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Modeling and Simulation of the Incident Radiative Heat Received on the Surface of a TPV Absorber from the Combustion of Palm Nut Shells

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Abstract:- Thermo photovoltaic (TPV) system technology is based on the phenomenon of direct conversion of radiation coming from a heat source into electrical energy by means of photovoltaic cells. One of the heat source means is radiative heat transfer from combustion. In this work, we proposed a model for the calculation of thermal fluxes on the surface of TPV absorber coming from the combustion of palm nut shells. For this, we modeled the combustion flame by a cylindrical approach. A radiative model for calculating the incident and net fluxes is presented and, from the first thermodynamics principle, a temperature model for the TPV absorber surface is derived. The obtained models are discretized and solve simultaneously using iterative scheme in MATLAB. From the simulations runs, results of the incident and net fluxes at the surface of the TPV absorber are represented and analysed. The effect of thermal convection on the fluxes is carried out. Further, sensitivity are performed for different TPV heat sink - absorber distances. The model proposed here is suitable for any incident and net fluxes investigation at the surface of the TPV absorber, necessary for any TPV system design.

Keywords:- *Thermo photovoltaic, combustion, heat transfer, biomass, numerical simulation.*

I. INTRODUCTION

During production of steam through boiler, energy is lost by radiative heat transfer from the combustion flame of a biomass fuel. The waste heat energy can be valorised using a TPV system.

TPV system have being proposed as power sources on their own such as portable electricity generation and combined heat and power generation system [1].

Henry H.Kolm had constructed an elementary TPV system at MIT in 1956 .But actual credit goes to Pierre Aigrain for laying foundation for modern TPV system. He is widely cited as the inventor of TPV based on the content of lectures he gave at MIT during 1960-1961 which, unlike Kolm's system is much more realistic. A review of the development of TPV is also presented in Nelson (2003) [2, 3, 4].

In the open literature, a TPV system is composed of a radiative heat source, normally in the range 1000–1800 K; a selective emitter and filters for spectral control; a PV cell; and a cooling system. In this study, we focused our attention on the first part of a typical TPV system which is the radiative heat source. The TPV system in figure 1 is considered, in which combustion of palm nut shells [5] is primary used as source energy for a boiler. Our aims are to determine, by numerical simulation the amount of radiative heat fluxes at the surface of TPV absorber coming from the waste heat energy and to therefore discuss the feasibility of TPV system based on the combustion of the nut palm shells.

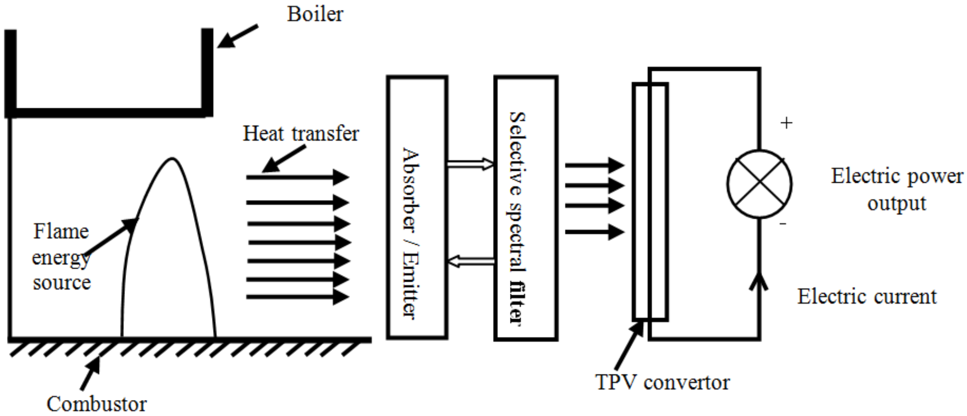

Fig. 1:- Thermo photovoltaic system [3,4]

II. MATHEMATICAL MODEL

A. Problem Formulation

During combustion of nut palm shells for heat power generation using boiler, the radiant heat from combustion flame is generally waste and unaccounted. Therefore, it is necessary to investigate the feasibility of a TPV system based on this waste heat radiative source by running simulation in order to evaluate the amount of heat fluxes received at the TPV absorber surface. The methodology applied here is based on the following:

- -Modeling of the flame;
- -Calculation of view factor using numerical integration
- -Modeling of radiative heat fluxes (incident and net)
- -Modeling of the average temperature at the TPV absorber surface.

B. Modeling of the flame

The combustion flame as summarized by [6, 7] can be modeled using conical or cylindrical approach in order to describe the reality. In this work, the flame geometry is modeled using a radiant cylindrical model (see figure 2) subdivided into 20 layers on the vertical direction each layer having a define temperature.

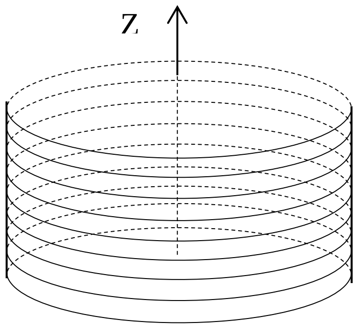

Fig. 2:- Modeling of the flame using cylindrical approach [6, 7]

From this geometrical model of the flame, parameters that characterized combustion flame such as the flame length and the flame temperature can be modeled as shown in [8, 9] as follow:

$$L_f = -1{,}02D + 0{,}0148Q^{\frac{2}{5}} \quad (1)$$

Where L_f is the flame length, m; D is flame diameter, m; Q is heat flux flow, w.

In equation (1) above, the heat flux flow is calculated as follow:

- For the flame development phase,

$$Q = RHR_f * A_{fi} * \left(\frac{t}{t_\propto}\right)^2 \quad (2)$$

RHR_f: maximum heat flux flow per unit of area of flame, KW/m2

A_{fi}: maximum surface flame area, m2

t: time, s

$t_\propto$: necessary time to attend maximum heat flux flow, s

-steady state phase,

$$Q = RHR_f * A_{fi} \quad (3)$$

- decrease flame phase,

$$Q = RHR_f * A_{fi} * \left(1 - \frac{t - t_{red}}{t_{fin} - t_{red}}\right) \quad (4)$$

With:

$$t_{red} = t_\propto + \frac{0{,}7q_{fi}}{RHR_{fi}} - 0{,}33t_\propto \quad (5)$$

$$t_{end} = t_{red} + 2 * \left[\frac{q_{fi}}{RHR_{fi}} - 0{,}33t_\propto - (t_{red} - t_\propto)\right] \quad (6)$$

$$q_{fi} = \frac{M_i * H_{ui}}{A_{fi}} \quad (7)$$

q_{fi}: load heat density per unit area, MJ/m^2

M_i: nut palm shells weight, Kg

H_{ui}: lower calorific power, MJ/Kg

t_{red} : time corresponding to the flame reduction phase, s

t_{end} : ending time of combustion, s

The temperature profile of the combustion flame is giving by

$$T_z = 20 + 0{,}25Q_c^{\frac{2}{3}}(z - z_o)^{-\frac{5}{3}} \quad (8)$$

Where

Tz is the flame temperature, °C;

Q_c: is the convective component of heat flux flow calculated as:

$$Q_c = 0{,}8Q, \text{ W}$$

z: elevation along the flame axis, m, (see figure 3)

z_0 is the virtual origin position , m given by

$$z_0 = -1{,}02D + 0{,}00524Q^{\frac{2}{5}} \quad (9)$$

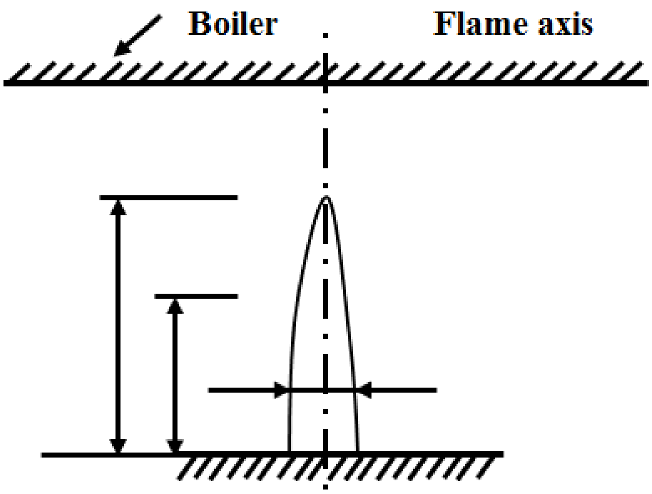

Fig. 3:- Flame modeling [8, 9]

C. Calculation of view factor using numerical integration

View factor is dimensionless factor that determines how much of a surface is visible to another surface and is a pure geometric property. According to [10, 11] view factor between two surfaces is defined using figure 4 below as:

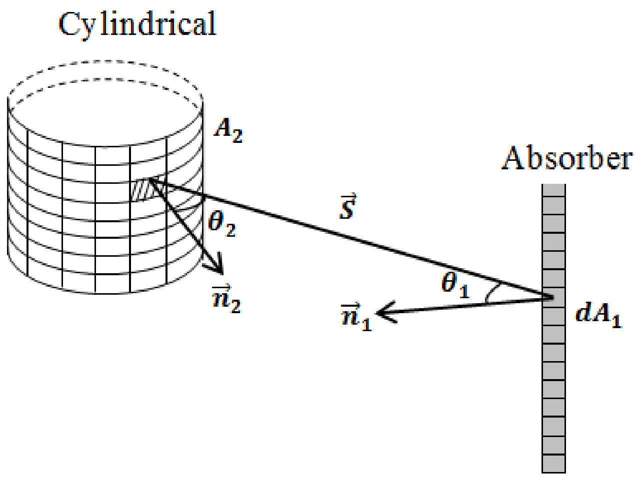

Fig. 4:- Radiation exchange between two surfaces [12]

$$F_{d1-2} = \int_{A_2} \frac{\cos\theta_1 \cos\theta_2}{\pi S^2} dA_2 \qquad (10)$$

Using transformation as in [13] we have:

$$\cos\theta_1 = \frac{\vec{S}.\vec{n_1}}{S}$$
(11)

$$\cos\theta_2 = -\frac{\vec{S}.\vec{n_2}}{S} \qquad (12)$$

Where :

$\vec{n_1}$: is unit vector normal of the elementary surface dA_1

$\vec{n_2}$: is unit vector normal of surface A_2

$\vec{S}$: vector between the two surfaces dA_1 and A_2

S: seperation distance of vector $\vec{S}$

F_{d1-2}: is the view factor between the two surfaces

Combining equatiions (11) and (12), we obtained

$$\frac{\cos\theta_1 \cos\theta_2}{\pi S^2} = -\frac{(\vec{S}.\vec{n_1})(\vec{S}.\vec{n_2})}{\pi S^4} \qquad (13)$$

By remplacing equation (13) into (10) and transforming the integral into discrete sum, yield

$$F_{d1-2} \cong \frac{-1}{\pi} \sum_i \frac{(\vec{S}.\vec{n_1})(\vec{S}.\vec{n_2})}{S^4} \Delta A_i \qquad (14)$$

Equation (14) is solved using numerical method.

D. Modeling of radiative heat fluxes (incident and net)

Radiative heat fluxes between two surfaces $dA1$ and $dA2$ are calculated as in [11] as follow:

$$Q_{d1-2} = \sigma\varepsilon^*(T_1^4 - T_2^4) dA_1 F_{d1-2}$$
(15)

Where

ε^* :is the equavalente emissivity , define by : $\varepsilon^* = \frac{\varepsilon_{flame}\varepsilon_{absorber}}{\varepsilon_{flame}+\varepsilon_{absorber}-\varepsilon_{flame}\varepsilon_{absorber}}$ (16)

σ: Constant of Stefan-Boltzmann (5.67*10^-8 W/m2.K4)

T_1 : is the flame temperature, $°k$

T_2 : is the absorber temperature, $°k$

Thus, the net radiative heat flux received by the absorber is calculated as

$$q_{d1-2} = \frac{Q_{d1-2}}{dA_1} = \sigma\varepsilon^*(T_1^4 - T_2^4) F_{d1-2}$$
(17)

In general, the net radiative heat flux on an absorber divided into m cells is given by

$$q_{rad,df_j} = \sum_{k=1}^{m} \sigma\varepsilon^* \left(T_{fi,k}^4 - T_{fi,j}^4\right) F_{df_j-k}$$
(18)

Where

$T_{fi,k}$: is the flame temperature at shell k; $°k$

$T_{fi,j}$: is the absorber temperature at shell j; $°k$

F_{df_j-k}: is view factor between shell j of absorber and shell k of flame.

From equation (20) the temperature of the absorber at shell j is been replaced by the average temperature T_c , hence :

$$q_{rad,df_j} = \sum_{k=1}^{m} \sigma\varepsilon^* \left(T_{fi,k}^4 - T_c^4\right) F_{df_j-k} \qquad (19)$$

The incident flux is given by: $q_{inc} = \sum_{k=1}^{m} \sigma\mathcal{E}_{fi} T_{fi,k}^4 F_{df_j-k}$ (20)

E. Modeling of the average temperature at the TPV absorber surface

From the first principle of thermodynamics, we have:

$$Q + \dot{W} = \dot{U} \qquad (21)$$

where

Q: is the total heat flux exchange

$\dot{W}$: is the total work done by the absorber
$\dot{U}$: is the change of internal energy
Considering that the total work done by the absorber is negligible, equation (24) becomes:

$$Q = \dot{U} \tag{22}$$

The balance heat as shown in the figure 6 below [10]:

$$q = q_{in} - q_{out} \tag{23}$$

where q_{in}=$q_{ra,flame}$, radiant heat from the flame and q_{out}=$q_{ra,air}$+q_{conv}, heat lost from radiant heat of air and convection. Equation (26) become

$$q = q_{ra,flame} - q_{ra,air} - q_{conv} \tag{24}$$

with,

$$q_{ra,feu} = \sum_{k=1}^{m} \sigma\varepsilon^* \left(T_{fi,k}^4 - T_c^4\right)F_{df_j-k} \tag{25}$$

$$q_{ra,air} = \sigma\varepsilon_a(T_c^4 - T_{air}^4)F_{compl} \tag{26}$$

$$q_{conv} = \alpha_c(T_c - T_{air}) \tag{27}$$

with $\propto_c = 1{,}78\Delta T^{0{,}25}$

The general equation when dividing the cylinder flame into m sections is:

$$q = \sum_{k=1}^{m} \sigma\varepsilon^* \left(T_{fi,k}^4 - T_c^4\right)F_{df_j-k} - \sigma\varepsilon_{abs}(T_c^4 - T_{air}^4)F_{compl} - \alpha_c(T_c - T_{air}) \tag{28}$$

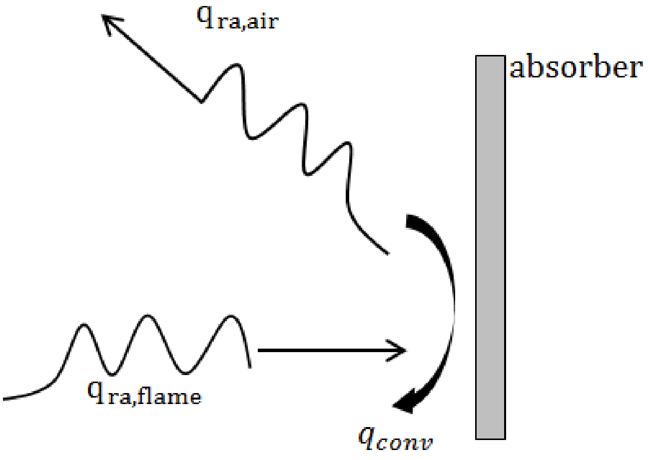

Fig. 5:- flux modeling

$$\dot{U} = \rho_{abs}c_pV\frac{dT}{dt} \tag{29}$$

where
ρ_{abs} : absorber density, kg/m^3
c_p : specific heat capacity, J/kgK calculated as in [9]
V : volume of the absorber, m^3
T : temperature, K
t: time , s

$$\rho_{abs}c_pV\frac{dT}{dt} = A_s\left[q_{ra,flame} - q_{ra,air} - q_{conv}\right] \tag{30}$$

$$\rho_{abs}c_pV\frac{dT}{dt} = A_s\left[\sum_{k=1}^{m} \sigma\varepsilon^*\left(T_{fi,k}^4 - T_c^4\right)F_{df_j-k} - \left[\sigma\varepsilon_{abs}(T_c^4 - T_{air}^4)F_{compl}\right] - \left[\alpha_c(T_c - T_{air})\right]\right] \tag{31}$$

$$\rho_{abs}c_p\frac{dT}{dt} = \frac{A_s}{V}\left\{\sum_k \sigma\varepsilon^*\left(T_{fi,k}^4 - T_c^4\right)F_{df_j-k} - \sigma\varepsilon_{abs}(T_c^4 - T_{air}^4)F_{compl} - \alpha_c(T_c - T_{air})\right\} \tag{32}$$

A_s: total surface of absorber

By using the forward finite difference method, equation (36) becomes

$$\rho_{abs}c_p(T)\frac{T_c^{t+1} - T_c^t}{\Delta t} = \frac{1}{V}\left\{A_s\sum_k \sigma\varepsilon^*\left(T_{fi,k}^4 - T_c^4\right)F_{df_j-k} - A_s\left(\sigma\varepsilon_{abs}(T_c^{4t} - T_{air}^4)F_{compl}\right) - A_s\left(\alpha_c(T_c^t - T_{air})\right)\right\} \tag{33}$$

RESULTS

From the models obtained, we run simulations in other to evaluate and analyze radiative heat fluxes at the surface of a TPV absorber for different cases. The absorber is divided in six sections of fifty centimeters on the elevation direction. Parameters used in these simulations are presented in table 1 below:

Parameters	Values
ρ_{abs}	2700, Kg/m^3
ρ_{air}	1.183, Kg/m^3
$\varepsilon_{absorber}$	0.92
ε_{flame}	1
σ	5.67*10^-8 ,W/m^2.K^4
M_i	100, Kg
H_{ui}	20*10^6, J/Kg
RHR_f	1000*10^3, KW/m^2
D	1, m

Table 1:- Operating parameters used in this study [5].

Case 1: In this first case we considered that the distance between the absorber and cylindrical flame is 1meter. We presented the net heat flux received at the absorber, and analyzed the effect of convection on the incident heat flux.

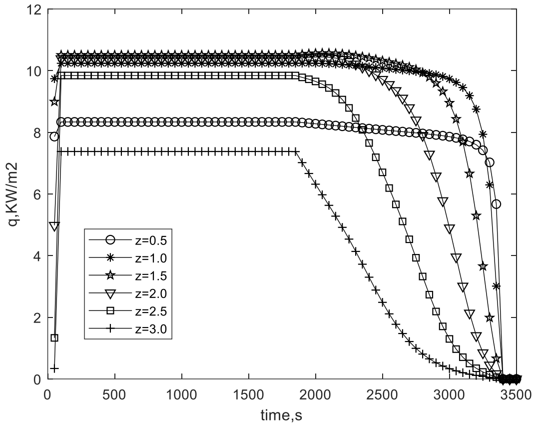

Fig. 6a:- incident heat flux profile without convection

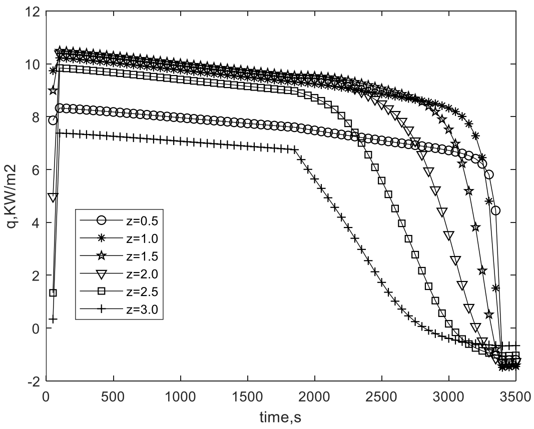

Fig. 6b:- incident heat flux profile with convection

From figure 6a shown above, the incident heat flux profile at the TPV absorber without convection is presented with time. Each curves in figure 6a represented the incident heat flux profile of each section of the absorber. We observed that each curve described the three phases of the flame which are: the flame development phase, steady state phase and decrease flame phase. It can also be seen that incident heat flux is more important at the centre region of the absorber particularly at position 1, 1.5and 2 meters than others positions. This corroborate with the cylindrical flame model. The range of the incident heat flux at the centre region is between 10 and 10.5 KW/m^2.

In figure 6b, the incident heat flux profile with convection is presented along the six sections of the absorber with time. We observed that the steady state phase decreases rapidly than that observed in figure 6a and that its end points are located in the negative value region comprise between 0 and -2 meters. This is because at the absorber surface the incident heat flux arriving is reduced by the effect of convection.

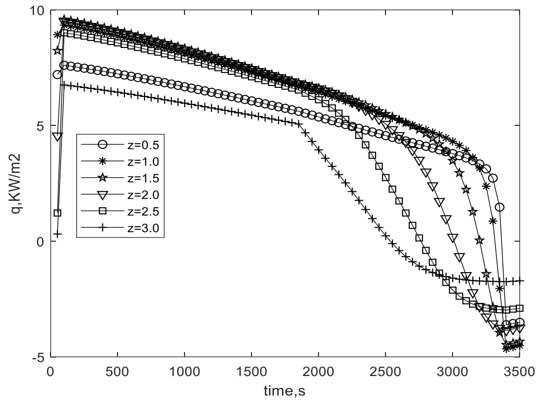

Fig. 7:- net heat flux profile at the TPV absorber surface

In this figure, we observed that the steady state phase decreases rapidly than that observed in figure 6b. Moreover, the end points values in this case are ranged between 0 and -4.8. This is due to the heat lost by convection and radiation at the absorber surface. It can also be seen that the maximum heat flux obtained in this case is ranged between 8 and 9 KW/m^2 which are less than that obtained in figures 6a and 6b.

Case 2 In this case, we now considered that the distance between the absorber and cylindrical flame is 2 meters. Net heat flux and incident heat with and without convection are presented as above.

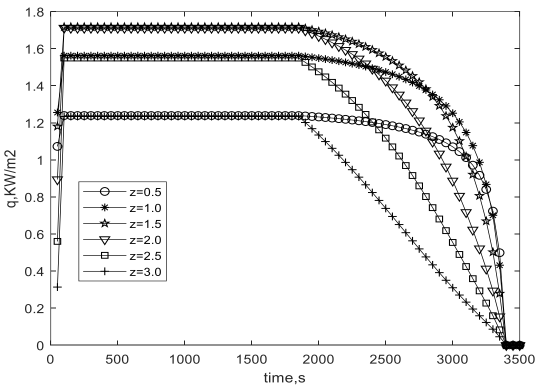

Fig.8a:- incident heat flux profile without convection

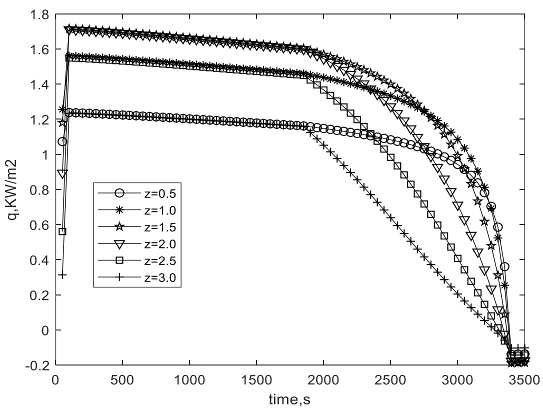

Fig. 8b:- incident heat flux profile with convection

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Figures 8a and 8b represented the incident heat flux with and without convection respectively for a position of two meters between the absorber and the cylindrical flame. It is shown that for this position the maximum heat fluxes obtained are almost 1/6 of those obtained in figures 6a and 6b respectively. This result shows the impact of the position of the absorber on the heat flux.

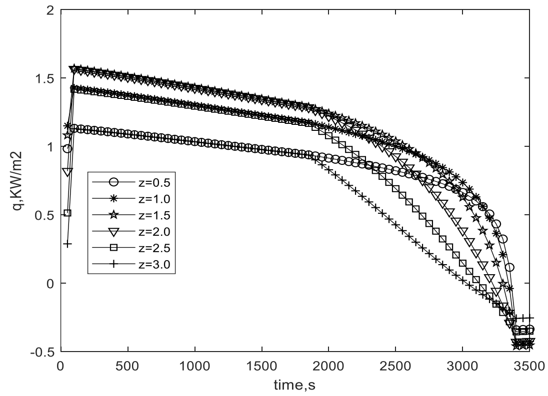

Fig. 9:- Net heat flux profile at the TPV absorber surface

As explained earlier, figure 9 shows the impact of the position of the on the net heat flux profile. It can also be seen that the maximum heat fluxes obtained at 2 meters is smaller than those in figure 7. This result shows that the optimum position at which heat fluxes are greatest is 1 meter. At this position we presented the average temperature profile at the absorber surface as can be seen in figure 10 below.

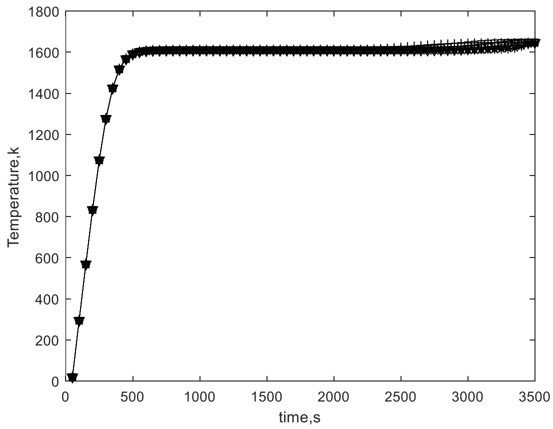

Fig. 10:- Average temperature profile at the absorber surface

Figure 10 represents the average temperature profile received at the absorber surface. It can be observed that the temperature increase from 0 to 1600K in less than 500 seconds and stabilised at this value until 3500 seconds. The maximum temperature of 1600K obtained during this simulation shows that the waste energy from the combustion of palm nut shells can be used as a radiative source of a TPV system. Because, from the open literature it is shown that a typical TPV radiative heat source is normally comprised in the range 1000–1800 K [14].

CONCLUSION

In this work, the waste heat energy resulting from the combustion of palm nut shells has been exploited as a radiative heat source for a TPV absorber system. For that we modeled the flame of combustion using cylindrical approach. Simulations were performed to evaluate the incident and net heat fluxes at the surface of the absorber. The effect of convection and radiative heat lost as well as the position between the absorber and the cylindrical flame, on the heat fluxes profile were analyzed. It comes out that the optimum position where the heat fluxes are maximum is 1 meter. Moreover, combustion heat lost has an impact on the heat flux. The average temperature was also presented. Finally, results obtained from the numerical simulations shows that radiative waste heat energy from the palm nut shells combustion can be used as radiative heat source for a TPV system.

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