Heated Air Ventilation with Transpired Solar Wall System during Winter Months: A Study of Sarguja District

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Abstract*-Transpired solar walls are a renewable energy technology that is readily available, and has considerable potential for application in new as well as existing buildings. Transpired solar wall use solar energy to preheat ventilation (outdoor) air as it is drawn into a building. Transpired solar wall technology is quite simple. A dark, transpired metal wall is installed on the south-facing side of a building, creating approximately a (20cm-30cm) gap between it and the building's structural wall. The dark-colored wall acts as a large solar collector that converts solar radiation to heat. Fans mounted at the top of the wall pull outside air through the transpired wall's perforations, and the thermal energy collected by the wall is transferred to the air passing through the holes. The fans then distribute the heated air into the building through ducts mounted near the ceiling or to the air-heater coils for further reheating, according to required temperature range of thermal comfort. By preheating ventilation air with solar energy, the technology removes a substantial load from a building's conventional heating system, saving energy, money, coal consumption in electricity generation and carbon-di-oxide emission in the environment. In the present study the applicability of transpired solar wall system is analyzed for climatic conditions of Sarguja district of state Chhattisgarh of India. A transpired solar wall system of size 2m×1m with other specified parameters and $450m^3/h$of volumetric air flow rate results at an average rate of saving of 4kWh electricity and 2.5kg coal consumption per day operated for 8 hours during daytime and increases temperature of supplied air minimum $3℃-4℃$ when average solar radiation is available. In this way transpired solar wall system may prove a better technology for rural areas, where sufficient electricity supply is unavailable, as it improves the thermal environment of the place under consideration with saving in electricity and coal consumption with reduction in environmental pollution.

Keywords- Ventilation; Transpired solar wall; thermal comfort; Coal consumption.

I. INTRODUCTION

The quality of air inside the residential space should be such that it should provide a healthy and comfortable indoor environment. Air inside the conditioned space is polluted by both internal as well as external sources. The pollutants consist of odours, various gases, volatile organic compounds and particulate matter. The internal sources of pollution include the occupants (who consume oxygen and release carbon dioxide and also emit odors), furniture, appliances etc, while the external sources are due to impure outdoor air. Indoor Air Quality can be controlled by the removal of the contaminants in the air or by diluting the air. The purpose of ventilation is to dilute the air inside the conditioned space. Ventilation may be defined as the 'supply of fresh air to the conditioned space either by natural or by mechanical means for the purpose of maintaining acceptable indoor air quality'. Generally ventilation air consists of fresh outdoor air plus any re-circulated air that has been treated. If the outdoor air itself is not pure, then it also has to be treated before supplying it to the conditioned space. The ventilation air must:

a) Dilute the odours inside the occupied space to a socially acceptable level
b) Maintain carbon dioxide concentration at a satisfactory level
c) Pressurizing the escape routes in the event of fire

Many researchers have reported various technologies of active and passive ventilation system like Trombe wall, Michel wall, solar chimney etc. are the recent technology to provide thermal comforts in the residential space. Gan, G.[1] in 1998 has invested A parametric study of Trombe wall for passive cooling of buildings. Ong, K. S., Chow, C. C. [2] in 2003 have studied the performance of a solar chimney and suggested the various favorable input conditions for the optimum utilization of the technology. J.Hirunlabh, W.Kongduang, P.Namprakai, J.Khedari [3] in 1999 Studied of natural ventilation of houses by a metallic solar wall under tropical climate. H.Y.Chan, S. Riffat, J. Zhu.Solar[4] in 2012 have analysed transpired solar facades for space cooling.

It has also been reported that to generate electricity from thermal power plants coal is used as main fuel and in developing countries like India coal is the main source of electricity generation in power plants. Moti L. Mittal[5] has mentioned that data available from Central Electricity Authority of India(CEA) the coal consumption by power plants to produce one unit of electricity differ from plan to plant and also depends the quality of coal available for operation. As an average generally 0.6 kg coal is consumed in producing 1kWh electricity.

In the present study performance of transpired solar wall system is evaluated using it as a heated air providing ventilation technology in the climatic condition of Sarguja district of state Chhattisgarh of India. The temperature in

Sarguja is less than the required temperature for thermal comfort in winter months i.e. from October to march, so air heating is required during these days which results in more electricity consumption. Therefore transpired solar wall is proposed to supply heated air in the residential space and related saving in electricity and coal consumption are finally calculated. The schematic diagram of transpired solar wall is as illustrated in Figure 1. The transpired metallic wall is heated by solar radiation. With the help of ventilation fans, the solar heated air is drawn through the holes of the transpired metal sheet. The heated air is then supplied to the heating coil or direct in the conditioned space according to required temperature via a connection to the HVAC intake. In this way a considerable amount of electrical energy can be saved by using this technology.

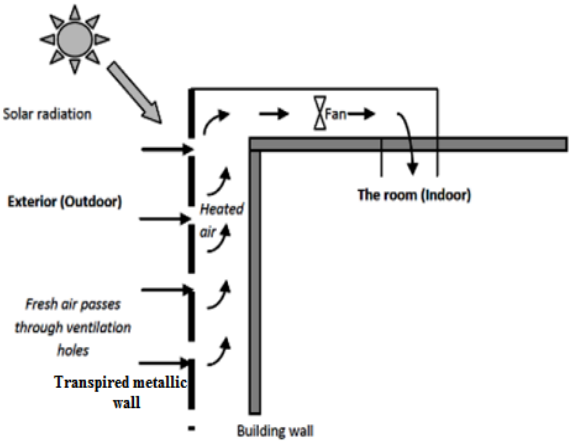

Figure 1. Schematic of transpired solar wall system

II. METHODOLOGY

Transpired plate is selected in this study for heating of air. Heat removal from habitation and mathematical modelling of transpired solar wall is explained.

Figure-2 illustrates the side view of the heating systems. The plate is made of black painted aluminium sheets. They are used as solar collectors that absorb heat from the solar radiation. Thermal performance of this system is investigated through mathematical models. The energy balance equations are established based on steady state one-dimensional heat transfer.

A simplified steady state mathematical model is developed to calculate temperature rise of the air. Therefore, the temperature equations are obtained by writing the energy balance equations in a matrix form, and solved by the matrix inversion method. The matrix algorithm is carried out using the MATLAB program.

Mathematical model of transpired plate collector:

Assumptions of heating system with transpired plate collector:

Due to the complication of heat transfer process of the unglazed transpired plate, some assumptions have been made as follows:

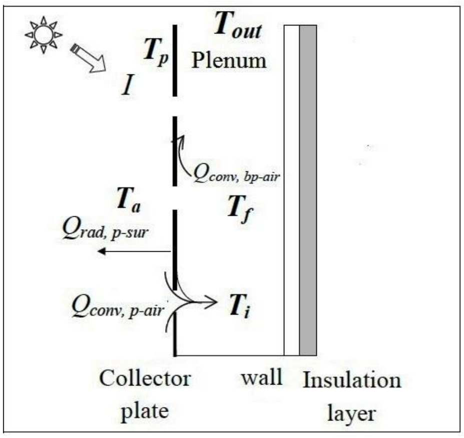

Figure 2. Heat transfer modes of transpired solar wall system

i). The radiation heat loss over the surface of the transpired plate is everywhere constant as this has been proved that it has a modest effect on the flow distribution.
ii). There is no heat loss through the insulated wall and side walls that attached with the aluminium plate.
iii). The convection losses to the ambient are negligible and have been verified by previous study.
iv). No reverse flow over the plate as the face velocities in this study are taken higher than 0.0125ms^{-1}.
v). The temperatures that are taken in the study which have the same height with the first row of holes from the bottom are taken as air temperatures reach the plenum after passing through the holes.
vi). The air properties maintain the same throughout the plenum.

Energy balance equations for transpired plate collector:

Energy balance equations are established for two components of the system, i.e. unglazed transpired plate and the air in the plenum. The heat transfers of the system are as shown in Figure 2.

The unglazed transpired collector:

The fans-assisted system draws the ambient air through the holes so that heat, which would otherwise be lost by convection, is captured by the airflow into the plenum. Thus, there will have very small amount of convection heat loss to the ambient which indeed can be neglected. Energy balance equation on an unglazed transpired plate is as shown in Equation (1).

$$I\alpha_p A_p = Q_{conv,p-air} + Q_{conv,bp-air} + Q_{rad,p-sur} \quad (1)$$

The plenum air:

The ambient air which heated by the front and hole of the transpired plate is further heated by the back-of-plate when flowing throughout the plenum. Energy balance equation of the air in the plenum is shown in Equation (2)

$$\Sigma \dot{m} c_p (T_{out} - T_i) = Q_{conv,bp-air} \quad (2)$$

A. Heat flux and coefficient of heat transfer for transpired plate collector

Convection heat transfer from the front and hole of transpired plate to the ambient air:

The convection heat transfer equations can be written in term of mass flow rate and heat flux as shown in Equations (3) and (4) respectively.

$$Q_{\text{conv,p-air}} = \Sigma \dot{m} c_p (T_i - T_a)/A_p \quad (3)$$
$$Q_{\text{conv,p-air}} = h_{c,tp}(T_p - T_i) \quad (4)$$

The convection coefficient is defined as Equation (4) where the $Nu_{c,tp}$ correlation is taken from reference[5]

$$h_{c,tp} = Nu_{c,tp} \times \frac{k_a}{d} \quad (5)$$

Convection heat transfer from the back of the transpired plate to the air in the plenum:

The coefficient is shown in Equation (6) and (7) and the $Nu_{f,tp}$correlation is taken from [5]

$$q_{conv,bp-air} = h_{f,tp}(T_p - T_f), \quad (6)$$

Where $T_f = (T_i + T_{out})/2$

$$h_{f,tp} = Nu_{f,tp} \times \frac{k_f}{H} \quad (7)$$

Radiation heat transfer from the front of transpired plate to the surrounding:

The radiation coefficient is given in Equation (8) where the emissivity (ε_p) of black paint is taken as 0.95.

$$q_r = h_r(T_p - T_a) = \sigma \varepsilon_p (T_p^4 - T_a^4) \quad (8)$$
$$h_r = \sigma \varepsilon_p (T_p + T_a)(T_p^2 + T_a^2) \quad (9)$$

Solar radiation:

The solar radiation intensity that absorbed by the transpired plate is given as Equation (10).The solar radiation intensity that absorbed by the plate is given as below where the absorptivity for black paint is taken as 0.95:

$$S = I\alpha_p \quad (10)$$

System efficiency:

The efficiency of the heating system is the ratio of the useful energy delivered to the total solar energy input on the plate, and it is given as:

$$\eta = \Sigma \dot{m} c_p (T_{out} - T_a)/IA_p \quad (11)$$

Heat exchange effectiveness:

The heat exchange effectiveness of the solar collector is defined as the ratio of the actual temperature rise of air to the maximum possible temperature rise:

$$\varepsilon_{HX} = \frac{(T_{out} - T_a)}{(T_p - T_a)} \quad (12)$$

substituting Equations (9) ,(4) and (6) for equation (1), the heat balance equation for the unglazed transpired collector

$$(h_{c,tp} + h_{f,tp} + h_r)\, T_p - \left(h_{c,tp} + \frac{h_{f,tp}}{2}\right) T_i - \left(\frac{h_{f,tp}}{2}\right) T_{out} = I\,\alpha_p + h_r T_a \quad (13)$$

For the plenum air, substituting Equation (5) for Equation (3) gives:

$$h_{f,tp} + \left(G\, c_p - \frac{h_{f,tp}}{2}\right) T_i - \left(G\, c_p + \frac{h_{f,tp}}{2}\right) T_{out} = 0 \quad (14)$$

Where $G = \Sigma \dot{m} c_p / A_p$ and $T_f = (T_i + T_{out})/2$

finally, Equations (3) and (4) are combined and give:

$$h_{c,tp} T_p - (\, G\, c_p + h_c)\, T_i = -G c_p T_a \quad (15)$$

Thus, Equations (14) to (15) can be written in a 3x3 matrix form:

$$\begin{bmatrix} (h_{c,tp} + h_{f,tp} + h_r) & -(h_{c,tp} + h_{f,tp}/2 & -(hf, tp/2) \\ h_{f,tp} & (Gc_p - h_{f,tp}/2) & -(Gc_p + h_{f,tp}/2 \\ h_{c,tp} & -(Gc_p + h_c) & 0 \end{bmatrix} \begin{bmatrix} T_p \\ T_i \\ T_{out} \end{bmatrix} = \begin{bmatrix} I\alpha_p + h_r T_a \\ 0 \\ -Gc_p T_a \end{bmatrix}$$

(16)

Equation (16) is then solved by using matrix inversion method and the iteration process is continued until the convergence value is smaller than 10^{-6}

Physical properties of air:

The required physical properties of air are calculated by using linear interpolation for air properties between suitable temperature ranges. [6]

B. Energy consumption of air-heating coil

The The momentary thermal energy consumption of a heating coil is calculated with the equation:

$$Q_{total} = q_v \times \rho \times (\, h_{out} - h_{in}) \times t_s \quad (17)$$

where

Qtotal = energy consumption for a time period in kJ
qvq_v= air flow rate over the coil in m^3/s
ρ = density of the considered air flow rate in kg/m^3
hout = enthalpy of the air at the outlet of the coil in kJ/kg
hin = enthalpy of the air at the inlet of the coil in kJ/kg
tst_s= period of time with steady in- and outlet conditions in s

Since the moisture content of the air does not change so it can be written:

$$Q_{total} = q_v \times C_p \times \rho \times (\, t_{out} - t_{in}) \times t_s \quad (18)$$

where

Qtotal = energy consumption for a time period t_s in kJ
qv = air flow rate over the coil in m^3/s
ρ = density of the considered air flow rate in kg/m^3
cp = specific heat of the air in kJ/kg ℃
tout = temperature of the air leaving the coil in
tin = temperature of the air entering the coil in ℃

t_s = period of time with steady in- and outlet conditions in s

Strictly considered the sensible heat increase of the water vapour is disregarded in the last formula. This is an acceptable assumption for normal applications in comfort installations where the moisture content of the air is relatively small.

III. STUDY OF AMBIKAPUR(SARGUJA DISTRICT) REGION

Ambikapur is a city in the Surguja district of the Indian state of Chhattisgarh. It is the district headquarters of Surguja, one of the oldest districts of Chhattisgarh. It was the capital of the Princely state of Surguja before Indian Independence. The name of the city is derived from the goddess Ambika (Mahamaya) Devi, who is the central figure of worship in the area. Mainpat, in the Surguja District, is a major tourist area near Ambikapur. It is also known as the "Hill station of Surguja" and the "Shimla of Chhatisgarh".

The average values of high and low temperatures, solar radiation and other geographical information is shown in table I and figure 3 below.

The characteristics of each climate differ and accordingly the comfort requirements vary from one climatic zone to another. Before proceeding further, it would be useful to define comfort and the conditions that affect it. According to ASHRAE,[7] thermal comfort is, “that condition of mind which expresses satisfaction with the thermal environment”. It is also, “the range of climatic conditions within which a majority of the people would not feel discomfort either of heat or cold”. Such a zone in still air corresponds to a range of 20 –30 °C dry bulb temperature with 30– 60 % relative humidity. Besides, various climatic elements such as wind speed, vapour pressure and radiation also affect the comfort conditions.

Thermal neutrality is another measure of comfort. It is defined as the temperature at which a person feels thermally comfortable, i.e. neutral [8]. Thermal neutrality is modeled using lab and field experiments and found to be highly dependent on the outdoor temperature and is given by:

$$T_{neutrality} = 11.9 + 0.534\, T_{outdoor} \qquad (19)$$

So if a system is able to bring the air temperature up to neutrality condition in the conditioned space then also that specific system can be considered applicable for the place under consideration.

From climatic data consideration and ‘thermal comfort’ point of view it is clear that temperature in winter months i.e. January, February, March, October, November and December is lower than the required temperature level for thermal comfort. So air heating is required, for which generally electrical air heater is used.

In the present study the performance of transpired solar wall system is analysed which is used to supply heated air in the conditioned space. Transpired solar wall system utilizes solar energy to heat the air at day time. In this way electrical energy consumption and finally coal consumption can be reduced, which is presented in the further sections.

Parameter	Value/ range
Solar radiation intensity per unit area, W	As indicated in figure
Suction velocity, ms^{-1}	0.04
Plenum depth, m	0.25
Porosity (ratio of hole area to total surface area), %	0.84
Pitch, m	0.012
Hole diameter, m	0.0012
Holes array geometry	Triangular
Height of the transpired plate, m	2.0
Width of the transpired plate, m	1.0
Area of the transpired plate, m^2	2.0
Plate thickness, m	0.001
Volumetric air flow rate of used fan, Cubic meter per hour. $m^3/hour$	450

The applicability of transpired solar wall system is analysed with taking the climatic conditions of Ambikapur as input and temperature increment by the system is calculated. The input data for analysis is shown in the table II PARAMETERS OF STUDY given below:

IV. RESULT AND DISCUSSION

As seen in figure 4 by using transpired solar metallic wall system temperature of air supplied to the indoor is increased. It is clear from figure 4 that an average increase of 3℃-4℃ is achieved for average value of solar radiation in the Ambikapur region. In the month of March and October the only transpired wall system is capable enough to provide the required neutral thermal comfort in the conditioned space(figure 5) which eliminates the use of external air heating system. While in the other winter months the heating load of the conditioned space over heating coil is reduced. From table III it is clear that the saving in electricity consumption is as an average of 4 units per day, if 8 hours working of the transpired system is considered during the day time, when the solar radiation is available. Similarly 2.5kg coal can be saved every day. It can be finally concluded that the transpired solar wall system may prove a beneficial technology when it is applied in ruler as well as urban areas as it uses renewable (solar) energy to heat air, improves thermal comfort of the indoor and saves electricity, coal consumption and finally reduces CO_2 and other gases emissions in the atmosphere during the electricity generation in thermal power plants.

TABLE I. CLIMATE DATA FOR AMBIKAPUR

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average high °C	23.5	26.9	32.0	36.9	39.5	35.5	29.7	29.3	29.8	29.4	26.5	23.7	30.23
Average low °C	8.7	11.4	15.7	20.9	24.7	24.8	23.2	22.9	22.1	18.1	12.2	8.5	17.77

Source: World Meteorological Organization[1]

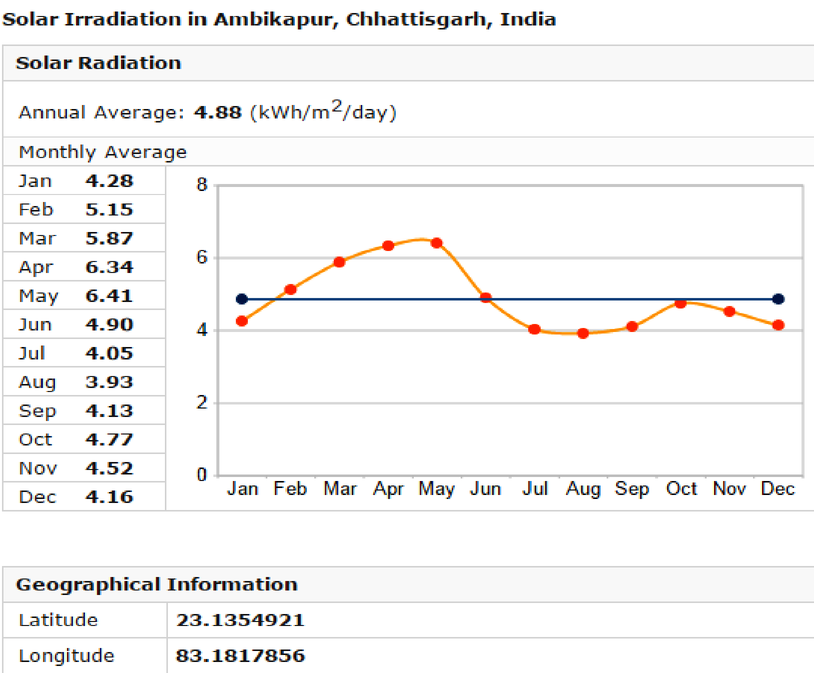

Figure 3. Solar radiation data of Ambikapur region (SOURCE: NREL)

TABLE III ELECTRICITY AND COAL CONSUMPTION SAVING DATA WITH PROPOSED SYSTEM

Month	Energy and electricity consumption By air-heater without transpired solar wall system		Energy and electricity consumption By air-heater with transpired solar wall system		Saving in electricity consumption with transpired solar wall system (kWh)	Saving in coal consumption with transpired solar wall system (kg)
	Energy consumption (kJ)	Equivalent Electricity consumption (kWh)	Energy consumption (kJ)	Equivalent Electricity consumption (kWh)		
January	49060.08	13.65	34732.8	9.65	4	2.4
February	37337.76	10.37	19537.20	5.43	4.94	2.964
March	18668.36	5.18	1302.48	0.36	4.82	2.892
October	8249.04	2.3	0	0	2.3	1.38
November	33864.48	9.41	17366.4	4.82	4.59	2.754
December	49928.4	13.87	36903.6	10.25	3.62	2.712

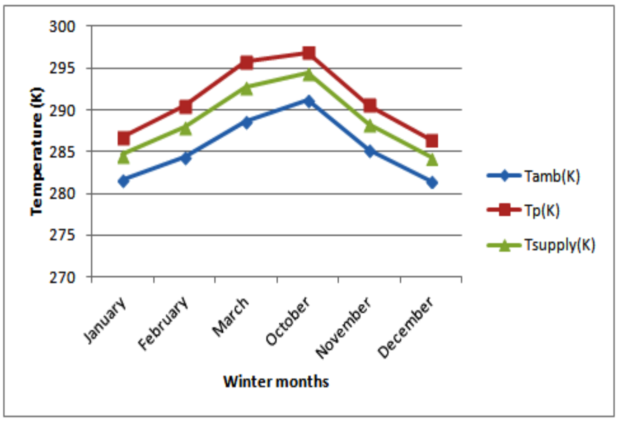

Figure 4. Temperature provided by the proposed system

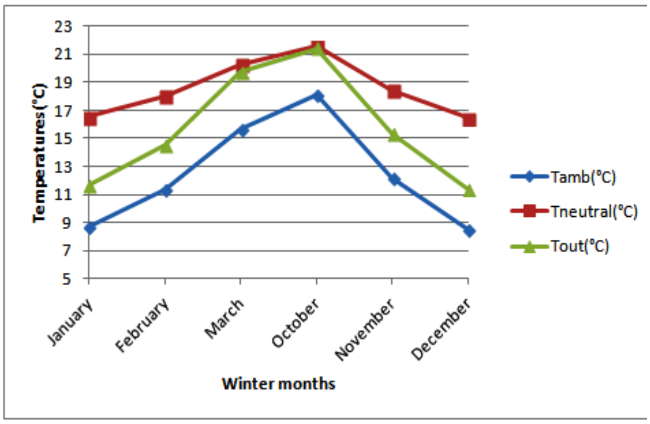

Figure 5. Performance of the system to get thermal comfort

V. Conclusion

In this way a study of performance of transpired solar wall system is analyzed for the climatic condition of Sarguja district and following conclusions can be drawn about the applicability of proposed system at place under consideration:

- With a size of 2mX1m of transpired wall system a single user can save, during winter months, 720 units of electricity, and associated cost, coal consumption, pollutant emission can also be reduced simultaneously for a operating time of 8 hours in a day is considered when solar radiation is available at mentioned average rate.
- Thus the proposed system is very beneficial for those rural areas where electricity supply is not regular and enough solar radiation is available as the system is capable enough to heat the air at required temperature range without external conventional source and only using solar radiation at day time.
- Transpired collectors are very reliable. They have no moving parts (other than the ventilation fans and dampers, which would be part of any ventilation system). There are no problems from leaking, freezing, or overheating. Even if the collector becomes dented, performance is not affected.
- Transpired solar walls are mostly maintenance free. Except for servicing of air distribution unit(fan belts, lubrication), the systems require minimal maintenance.
- The transpired solar wall systems are easy to install in new buildings and retrofitting.

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