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Computation of Heat Transfer in a Flat Plate Solar Collector System Using Energy Balance Method

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Abstract

Input parameters measured from a prototype designed flat plate solar collector system in Benin Metropolis was employed in this study. A model was developed using energy balance method, the developed model was then computed using Explicit Finite Difference Method in MATLAB environment to predict the thermal behavior of the system. The principles and laws of thermodynamics were used in the modelling process. From the model developed, 330K, 370K and 320K were obtained as outlet water temperature, absorber plate temperature and glass temperature respectively. An optimal insulation thickness of 0.05m, 0.06m and 0.07m were achieved. 0.020m, 0.024m and 0.026m were obtained as optimal design condition for thickness of housing and this is with respect to the input parameters considered

1. Introduction

Solar is a renewable energy resource that has contributed positively to the energy sector and the world at large [1]. Solar energy is a combination of photon and thermal energy captured and applied over a range of ever-evolving technologies such as solar collector plate, solar thermal energy, molten salt power plants, artificial photosynthesis etc [2].

The amount of solar energy depends basically on the astronomical geometric parameter such as the actual distance from sun to earth. Since the earth moves around the sun on an elliptical orbit, the sun-earth distance is a function of the day. With regard to the mean value of the earth-sun distance, the sum of the energy per unit area obtained from the sun exterior of the earth's atmosphere, known as the solar constant, is approximately 1367W/m^2. Furthermore, the earth's cross-sectional area is estimated to be 127400000km^2 and the total power released to the earth by the sun is estimated to be 1.75 × 1014 kW [3].

While passing through the atmosphere a major part of the incident energy from the sun is suppressed by reflection, scattering or absorption by air molecules, clouds and particulate matter also called aerosols. Due to this, only 60% (approximately 1.05×10^{14} kW) of sunlight from the sun to the earth's atmosphere reaches the earth's surface [4].

In recent times, solar energy collectors have been used in transforming solar radiation energy from the sun to the internal energy of the transport medium and working fluid. One of the major components of any solar thermal system is the solar collector. This is a device which uses the incoming solar radiation energy, converts it into heat and transfers this heat (form of energy) to a fluid (usually water, air or oil) passing through the tubes of the collector. The solar thermal energy that is collected comes from circulating fluid either directly to the hot water or space conditioning system or to a thermal energy storage tank from which can be drawn for use at night or cloudy days [5]. [6] carried out an investigation on a polymer collector in which the solar energy was directly absorbed by the black colored working fluid. The model was validated both experimentally and through computational fluid dynamics (CFD) under steady-state conditions. From the CFD model validation, parameters obtained for temperature and velocity distribution across the solar collector surface area were found to be in agreement with the experimental results. The performance was obtained by CFD under steady-state conditions. [7] developed a 3-dimensional numerical model for solar collector considering the multidimensional and transient character of the problem. Effect of non-uniform flow on the solar collector performance was quantified and the degree of deterioration of collector performance was analyzed. The analysis showed that deterioration increased with increase in non-uniformity of the flow. The results indicated that collector efficiency does not change reasonably even when the flow at the outer risers is 1.5 times the flow of the central one but the outlet temperatures for each tube differs.

Angular solar relations analysis of a flat plate solar collector was experimentally conducted by [8] using a prototype designed flat plate solar collector system. Average declination angle of 14.6675, average zenith Angles of the sun of 22.1850, average incidence angle of 21.7650, average solar Azimuth angle of 77.0625 and average ratio of beam radiation of 1.0875 were obtained respectively. The average radiation on a tilted surface was obtained as 1025.3258w/m^2 for enhanced flat plate solar collector design. The tilt angle for several cities in Saudi Arabia was optimized by [9] using MATLAB model. Adjustment of tilt angle of the solar collector was suggested as six times annually. For optimum tilt angle, frequent adjustments was suggested in the months near equinox, due to rapid change in the direction of the sun compared to solstices.

In this study, MATLAB was employed in the computation of heat transfer in a flat plate solar collector system using energy balance method. Equations considered were energy balance of glass cover, energy balance of absorber plate and energy balance of the water stream.

2. Methodology

The model was developed using energy balance method and then computed using explicit finite difference method in MATLAB solver. MATLAB codes were written to provide access to matrix and data structures provided by the LINPACK (Linear system package) and EISPACK (Eigen system package) projects. MATLAB is a high-performance language which is capable of performing technical computing. It combines visualization, computation and programming environment. The MATLAB software provides a modern programming language environment as well as complex data structures containing in-built editing and debugging tools. The constant parameters and variable parameters were also considered in the process. For effective modelling, energy balance in the glass, energy balance in the absorber plate and energy balance of the water stream were considered as follows:

2.1 Energy Balance of the Glass Cover

The small thickness of the glass covering the solar flat plate collector makes it reasonable to consider a uniform glass temperature distribution through the whole part of the glass cover. Considering the constant properties of the glass material, the governing equation can be derived from an energy balance in a differential volume of thickness (δ), area (A_c) and time variation over period of the day. The heat energy received by the collector is given by Equation 1, solar energy emitted through the glass is given by Equation 2, heat transfer between absorber and glass is given by Equation 3, heat transfer between the glass and atmosphere is given by Equation 4 and heat energy emitted from the absorber to the glass is given by Equation 5.

$$H_g = (m_g C_g)\frac{dT_g}{dt} \quad (1)$$

$$H_S = A_C I_T \alpha_g \quad (2)$$

$$H_{pg} = A_C h_{pg-cp}(T_p - T_g) \quad (3)$$

$$H_{ga} = A_C h_{ga-wv}(T_g - T_a) \quad (4)$$

$$Hr_{pg} = \sigma A_p(T_p^4 - T_g^4)(m_g C_g)\frac{dT_g}{dt} = A_C I_T \alpha_g + A_C h_{pg-cp}(T_p - T_g) - A_C h_{ga-w}(T_g - T_{am}) + \sigma A_p(T_p^4 - T_g^4) \quad (5)$$

The radiative heat transfer coefficient between the plate and the cover is given by Equation 6, the radiative heat transfer coefficient between the cover and the sky is given by Equation 7, the convective heat transfer coefficient between the plate and the cover is given by Equation 8, the top loss coefficient for a single glass cover is given by Equation 9.

$$h_{pg} = \frac{\sigma(T_p^2 + T_g^2)(T_p + T_g)}{\frac{1}{\epsilon_p} + \frac{1}{\epsilon_g} - 1} \quad (6)$$

$$h_{ga} = \epsilon_g \sigma(T_g^2 + T_s^2)(T_g + T_s) \quad (7)$$

$$h_{cp} = \frac{N_u K_a}{L_a} \quad (8)$$

$$U_T = \left(\frac{1}{h_{cp} + h_{pg}} + \frac{1}{h_{wv} + h_{ga}}\right)^{-1} \quad (9)$$

2.2 Energy balance of absorber plate

A small thickness of the absorber plate was considered for a uniform plate temperature distribution through the whole part of the absorber plate. Applying the energy balance for the absorber plate zone, using the thermo-physical properties of the absorber material and considering the solar irradiance on the absorber plate in the solar flat plate collector, the radiation and convection heat transfer between the absorber and the glass cover, the conduction and convection heat transfer between the absorber and the insulation zone and the heat transfers by convection with the fluid flow were considered. The heat energy gained by the plate is given by Equation 10, solar energy absorbed by the plate is given by Equation 11, the heat transfer between the plate and glass is given by Equation 12, heat transfer between plate and water is given by equation 13, heat transfer between the absorber and insulation is given by Equation 14, heat transfer between the insulation and housing is given by Equation 15, heat energy emitted from the absorber to the glass is given by Equation 16.

$$H_p = m_p c_p \frac{dT_p}{dt} \quad (10)$$

$$H_S = A_p I_T \alpha_g \tau \quad (11)$$

$$H_{pg} = A_p h_{pg-cp}(T_p - T_g) \quad (12)$$

$$H_{pw} = A_f h_f(T_p - T_f) \quad (13)$$

$$H_i = K_i \frac{A_i}{\delta_i}(T_p - T_i) \quad (14)$$

$$H_h = K_h \frac{A_h}{\delta_h}(T_i - T_h) \quad (15)$$

$$Hr_{pg} = \sigma A_p(T_p^4 - T_g^4) m_p c_p \frac{dT_p}{dt} = A_p I_T \alpha_g \tau + A_p h_{pg-cp}(T_p - T_g) - A_f h_f(T_p - T_f) - K_i \frac{A_i}{\delta_i}(T_p - T_i) - K_h \frac{A_h}{\delta_h}(T_i - T_h) - \sigma A_p(T_p^4 - T_g^4) \quad (16)$$

2.3 Energy balance of the water stream

Applying the heat energy balance to the system helps to show and demonstrate the effect of heat gained and losses within the system. The energy balance describing the heat transfer between the water, pipe, absorber plate and the glass cover is expressed in the following Equation. Net heat gained by the water is given by Equation 17, heat energy transfer to the water is given by Equation 18, output heat energy is given by Equation 19

$$H_w = m_w c_w \frac{dT_w}{dt} \quad (17)$$

$$H_{pw} = A_f h_f(T_p - T_f) \quad (18)$$

$$H_O = m_f c_w(T_{wo} - T_{wi}) \quad (19)$$

The initial input parameters used for the modelling and simulation of the system is presented in Table 1.

Table: 1 Initial input parameters for the model

Parameters	Value
Emmitance of plate	0.84
Emissivity of glass	0.04
Heat capacity of glass (KJ/kg.K)	0.80
Heat capacity of absorber plate (kJ/kg.K)	0.90
Heat capacity of water (KJ/kg.k)	4.18
Area of collector (m^2)	0.84
Area of fluid pipe (m^2)	0.047
Insulation thickness (m)	0.05
Housing thickness (m)	0.02
Mass of glass (kg)	18.8
Mass of absorber plate (kg)	8.93
Mass flow rate (kg/s^2)	0.03
Wind velocity (m/s)	1.648
Initial glass temperature (K)	315
Initial water inlet temperature (K)	305
Initial housing temperature (K)	315
Initial insulation temperature (K)	325
Thermal conductivity of insulation (glass wool) (W/mk)	0.034
Thermal conductivity of housing (W/mk)	0.12
Thermal conductivity of air (W/mk)	0.024
Thermal conductivity of copper (W/mk)	386
Thermal conductivity of aluminium (W/mk)	239
Transmittance of glass	0.94
Radiation on a tilted surface (W/m^2)	937.18

3. Results and Discussions

Figure 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 shows the temperature of plate, temperature of glass, and the temperature of water from initial to final conditions with respect to time.

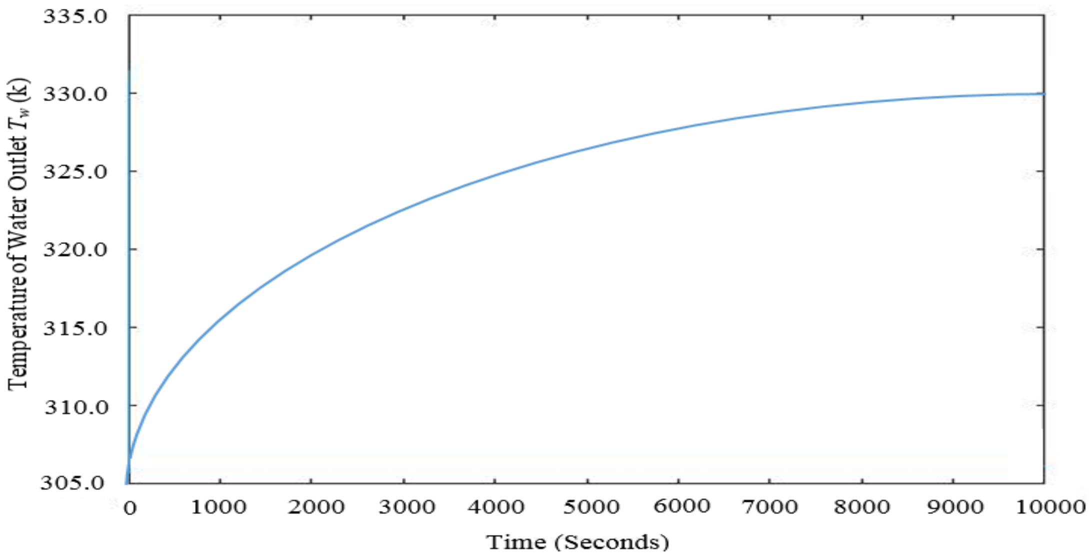

Figure 1: A graph of outlet temperature against time

Figure 1 shows the thermal behavior of the collector system, the model was able to simulate the behavior of the collector for 10000seconds and the temperature of water achieved was about 330K.

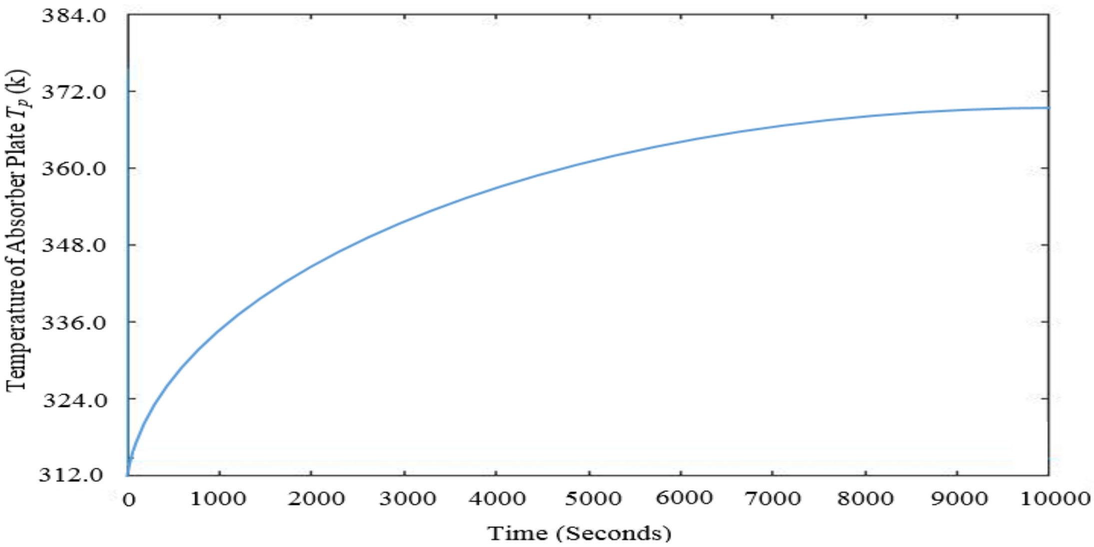

Figure 2: A graph of absorber plate temperature against time

As shown in Figure 2, the graph of absorber plate temperature against time indicates the temperature distribution on the absorber plate within a time frame of 10000 seconds. A temperature of about 370K was achieved.

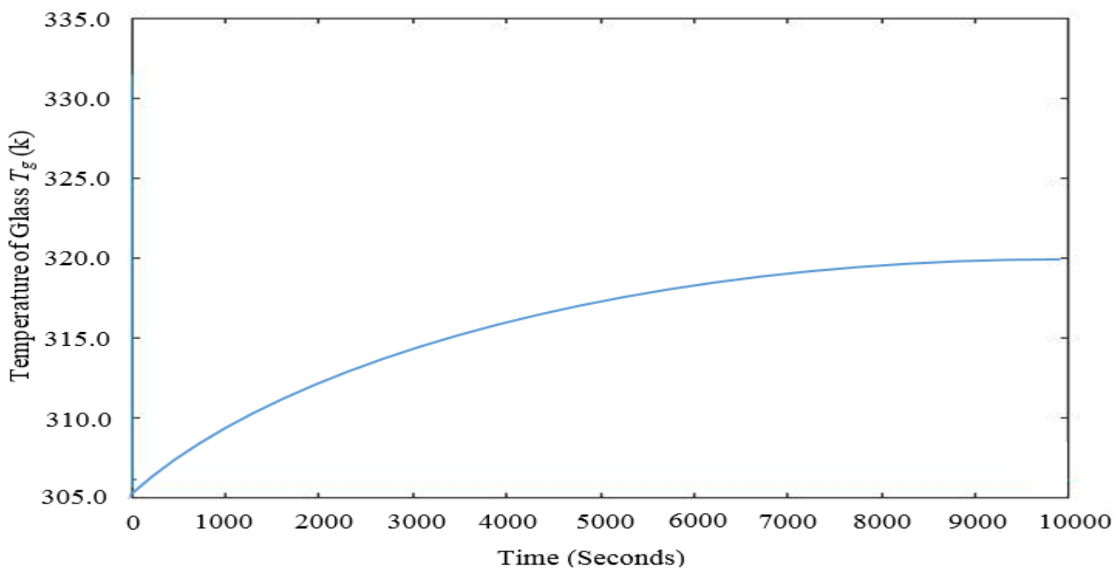

Figure 3: A graph of glass temperature against time

Figure 3 shows the effect of temperature on the glass of the collector system and its distribution over its surface area. The glass temperature got up to 320K.

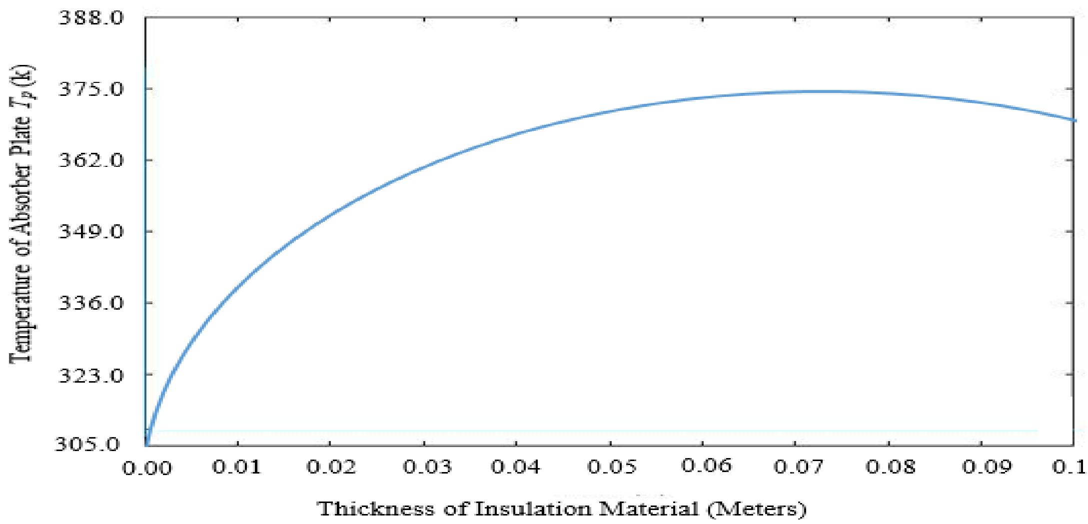

Figure 4: A graph of absorber plate temperature against insulation thickness

Figure 4 shows the thermal behavior of the absorber plate when the insulation thickness is varied with respect to time, from the graph it shows that a temperature of 375K was achieved considering insulation thickness of 0.05m, 0.06m, 0.07m. The insulation thickness within this range of values are parameters that can yield maximum output for optimum conditions.

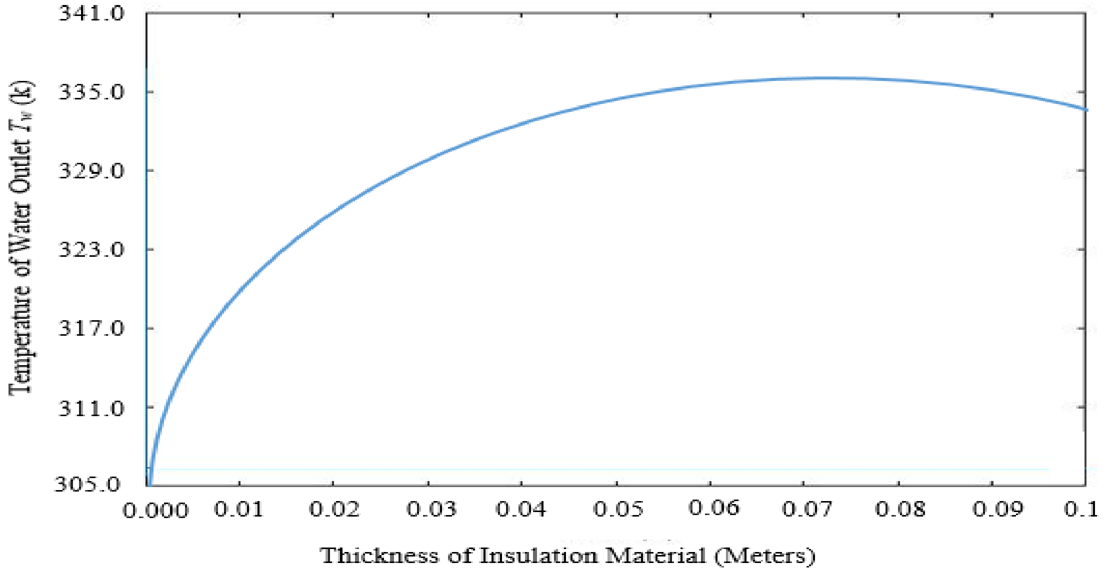

Figure 5: A graph of outlet water temperature against insulation thickness

The graph in Figure 5 describes the effect of insulation thickness on outlet water temperature, from the graph it shows that at a range of insulation thickness (0.05m, 0.06m and 0.07m), an outlet temperature of 335K was achieved.

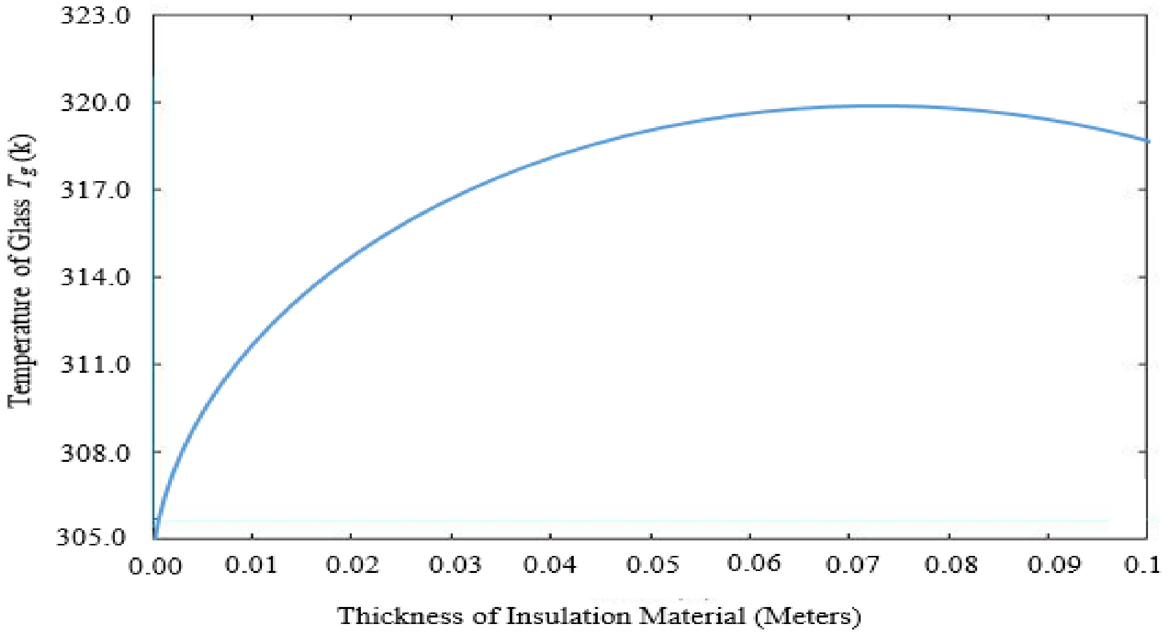

Figure 6: A graph of glass temperature against insulation thickness

Figure 6 shows that a temperature of 320K was achieved as the glass temperature at an insulation thickness range of 0.07m. 0.05m and 0.06m can also be considered, the temperature starts dropping at 0.08m. Hence 0.07m, 0.05m and 0.06m are optimum design parameters that can improve the overall efficiency of the solar collector.

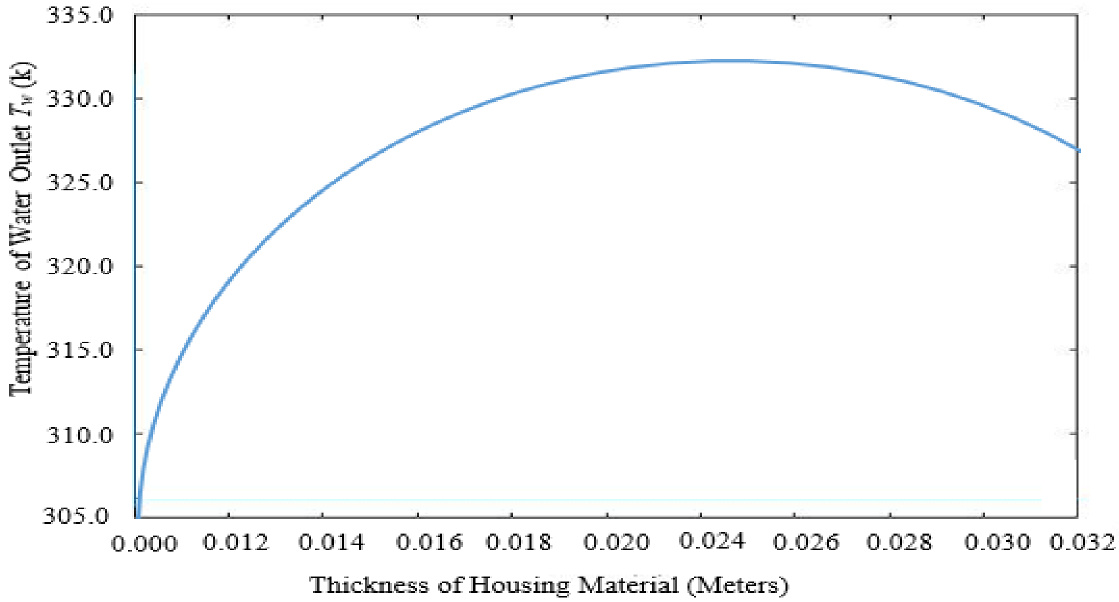

Figure 7: A graph of outlet water temperature against housing thickness

Figure 7 indicates that housing thickness of range (0.020m, 0.024m and 0.026m) achieved an outlet temperature of 333K. This indicates that at the range of the above housing thickness considered, the system performance can improve if they are used as design parameters for optimum conditions.

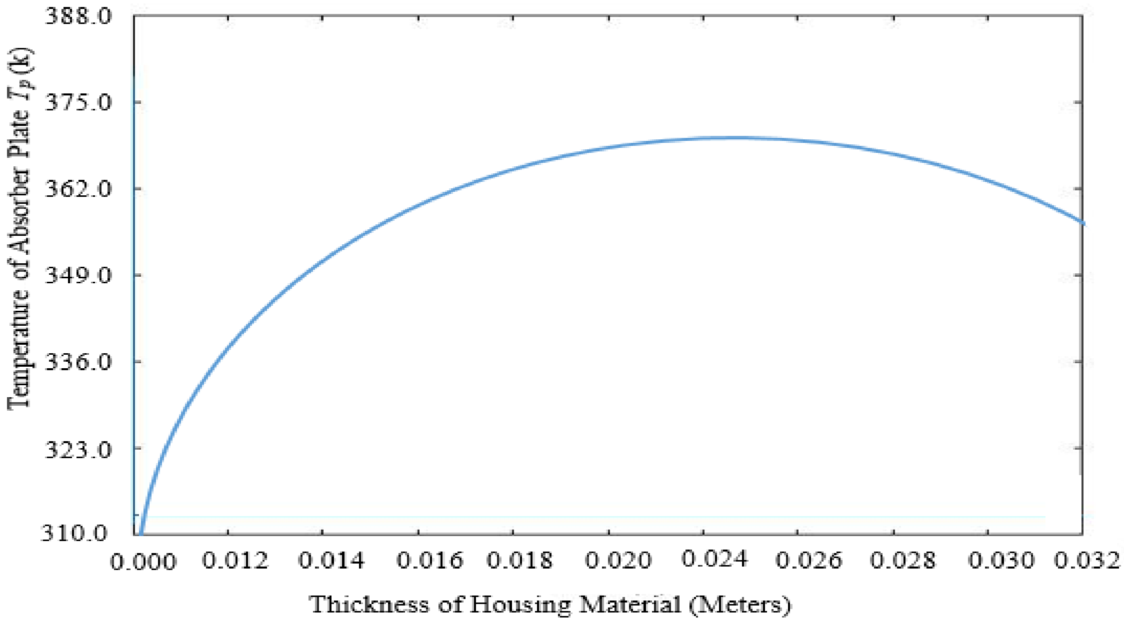

Figure 8: A graph of absorber plate temperature against housing thickness

Figure 8 indicates that a temperature of 370K was achieved at a range of 0.020m, 0.024m and 0.026m respectively. The range of housing thickness shown to yield a high absorber plate temperature are best considered as optimum conditions for design.

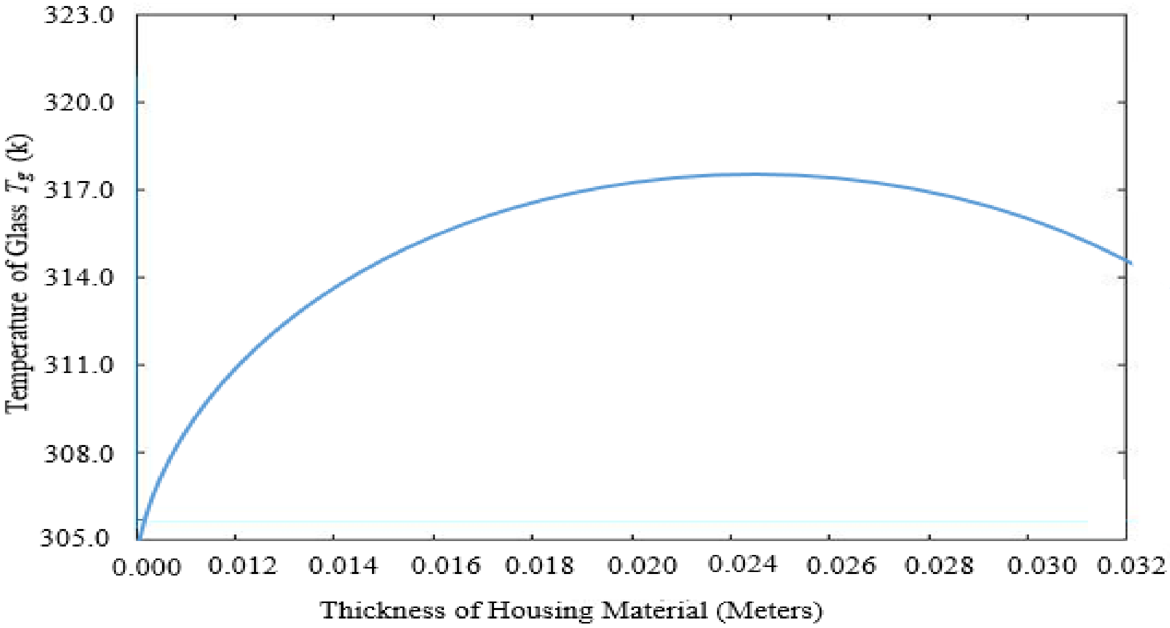

Figure 9: A graph of glass temperature against housing thickness

Figure 9 shows that the glass attained a temperature of about 318K within a housing thickness range of 0.020m, 0.024m and 0.026m. The graphs present a thermal description of the glass, and the housing thickness within this range is valuable for optimum conditions for better performance of the overall system.

4. Conclusion

A thermodynamic model has been successfully developed using energy balance method and solved with MATLAB to predict the output temperature of water, glass and absorber temperature of a flat plate solar collector. Outlet water temperature, absorber plate temperature and glass temperature of 330K, 370K and 320K as well as optimal insulation thickness of 0.05m, 0.06m and 0.07m were obtained from the model developed. The model considered the heat transfer between the absorber plate, insulation and housing which provided a more realistic assumptions and simplified approach to studying the thermal behavior of a flat plate collector system.

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