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Analytical Analysis of Roof Top Solar Chimney for Power Generation

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Abstract: The solar chimney is a technology, which has been already proved of being capable to generate electrical energy from the sun. On the other hand, the solar chimney has been used on the roof of housing for ventilation purpose. Since the sun is not available during night and cloudy days, there should be another source of input to guarantee continuous operation of the system. Present study is the development of experimental, computational and mathematical models of "On Roof Solar Chimney" for small-scale power generation. The objective of the present study is to review the similar works and to present a mathematical model of a solar chimney operation and analyze the analytical result. The model involves the energy and mass transportation in the system under steady state conditions. Heat transfer equations were set up to determine the boundary temperatures at the surface of the glass cover, the rear solar heat absorbing wall and the air flow in the channel using a thermal resistance network. Results showed the transient behavior of the system during the day. With model area of 15 m^2, the highest velocity of 0.17 m sec^{-1} is predicted at around the mid day time. The mass flow rate increases as the solar radiation increase. The area is a vital parameter in the successful application of the technique. Also enhancement technique to rise up the collector temperature would improve the performance considerably.

Key words: Heat transfer coefficient, mass flow rate, solar radiation

INTRODUCTION

The energy demand in the world is increasing very fast due to the increasing number of developing countries and further growth of energy consumption in developed countries has led to a global effort to develop and use alternative energies such as wind, solar, hydro, biomass, etc. Among these, sun is a primary source of energy and all form of energy on the earth are derived from it. Solar energy with its endless origin and being free from pollution and its safety use may be the answer to the energy problems of the coming centuries. It is also one of the intermittent forms of energy and therefore requires the methods of utilization, which are different from those of the conventional form of energy. If we make the solar energy as a target of day-to-day consumption of energy in various forms, then at least 60% of our energy requirements shall come from solar energy sources (Ghosh, 1997).

The solar chimney consists of a chimney coupled with a translucent collector, which heats the air near the absorbing media and guides it to the base of a tall chimney. The buoyant air ascends in the chimney and electricity is generated by the warm air moving through one or more wind turbines at the base of the chimney.

In 1981, a solar chimney power plant was built in Manzanares, Spain. Which was funded by the German Ministry of Research and Technology (BMFT), has been a significant milestone in the development of solar chimney technology, as it has motivated many researches to further study on the potential of generating power using solar chimneys.

Throughout the day, solar energy is being partially absorbed by earth surface, which is covered in part by buildings and houses. Solar chimney is an effort to develop a new technique to utilize the outside surface of houses roof to accumulate solar radiation. Suitable absorbing medium is required to be investigated for use as absorbing and storage media of solar radiation. The thermal energy will convert to kinetic energy in the adjacent air particles resulting in stream flow. By installing a transparent cover, the flow is guided to operate a Savonius wind rotor mounted horizontally on top of the structure.

In Spain 50 kW experimental plant was built which produced electricity for eight years, thus proving the feasibility and reliability of this novel technology. The chimney tower was 194.6 m high and the collector had a radius of 122 m. It produced an upwind velocity of 15 m sec^{-1} under no load conditions. Operating costs of

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this chimney were minimal. Fundamental investigations for the Spanish system were reported by Haaf (1983). In which a brief discussion of the energy balance, design criteria and cost analysis was presented. Pasumarthi and Sherif (1997) developed a mathematical model to estimate the temperature and power output of solar chimneys as well as to examine the effect of various ambient conditions and structural dimensions on the power output.

Von Backstrom and Gannon, (2000) presented a one-dimensional compressible flow approach for the calculation of all the thermo-dynamic variables as dependence on chimney height, wall friction, additional losses, internal drag and area exchange. They developed an analysis of the solar chimney including chimney friction, system turbine, exit kinetic losses and a simple model of the solar collector. The use of solar chimneys in areas as crop drying and ventilation is considered beyond the scope of the present work. Ong (2003) proposed a mathematical model of heat transfer in a steady state for a solar chimney, and contrast the model with a real solar chimney. Bernardes (2003) developed solar chimneys, aimed particularly at a comprehensive analytical and numerical model to estimate power output of solar chimneys as well as to examine the effect of various ambient conditions and structural dimensions on the power output. Gannon and Backstrom (2004) presented analytical equations in terms of turbine flow and load coefficient and degree of reaction, to express the influence of each coefficient on turbine efficiency. Berdahl and Martin (1984) designed a solar chimney system for power production at high latitudes, and its performance has been evaluated. A mathematical model and a code on MATLAB platform have been developed based on monthly average meteorological data and thermodynamic cycle. Pretorius and Kroger (2005) studied the influence of convective heat transfer equation, more accurate turbine inlet loss coefficient, quality of collector roof glass and various type of soil on the performance of a large scale solar chimney power plant. Results indicate that the new heat transfer equation reduces plant power output considerably.

Fluri and Backstrom (2008) investigated analytically the validity and applicability of the assumption that, for maximum fluid power, the optimum ratio of turbine pressure drop to pressure potential (available system pressure difference) is 2/3. A more comprehensive optimization scheme, incorporating the basic collector model of Schlaich in the analysis, showed that the power law approach is sound and conservative. Castillo (1984) have proposed dimensionless variables to guide the experimental study of flow in a small-scale solar chimney. Computational Fluid Dynamics (CFD) methodology was employed to obtain results that are used to prove the similarity of the proposed dimensionless variables. Bhatti and Shah (1987) studied analytical and numerical theory of roof top solar chimney for ventilation purpose. In 2008 they studied the inclination angle on space flow pattern and applied to roof solar chimney and to enhance the natural ventilation. Chungloo and Limmeechokchai,(2008) applied CFD technology for simulation to the roof solar chimney for ventilation purpose.

The main objective of the this study is to present the development of the utilization of the solar as energy source by using the solar chimney technique. Also, a modification is suggested to use the roof top solar chimney as a system for solar energy conversion to generate small scale of power. For that, a mathematical model is established and presented based on thermal and mass balances. Preliminary results have been predicted and presented to show the applicability of the technique.

WORKING PRINCIPLES OF ROOF TOP SOLAR CHIMNEY

For the system to be in ideal conditions, different geometries could be tested in order to find the most suitable in attaining the optimum power. Using CFD simulation of the solar chimney under various conditions is made to determine the most optimum performance of the small-scale chimney. The results from the analytical and CFD simulation are compared with experimental model measurements. A solar chimney consists of three main components; a: the solar collector or the greenhouse, b: the chimney and c: the turbine.

The cover and collector are inclined at an angle, θ and at a perpendicular distance, d apart. Due to the distance between the cover and the collector, a pathway is created for air flow. During sunny days, solar radiation will penetrate the transparent cover and heat up the collector. The thermal energy transfers to the air in the pathway causing an increase in the air temperature. The hot air rises and exits at the top while cooler air is drawn in from the bottom, providing a continuous air flow. Ambient air at temperature, T_a enters the pathway from the bottom of the chimney and flows upward to the top and exits at temperature, T_{ext} and velocity of V_{ext}. A Savonius rotor linked to generator is to be installed in the chimney to convert the kinetic energy of the airflow to electric power. A schematic diagram of the Rooftop solar chimney has been shown in Fig. 1.

Solar radiation (I) passes through the transparent cover, with some energy reflected from the cover, $q_{ref,cover}$ and some energy absorbed by the cover, $q_{abs,cover}$. The remaining energy, I_τ reaches the collector which is painted

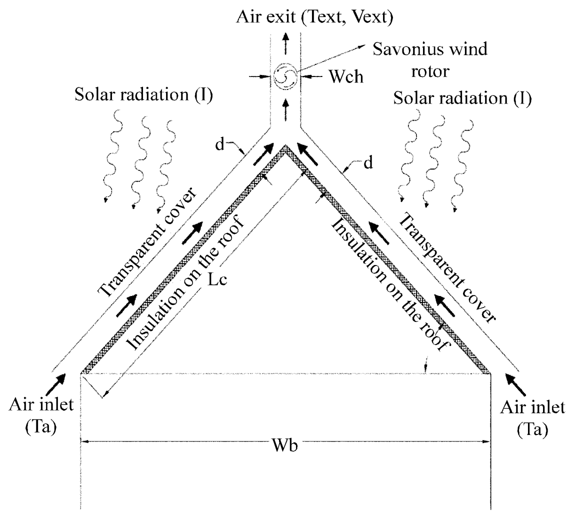

Fig. 1: Schematic of roof-top solar chimney (Ghosh, 1997)

black to enhance heat absorbance. Upon striking the collector, the energy further dissipates into two main components; the energy irradiated from the collector, $q_{rad,\ collector}$ and the energy absorbed by the collector, $q_{abs,,collector}$. The heat absorbed by the collector is transferred to the adjacent air by convention. Due to the heat transfer, $q_{conv,air}$ from the collector surface, the air gains kinetic energy. The power output from the rotor is influenced by the energy of the air. Hence, the ultimate goal is to maximise the energy transferred to air, $q_{conv,air}$.

MATHEMATICAL MODELING

Solar radiation on tilted surfaces: In order to find the beam energy falling on a surface having any orientation, it is necessary to convert the value of beam flux from the sun to an equivalent corresponding to the normal surface. The total solar radiation is the sum of beam , I_b and diffuse radiation, I_d on a surface:

$$I_g = I_b + I_d \tag{1}$$

The declination, δ: The declination δ is the angle made by the line joining of the centers of the sun and the earth with its projection on the equatorial plane. Cooper has given the relation for calculating the declination (Padki and Sherif, 1992):

$$\delta = 23.45 \sin [360/365\ (284+n)] \tag{2}$$

where, n is the day of the year.

Local apparent time is the time used for calculating the hour angle (ω). This can be obtained from the standard time observed on a clock by applying two corrections. The first correction arises because of the difference between the longitude of a location and the meridian on which the standard time is based. The correction has a magnitude of 4 min for every degree difference in longitude. The second correction called the equation of time correction is due to the fact that the earth's orbit and rate of rotation are subject to small fluctuations:

$$\text{Local apparent time} = \text{Standard time} + 4(L_{st}-L_{loc})+E$$

Where:

$$E = 229.2\ (0.000075+0.001868 \cos B-0.032077 \sin B- 0.014615 \cos 2B-0.04089 \sin 2B$$

where, $B = (n-1)360/365$

Hour angle (ω) Is defined as:

$$\omega = 15(t-t_c-12) \tag{3}$$

The angle of incidence of beam radiation on a surface is:

$$\cos\theta = \sin\delta \sin\phi \cos\beta - \sin\delta \cos\phi \sin\beta \cos\gamma + \cos\delta \cos\phi \cos\beta \cos\omega + \cos\delta \sin\phi \sin\beta \cos\gamma \cos\omega + \cos\delta \sin\beta \sin\omega \sin\phi \tag{4}$$

The zenith angle (θ_z): It is the angle made by the sun's rays with the normal to a horizontal surface. In this case the surface is assumed to be horizontal surface, β is 0°:

$$\cos\theta_z = \cos\theta \cos\delta \cos\omega + \sin\theta \sin\delta \tag{5}$$

It is often necessary for calculation of daily solar radiation to an integrated daily extraterrestrial radiation on a horizontal surface:

$$I_o = [(12*3600\ G_{sc})/\pi]\ (1+0.033 \cos (360n/365)\times[\cos\theta \cos\delta (\sin\omega_2-\sin\omega_1)+(\pi(\omega_2-\omega_1)/180) \sin\theta \sin\delta] \tag{6}$$

where, ω_2 and ω_1 limits as time rather than hours.

The effect of atmosphere in scattering and absorbing radiation is visible with time as atmospheric conditions and air mass change. Duffie and Beckman (1991) has presented a method of estimating the beam radiation transmitted through clear atmosphere which takes in to account of zenith angle and altitude for a standard atmosphere and for four climate types. The atmospheric transmittance for beam radiation (τ_b) is given by:

$$\tau_b = a_0 + a_1 \exp(-k/\cos\theta_z) \quad (7)$$

The constant:

$$a_0 = 0.4237 - 0.00821(6\text{-ht})^2$$
$$a_1 = 0.5055 + 0.00595(6.5\text{-ht})^2$$
$$k = 0.2711 + 0.01858(2.5\text{-ht})^2$$

Therefore, the beam radiation is:

$$I_b = I_o\, \tau_b \cos\theta_z \quad (8)$$

Liu and Jordan (1960) have developed an empirical relationship between the transmission coefficients for beam and diffuse radiation:

$$I_d = I_o\,(0.271 - 0.294\,\tau_b) \quad (9)$$

Beam radiation: The ratio of the beam radiation flux falling on a tilted surface to that falling on a horizontal surface is called the tilt factor (r_b) for beam radiation:

$$r_b = \cos\theta \,/\, \cos\theta_z \quad (10)$$

Diffuse radiation: The tilt factor r_d for diffuse radiation is the ratio of the diffuse radiation flux falling on the tilted surface to that falling on a horizontal surface:

$$r_d = (1+\cos\beta)/2 \quad (11)$$

Reflected radiation: The tilt factor on reflected radiation is given by:

$$r_r = \rho(1-\cos\beta)/2 \quad (12)$$

Flux on tilted surface (I_t): The ratio of flux falling on a tilted surface at any instant to horizontal surface is:

$$I_t = (1 - I_d/I_g)\, r_b + (I_d/I_g)\, r_d + r_r\,(e) \quad (13)$$

Thermal analysis: The main objective of the mathematical model was to predict the airflow rate through the solar chimney with inclined absorber. For predicting the performance of solar chimney, study of the heat transfer through natural convection was conducted. Major parameters in this study are temperature of absorber and glass surface, temperature of air inlet and outlet, ambient temperature, flow velocity, area of inlet and outlet opening. Writing energy balance equations for absorber surface, glass surface and air column and solving them for (T_g), (T_c) and (T_f) to calculate airflow rate have sought a mathematical solution. Air enters the chimney at the bottom opening with an inlet temperature, ($T_{f,i}$) which is assumed equal to the uniform room air temperature (T_r). Hot air exits from the top of the chimney at outlet temperature ($T_{f,o}$). Temperatures at the surfaces of the glass (T_g) and wall (T_w) are assumed to be uniform. The inlet opening at the bottom of the chimney is assumed to be equal to or smaller than the top outlet opening. Resistance to flow due to friction along the surfaces is assumed negligible compared to the pressure drops at the inlets and outlet openings.

The thermal network for the physical model considered is shown in Fig. 2 . The following equations may be written by considering the heat balance at the points:

$$\dot{q}'' = M(T_f - T_{f,i})$$

$$T_f\, h_g T_g - (h_g + h_w + M)\, T_f + h_w T = -MT_{f,1}$$

At the glass (T_g):

$$S_1 + h_{rwg}(T_c - T_g) + h_g(T_f - T_g) = U_t(T_g - T_a) \quad (14)$$

At the collector (T_c):

$$S_2 = h_c(T_c - T_f) + h_{rcg}(T_c - T_g) + U_b(T_c - T_r) \quad (15)$$

Mean air temperature in the air channel T_f:

$$h_w(T_c - T_f) = h_g(T_f - T_g) + q'' \quad (16)$$

The mean air temperature also calculated from:

$$T_f = \gamma T_{f,o} + (1-\gamma) T_{f,i} \quad (17)$$

The heat transferred to the air stream flowing upwards under natural convection in the air gap between the glass and wall. The useful heat transferred to the air flowing in the gap is given by:

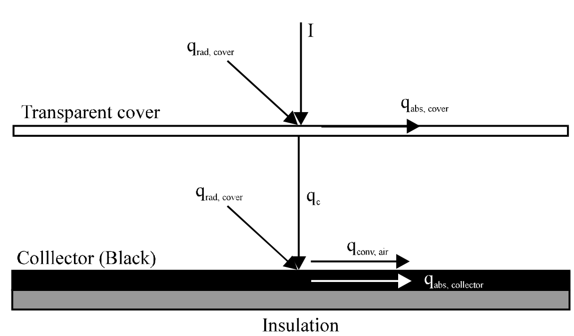

Fig. 2: Solar energy pathways

$$\dot{q}''\,WL = m^{\bullet}\; c_f\;(Tf,o\; -Tf,i) \tag{18}$$

substitute the value of $T_{f,o}$ from Eq.17, we get:

$$\dot{q}''=\frac{\dot{m}c_f\,(T_f - T_{f,i})}{\gamma WL} \tag{19}$$

Introducing:

$$M=\frac{\dot{m}\,c_f}{\gamma WL} \tag{20}$$

Then, the useful heat transferred may be expressed as:

$$\dot{q}''=M(T_f - T_{f,i}) \tag{21}$$

Heat transfer coefficients and fluid properties may be evaluated at the respective mean temperatures. By substitution, we obtain:

$$T_g{:}(h_g+h_{rcg}+U_t)T_g\text{-}h_gT_f\text{-}h_{rcg}T_c=S_1+U_tT_a \tag{22}$$

$$T_c{:}\text{-}h_{rcg}T_g\text{-}h_cT_f+(h_c+h_{rcg}+U_b)T_c=S_2+U_bT_r \tag{23}$$

$$T_f{:}\text{-}h_gT_g\text{-}(h_g + h_\omega + M)T_f + h_\omega T_\omega = \text{-}MT_{f,1} \tag{24}$$

The mean temperatures are determined by arranging (22) (23) and (24) in matrix form as:

$$[A]\,[T] = [B]$$

Which may be determined by matrix inversion, as:

$$[T] = [A]^{-1}\,[B]$$

Air flow analysis: The volumetric air flow rate at the outlet opening for uniform air temperature is given by:

$$\dot{V}=C_d\frac{A_o}{\sqrt{1+A_r}}\sqrt{\frac{2gL(T_f - T_r)}{T_r}} \tag{25}$$

The air mass flow rate is thus:

$$\dot{m}=C_d\frac{P_{f,o}A_o}{\sqrt{1+A_r}}\sqrt{\frac{2gL(T_f - T_r)}{T_r}} \tag{26}$$

where, $A_r = A_o/2A_i$

The air velocity is then:

$$u_i=\frac{\dot{m}}{P_rA_j} \tag{27}$$

Radiation heat transfer coefficient from glass cover to sky: The radiation heat transfer coefficient from the top glass surface to the sky referred to the ambient temperature is obtained:

$$h_{rs} = \sigma\epsilon_g(T_g+T_s)(T_g^2+T_s^2)(T_g\text{-}T_s)/(T_g\text{-}T_a) \tag{28}$$

The sky temperature was calculated as:

$$T_s = 0.0552T_a^{1.5}$$

Heat transfer convection from glass cover due to wind: The convection heat transfer due to wind is:

$$h_{wind} = 5.7+3.8\;V \tag{29}$$

U_t is the overall top heat loss coefficient from glass cover to ambient, due to the combined effect of convection by wind, radiative heat transfer from glass cover to sky:

$$U_t = h_{wind}+h_{rs} \tag{30}$$

Heat transfer between collector and glass: The radiation heat transfer coefficient between collector and glass cover may be obtained from:

$$h_{rcg}=\sigma(T_g^2+T_c^2)(T_g+T_c)/(1/\epsilon_g+1/\epsilon_c\text{-}1) \tag{31}$$

In the present study, the flow has been examined whether it is free or forced convection and the criteria to estimate the heat transfer coefficient in the present work; the flow has been examined whether it is free or forced convection and the criteria to estimate the heat transfer coefficient in the gab is selected accordingly. In determining the mean convection heat transfer coefficient, $\bar{h}$, the combined (forced and natural) convection model is considered. Based on the combined convection model, the resultant Nusselt number Nu_c is related to the Nusselt numbers of forced convection Nu_F and natural convection Nu_N as:

$$Nu_C{}^n = Nu_F^n + Nu_N^n \tag{32}$$

Where:

$$Nu_F = 0.664Re_{Lc}^{1/2}\,Pr^{1/3} \tag{33}$$

and for forced turbulent flow, and $0.6 < Pr < 60$:

$$Nu_F = 0.0296Re_{Lc}^{4/5}\,Pr^{1/3} \tag{34}$$

For the natural convection:

$$Nu = 1 + 1.446\left[1 - \frac{1708}{Ra\cos\beta}\right] \quad (35)$$

For 1708 < Ra cos β < 5900:

$$Nu = 0.229(Ra\cos\beta)^{0.252} \quad (36)$$

for 5900 < Ra cosβ < 9.23×10^4:

$$Nu = 0.157\ (Ra\cos\beta)^{0.258} \quad (37)$$

For 9.23×10^4 < Ra cos β < 10^6

Solar radiation: According to Ghosh and Tiwari (2008), the solar radiation heat flux absorbed by the glass cover is given by:

$$S_1 = A_1\alpha_1 I_t \quad (38)$$

and the solar radiation heat flux absorbed by the blackened wall is given by:

$$S_2 = A_2\tau\alpha_2 I_t \quad (39)$$

Instantaneous efficiency: The instantaneous efficiency of heat collection by the solar chimney is calculated:

$$\eta = \frac{\dot{m}c_f(T_{f,o} - T_{f,i})}{WLH}\times100 \quad (40)$$

The produced electrical power, p_e in watts is evaluated by:

$$p_e = \eta_{generator}\times c_p\times 0.5\rho v^3 A_{rotor} \quad (41)$$

RESULTS AND DISCUSSION

Theoretical performance of solar chimney was calculated. From the graph we can see that if the intensity of solar radiation increases correspondingly increases the temperature of air, mass flow rate and velocity of air.

Figure 3 shows the intensity of the solar radiation from morning 8 am to 6 pm From the graph it is noticed that intensity of solar radiation is maximum at 12pm to 1pm and after that it starts to decrease.

From Fig. 4, it can be seen that mass flow rate inside the solar chimney increases corresponding increase the intensity of solar radiation. It reaches maximum at 1pm after that start to decrease.

Same thing happens in the case of velocity also, as in Fig. 5. It reaches its maximum point in between 12 to 2 pm.

Figure 6 shows that the overall performance of solar chimney. Performance of chimney starts to increase from

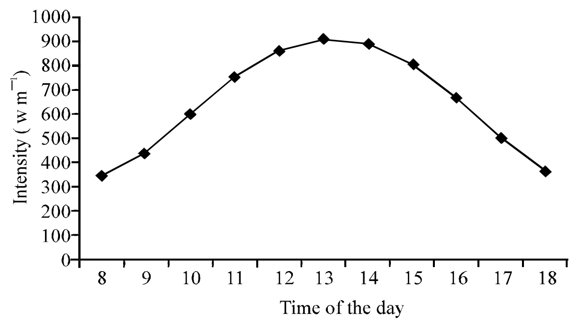

Fig. 3: Intensity of solar radiation

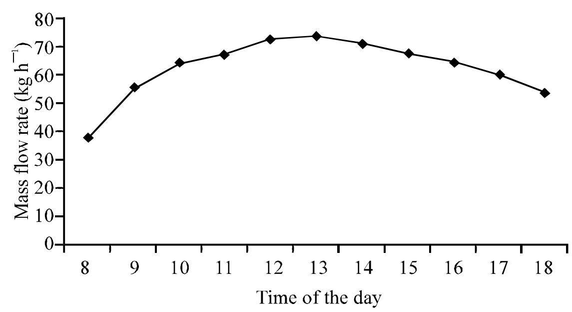

Fig. 4: Transient behavior of the mass flow rate in the system

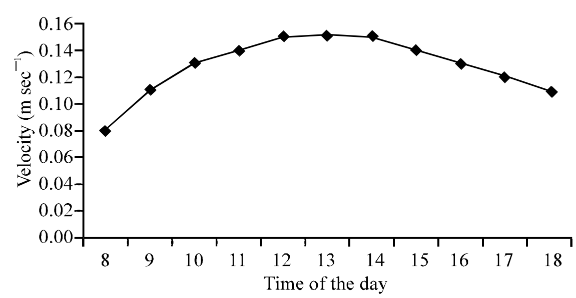

Fig. 5: Velocity values of air at chimney base during the day time

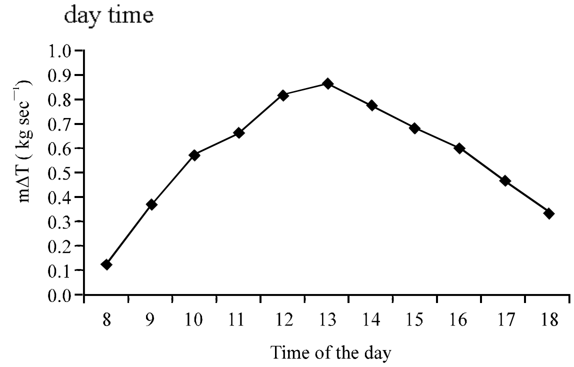

Fig. 6: Hourly performance index of system

8 am up to 1 pm. At 1 pm it reaches its maximum performance after that start to decreases. At 6 pm the performance of RTSC is very low, in this case we must use any back up source of heat.

CONCLUSION

Roof Top Solar Chimney is the subject of investigation in the present project. Roof top solar chimney is slightly modified version of the traditional solar chimney power plant that has been built around the world. To make the system more efficient, enhancing heat resource is proposed to be utilized. This system will be modeled and studied under various operational conditions and different geometries. The chimney operation is modeled under the assumption of solar operational mode by specifying the heat transfer and the fluid flow mechanism. The modeling tools are analytical and computational. The chimney operation is modeled under the assumption of solar operational mode by specifying the heat transfer and the fluid flow mechanism. From the analytical result after the 6 p.m. the performance of chimney is very low. To develop the technique for small-scale power generation, there are two requirements. First is to enhance the solar energy conversion by better absorbing media. Secondly is the use of thermal backup to allow continuous operation of the system during night and cloudy days.

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NOMENCLATURE

A_o, A_i : Cross sectional areas of outlet and inlet to air flow channel
A_r : Ratio of A_o/A_i
C_f : Specific heat of air
Cd : Coefficient of discharge of air channel inlet
d : Distance between collector and glass
h_g : Convective heat transfer coefficient between glass cover and air channel.
h_c : Convective heat transfer coefficient between collector and air.
h_{rs} : Radiative heat transfer coefficient between glass cover and sky.
h_{rcg} : Radiative heat transfer coefficient between collector and glass
h_{wind} : Convective wind heat loss coefficient
$m^{\cdot}$: Mass flow rate
q" : Heat transfer to air stream
S_1 : Solar radiation heat flux absorbed by glass cover
S_2 : Solar radiation heat flux absorbed by collector
T_a : Ambient temperature
T_f : Mean temperature of air in channel
$T_{f,i}$: Inlet temperature of air in channel
$T_{f,o}$: Outlet temperature of air in channel
T_g : Mean glass cover temperature
T_s : Sky temperature
T_c : Mean collector temperature
U_b : Overall convective heat transfer coefficient between collector and air channel
U_t : Overall convective heat transfer coefficient from top of glass cover
α_1 : Absorptivity of glass
α_2 : Absorptivity of collector
γ : Constant for mean temperature approximation
ϵ_g : Emissivity of top of glass cover
A1 : Area of the transparent cover
A2 : Area of the collector

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