The Parameters Change with Different Operation Conditions of Solar Chimney Power Plant Model

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Abstract- **The solar chimney power plant is one of the modern models studied on the world. This study presents an engineering and numerical analysis of solar chimney with different parameters. Also, it studies the comparison of two collector base shapes(circular and hexagonal) depend on the five storage material types and their effects on the heat transfer, velocity, efficiency, etc. inside the solar chimney system by considering the solar array intensity equations and the energy equation to calculate the heat transferred and stored by applying the laws of CFD. The finite volume method is used to analyze the geometry physical model by applying a commercial Fluent 6.3 code with Gambit 2.3. The obtained results show that the efficiency of solar chimney is increased by increasing the area of solar glassed collector with circular base shape than the others of polygonal or rectangular one because the circular was covered large area of system. So, the circular ground collector shape for thermal storage is the favour because it is the better to increase the velocity of entering air and to increase the efficiency of turbine. In addition to that the black Pebble storage plate is the better material for heat storage which is convected to air passed for operation of turbine than the other types aluminum, tar, copper and steel seriously.**

Keywords: solar energy, power tower, power chimney, renewable.

I. Introduction

The evolution of life and industry make the demand for fuel and energy increases, and has become necessary to think seriously and alternative energy. Solar energy one of the most alternative energies where there is (cheap price, available widely and there is no side effects on the environment or to humans and other neighborhoods).

The most important application of solar energy is the solar chimney, which principle work is the basic change in the density of the air inside the solar collector after exposure to solar radiation directly from the sun which reduces its density rises upwards and rotates the turbine at the entrance of the chimney . The most important means to increase the efficiency of solar chimney is a plate type Storage where it stores the heat inside during exposure to radiation, which contributes to increase the temperature of the air inside the solar chimney.

The design of solar chimney was produced by professor Schaich in 1978 [1].Before 1980, the design was built in Manzanares, Spain. The first one to describe the principles and construction of the pilot plant was Haff in 1984 by large plants design in Manzanares [2].

In 1997, a chimney was built in Florida University [3] and in Turkey by Klink [4].

The temperature and pressure for air in solar chimney have been more investigation and simulations by Lodhi [5], Pastohr et al. [6], Schlaich et al. [7].

Chaichan.M.T. was presented practical results of a prototype of a solar chimney by basement kind effects on air temperature of a Solar Chimney [8]. Hannun et. al. [9] presented a numerical study to predict the parameters of solar chimney and concluded that the position of chimney is very suitable for promoting and building the power turbine since the air velocity range inside the chimney was between (33 - 54 m/s) for different solar flux. Backstrom and Fluri [10] developed two analyses for finding the optimal ratio of turbine pressure drop to available pressure drop in a solar chimney power plant to be 2/3 for maximum fluid power and using the power law model for this prediction. Tingzhen et. al. [11] carried out numerical simulations on the solar chimney power plant system which divided into three regions: the collector, the chimney and the turbine, and the mathematical models of heat transfer and flow had been setup for these regions. Ming et. al. [12] performed to analyze the characteristics of heat transfer and air flow in the solar chimney power plant system with an energy storage layer. They used different mathematical models for the collector, chimney and the energy storage and the effect of solar radiation on the heat storage characteristic of the energy storage layer. Nizetic et. al. [13] analyzed the feasibility of solar chimney power plants for small settlements and islands of countries in the Mediterranean region; they used 550 m height of chimney with collector roof diameter of 1250 m to produce 2.8 – 6.2 MW of power.

In this study we are trying to investigate the effect of many available materials which give us the biggest energy storage, and provided that they are cheap and easily obtained, as well as a fundamental prerequisite to be environmentally friendly and does not have any contaminants(Renewable and no fuel ,no combustion). So, The validity of this study provides a numerical analysis code compared with MATLAP program.

2. Physical model

The case study model design is done by the comparison of the chimey systems on the world. The collector base diameter is 4 meter, hieght of glass collector 0.1175 meter, chimney diameter 0.047 meter of 12 meter hieght (as shown in Fig. 1).Many researchers studied the phase change materails (such as wax) but in this study there are five types of storage materials, the black Pebble, aluminum, tar, copper and steel. So, two glass collector design is done; circular and hexagonal shape. Storage material specification used in the power plant model is in table (1):

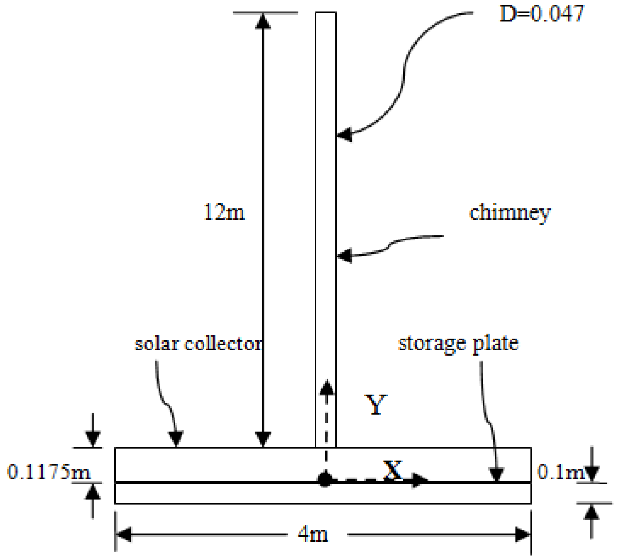

Fig. 1 Physical model

Table (1) the storage material specifications

martial	Density kg/m^3	Specific heat energy kJ/kg.k
Black pebble	2080	0.84
Black steel	7850	0.49
Tar	1153	1.47
Black Aluminum	2712	0.91
Black Copper	8940	0.39

3. Mathematical Models:

The presented analysis in this paper is based on the following simplifying assumptions:

1. Uniform heating of the solar collector surface and storage plate.
2. No heat loss from the chimney walls.
3. the storage plate is insulated from ground .
4. The frication loss of air in solar chimney is negligible .
5. The density and temperature variation of air in solar collector is linear[14]

The storage plate can be represented as the following showing in the block diagram of Fig. (2):

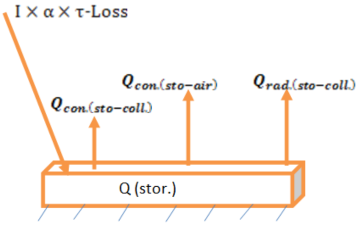

Fig. 2 thermal analysis of storage plate

By applying general low for energy conservation:

$$E^o_{in} + E^o_g - E^o_{out} = E^o_{sto.} \quad \ldots\ldots\ldots\ldots\ldots (1).$$

$(I\times \alpha \times \tau\text{- Loss})=Q_{Con.(sto.\text{-inside air})}+ Q_{Con.(sto.\text{-coll.})} + Q_{Rad..(sto.\text{-air})} + Q_{Storage\ plate}$ (2)

Where :

Let : $\alpha \times \tau= 0.9$

$Loss=\sigma(T^4_{coll.}\text{- }T^4_{out})+h_{wind}(T_{coll.}\text{-}T_{out})$ (3)

The wind convection heat transfer is [15]:

$h_{wind}=5.47+3.95\times V_{wind}$ (4)

$Q_{Con.(sto.\text{-inside air})}=h_{Con.(sto.\text{-inside air})}\ (T_{stor.}\text{-}T_{mean})$ (5)

$Q_{Con.(sto.\text{-coll.})} =h_{Conv.(sto.\text{-coll.})}\ (T_{stor.}\text{-}T_{coll.})$ (6)

$Q_{Rad..(sto.\text{-coll})} =h_{Rad.(sto.\text{-coll.})}\ (T_{stor.}\text{-}T_{coll.})$ (7)

Where the radiation heat transfer coefficient between the storage plat and the collector is [16]:

$$h_{Rad.(sto.\text{-coll.})} = \frac{\sigma(T_{Collector}+T_{Storage\ Plate})(T^2_{Collector}+T^2_{Storage\ Plate})}{(1/\epsilon_{Collector})+(1/\epsilon_{storage})-1} \quad (8)$$

The convection heat transfer coefficient between storage plate and the inside air and between the storage plat and the collector is [17]:

$h_{Conv.(sto.\text{-inside air})}=h_{Conv.(sto.\text{-coll.})}= =(K_{mean}/d_h)\times Nu_{mean}$ (9)

The Nusselt's number can be represented by [16]:

$Nu_{mean}=0.5\times Ra^{0.25}$ for $2\times10^4<Ra<8\times10^7$ (10)

$Nu_{mean}=0.15\times Ra^{0.33}$ for $8\times10^7<Ra<8\times10^{11}$ (11)

The collector has a circular geometry with radius(R) and height (h) , the hydraulic diameter is [18]:

$$d_h = \frac{4(2\pi R\times h)}{2(2\pi R+h)} \cong 2h \ldots\ldots\ldots\ldots\ldots (12).$$

The Rayleigh number can be found from [17] :

$$Ra = Gr\ Pr = \frac{g\beta(T_{stor.}-T_{mean})d_h^{\,3}}{\nu^2}\ Pr \ldots\ldots(13).$$

The coefficient of volumetric thermal expansion (β) can be found from :

$$\beta = \frac{1}{T_{mean}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14).$$

Where the (T_{mean}) is the mean temperature of air inside collector can be found from [19]:

$$T_{mean} = \sqrt[3]{\frac{(T_{Coll.}+T_{Storage})(T^2_{Coll.}+T^2_{Storage})}{4}} \quad (15)$$

The energy storied in storage plate is:

$Q_{sto.}=m_{materail}\times C_{materail}\times\frac{(T_{sto.}-T_{mean})}{dt}$ (16)

Now sub. Eq(3), Eq(5), Eq(6), Eq(7), and Eq(16) in Eq(2) :

$I\times \alpha \times \tau\text{- }\sigma(T^4_{coll.}\text{- }T^4_{out})\text{-}h_{wind}(T_{coll.}\text{-}T_{out}) = h_{Conv.(sto.\text{-inside air})}(T_{stor.}\text{-}T_{mean}) + h_{Conv.(sto.\text{-coll.})}(T_{stor.}\text{-}T_{coll.})+ h_{Rad.(sto.\text{-coll.})}(T_{stor.}\text{-}T_{coll.})+$

$m_{materail}\times C_{materail}\times\frac{(T_{sto.}-T_{mean})}{dt}$ (17)

The efficiency of solar collector is given below [20]:

$$\eta_{Coll.} = \frac{(I \times \alpha \times \tau) - Loss}{I} \ldots\ldots\ldots\ldots.. (18).$$

The maximum mechanical power taken up by the turbine[20] :

$$P_{max.} = \left(\frac{2}{3}\right) \times \frac{\eta_{Coll.} \times g \times H_{Ch.} \times A_{Coll.} \times I}{C_P \times T_o} \ldots.. (19).$$

The air velocity in chimney can be found as (approximation for ideal gas)[21]:

$$V_{Ch.} = \sqrt{\frac{2 \times g \times H_{Ch.} (T_{exit\,Coll.} - T_{inlet\,Coll.})}{T_{inlet\,Coll.}}} \ldots (20).$$

let : $T_{inlet\,Coll.} = T_{out}$, $T_{exitColl} = T_{inlet\,Ch.}$

Where:

$T_{exitColl.} = 2T_{mean} - T_{inletColl\ldots}$ (21)

4. Results and Discussion:

4-1. MATLAP results

The results of this paper are done by using MATLAP program by substituting the values of materials that mentioned in physical model for Nasiriya city (Iraq) conditions. So, the results are done for three different days of year (January, March and July). MATLAP program is done according to flow chart(as shown in Fig.18) . By using eq.(17) the temperature of storage plate of five materials can be found as shown in Fig.(3.,4and 5) . The temperature of the black pebble storage material is the largest than others because the value of ($m_{material} \times C_{material}$) is low while it is high for steel in comparison with aluminum, tar and copper. This means that the solar chimney system might accumulate high heat storage at the same time to raise the temperature of air pass throughout the chimney by decreasing the density of neighboring air and increase its velocity (as shown in Fig.6,7 and 8) by using eq.(20).We note the velocity of air with black pebble storage plate is the largest than others because the heat transfer from storage plate to neighboring air is more than others.

The circular and hexagonal shape for collector have indicated the obvious difference of maximum mechanical power (as shown in Fig.9,10 and 11) for black pebble storage material, the maximum mechanical power of circular collector is higher than that for hexagonal because the area of circular collector is higher than that for hexagonal.

4-2. CFD computer code results

The computational fluid dynamics (CFD) are used in this paper as by finite volume method with FLUENT 6.3 and GAMBIT code. The solar chimney power plant system model was designed by using GAMBIT to reach the number of nodes 87226, the mesh was cooper scheme type of size 0.03 examined by using the normal methods of code. So, exporting the mesh to FLUENT with using three dimensional density based model, implicit, steady, realizable k-ε turbulent model, discrete transfer radiation model (DTRM), solar ray tracing. The glass canopy is used as semi-transparent material but the storage base and chimney are oblique material for processing of solar flux passing through the system. Two cases were processed by the computer as minimum expected solar power flux on the location of Nasiriya city 200W/m^2, and maximum value 800W/m^2[9].

Fig. 17 denotes the average temperature values for the two cases of solar flux on the vertical axis Y of domain, the 200W/m^2 system gives increase temperature range from the base to cover (0-325)K, but was (0-341)K for the second case model (800W/m^2), the chimney has a constant average temperature because there is no accumulation of heat inside it(the velocity change is very low). These ranges of temperature support the previous results of this paper. So, the temperature ranges of whole domain demonstrated in Fig. 13 which show the low range at the inlet vent of chimney since the air temperature was low before the inlet. The maximum temperatures are at the canopy edge as a result to interring the arrays and at the storage plate because it stores and reflect the arrays to the neighboring air inside the chimney base. The air layer between the cover and base has gradually temperature degrees. The temperature range of the system is closed to the temperature of present study found by MATLAB program and the previous study [8] that shown in Fig.12.

Fig. 14 shows the steady solar heat flux of system for both cases of beam solar flux. The minimum heat flux was below the storage layer because it is thermally insulated. Then the temperature was increased at the storage edge since it absorbs the heat. The curve of temperature trends to decrease at the mid space between the storage and glass cover as a result to low heat gain of air. The temperature of glass canopy is the largest because the solar heat flux is highest since the absorptivity, reflectivity and transmissivity properties of glass. These temperature gradients were offered in Fig. 15 for both study cases 200 and 800W/m^2. The pathline of air flow of domain is demonstrated in Fig. 16 which indicates the air velocity inside the chimney system.

5. Validity of work:

It may be validate this study by comparing some results with previous studies. A previous study [8] was on 15 September in Baghdad city for Chimney's dimension: (0.2m Chimney's diameter, 6m Collector's diameter) for black pebbles storage while present study was on 14 March. It is observed that the temperature curve of outflow air from the chimney for present study closed to that of previous study [8] as shown in Fig.12. The temperatures of ambient for present study were among 30-37 C^o, but for [8] were 28-36 C^o. The maximum temperature of air inside the system for present study was 54.8 C^o but was 58 C^o for previous work [8]. The range of temperature for this paper was lower than [8] because of the difference between the theoretical present study with practical previous work .

6. Conclusions

From the above results for chimney power plant design and its analysis, the following statements can be concluded:

1. The temperature inside the chimney for many designs is not more than 370 K for many studies in addition to this paper.
2. The higher temperature degrees for the system of chimney happen at the midday to the afternoon (i.e. 12.00 to 01.30 PM.) because the heat transferred by solar arrays is

vertical to the collector with low heat losses as a result to increasing the temperature of surrounding.

3. The better material was used for storage base is the black pebble because the value of ($m_{material} \times C_{material}$) is lower than aluminum, tar, copper and steel.

4. Increasing the canopy area of semi-transparent material will increase the heat stores, heat flux to the neighboring air to increase the air flow speed.

5. Curved design must be done for the joint space between the canopy and chimney to insure low friction loss of air with wall and increase the velocity of air pass throughout the chimney.

7. Nomenclature

$A_{Ch.}$=the area of chimney (m^2) .
$C_{materail}$=the specific heat energy of material (KJ/Kg.K).
d_h=the hydraulic diameter of Solar Collector (m).
E_g^o= the rate of Energy generation inside the system (W).
E_{in}^o=the rate of Energy inside the system (W).
E_o^o= the rate of Energy outside the system (W).
E_s^o= the rate of Energy stored in the system (W).
g=the gravitational acceleration constant 9.8066 (m/s^2).
h=the height of inlet solar collector (m).
$H_{Ch.}$=the Chimney's height (m) .
$h_{con.\ (stor-air).}$=the convective heat transfer coefficient for storage plate –Air inside collector ($W/m^2.K$).
$h_{con.\ (stor-coll).}$= $h_{con.\ (stor-air).}$=the convective heat transfer coefficient for storage plate –inside collector ($W/m^2.K$).
$h_{rad.\ (stor-coll).}$= the convective heat transfer coefficient for storage plate –inside collector ($W/m^2.K$).
h_{wind}=the wind heat transfer coefficient ($W/m^2.K$).
I=incident solar radiation (w/ m^2).
K_{mean}=the air thermal conductivity ($W/m^2.K$).
$P_{max.}$= The maximum mechanical power taken up by the turbine (KW).
m=the mass of material (kg).
R=the radius of solar collector (m) .
R_a=the Ralyeigh number .
t=the time (s).
$T_{coll.}$ =the temperature of cover collector (K).
T_{mean} =the mean temperature of air inside collector (K).
$T_{exit\ Coll.}$ =the temperature of air exit to Solar Collector (K).
$T_{inlet\ Coll.}$=the temperature of air inlet to Solar Collector (K).
T_{out}= the temperature of ambient (K).
$T_{sto.}$=the temperature of storage plate (K).
Q=the heat energy (W).
$V_{ch.}$=the velocity of air inlet to Chimney (m/s).
V_{wind}= the velocity of wind (m/s).

Greek Symbols:

τ = the transmittance of solar collector.
α = the absorbance of solar collector.
σ= Steven- Boltzmann constant (5.67×10^{-8}) ($W/m^2.K^4$).
ν=Kinematic viscosity of inside collector air (m^2/s).
$\epsilon_{coll.}$=emissivity of solar collector .
$\epsilon_{stor.}$= emissivity of storage plate .

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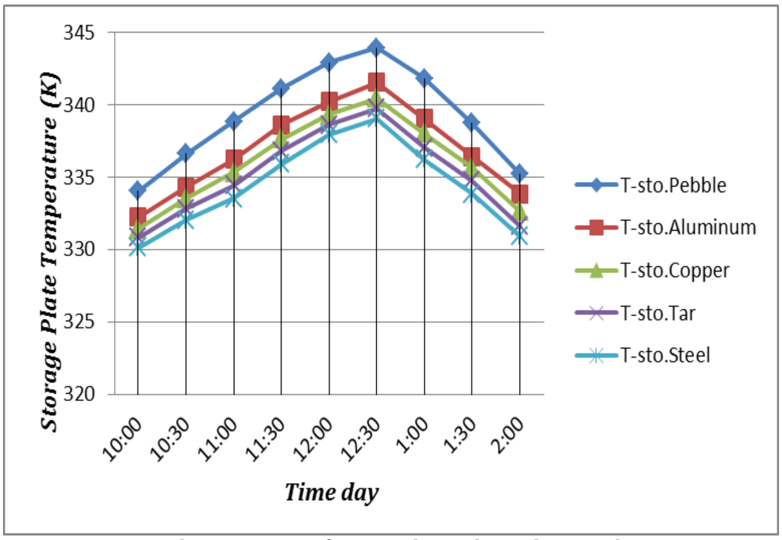

Fig. 3 The temperature of storage plate and time day at 1July

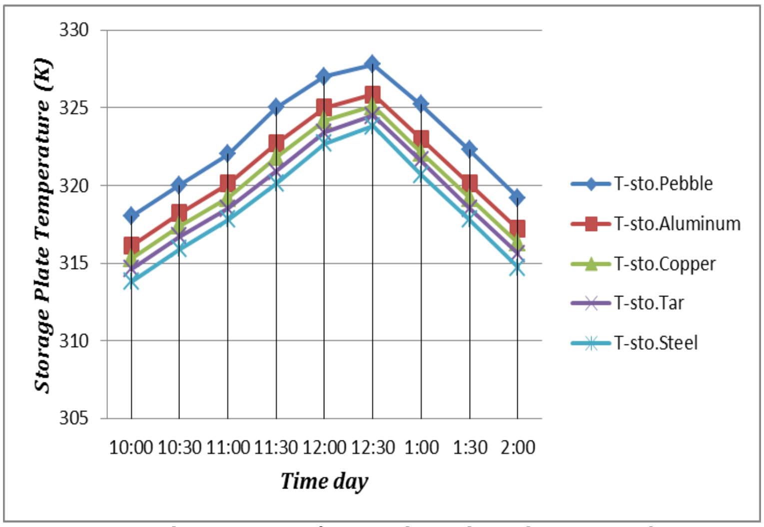

Fig. 4 The temperature of storage plate and time day at 14 March

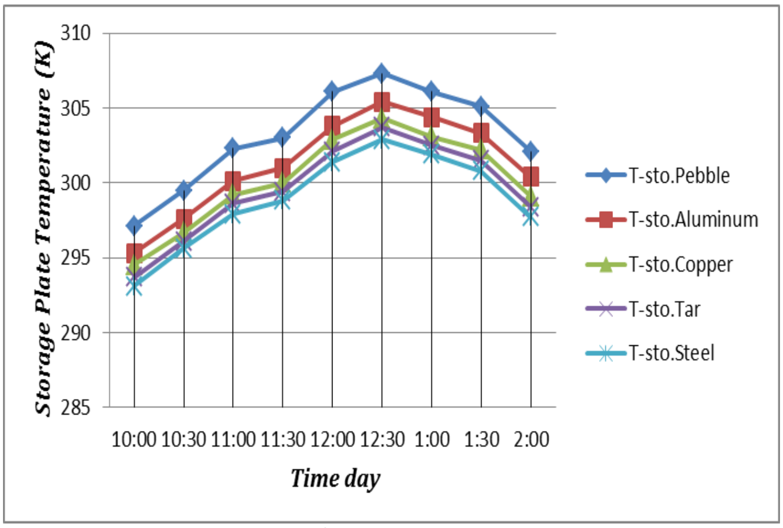

Fig. 5 The temperature of storage plate and time day at 15 January

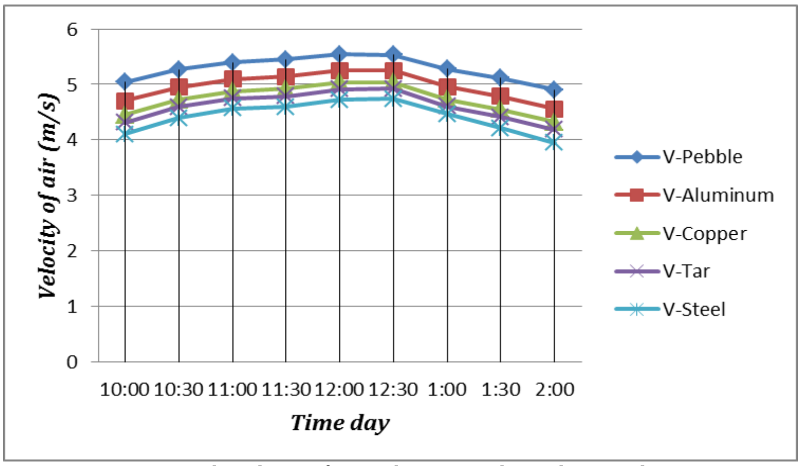

Fig. 6 The velocity of air in chimney and time day at 1July

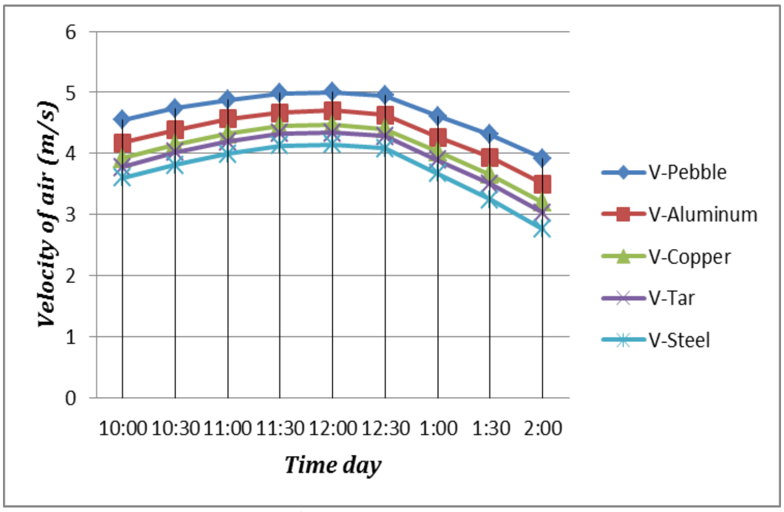

Fig. 7 The velocity of air in chimney and time day at 14 March

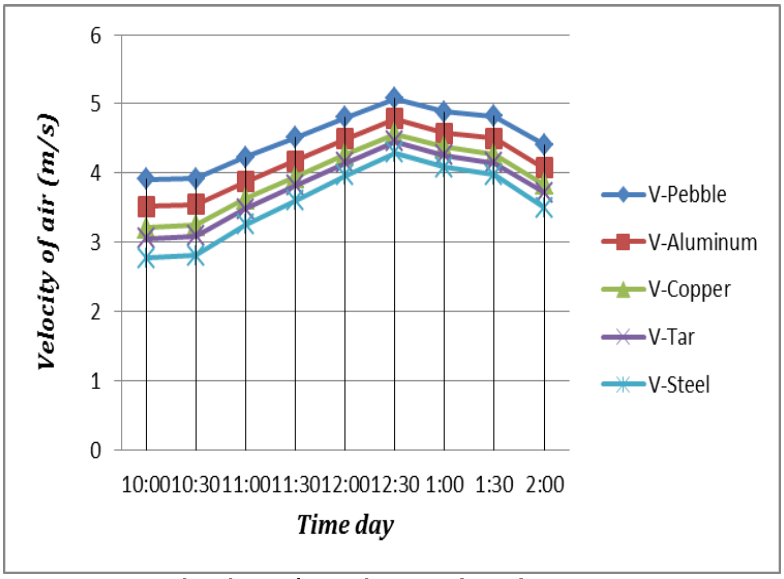

Fig.8 The velocity of air in chimney and time day at 15 January

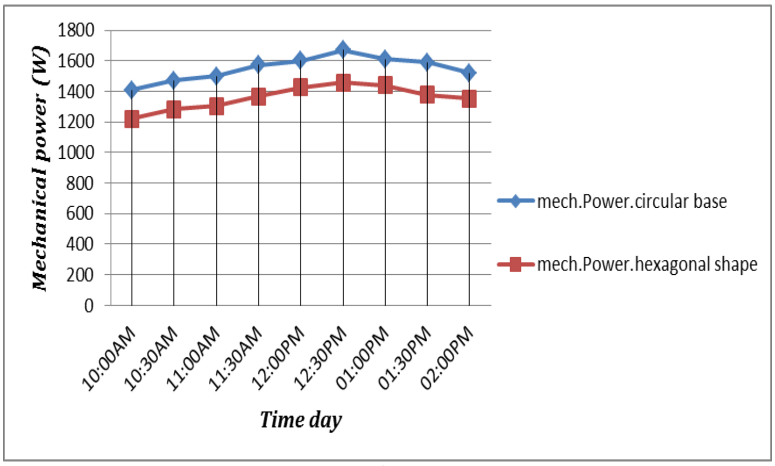

Fig.9 The mechanical power of chimney and time day at 1July

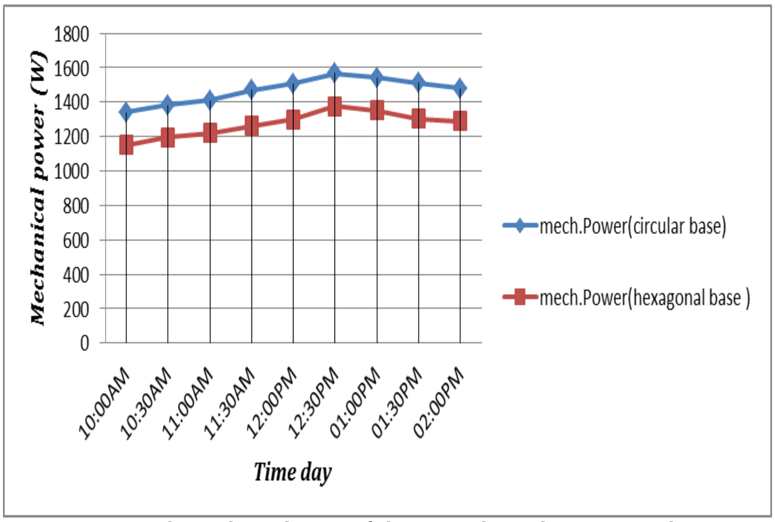

Fig.10 The mechanical power of chimney and time day at 14 March

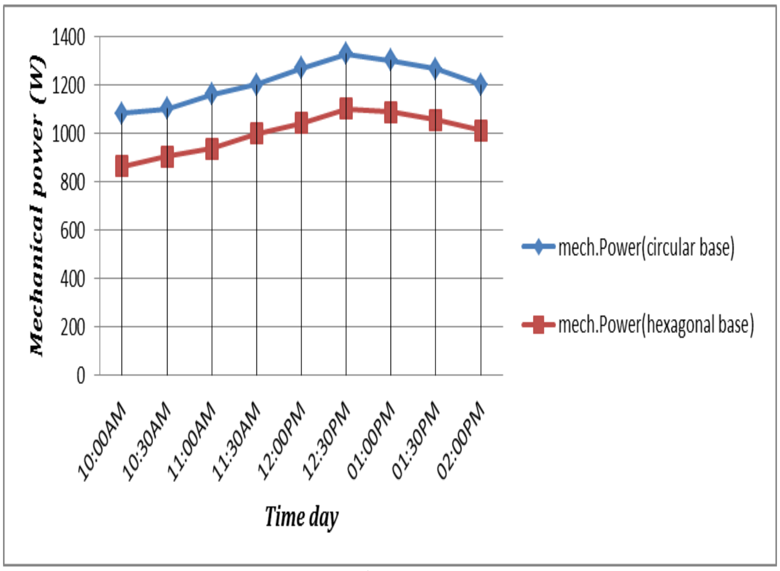

Fig.11 The mechanical power of chimney and time day at 15 January

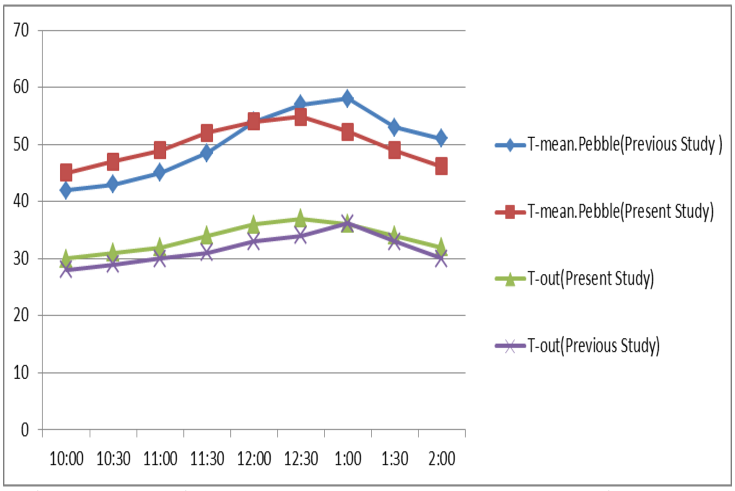

Fig.12 The temperature comparison of air in centroid of solar collector and time day with storage plate of black pebble at 14 March for present study with 15 September for previous study [8]

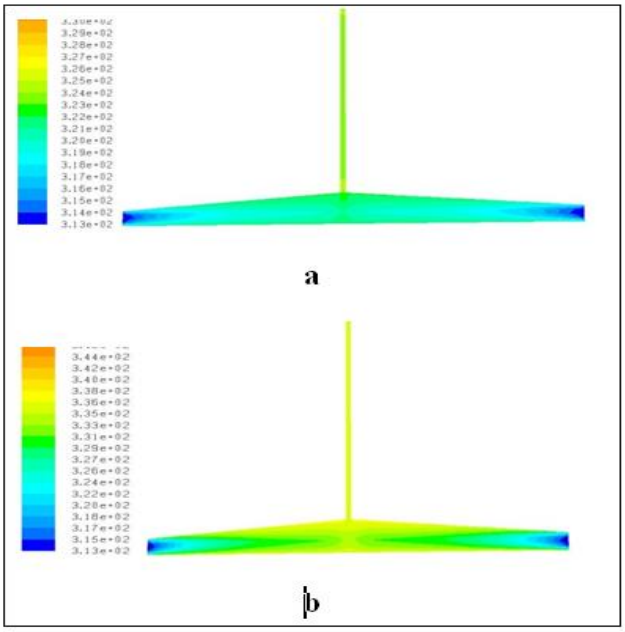

Fig. 13 Temperature contour for different solar flux a- 200W/m^2, b- 800W/m^2

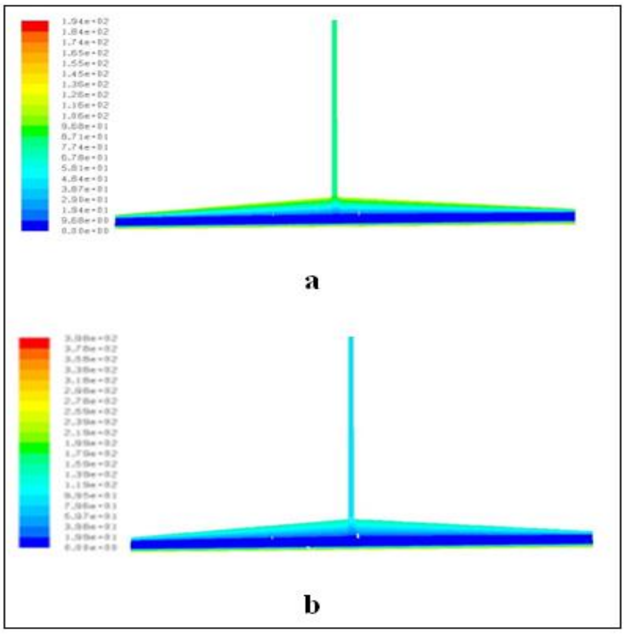

Fig. 14 Solar heat flux (W/m^2) for two cases of beam solar arrays a- at 200W/m^2, b- at 800W/m^2

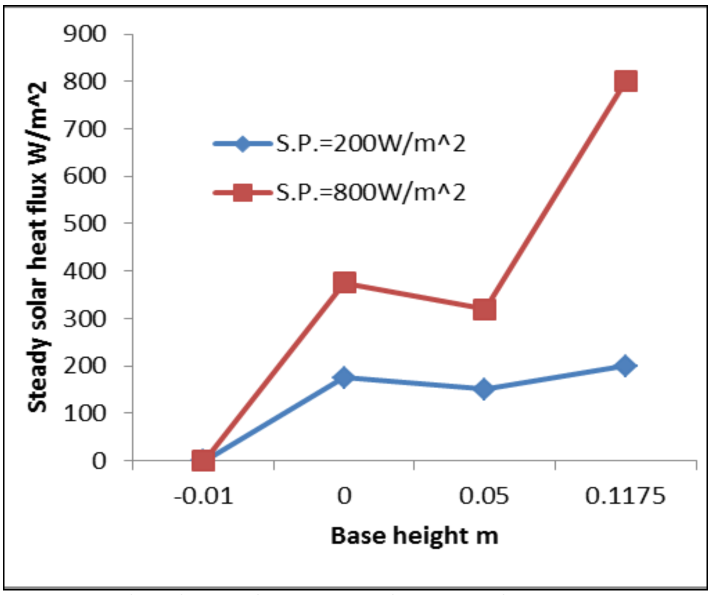

Fig. 15 The steady solar heat flux of system for both cases of beam solar flux(the coordinates according to Fig.1)

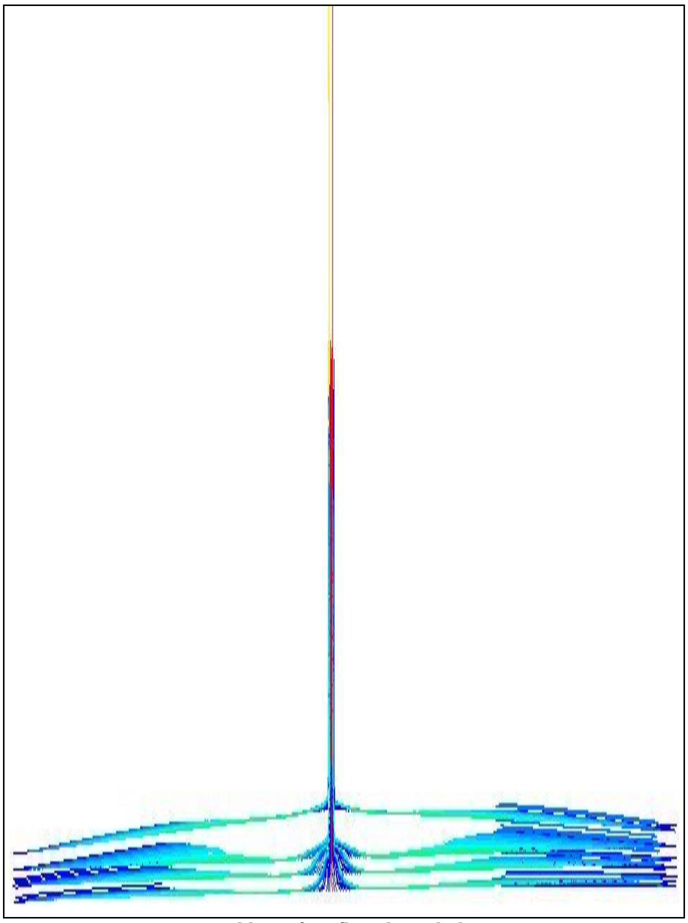
Fig. 16 Pathline of air flow through the system

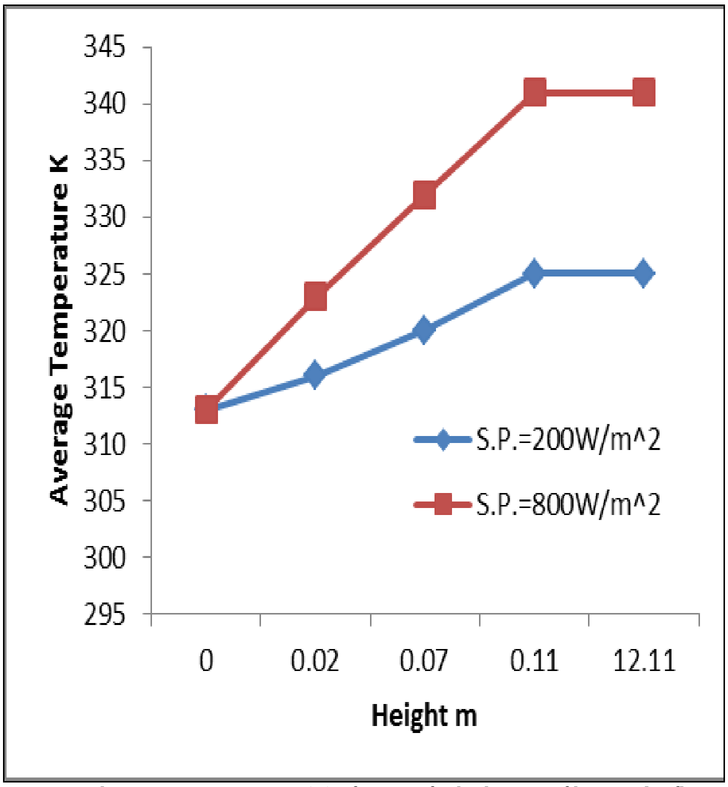

Fig. 17 The average temperature (K) of system for both cases of beam solar flux

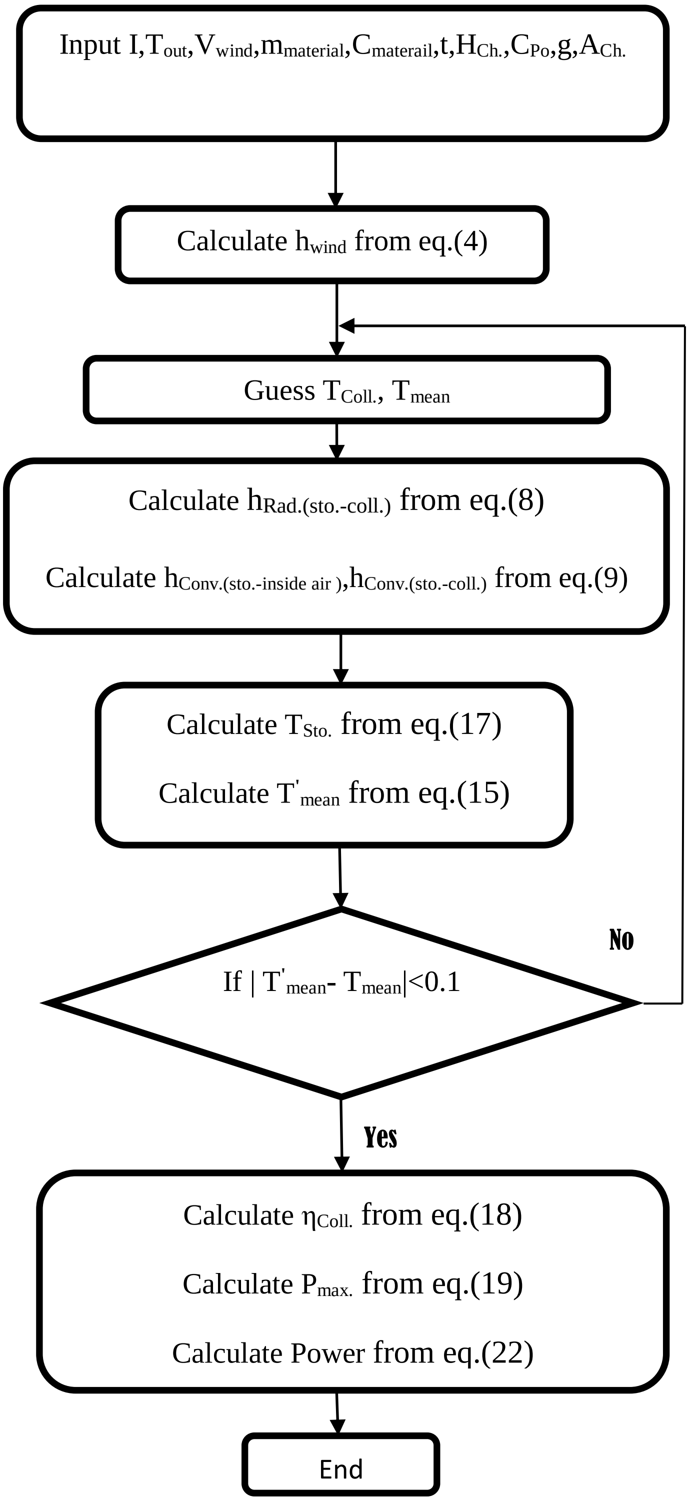

Fig. 18 Flow-chart of MATLAP Program