, the model proposed is based on the following seven assumptions: The thermo physical properties of the PCM are independent of temperature, but different for solid and liquid phases, the heat transfer fluid is incompressible and it can be considered as a Newtonian fluid, the PCM is in perfect contact with the absorber, the PCM is homogenous and isotropic, the inlet velocity and inlet temperature of the heat transfer fluid are constant, no thermal expansion during melting process and the heat transfer in the direction of the transfer fluid is ignored. The mathematical modeling of the heat transfer processes of a flat plate solar collector with PCM consist of both the solar radiation which is the source of the solar energy and the solar collector. The solar collector is further divided into seven sections has follows: The glass cover, absorber plate, air gap, transfer fluid, collector efficiency factor, collector heat removal factor and phase change materials.

— Global Solar Radiation

Global solar radiation is the total amount of solar energy received by the earth's surface, usually expressed as W/m². About 99 percent of global solar radiation has wavelengths between 300 and 3000 nm. This includes ultraviolet (300-400 nm), visible (400-700 nm), and infrared (700-3000 nm) radiation. Perrin Brinchambaut [12] proposed a theoretical model based on the following correlations. The solar irradiance is calculated as:

$$I = A\cos\theta_1 \exp\left(-\frac{1}{B\sin(h+2)}\right) \tag{1}$$

where h is the sun's height and θ_1 is the direct incident angle.
The diffuse irradiance is expressed as

$$D = \left(\left(\frac{1+\cos\beta}{2}\right)D_h += \left(\frac{1-\cos\beta}{2}\right)\rho G_h\right) \tag{2}$$

where β the tilt is angle of the collector and ρ is the albedo
D_h and ρG_h are further expressed as:

$$D_h = A'(\sin(h))^{0.4} \tag{3}$$

$$G_h = A''(\sin(h))^{B''} \tag{4}$$

The constants B, A', A'' and B'' depends on atmospheric state with time.
The energy balance equations for all of the seven components of the solar collectors mentioned earlier with temperature dependent equations is obtained for each of the components.

» **Glass covering**

According to Zueva and Magiera [14], the glass covering can be thus be written as:

$$c_g\rho_g V_g \frac{dT_g}{dt} = \left(h_{g.am}(T_{am} - T_g) + h_{r1}(T_{ab} - T_g) + h_{c1}(T_a - T_g) + aG\right)p\Delta Z \tag{5}$$

where: c = specific heat, ρ= density, V = volume, T = temperature, t = time, h = heat transfer coefficient, a = absorption coefficient, G = heat flux of solar radiation, p = tube pitch, Δz = spatial size of control volume
Subscripts notation: am = ambient, g = glass cover, a = air gap, ab = absorber, r = radiation c = convection
According to Duffie and Beckman [15], the heat transfer coefficients by convection are calculated respectively as:

$$h_{cv,am} = 3.9 v_{wind} + 5.62 \tag{6}$$

$$h_{cv,a} = \frac{Nu\lambda_a}{e_a} \tag{7}$$

v_{wind}, λ_a, e_a are the wind velocity, air thermal conductivity and the air gap thickness respectively.
The Nusselt number is calculated as follows:

$$Nu = \left(0.006 - 0.017\left(\frac{\beta}{90}\right)\right) \tag{8}$$

Gr is the Grashoof number expressed as:

$$Gr = g\left(\frac{(T_{as} - T_c)e_a{}^3}{V^2 T_a}\right) \tag{9}$$

The heat transfer coefficient by radiation is expressed as:

$$h_{r,c-as} = e_c\, s\, (T_c^2 + T_{as}^2)(T_c + T_{as}) \tag{10}$$

where T_{as} is the temperature of the air- space

The heat transfer coefficient by radiation on the absorber is expressed as:

$$h_{r,c-ab} = s \frac{(T_c^2 + T_{ab}^2)(T_c + T_{ab})}{\frac{1}{e_c} + \frac{1}{e_{ab}}} \qquad (11)$$

According to Duffie and Beckman [15] T_{as} is expressed as:

$$T_{as} = 0.0553 T_{am}^{\frac{3}{2}} \qquad (12)$$

» **The absorber plate**

According to Shiv et al, [16] the transient thermo-physical properties of the absorber material are considered when a heat energy balance is to be applied to the absorber zone. The solar irradiance on the absorber zone in the solar collector control volume, the radiation between the absorber and the glass cover, the conduction between the absorber and the insulation zone and the heat transfers by convection with the fluid flow need to put into consideration. The following relation gives:

$$C_{ab}(T_{ab})\rho_{ab}(T_{ab})V_{ab}\frac{dT_{ab}}{dt} =$$
$$\left[G(\tau_a) + h_{r1}(T_g - T_{ab}) + h_{c1}(T_a - T_{ab}) + \frac{k_i}{\delta_i}(T_i - T_{ab})\right] p\Delta Z + \pi d_{in} h_f \Delta Z (T_f - T_{ab}) \qquad (13)$$

where: (τ_a) = Effective transmittance absorption coefficient, k = thermal conductivity, δ = thickness, d = diameter, Subscripts: i = insulation, f = working fluid, in = inner.

» **Air gap of the flat plate collector**

$$\rho_a V_a C_a \frac{dT_a}{dt} = h_{cv,c-a}S_c(T_{c-} T_a) + h_{cv,ab-a}S_{ab}(T_{ab-} T_a) + U_{loss,e}S_{a,e}(T_{am-} T_a) \qquad (14)$$

According to Ahmad [17] the heat exchange coefficient by convection can be estimated using (7)

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \qquad (15)$$

Based on Incropera, et al., [18] the bottom loss and side loss coefficient of the collector is given as:

$$U_{loss,b} = \frac{1}{\frac{e_{ins,b}}{\lambda_{ins,b}} + \frac{1}{h_{cv,wind}}} , U_{loss,s} = \frac{1}{\frac{e_{ins,s}}{\lambda_{ins,s}} + \frac{1}{h_{cv,wind}}} \qquad (16)$$

The thermal heat exchange with the phase change materials during charging and discharging modes are expressed as follows:

$$Q_{ab,PCM} = -\lambda_{PCM,i}S_{PCM}\frac{dT_{PCM,i}}{dx} \qquad (17)$$

$$Q_{ab,PCM} = \lambda_{PCM,i}S_{PCM}\frac{dT_{PCM,i}}{dx} \qquad (18)$$

where i = solid when the phase change material is in the solid state and i = liquid when the phase change material is in the liquid state.

» **Heat transfer fluid**

According to Klein, et al.[19] the heat exchange coefficient of the collector can be determine as putting the tube cross section of the solar collector into consideration A_{htf} the conservation energy equation for the HTF becomes

$$\rho_{htf}c_{htf}\frac{\partial T_{htf}}{\partial t} = -\frac{c_{htf}m_{htf}}{A_{htf}}\frac{\partial T_{htf}}{\partial x} + \frac{hpD_i}{A_{htf}}(T_{w-} T_{htf}) \qquad (19)$$

The thermal resistance of the wall is assumed to be negligible, the conservation energy equation of the wall now becomes:

$$\rho_w c_w \frac{\partial T_w}{\partial t} = \frac{hpD}{A_w}(T_{htf} - T_w) + \frac{1}{s_w}\left(\frac{k_w A_w^1}{A_w} + \frac{k_{pcm}A_{pcm}^1}{A_w}\right)(T_{pcm-} T_w) \qquad (20)$$

where: A_w = Cross sectional area of the wall, k_w and k_{pcm} are the thermal conductivity of the wall and the PCM respectively

The heat transfer conduction within the PCM in the axial direction is negligible, therefore the conservation energy equation in the first cell of the PCM alternate to the wall becomes:

$$\rho_{pcm}\frac{\partial H_{pcm}}{\partial t} = \frac{1}{s_w}\left(\frac{k_w A_w^1}{A_w} + \frac{k_{pcm}A_{pcm}^1}{A_w}\right)(T_{pcm-} T_w) + \frac{1}{s_w}\frac{k_{pcm}}{A_{pcm}}\left(\frac{H_{pcm}^{J+1}}{A_w} - \frac{H_{pcm}^j}{A_w}\right) \qquad (21)$$

The energy conservation equation for the generic cell of the PCM becomes:

$$\rho_{pcm}\frac{\partial H_{pcm}}{\partial t} = \frac{k_{pcm}}{c_{pcm}}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial H_{pcm}}{\partial r}\right)\right) \qquad (22)$$

» **Phase change materials**

This process consist of both the charging and the discharging when the PCM is in the solid state, solid –liquid and liquid state

— Charging phase:

During this phase the water mass flow rate can be calculated from the heat released through solar radiation.

Mass flow rate of water is expressed as:

$$m_w = \frac{GA_{collectors}}{1000 \times Cp_w \times \Delta T_w \times n} \tag{23}$$

where: m_w, Water mass flow rate($\frac{kg}{s}$), G, Radiation($\frac{W}{m2}$), A, Area of the collector (m^2), Cp_w, Specific heat of water($\frac{kJ}{kgK}$), ΔT_w, the heat transfer fluid temperature difference and n,number of tubes in the solar collector.

According to Laouadi and Lucroix[20] the finite-difference formulation of the time derivative can be written for the solid phase as follows;

  » **Solid phase:**

$$T_{PCM_{m+1}} = T_{PCM_m} + \frac{m_w C_{pw} \Delta T_w}{\rho_s V_{PCM} Cp_s} \Delta t \tag{24}$$

where: T_{PCM_m}, Temperature of PCM at m element(°C), ρ_s, Density of PCM at solid phase($\frac{kg}{m^3}$), V_{PCM}, PCM volume (m^3), Cp_s, PCM specific heat at solid phase ($\frac{kJ}{kgK}$), Δt, time differential (s).

The same finite-difference formulation of the time derivative can be applied to the mushy and liquid phase as follows;

$$\gamma_{m+1} = \gamma_m + \frac{m_w C_{pw} \Delta T_{w,mushy}}{\rho_L V_{PCM} h_L} \Delta t \tag{25}$$

Heat along the tubes of the collector according to Senthilkumar, et al. [21] is expressed as,

$$Q_{tube} = \rho_L V_{PCM} h_L \gamma_m \Delta t \tag{26}$$

where: γ_m, Liquid fraction at elementh_L, PCM latent heat$\left(\frac{kJ}{kg}\right)$, ρ_L, Density of PCM at liquid phase($\frac{kg}{m^3}$),Q_{tube}, Heat along each tube(kJ),

The finite-difference formulation of the time derivative can be applied to the liquid PCM as follows;

$$T_{PCM_{m+1}} = T_{PCM_m} + \frac{m_w C_{pw} \Delta T_w}{\rho_L V_{PCM} Cp_L} \Delta t \tag{27}$$

  » **Discharging phase**

This is the stage when the phase change material experiences phase change from liquid to mushy and solid. The rate of useful energy gain in this stage becomes less than the rate of the thermal losses, at this point the PCM starts to solidify. The water mass flow rate of heat transfer fluid during the discharge process can be calculated as follows;

$$m_w = \frac{Q_{charging}}{Cp_w \times \Delta T_w \times n} \tag{28}$$

The total heat absorbed during the charging phase by the phase change materials in all of the three stages is expressed as:

$$Q_{charging} = m_{PCM}(Cp_s \Delta T_s + h_L + Cp_L \Delta T_L) \times n \tag{29}$$

where: m_{PCM} is the mass of the phase change material per finite different element.

3. RESULTS AND DISCUSSION

The systems of equation (1) through (29) has been numerically solved for using the finite difference scheme for the adopted phase change materials (eutectic metallic salts) and the results obtained during the course of the experiment are plotted as shown in Figure 4 to 7. Global, ambient condition, glass condition, water inlet conditions, heat transfer fluid temperature with respect to time, solar insolation and water outlet condition.

Figure 4 presents the time variation of solar insolation (W/m²) measured at the site where the research was conducted. It is clear that the intensity of radiation depends upon the hour of the day and the period of the year. From the graph it can be deduced that the solar irradiance at 9:30 Am was observed to be 690W/m² through the aid of an XM 1400 dual transmission meter and the intensity kept on increasing with time till it gets to its peak at 4:00 pm. At this time 1050W/m² was recorded which can be said to be progressive with respect to the result obtained in heating the water. A decline was observed at some minutes past 4:00pm and at 4:30pm. 990W/m² was recorded which was s a negative 60 W/m² compared to the previous reading. At about 7:00pm the

graph shows an irradiance of 0 W/m² down to the hour of 8:00pm. The graph curve however, defines solar irradiation as a measure of solar irradiance with time.
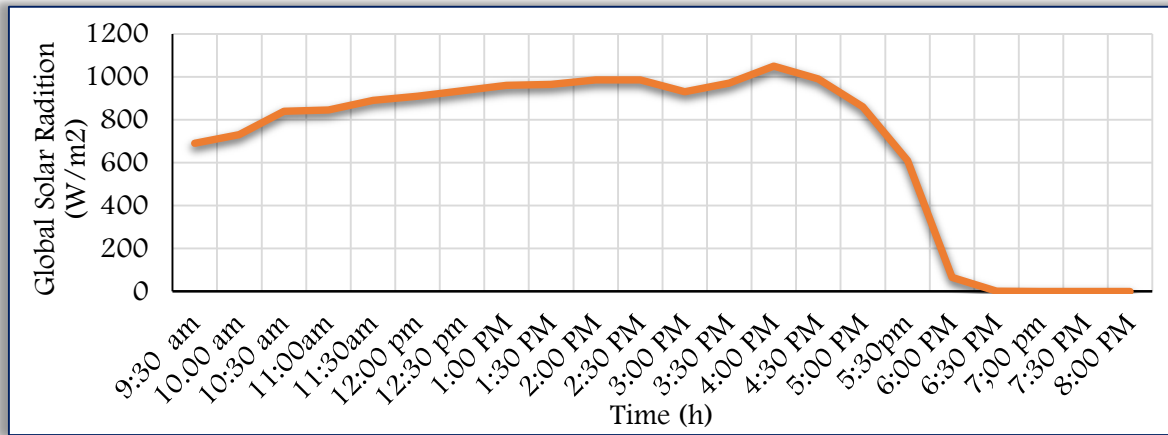

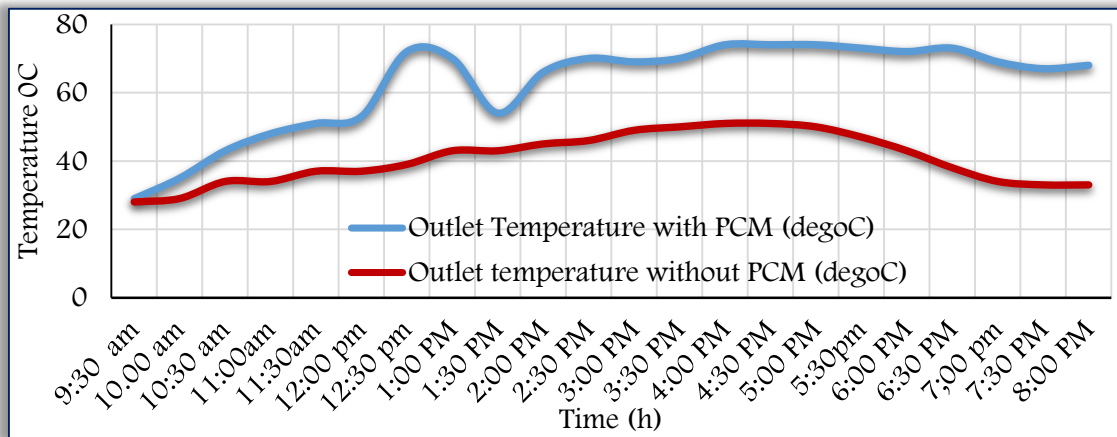Figure 4. Global solar radiation against time

Figure 5. Hourly variations of outlet water temperature without and with PCM

Figure 5 shows the temperature variations of outlet water temperature without and with PCM as a function of time. For both cases, the temperatures increase with time till it reaches a maximum values and then decreases afterwards. The highest water temperatures reached for the collector without and with a phase change material are approximately 74 and 51⁰C, respectively. This was as a result in the rise of solar intensity experience during that day till 4.30 pm. It was observed that for the case without PCM, all the absorbed solar radiations are used to heat the transfer fluid, contrary to the case where the PCM is used.
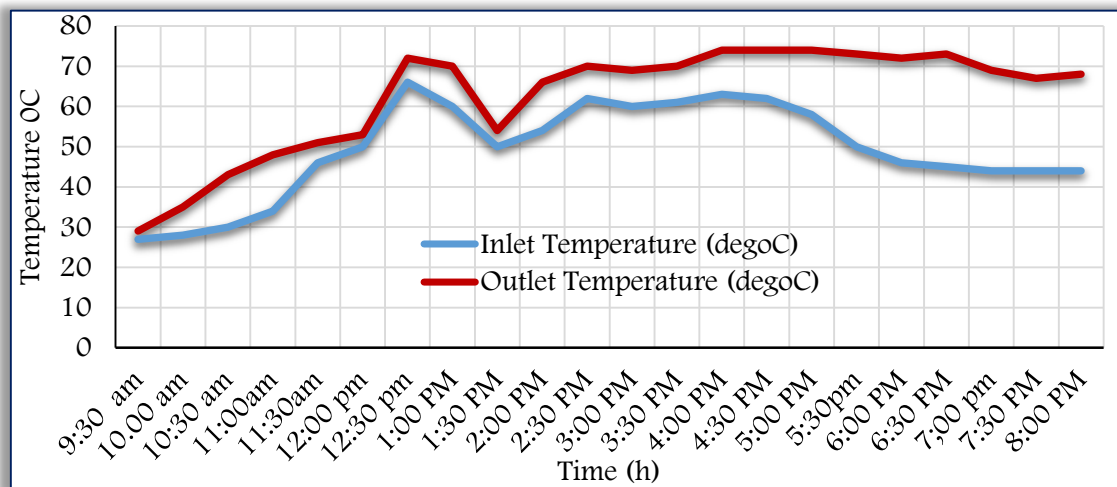

Figure 6. Effect of inlet temperature on outlet water temperature

The effect of inlet water temperature on its outlet temperature was shown in Figure 7. The maximum inlet temperature of 63⁰C was observed around 4.pm. The temperature however is not

steady, it fluctuates upward and backward, this was as a result of non-uniform temperature distribution at each of the respective nodes of the collector. An increase in inlet temperature leads to a rise in outlet water temperature. A maximum steady temperature of 74^0C was recorded at the outlet. The rise is mostly enhanced at higher inlet water temperature.
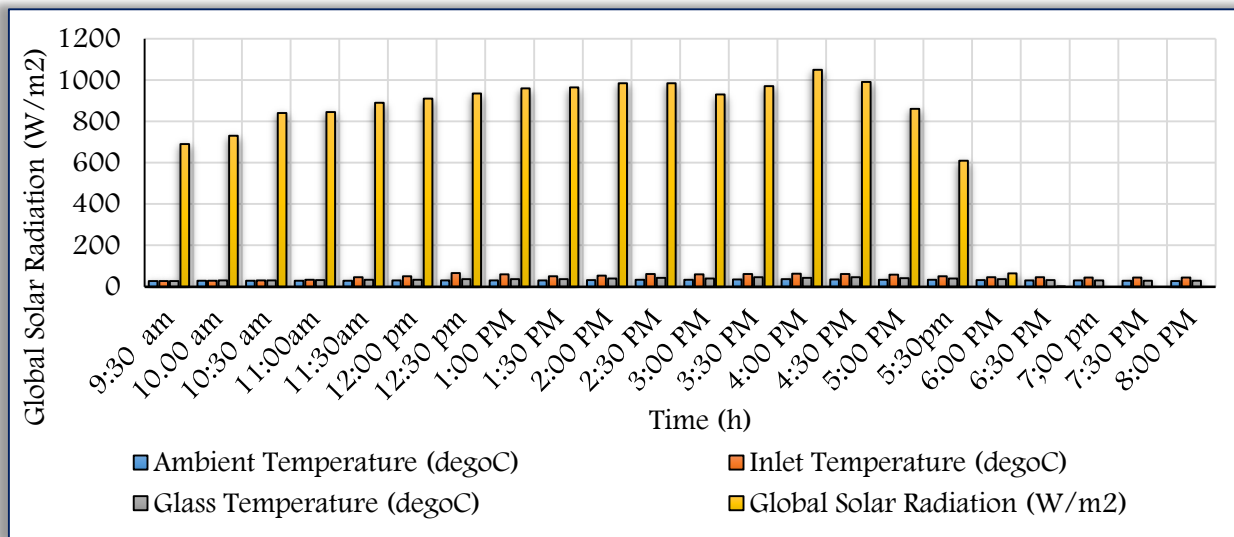

Figure 7. Ambient temperature, Inlet temperature and Glass temperature against Global solar radiation.
Figure 7 shows the global solar radiation against ambient, inlet, and glass temperature parameters. The temperature parameters increase with global solar radiation with respect to time. However, a maximum temperature of 36^0C and 63^0C was recorded for both ambient and inlet temperature around 4pm, while the glass temperature was at its peak around 3:30 pm with a temperature of 46^0C. The rise in all the temperature parameters was enhanced by global solar radiation with respect to time. The result of the formulation of the adopted PCM is shown in the Table below, this comprises the specification and composition of some selected eutectic PCM.

Table 1: Formulation of the PCM

Material	Composition (g)	Melting Point (^{0}C)	Latent heat (kJ/kg)
$LiNO_3+NH_4NO_3+NaNO_3$	2.5+6.5+1	79.5	112
$LiNO_3+NH_4NO_3+HNO_3$	1.77+3.9+1	80.5	114
$LiNO_3+NH_4NO_3+NH_4Cl$	5.4+13.6+1	81.4	109
$LiNO_3+NH_4NO_3+NaNO_3+NaCl$	1.77+2.94+1+1	84.4	119

It is evident that the melting point and latent heat of the first, two samples progresses progressively, while the third sample has a latent heat of 109kJ/kg and a melting point of 81.4^0C. Latent heat in this case is the amount of heat required to bring about a change of state in a substance, and the substance been referred to here is the eutectic mixtures samples detailed in Table 1. The mixture of salt water and air contains heat and part of this heat is represented by sensible temperature which is measured by the aid of a thermometer while the latent heat is the energy that was used to evaporate the moisture in the salt that the air contains. If the air contains a great deal of water vapour, its latent heat will be high. The last sample which consists of four different salts with melting point of 84.8^0C and latent heat of 119 kJ/kg was the adopted sample because its latent heat supersedes that of others and the most importantly its melting point. The melting phase is termed important because it is a physical process that results in the phase transition of the eutectic mixture of the salts from solid to liquid. The longer it takes for this eutectic mixture to dissolve the better its phase change properties. The sum of the sensible and latent heat of the air in each of the respective samples is referred to as "enthalpy" sometimes called "total heat. It was observed from Figure 8 that that the higher the solar radiation the higher the PCM temperature at the water outlet.
The result presented shows thermal energy influenced by solar radiation intensity actually raises water temperature. In addition, the water temperature (inlet & outlet) are both impacted by the amount of heat absorbed and released by PCM, It is evident that higher solar radiation leads to higher PCM temperatures and higher heat absorbed by the water. Temperature was considered as the most significant parameter in the solar water heating system. In order to validate the experimental model, Figure 9 was constructed to compare the experimental result with the data obtained from literature.
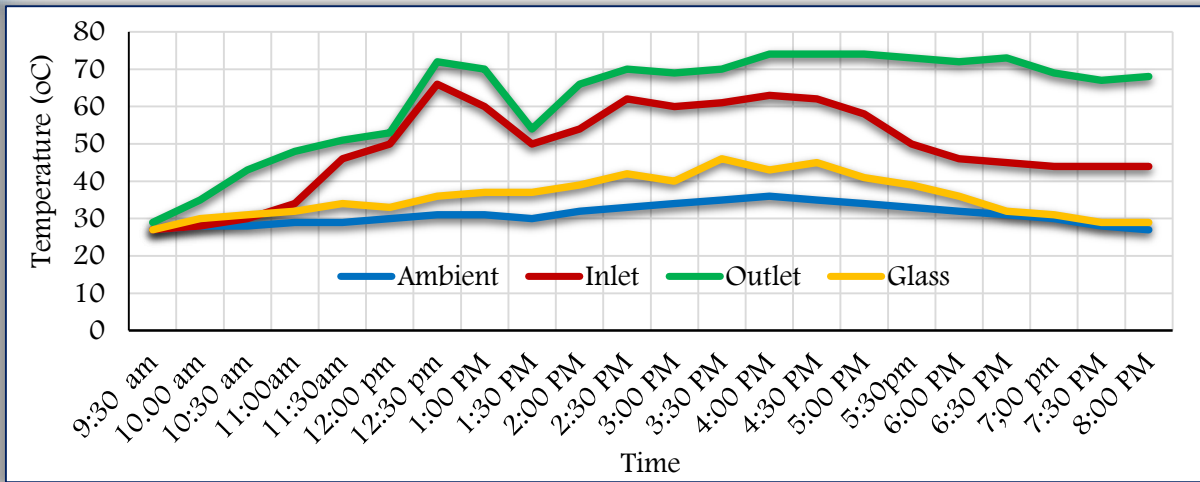
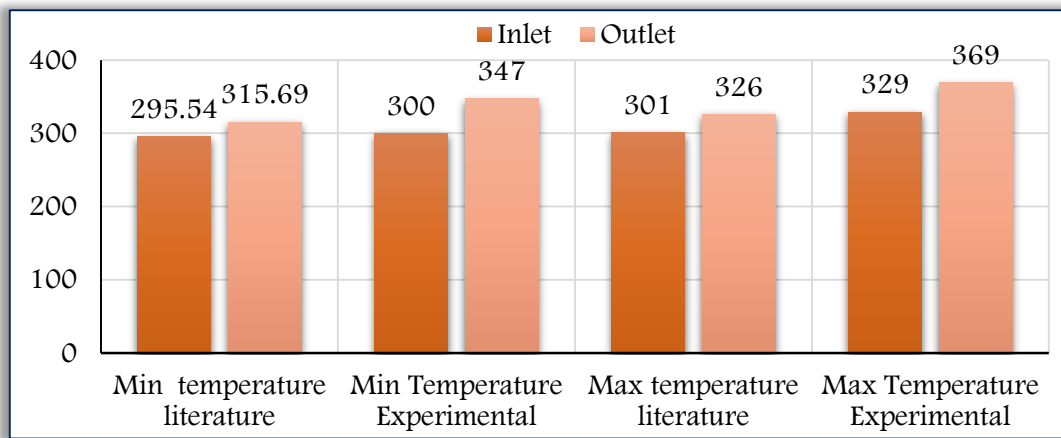Figure 8. The variation of ambient, water inlet, water outlet and glass temperatures with time

Figure 9. Comparison between the results obtained from literature and experimental results

4. CONCLUSION

A one dimensional theoretical model for a flat plate solar collector with phase change material was developed to investigate the thermal performance of the system. In the course of this study, the heat transfer characteristics of adopted phase change material integrated in solar collector of a thermal storage process was modeled and analysed and as well compared to experimental data at both inlet and outlet conditions. The numerical model presented, predicted the heat transfer characteristics during phase change material and interactions between the heat transfer fluids. The experimental data was also validated with the numerical model. The results presented shows that the heat absorbed during the charging process increases at higher water mass flow rates and decreases during discharging process at higher water mass flow rates and it was also observed that the time needed to complete melting and solidification modes are not linear with the mass flow rate and the PCM.

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