Enhancement of natural ventilation of a circular greenhouse with double wall solar chimney

D. Misra¹*, S. Ghosh²
Indian Institute of Engineering Science and Technology, Shibpur, India-711103

Corresponding author’s e-mail: dmbesu@gmail.com

Abstract. The study has been devoted to develop an energy efficient agricultural greenhouse system. To serve this purpose a circular greenhouse with double walled vertical hollow cylindrical type solar chimney has been selected. The circular shape is beneficial to allow the outside wind from any direction. The solar chimney is constructed with double wall- the outer wall is made of fibre reinforced plastic (FRP) sheet to transmit solar radiation and the inner wall is made of blackened aluminium sheet to absorb solar radiation. Thus ventilation is occurred by solar as well as wind effect. It is found that 0.6-0.8 air change per minute (ACM) ventilation rate could be obtained, when total radiation intensity level remains 100-600 W/m² as well as the ambient temperature remains 30°C. It is found that solar chimney a circular greenhouse can improve ventilation rate 1.6-1.7 times.

1. Introduction
Effective climatic control is the primary requirement of a greenhouse for quality production of plant. Ventilation of a greenhouse is a very important factor in this context especially during hot and humid conditions. Proper ventilation can ensure a constant air temperature around the plant, maintains carbon dioxide and oxygen level, and regulates the humidity level of the air around the plant. Generally, greenhouses are provided with either natural or artificial ventilation system. Conventional naturally ventilated greenhouses cannot meet desired ventilation rate all over the year. Artificial ventilation depends on the exhaust fan, which requires a constant energy supply. Thus, in order to save energy, a non-traditional naturally ventilated greenhouse design concept could be undertaken, which could meet the desired ventilation rate throughout the year. Many research works have been done on naturally ventilated greenhouses to predicted the ventilation rate as well inside temperature. Ganguly and Ghosh (2009) [1], Teitel and Tanny (1999) [2], Boulard et al. (1999) [3], Kittas et al. (1997)[4], identified that position of ventilators, wind speed, effective height etc. on ventilation rate. Ventilation using solar chimney has been studied out for room ventilation. No of work related to solar chimney greenhouse ventilation still has not done. Notable work related to solar chimney room ventilation had been done by Bansal et al. (2005) [5], Ong (2003a) [6], Ong and Chow (2003b) [7], Mathur et al. (2006) [9], Burek and Habed (2007) [10], Bassiouney and Korah (2008) [11], Tan and Wong (2013) [12], Saleem et al. (2017) [13]. They had considered glass covered chimney with rectangular black absorber plate fitted one of the side wall of a room to investigate the air flow rate, temperatures at different position of the solar chimney.

2. Proposed solar chimney ventilated circular greenhouse
A circular greenhouse of 117 m$^2$ ground covered area and 10 m high chimney has been considered. The solar chimney is fitted at the central position at a height of 4 m from the ground. The chimney is cylindrical in shape and formed by twin walls situated concentrically. The outer diameter of the chimney is 1.4 m and the inner diameter is 1.0 m. The outer wall of solar chimney is built of FRP (Fibre Reinforced Plastic) and the inner wall is built of blackened aluminum so as to act as absorber of solar heat. There is stagnant air between two concentric cylinders, as it is properly sealed. The ends are covered by FRP between the FRP and absorber wall. Aluminum tube absorber wall converts solar energy into heat for use in air heating. The arrangement of solar chimney is shown in Figure 1.c, while plan and elevation of the greenhouse are shown in fig.1a and fig.1.b. Fig.1.a shows the different parts of the greenhouse- A and C indicate part of the wall covered by polyethylene, while B is space in the
wall provided for roll up insect proof curtain. The section B, which is continuous and uniform and situated 0.5 m above the ground and has 1.5 m height, is responsible for air flow from outside to the greenhouse interior. Thus, the wind can freely flow at any direction and assists in ventilation. The greenhouse air is allowed to pass through the inner cylindrical channel of the chimney. The canopy (portion D) and outer chimney covers (portion E) are made of FRP. Shade nets are aligned with the canopy inside the greenhouse to check the excess solar radiation.

3. Thermal Modelling
To model the heat interactions and the air flow characteristics of the solar chimney, some simplifying assumptions are considered, which are as follows:
(i) The inlet air temperature of the solar chimney is considered to be the greenhouse air temperature.
(ii) Resistance to the air flow is not taken into account.
(iii) Air inside the chimney is assumed to be a non-radiating heat absorbing fluid.
(iv) Neglecting heat absorption of the other greenhouse constructional elements.

3.1 Heat gain by the greenhouse air can be written as:

\[ m_gh C_p \frac{dT_{gh}}{dt} = Q_i - h_a A_c (T_{gh} - T_a) - m_c C_p (T_c - T_{gh}) \]  \hspace{1cm} (1)

The first part of the right hand side of the Eq. (1) represents net radiant heat received by the greenhouse air \((Q_i)\), given by

\[ Q_i = A_c I \tau (1 - SF) \] \hspace{1cm} (2)

Where S.F is the shading factor.

The second part of the right hand side of the Eq. (1) represents convection heat exchange in-between greenhouse air and ambient and third part represents ventilated heat.

To solve the Eq. (1), it needs an initial value of mass flow rate of the air, which could be computed from the following expression.

In the present greenhouse system, mass flow rate occurs due to variation of the solar chimney air temperature against ambient temperature as well as wind effects. An expression for mass flow rate of air through the chimney was suggested by Bansal et al. (2005) considering only the thermal buoyancy effect. Ganguly and Ghosh (2009), in their naturally ventilated greenhouse model, considered both thermal buoyancy and wind effects. The total mass flow rate through the solar chimney greenhouse, along with the same line considering the effect of height of the greenhouse and chimney height can be expressed as:

\[ m_v = \rho_v C_d \left[ \left( \frac{A_1 A_2}{A_1^2 + A_2^2} \right) \sqrt{\frac{T_{fa} - T_a}{T_a}} \left( H_{gh} + H_{chimney} \right) + \left( \frac{A_1 + A_2}{2} \right) C_w v_w \right] \] \hspace{1cm} (3)

In order to compute the mass flow rate of air, where solar chimney is being used, the air temperature of the solar chimney must be calculated. This can be done by computing the temperatures for the various sections through the energy balances for the chimney cover, stagnant air, absorber wall and the flowing air through the chimney.

3.2 Energy balance equation of solar chimney
Heat interaction, occurred in the solar chimney components, mainly chimney cover, stagnant air, absorber wall and the flowing air into the chimney, can be expressed in the following manner:

3.2.1 Energy balance equation of solar chimney cover

\[ S_{cc} A_{cc} + h_{ac} A_{ab} (T_{ab} - T_{cc}) + h_{ac} A_{cc} (T_{cc} - T_{wa}) = h_c A_{cc} (T_{cc} - T_a) + U_t A_{cc} (T_{cc} - T_u) \] \hspace{1cm} (4)

In the Eq. (4), the first part of the left hand side indicates radiant heat absorbed by cover of the solar chimney, the second part of the left hand side indicates radiant heat coming from absorber wall, the
first part of the right hand side indicates convective heat transfer from cover to stagnant air, the second part of the right hand side indicates overall heat transfer from chimney cover to ambient air.

Radiation heat flux absorbed by the chimney cover (\(S_{cc}\)) of the Eq. (4) is given by

\[ S_{cc} = \alpha_{cc} I_{t} \]  

(5)

The radiative heat transfer coefficient (\(h_{rac}\)) of the Eq. (4) can be expressed as (Bansal et al., 2005):

\[ h_{rac} = \sigma(T_{cc}^{2} + T_{sky}^{2})(T_{cc}^{2} + T_{sky}^{2})(T_{cc} - T_{sky})/(T_{cc} + T_{sky})/T_{cc} - T_{a} \]  

(6)

The overall top heat loss coefficient (\(U_{t}\)) of the Eq. (4) is the summation of convective heat transfer coefficient due to wind, radiative heat transfer coefficient between the chimney cover and the sky, and heat transfer coefficient of cover, written as (Mathur et al., 2006):

\[ U_{t} = h_{w} + h_{rcs} + h_{c} \]  

(7)

In the Eq. (7), the heat transfer coefficient caused by wind (\(h_{w}\)) is written as (Ong and Chow, 2003):

\[ h_{w} = 5.7 + 3.8v_{w} \]  

(8)

The radiative heat transfer coefficient (\(h_{rcs}\)) of the Eq. (7) between the chimney cover and the sky, given by (Bansal et al., 2005)

\[ h_{rcs} = \sigma\epsilon_{cc}(T_{cc} + T_{sky})(T_{cc}^{2} + T_{sky}^{2})(T_{cc} - T_{sky})/(T_{cc} + T_{sky}) \]  

(9)

The sky temperature (\(T_{sky}\)) of the Eq. (9) is expressed as:

\[ T_{sky} = 0.0552I_{a}^{1.5} \]  

(10)

3.2.2 Energy balance equation of stagnant air

\[ h_{sa}A_{sa}(T_{sa} - T_{cc}) + h_{c}A_{cc}(T_{cc} - T_{sa}) = m_{sa}C_{p}(T_{sa} - T_{a}) \]  

(11)

In the Eq. (12), the first part of the left hand side indicates convective heat transfer from absorber wall to stagnant air, the second part of the left hand side represents convective heat transfer from chimney cover to stagnant air, and the first part of the right hand side represents heat gain by stagnant air.

3.2.3 Energy balance equation of absorber wall

\[ S_{ab}A_{ab} = h_{sf}A_{ab}(T_{aab} - T_{fa}) + h_{sa}A_{ab}(T_{ab} - T_{sa}) + h_{rcs}A_{ab}(T_{ab} - T_{cc}) \]  

(12)

In the Eq. (12), the First part of the left hand side indicates radiant heat gain by absorber wall, the first part of the right hand side of the Eq. (12) indicates convective heat transfer from chimney cover to flowing air, the second part of the right hand side indicates convective heat transfer to stagnant air, the third part of the right hand side indicates radiant heat transfer from absorber to the chimney cover.

Solar radiation gained by absorber wall is given by

\[ S_{ab} = \alpha_{ab} \tau_{ab} I_{t} \]  

(13)

3.2.4 Energy balance equation of flowing air stream of the chimney

\[ h_{af}A_{ab}(T_{ab} - T_{fa}) = m_{b}C_{p}(T_{flow} - T_{fa}) \]  

(14)

In the Eq. (14), the first part of the left hand side indicates convective heat transfer from absorber to the flowing air stream of the chimney, the first part of the right hand side represents useful heat gain of the flowing air stream.

The heat transfer co-efficient of the flowing air stream can be written as (Incropera and Dewitt, 2006):

\[ h_{af} = \frac{Nuk_{f}}{d_{cc}} \]  

(15)

Mean air temperature of fluid could be estimated by
\[ T_{fa} = \gamma T_{fa0} + (1 - \gamma)T_{fa1} \]  

(16)

Where \( \gamma \) represents the mean temperature approximation coefficient and the value is taken as 0.74 (Ong and Chow, 2003).

Air properties, which are evaluated and updated at the respective mean temperatures (Incropera and Dewitt, 2006).

The five energy balance equations Eq. (1), Eq. (4), Eq. (11), Eq. (12) and Eq. (14) and a mass flow rate equation Eq. (3) are to be solved for six unknown variables (\( T_{cc}, T_{sat}, T_{ab}, T_{fa}, T_{gh}, \) and \( m_i \)). In solving these equations other parameters (heat transfer coefficients, absorbed radiant energies etc) are calculated from their relevant equations as stated above. The model equations as described above are integrated in programme code using EES software. An initial guess is made for \( T_{fa} \) and \( T_{gh} \); accordingly first estimate of \( m_i \) and \( T_{gh} \) are made using Eq. (1) and Eq. (3). Then other four equations are solved simultaneously for the other unknowns. The calculation loop is repeated until the temperature parameters are stabilized. Temperature of the ambient air and solar radiation intensities are taken from the published book of G.N Tiwari (2002) for the climatic data of Kolkata.

**Table 1. Input parameters**

| Parameter          | Value                  | Parameter          | Value                  |
|--------------------|------------------------|--------------------|------------------------|
| Covered area, \( A_c \) | 173 [by design]        | \( \tau_{cc} \)   | 0.78 (Ganguly and Ghosh, 2007) |
| Chimney area, \( A_o \) | 0.785 [by design]      | \( C_d \)       | 0.6 (Boulard et al. 1999)   |
| Side vent area, \( A_s \) | 56.54 [by design]     | \( C_w \)       | 0.14 (Boulard et al. 1999)   |
| \( \varepsilon_{cc} \)  | 0.94 (Rachmat, 1999)  | Greenhouse volume, \( G_{vol} \) | 349 [by design] |
| \( \varepsilon_{ab} \)  | 0.95 (Ong and Chow, 2003b) | \( h_{c} \) | 4.5 (Ganguly and Ghosh, 2007) |
| \( \alpha_{cc} \)       | 0.07 (Rachmat, 1999)  | \( h_{as} \)     | 10 (Incropera and Dewitt, 2006) |
| \( \alpha_{ab} \)       | 0.95 (Ong and Chow, 2003b) | \( v_{w} \) | 1.2 (Misra & Ghosh, 2013) |

4. Results Discussion

Theoretical results of the solar chimney greenhouse have been presented here. Table 2 shows the typical performance of a solar chimney greenhouse considering total solar radiation intensity 400 W/m\(^2\) and ambient temperature 30\(^o\)C. It is found that ventilation rate obtained from the solar chimney greenhouse is more than the greenhouse with no solar chimney. It is also seen that with less shading, the ventilation rate of air is more as air receives more solar heat gain. Thus, depending upon plant tolerance level, shading can be provided into the greenhouse. Table 3 shows ventilation rate of air influences on chimney height. Increase in chimney height ventilation rate increases.

**Table 2. Ventilation rate of the greenhouse with and without solar chimney**

| \( I_t = 400 \text{W/m}^2, T_a = 30^\circ \text{C} \) | Ventilation rate (ACM) with solar chimney | Ventilation rate (ACM) without solar chimney |
|-------------------------------------------------|----------------------------------------|-------------------------------------------|
| \( 0.673 \) (S.F=0.75)                          | 0.782 (S.F=0.5)                        |
| 0.42 (S.F=0.75)                                 | 0.46 (S.F=0.5)                         |

**Table 3. Ventilation rate of the greenhouse for different height of solar chimney**

| \( I_t = 400 \text{W/m}^2, T_a = 30^\circ \text{C} \) | Height of the solar chimney (m) | Ventilation rate (ACM) |
|---------------------------------------------------|--------------------------------|------------------------|
|                                                   | 10                             | 0.673                  |
|                                                   | 15                             | 0.703                  |
|                                                   | 20                             | 0.734                  |
|                                                   | 25                             | 0.768                  |
|                                                   | 30                             | 0.804                  |
5. Conclusion
In the present study, a theoretical prediction of ventilation rate with and without using solar chimney has been presented for a circular greenhouse. The performance results have been obtained considering a constant shading of the greenhouse canopy. It is understood that using double wall solar chimney ventilation rate can be enhanced satisfactorily.

References
[1] Ganguly A and Ghosh A 2009 Model development and experimental validation of a floriculture greenhouse under natural ventilation Energy and Buildings 41 521–527
[2] Teitel M and Tanny J 1999 Natural ventilation of greenhouses: experiments and model Agricultural and Forest Meteorology 96 (1–3) 59–70
[3] Boulard T, Haxaire R, Lamrani M A, Roy J C and Jaffrin A 1999 Characterization and modeling of the air fluxes induced by natural ventilation in a greenhouse Journal of Agricultural Engineering Research 74 (2) 135–144
[4] Kittas C, Boulard T and Papadakis G 1997 Natural ventilation of a greenhouse with ridge and side openings: sensitivity to temperature and wind effects Transactions of ASAE 40 (2) 415–425
[5] Bansal N K, Mathur J, Mathur S and Jain M 2005 Modeling of window-sized solar chimneys for ventilation Building and Environment 40 1302–1308
[6] Ong K S 2003a A mathematical model of a solar chimney Renewable Energy 28 1047–1060
[7] Ong K S and Chow C C 2003b Performance of a solar chimney Solar Energy 74 1–17
[8] Roy J C, Boulard T, Kittas C and Wang S 2002 Convective and Ventilation Transfers in Greenhouses Part 1: the Greenhouse considered as a Perfectly Stirred Tank Biosystems Engineering 83(1) 1–20
[9] Mathur J, Bansal N K, Mathur S, Jain M and Anupma 2006 Experimental investigations on solar chimney for room ventilation Solar Energy 80 927–935
[10] Burek S A M and Habeb A 2007 Air flow and thermal efficiency characteristics in solar chimneys and Trombe Walls Energy Buildings 39 2007 128–135
[11] Bassiouney R and Koura N S A 2008 An analytical and numerical study of solar chimney use for room natural ventilation Energy Buildings 40 865–873.
[12] Tan A and Wong N 2003 Parameterization Studies of Solar Chimneys in the Tropics Energies 6 145–163
[13] Saleem A A, Bady M, Ookawara S, Ali K and Abdel-Rahman 2017 Achieving standard natural ventilation rate of dwellings in a hot-arid climate using solar chimney http://dx.doi.org/doi:10.1016/j.enbuild.2016.10.001
[14] Tiwari G N 2002 Solar Energy-Fundamentals, Design, Modeling and Application Narosa Publishing House New Delhi India
[15] Tiwari G N and Goyal R K 1998 Greenhouse Technology Narosa Publishing House New Delhi India
[16] Rachmat R and Horibe K 1999 Solar heat collection characteristics of a fiber reinforced plastic drying house Transactions of the ASAE. 42(1)149-157
[17] Incropera F P and Dewitt D P 2006 Fundamental of heat and mass transfer, 6th Edition John Wiley and Sons, New Jersey