Thermal Performance Optimization of Flat Plate Solar Collector using MATLAB

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ABSTRACT

Solar flat plate collectors are one of the very important solar system components as they serve the purpose of heating up the ambient air/water for domestic and industrial uses like drying, cooking, thermal power generation, etc. It is therefore of significance that such flat plate collectors be appropriately designed for optimum performance and reliability at the point of usage. A solar flat plate collector needs to maximize its solar energy collection ability and have a good heat removal factor ability; which are achievable by properly configuring and sizing of its components. This research work presents the coding system for the parametric optimization study to determine the absorber plate thickness, back insulation thickness and tilt angle of a flat plate collector by using a written computer program in MATLAB R2013b base on appropriate equations and computed system parameters used for the research.From the study carried out, it was found that the heat removal factor does not respond significantly to changes in the absorber plate thickness. In order to maximize the heat removal factor, the absorber plate thickness of 1.5×10^{-5} *m with a heat removal factor of 0.7454 was determined. The back-insulation thickness for the solar flat plate collector was found to be 0.0235 m using sawdust with thermal conductivity of 0.06 W/mK as the insulating material.The study also revealed that the amount of solar energy collected on a flat plate collector surface can be affected by the choice of the orientation of the flat plate collector. For maximum solar collection in the considered geographical location of Zaria, the tilt angle for the solar flat plate collector was found to be* 20^0*, tilted from the horizontal facing the south with* 2.22×10^7 J/m^2day^{-1} *solar insolation collected on the flat plate collector.*

Keywords: *Heat removal factor, coding system, parametric optimization, absorber plate thickness, computer program, MATLAB R2013b*

1.0 INTRODUCTION

A flat plate collector (FPC) functions majorly by collecting solar energy and transforming it into thermal energy with water/air serving as the working fluid. FPCs are designed for use in the medium temperature range of about 60 and 100°C [1]. In recent times, the FPC has found the widest range of application of the many solar collector systems being developed presently. The FPC has known characteristics; and when compare to other types of collector, it is reported to be the least expensive and easiest to construct, install and maintain [2].

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The solar air FPC is further reported to be compact and less complicated; no additional working fluid other than air is required as heat-transfer medium, the problem of corrosion is eliminated, air leakages does not amount to any serious issue, the issue of having the working fluid freeze does not arise, rise in pressure is comparatively low, the equipment can be made with less and cheaper materials and the use and maintenance of the solar air FPCs are simpler as compare to those of water heaters [1].

By proper configuration and sizing, a solar flat plate collector can be made to maximize its solar energy collection ability and have a good heat removal factor; which are common factors in evaluating the performance of a FPC. Duffie and Beckman (2013) reported that an indication of an inherently low heat removal factor will generally lead to the poor output of a collector [3]. The maximum heat is transferred to the fluid circulating in the collector when the heat removal factor is maximum. Rosli *et al.* (2014) for instance stressed that to get the heat removal factor improved upon and hence the energy conversion efficiency of the flat plate collector, its components must be properly sized and arranged and maintained in a manner that the temperature of the solar collector is almost equal to the temperature of the inlet fluid [4]. Struckmann (2008) also acknowledged that an improvement of a collector's heat removal factor implies a corresponding improvement on the gain of the useful energy of such a collector leading to a better system thermal performance [5].

In a bid to improve on the performance of FPCs, many research works, both theoretical and practical have been ventured into in recent times.Rehman and Siddiqui (2012) for instance, reported a web-based simulation tool development discussion with interactive map for obtaining optimum tilt angles for a solar collector [6]. Assumption was made for the isotropic sky model and the climatic data they took from NASA SSE. The results obtained through their tool for the world's different regions were compared with those of literature. High values of correlation coefficients were reported between the two results. An inclined solar air heater was studied by Aboul-Enein *et al.* (2002) [7]. The air heater was made with and without thermal storage material for drying crop. The air heater is designed in such a way that various storage materials can be inserted under the absorber plate geared towards improving the drying process. A mathematical model was also achieved for the air heater's thermal performance. Yeh and Lin (1995) investigated experimentally and theoretically the collector aspect ratio's effect on the efficiency of energy collection of solar air heaters of flat-plate at constant collector area with different rate of flows [8]. It was reported that the energy collection efficiency increased with collector aspect ratio and mass flow rate. The predictions made theoretically were reported to reasonably agree with those of the experimental. Lampert (1987), presented the properties of optical materials and coatings in detail; these predominantly would increase the performance of the solar thermal system [9]. It was suggested that to reduce the radiative loss of the flat plate collector top surface to the atmosphere, a low emittance coating material for glazing should be selected, which reduces the heat loss. Ahmad (2001) designed and constructed a cylindrical solar collector with dimensions as; 0.36 m diameter and 5 m length and with a black interior band which is covered using transparent insulation [10]. By drying farm product, when the collector was affixed with a greenhouse dryer, the dryer produced about a 10°C higher temperature than that of the ambient.

As suggested by Rosli *et al.* (2014) many available parts of solar flat plate collectors are however not properly sized and configured especially by optimization/simulation processes which help in minimizing material wastage by not necessarily having to run numerous experiments before achieving the rightful designs [4].

This work therefore presents an optimization procedure (written computer program in MATLAB R2013b based on appropriate equations and computed system parameters) used in the selection/sizing of the absorber plate, the back insulation of a solar flat plate collector and the angular orientation of the collector to achieve maximum heat removal effect.

2.0 THEORETICAL BACKGROUND

2.1 Absorber Plate Thickness

Collector heat removal factor, F_R:This quantity gives the ratio of the actual useful energy gained by the collector to that gained by the air. It can be expressed as [3]:

$$F_{\mathrm{R}} = \frac{\dot{m}c_{\mathrm{p}}}{A_{\mathrm{c}}U_{\mathrm{L}}}\left[1 - \exp\left(-\frac{A_{\mathrm{c}}U_{\mathrm{L}}F'}{\dot{m}c_{\mathrm{p}}}\right)\right] \tag{1}$$

where:F^1 is collector efficiency factor, $\dot{m}$is fluid mass flow rate,A_c is the area of the collector, U_L is the overall heat loss, C_p is the specific heat of fluid.

The collector efficiency factor,$F^1$is a factor that expresses the ratio of actual useful heat collection rate to that of the useful heat collection rate when the temperature of the collector absorber plate is at the temperature of the local fluid. This is given by:

$$F' = \frac{1}{1+\frac{U_L}{h_1+\frac{1}{\frac{1}{h_2}+\frac{1}{h_r}}}} \tag{2}$$

where: h_1 is the convective heat transfer coefficient from the absorber plate to the fluid,$h_2$is the convective heat transfer coefficient from the fluid to the collector cover, $h_r$is the radiative heat transfer coefficient from the absorber plate to the collector cover.

The radiative coefficient, h_r is given as [3]:

$$h_{\mathrm{r}} = \frac{\sigma_t\left(T_{pm}^2 + T_a^2\right)\left(T_{pm} + T_a\right)}{\frac{1}{\varepsilon_p}+\frac{1}{\varepsilon_g}-1} \tag{3}$$

where σ_t is the absorber plate thickness, m, $\varepsilon_{\mathrm{p}}$is the emittance of the absorber plate, ε_g is the emittance of the glazing, T_a is the atmospheric temperature, T_{pm} is mean absorber plate temperature.

The expression for estimating the plate temperature, T_p which can also be equated to the mean plate temperature, T_{pm} is given as:

$$T_{\mathrm{p}} = T_{\mathrm{in}} + 20^o C = T_{\mathrm{pm}} \tag{4}$$

where T_{in} is the temperature with which the fluid enters the collector.

Overall heat loss of the collector,U_L:The overall heat loss of the collector U_L can be found by considering the heat loss from the collector through the cover of the glass (top loss), its back (back loss) and its sides (edge loss).

Top heat loss coefficient, U_T:The total top loss coefficient can be gotten by considering the convective and radiative heat transfer coefficients. The convective heat transfer coefficient between the absorber plate and the cover of the glass inclined at an angle β to the horizontal is given by [11]:

$$h_{1\mathrm{c}} = \frac{N\mathrm{uk}}{L_{\mathrm{c}}} \tag{5}$$

where k is the thermal conductivity of air,L_c is the characteristic length and *Nu*is the*Nusselt* number.

The value of the *Nusselt* number, given air as a medium can be obtained from the expression [12]**:**

$$Nu = 1 + 1.44\left[1 - \frac{1708}{Ra\cos\beta}\right]^{+}\left(1 - \frac{\sin(1.8\beta)^{1.6}\times 1708}{Ra\cos\beta}\right) + \left[\left\{\frac{Ra\cos\beta}{5830}\right\}^{1/3} - 1\right]^{+} \quad (6)$$

where *Ra*=*Rayleigh* number. For $0 \le Ra \le 10^5$ and $0 \le \beta \le 60^0$

The notation $[\ ]^{+}$ denotes that only positive value of the term is to be considered, negative value is taken to be zero.

The *Rayleigh* number, *Ra* is given by [13]:

$$Ra = \frac{gB\Delta T\, L_c^3}{\alpha\upsilon} \quad (7)$$

where B is thermal expansion coefficient, ΔT is temperature difference between inlet and outlet, $v$is kinematic viscosity of air, $\alpha$is thermal diffusivity, g *is* acceleration due to gravity.

The convective heat transfer coefficient between the glass cover and the ambient air is given by [14]:

$$h_{2c} = 2.8 + 3.0V_a \quad (8)$$

where $V_a$is thewind speed.

The radiative heat transfer coefficient between the absorber plate and the glass cover is given by [11]:

$$h_{1r} = e_{ff}\sigma\left[\frac{\left((T_p+273)^4 - (T_g+273)^4\right)}{T_p - T_g}\right] \quad (9)$$

where T_p is the absorber plate temperature, T_g is the glass cover temperature, e_{ff} is the effective emissivity σ is the *Stefan Boltzmann's* constant = 5.67 x 10^{-8} W/m^{2}K^4.

The effective emissivity of absorber plate and glass cover is given by:

$$e_{ff} = \left(1/e_p + 1/e_g\right)^{-1} \quad (10)$$

The radiative heat transfer coefficient h_{2r} between the glass cover and the surroundings depends on the radiation with the sky.The sky temperature, $T_{sky}$is given by [11]:

$$T_{sky} = T_a - 6 \quad (11)$$

The radiative heat transfer coefficient, h_{2r}, is given by:

$$h_{2r} = e_g\sigma\left[\frac{\left((T_g+273)^4 - (T_{sky}+273)^4\right)}{T_g - T_{sky}}\right] \quad (12)$$

The total top loss coefficient from the collector plate to the glass cover can be expressed from the relation:

$$h_1 = h_{1c} + h_{1r} \tag{13}$$

From the glass cover to the surrounding is given as:

$$h_2 = h_{2c} + h_{2r} \tag{14}$$

Therefore, the effective total top loss coefficient,U_T from the absorber plate to the surroundings can be obtained from [11]:

$$U_T = \left(\frac{1}{h_1} + \frac{1}{h_2}\right)^{-1} \tag{15}$$

The value of U_T is calculated by the method of iteration, since $T_g$is usually not known. A value of $T_g$was initially assumed so that h_{1r}, h_{2r}, $h_1$and $U_T$can be calculated, and afterwards a new value of T_g re-calculated from the equation:

$$T_g = T_p - \frac{U_T}{h_1}\left(T_p - T_a\right) \tag{16}$$

Back loss coefficient, U_b:The total back loss coefficient can be obtained from [3]:

$$U_b = \frac{K_{bi}}{L_{bi}} \tag{17}$$

where, k_{bi} is thermal conductivity of the insulation material, L_{in} is the thickness of bottom insulation.

Edge loss coefficient, U_e:The edge loss coefficient can be obtained from [3]:

$$U_e = \frac{K_{ei}}{x_{ei}} \cdot \frac{A_e}{A_c} \tag{18}$$

where, $k_{ei}$is thermal conductivity of edge insulation material,$A_e$is edge insulation area, x_{ei} is insulation thickness at the edge. Thus, the overall heat loss coefficient,U_L is the total sum of the top, bottom and edge loss coefficients, and is given by:

$$U_L = U_T + U_b + U_e \tag{19}$$

2.2 Tilted Angle of the Flat Plate Collector

Solar collector orientation: To best receive the maximum solar radiation rays during the seasons of drying, solar collectors are tilted so that they are nearly perpendicular to the energy rays.The optimum thermal performance of the collector for all year round is gotten when the collector is faced south in the northern hemisphere [15]. The inclination of collectors allows for easy runoff of water and enhances air circulation [16].

Tilted or orientation of the solar FPC:The equation used for the optimization of the tilt angle is a model developed by Reindl *et al*., (1990) [17]; and Young *et al.* (2012) [18] which is a modification of the model in [19] and that of [20], modified to take into consideration the circumsolar diffuse and horizontal brightening components on a surface tilted. This model is referred to as the *Hay–Davies–Klucher–Reindl* (HDKR) diffuse model. This HDKRmodel estimates the total radiation on a surface that is tilted as [18]:

$$H_{\mathrm{T}} = (H_{\mathrm{b}} + H_{\mathrm{d}}A_{\mathrm{i}})R_{\mathrm{b}} + H_{\mathrm{d}}(1 - A_{\mathrm{i}})\left(\frac{1+\cos\beta}{2}\right)\left[1 + f\sin^3\frac{\beta}{2}\right] + H\left(\frac{1-\cos\beta}{2}\right) \tag{20}$$

where$H_{\mathrm{b}}$is the total beam radiation on horizontal surface, $\beta$is the angle of tilt of the surface, H is the monthly daily solar radiation on a horizontal surface,H_{d} is the total diffuse radiation on horizontal surface,H_{T} is the solar radiation on a tilted surface,$f$is the square-root of ratio of beam to total radiation, A_{i} is an anisotropic index. It is a function of the transmittance of the atmosphere for beam radiation. It is expressed as:

$$A_{\mathrm{i}} = \frac{\bar{H}_{\mathrm{b}}}{\bar{H}_{\mathrm{o}}} \tag{21}$$

Note that*f*is the square-root of ratio of beam to total radiation given as:

$$f = \left(\frac{H_{\mathrm{b}}}{H}\right)^{½} \tag{22}$$

where the beam component can be calculated as:

$$H_{\mathrm{b}} = H - H_{\mathrm{d}} \tag{23}$$

$R_{\mathrm{b}}$is the geometric factor*;*surfaces that are tilted toward the equator in the northern hemisphere, the geometric factor is given as [3]:

$$R_{\mathrm{b}} = \frac{\cos(\varphi+\beta)\cos\delta\sin\omega_{\mathrm{s}}' + \left(\frac{\pi}{180}\right)\omega_{\mathrm{s}}'\sin(\varphi+\beta)\sin\delta}{\cos\varphi\cos\delta\sin\omega_{\mathrm{s}} + \frac{\pi}{180}\omega_{\mathrm{s}}\sin\varphi\sin\delta} \tag{24}$$

where

$$\omega_{\mathrm{s}}' = \min\left\{\begin{matrix}\cos^{-1}(-\tan\varphi\tan\delta) \\ \cos^{-1}(-\tan(\varphi+\beta)\tan\delta)\end{matrix}\right\} \tag{25}$$

The term, “min” means that the smaller of the two values in the bracket.
ω_s is the sunset hour anglewhich is given by:

$$\omega_{\mathrm{s}} = cos^{-1}(-\tan\varphi\tan\delta) \tag{26}$$

φ is the latitude of the location
δ is the angle of declination whichcan be determined as [21]:

$$\delta = 23.45\sin\left[\frac{360}{365}(284 + n)\right] \tag{27}$$

where n is the number of days in a year, with 1st January being n = 1, n =32 for 1st February, etc.

3.0 COMPUTATIONAL SETTINGS

3.1 Materials

The diagram for the collector plate is shown in Figure 1.

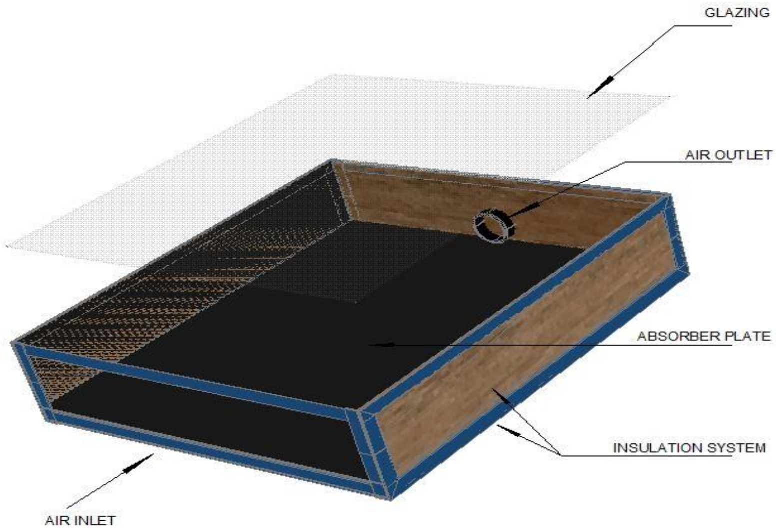

Figure 1: The diagram of the flat plate collector

3.1.1 The solar collector/description of parts

This is a rectangular metal frame box overlaid at the bottom with plywood, then with an aluminum absorber plate with sawdust sandwiched in between them and covered at the top with a transparent glass cover. The solar collector plate provides the platform where the solar energy is harvested. It heats up the air passed into use. The flat plate collector consists of the followings:

Absorber plate: This helps in increasing the intensity of solar insolation received by the collector plate. The aluminum sheet was selected for this work because it has a reasonable absorptance and low long wave emittance, durable and easy to handle.

Glazing or glass cover: The collector was covered on the top with a transparent plain glass to help increase the intensity of solar insolation falling on the absorber plate.

Insulation: This minimizes the heat loss to the surrounding. Common available insulating materials include; polyurethane form, expanded polystyrene, fiber glass, sawdust, cork and plywood used to minimize heat loss from the collector. The sawdust was used because it has low thermal conductivity, economically cheap and readily available. The sawdust was sandwiched in between the bottom of the collector and the absorber.

3.1.2 Working principle of the collector

The flat plate solar collector is opened at one end for air entrance and other end linked to the drying chamber. The collector is normally energized by the rays of the sun enteringvia the glazing cover, which traps the heat from the sun by converting high frequency, low wavelength radiations into low frequency, high wavelength radiations (greenhouse). The intensity of the trapped sun's rays is enhanced by the absorber sheet painted black; thetrapped energy then heats up the inside air of thecollector. The greenhouse effect achievedwithin the collector drive the air current from the inlet to the outlet of the collector setting a thermo-siphoning effect creating an updraft of the heated air into the chamber of use.

3.2 Method

Computed and design conditions/assumptions used in parametric optimization

The computed and design conditions/assumptions used in the parametric optimization of the absorber plate thickness and the tilt angle are given in Table 1.

Table 1: Computed parameters used for the parametric optimization process

Parameter	**Remark**
Mass flow rate of air, $\dot{m}$	0.0024 kg/s
Heat capacity of air, C_p	1.005 KJ/kgK
Collector efficiency factor, F'	0.746
Area of collector, A_c	0.423 m^2
Convective heat transfer coefficient from the absorber plate to the fluid, h_1	9.436 W/m^{2}K
Convective heat transfer coefficient from the fluid to the collector cover, h_2	15.870 W/m^{2}K
Radiative heat transfer coefficient from the absorber plate to the collector cover, h_r	1.674x10^7 W/m^{2}K
Top loss coefficient, U_T	5.91 W/m^{2}K
Back loss coefficient, U_b	2.60 W/m^{2}K
Edge loss coefficient, U_e	0.09 W/m^{2}K
Overall loss coefficient, U_L	8.60 W/m^{2}K
Atmospheric temperature, $T_a$and mean absorber plate temperature, T_{pm}.	302.4 K, 318.5 K
Emittance of the absorber plate,ε_p; emittance of the glazing, ε_g	0.95 [11], 0.88 [11]
Total beam radiation on horizontal surface,H_b	12.8 MJ/m^2/day [22]
Total diffuse radiation on horizontal surface, H_d	8.900 MJ/m^2/day
Anisotropic index,A_i	0.340
Square-root of ratio of beam to total radiation, f	0.768
Geometric factor,$\bar{R}_b$	0.908
Monthly average daily solar radiation on a horizontal surface, H	21.70 MJ/m^2/day [22]
Sunset hour angle,ω_s	92.72°
Angle of declination, δ for n =228	13.50°
Latitude,φ of the location (Zaria)	11.20°

Equations (1)to (3) and computed results presented in Table 1 (obtained from Equations (4)to(19)) were rewritten in MATLAB codes (Appendix A) as a script on the MATLAB editor and run using MATLAB R2013b function work environment. This gave the result which was then used to deduce the absorber plate thickness in relation to heat removal factor as presented in Figure 2.

Equation (20) and computed results presented in Table 1 (obtained from Equations (21) to (27) were rewritten in MATLAB codes (Appendix B) as a script on the MATLAB editor and run using MATLAB R2013b. The result obtained was used to deduce the angle of tilt of the collector in relation to solar radiation collected on the collector surface as presented in Figure 3.

4.0 RESULTS AND DISCUSSION

Results obtained from the parametric optimization of the flat plate collector parts are presented in Figures2 and 3.Figure 2 shows the effect of varying the absorber plate thickness of a single glazing flat plate solar collector on the heat removal factor. As the absorber plate thickness was varied from A to B, that is from 5×10^{-6} m to 1.5×10^{-5} m (200% increment), there was a considerable increase in the heat removal factor from 0.7431 to 0.7454, with a percentage increase of 1.90%. After this point (AB), there was no more improvement in the heat removal factor. From B to C, the percentage increase in the thickness of the plate is 1266.70% with just a percentage increase of 0.161% in the heat removal factor. This means that much material was used up to achieve the little heat removal factor as compared to AB. Moving from C to D, the percentage increase in the thickness of the plate is 102.44% and that of the heat removal factor remained unchanged (0.0%). No extra gain in heat removal factor at this stage, CD. In comparison, lesser material was used from A to B to achieve the highest heat removal factor. Point B with an absorber plate thickness of 1.5×10^{-5} m and the heat removal factor of 0.7454 was chosen since it has the optimized values.

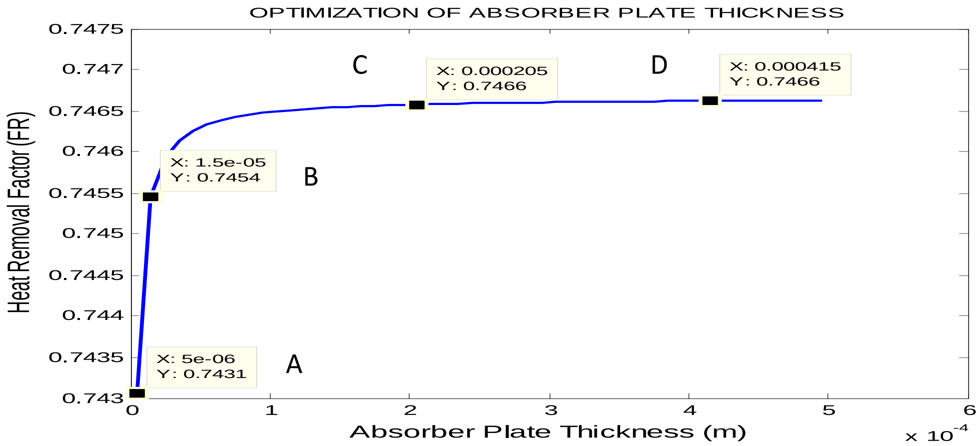

Figure 2: Variation of the heat removal factor and absorber plate thickness

From the plotted values of solar radiation on the collector surface against the collector tilt angle shown in Figure 3, it can be seen that as the collector plate tilt angle was increased from 0° there was a considerable rise in the solar radiation collected on the collector plate. This rise continued to the point where the tilt angle of the collector plate was 20°; after this point further increase in the tilt angle resulted in a decrease in the solar radiation collected on the collector plate. Hence, 20° was chosen as the optimum value for the tilt angle of the solar collector plate; with 2.22×10^7 J/m^{2}day^{-1} solar insolation collected on the flat plate collector. The solar collector plate in this work was therefore tilted at 20° which approximately agrees with the findings of [23-24]who suggested latitude of the location plus ten as the optimum tilt angle of a collector plate. Thelatitude for Zaria, Nigeria is 11.2°.

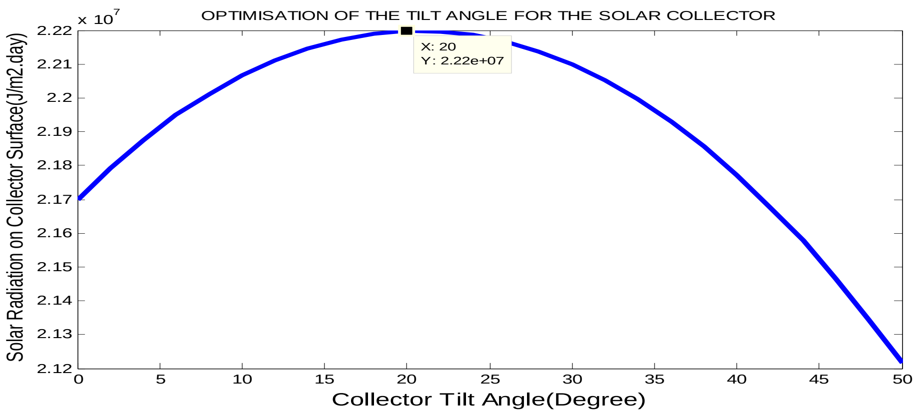

Figure 3: Variation of solar radiation on the collector surface and collector tilt angle

Figure 4 shows the effect of varying the thickness of insulation material on the back heat loss of the collector plate. The interest here is conserving the largest heat with the least material. With point A chosen as the reference point, since it gives a clear cut where the back heat loss is conspicuously reduced; four other points (B, C, D and E) with approximate equal intervals were selected. Moving from point A to B, the difference in heat loss is much (12.696 W/m^{2}K) with 0.01 m of insulating material needed. B to C had a reduction of 1.891 W/m^{2}K in heat loss, still with 0.01 m of insulating material needed. Although the reduction in heat loss from D to E was significantly the least (0.609 W/m^{2}K), more insulating material (0.016 m) was needed to achieve this as compared to that of C to D that needed the least insulating material (0.009 m) to achieve a heat loss of 0.707 W/m^{2}K. It is therefore, more economical to choose of values from C to D which still offered an approximate same heat conservation to that of D to E. Therefore, 0.0235 m back material thickness with the back heat loss of 2.60 W/m^{2}K were chosen as the optimal values.

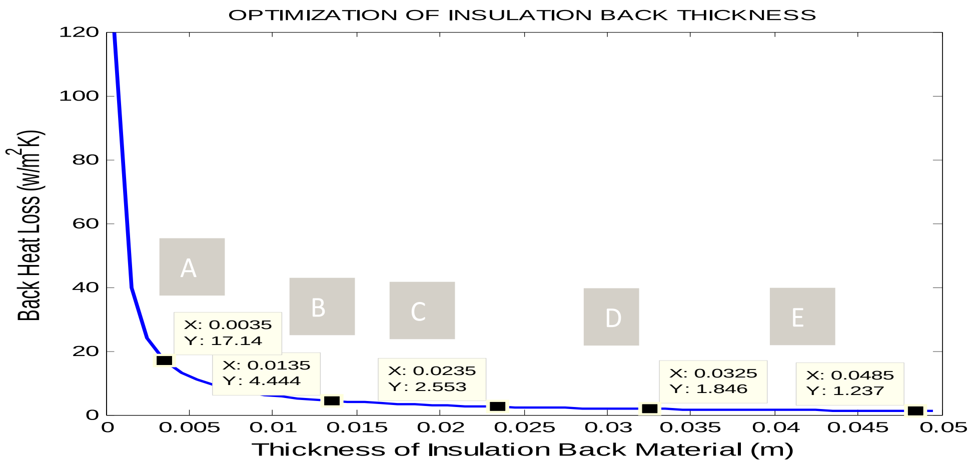

Figure 4: Back heat loss against thickness of insulation back material

5.0 CONCLUSION

The coding for the parametric optimization study to determine the absorber plate thickness and tilt angle of a flat plate collector by using written a computer program in MATLAB R2013b based on appropriate equations and computed system parameters was successfully carried out. From the result of the parametric optimization studies, to maximize the heat removal factor, the absorber plate thickness of 1.5x10^{-5} m with a heat removal factor of 0.7454 was determined. Also, for maximum solar collection in the considered geographical area, the tilt angle for the solar flat plate collector was determined to be 20^0, tilted from the horizontal facing the south with 2.22×10^7 J/m^{2}day^{-1} solar insolation collected on the flat plate collector.

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Appendix A

Codes for parametric optimization of the absorber plate thickness

```
% clear all;
    close all;
    %----- OPTIMIZATION OF ABSORBER PLATE THICKNESS-----
    DELTA_T=0.0005:0.0001:0.050 %ABSORBER PLATE THICKNESS
    E_P=0.95 % emissitivity of plate
    E_g=0.88 % emissitivity of glass
    T_pm=318.5 % degree Kelvin
    T_a=302.4 % degree Kelvin
    T1=(T_pm^2)+(T_a^2)
    T2=T_pm+T_a
    Q=DELTA_T*(T1*T2)
    P =(((E_P)^-1)+((E_g)^-1))-1
    hr=Q/P
```

```
%--------------heat convective factor------------------------
U_L=8.60 %W/m^2K overall heat loss coefficient
h1=9.436%W/m^2K
h2=15.870%W/m^2K
H=(((h2).^-1)+((hr).^-1)).^-1
H_1=h1+H
H_UL=1+(U_L./H_1)
F_prime=(H_UL).^-1 % collector efficiency factor

%-----collector efficiency factor------------
Ac=0.423 %m^2 area of collector
Cp=1.005 %KJ/kg %specific heat capacity of air
m_dot=0.0024 %kg/s mass flow rate of air
%-----------%%%%----------------
M1=(m_dot*Cp)
M11=(Ac*U_L)
M2=(Ac*U_L*F_prime)
M3=(-(M2/M1))
F_R1=(M1/M11)
%F_R2=(1-(exp(M3)))
F_R2=(1-(M3))

F_R=(F_R1)*(F_R2)%heat removal factor
%-------------collector heat removal factor--------------
plot(DELTA_T,F_R,'linewidth',2)
xlabel('Absorber Plate Thickness(m)','fontsize',12)
ylabel('Heat Removal Factor(FR)','fontsize',12)
title('OPTIMIZATION OF ABSORBER PLATE THICKNESS')
grid off
```

Appendix B

Codes for parametric optimization of tilt angle

```
% clear all;
close all;
%---------------- OPTIMIZATION OF TILT ANGLE-------------
Gsc=1367% SOLAR CONSTANT
LT=11.2% LATITUDE OF THE PLACE (ZARIA)
% THE RECOMENDATION FOR DAYS OF THE MONTH
n1=[228]'%recommended average day of the year
for i =1:length(n1)
beta=0:2:50%variation of tilt angle to be optimized
P=pi/180 %factor for the conversion from radiation to degree
DELTA=23.45*sin(2*pi*((n1(i) +284)/365))% DELTA is the declination angle, this is
the equation for monthly declination of sun
%--------sunset angle in degrees
W_S=(acos(-tan(LT*P)*tan(DELTA*P)))*1/P % The monthly sunset
W_Sb= (acos(-tan((LT+beta)*P)*tan(DELTA*P)))*1/P
W_S1=min(W_S,W_Sb) %minimum means the smallest of the two in the bracket

%-----extraterrestrial solar radiation-------
A1=86400*Gsc/pi;
A2=(1+0.033*cos(360*n1(i)*P/365));
A3=cos(LT*P)*cos(DELTA*P)*sin(P*W_S)+(pi*W_S*sin(P*LT)*sin(P*DELTA)/180)
;
H0=A1*A2*A3 % THIS IS THE AVERAGE ANUAL EXTRATERRISTRAL SOLAR
RADIATION
```

```
H=[21.7]*1e6 %annual average solar radiation of location
KT=H/H0
g=0
%-----------------------------------------------------------------
Hd=[8.9]*1e6 %calculated value of total diffuse radiation on horizontal surface
Hb=[1.28]*1e7 %simulated trynsis value of total beam radiation on horizontal surface
% ---------------------------------------------------------------
Rb1=cos((LT+beta)*P).*cos(DELTA*P).*sin(W_S1*P)
Rb2=(pi/180)*W_S1.*sin((LT+beta)*P).*sin(DELTA*P)
Rb3=cos(LT*P)*cos(DELTA*P)*sin(W_S*P)
Rb4=(pi/180)*W_S*sin(LT*P)*sin(DELTA*P)
Rb=(Rb1+Rb2)/(Rb3+Rb4) %monthly average ratio of beam radiation on a tilted surface
to beam radiation on a horizontal surface
HT1=(Hb+(Hd*0.340))*Rb
HT2=Hd*(1-0.340)*((1+cos(P*beta))/2)
HT3=[1+(0.768*(sin(P*beta)/2).^3)]
HT4=(H*(1-cos(P*beta))/2)
HT5=(HT2).*HT3
HT=HT1+HT4+HT5 %monthly average value of total radiation on a tilted surface

% -------------------------------------------------------------------
plot(beta,HT,'linewidth',2)
xlabel('Collector Tilt Angle(Degree)','fontsize',12)
ylabel('Solar Radiation on Collector Surface(J/m2.day)','fontsize',12)
title('OPTIMIZATION OF THE TILT ANGLE FOR THE SOLAR COLLECTOR')
grid off
```