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THERMAL MATHEMATICAL MODEL OF A SOLAR CHIMNEY FOR PASSIVE VENTILATION

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Abstract: The new designs of homes and buildings contemplate the use of alternative sources and ventilation plays an important role. Ventilation can be induced by passive and active systems, the latter using mechanical means, which causes high electrical energy consumption. Within the passive ventilation systems we can mention Wind Towers, Trombe Walls, Double Facades and **Solar Chimneys**, each of these systems are capable of inducing air through the premises using natural energy sources such as wind and/or solar energy. This work presents the detailed energy balance of a solar chimney and its solution algorithm.
Keywords: Solar irradiance, Clear sky model, Campeche.

INTRODUCTION

It is estimated that more than 90% of the time, on average, people carry out their activities within a built space, where the temperature and humidity conditions are not always adequate. This is particularly true in a wide variety of contemporary buildings that, due to their inadequate design conditions: orientation and materials used, present conditions outside the comfort zone. To access such conditions, mechanical air conditioning systems must normally be used, whose energy consumption can become excessive, with consequences for the environment.

The new designs of homes and buildings contemplate the use of alternative sources and ventilation plays an important role. Ventilation is a term that encompasses most of the variables of human comfort, and is currently considered one of the primary strategies in the design of homes and buildings.

Ventilation can be classified into two types: forced ventilation and natural ventilation. Forced ventilation makes use of mechanical means such as fans and extractors, while natural ventilation does so through passive means that take advantage of natural forces such as wind, buoyancy forces due to differences in densities caused by thermal gradients coming from of solar energy. The use of passive systems to naturally ventilate a building is an old technique, perhaps not completely perfected, and has regained importance during the last three decades. A passive system can be defined as a device that is simple in construction and operation, and that can take part of the same building structure. Unquestionably, naturally ventilated buildings use less electrical energy than mechanically ventilated ones, which is why these systems have taken on great importance in recent years [1].

Within the passive ventilation systems we can mention Wind Towers, Trombe Walls, Double Facades and Solar Chimneys, each of these systems are capable of inducing air through the premises using natural energy sources such as wind and/or solar energy [2].

Various national [1 and 3] and international [2 and 4-10] studies, to name a few, highlight the interest of the current scientific community in the study and application of solar chimneys in building ventilation. Without a doubt, numerical simulation is widely used for the study and design of these systems [6 and 9]. Therefore, this first work aims to verify the implementation of the mathematical model proposed by Ong in 2003 [11] in the numerical calculation software Scilab, for the simulation of a solar chimney.

METHOD DESCRIPTION

Figure 1 shows a cross section of the physical model of the wall-type chimney, the parts that make it up are, from left to right, room, thermal insulator, absorber plate with a matte black finish (because it has a greater absorptivity whose purpose, as its name indicates, is to absorb the greatest possible solar radiation), hollow channel for correct air flow and the cover, which must be made of a semi-transparent material with the highest possible transmissivity. Incident solar radiation manifests itself in three ways, which are: transmission, reflection and absorption in the cover, most of this energy is retained in the absorber plate where energy losses are associated with heat transfer processes: conduction, convection and radiation. The air enters the chimney at room temperature (Tf,i). The air is considered to be at room temperature (Tr) and is assumed constant. On the other hand, at the exit of the chimney only warm air is considered, at a temperature (Tf,o) of the upper part of the chimney. The temperatures on the surfaces of the semitransparent cover (Tg) are all assumed to be uniform. The friction resistance of the air flow over all surfaces is considered negligible.

MATHEMATICAL MODEL

The thermal network representing the steady-state heat flows for the considered physical model is shown in Figure 2.

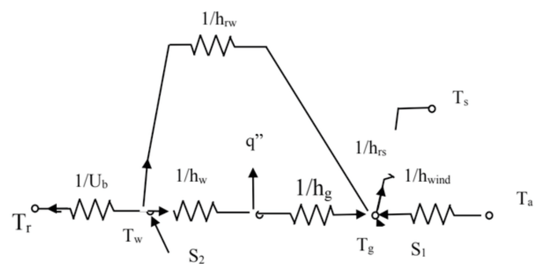

Figure 2: Thermal network of the solar chimney. Ong,

The energy balance in each element of the chimney, the glass cover, the air between the channel and the absorber plate, results in equations based on the heat transfer coefficients and the energies that are absorbed per unit area. of these elements, resulting in the following equations:

$$T_g: (h_{g+}h_{rwg} + U_t)T_g - h_g T_f - h_{rwg} T_w = S_1 + U_t T_a \quad (1)$$

$$T_f: h_g T_g - (h_g + h_w + M)T_f + h_w T_w = -MT_{f,1} \quad (2)$$

$$T_w: -h_{rwg} T_g - h_w T_f + (h_w + h_{rwg} + U_b)T_w = S_2 + U_b T_r \quad (3)$$

The total coefficient of heat transfer loss in the semi-transparent cover to the environment is given by:

$$U_t = h_{wind} + h_{rs} \quad (4)$$

Equations (1) - (3) written in matrix form:

$$\begin{bmatrix} (h_{g+}h_{rwg} + U_t) & -h_g & -h_{rwg} \\ h_g & -(h_g + h_w + M) & h_w \\ -h_{rwg} & h_w & (h_w + h_{rwg} + U_b) \end{bmatrix} \begin{bmatrix} T_g \\ T_f \\ T_w \end{bmatrix} = \begin{bmatrix} U_t T_a + S_1 \\ -MT_{f,1} \\ S_2 + U_b T_r \end{bmatrix}$$

We can interpret the matrix as follows:

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

To obtain the temperature vector it can be determined by inverting the matrix and it would look like:

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

Where the convective and radiative heat transfer coefficients are given by:

$$h_{rs} = \frac{\sigma\, \varepsilon_g\, (T_g + T_s)(T_g^2 + T_s^S)(T_g - T_s)}{(T_s - T_a)} \quad (5)$$

$$h_{r,w-g} = \frac{\sigma\, (T_g^2 + T_W^S)(T_g + T_W)}{(\frac{1}{\varepsilon g} + \frac{1}{\varepsilon w - 1})} \quad (6)$$

$$h_{wind} = 5.7 + 3.8\, V. \quad (7)$$

The sky temperature is given by Swinbank [12] as:

$$T_s = 0.0552\, T_a^{1.5} \quad (8)$$

For natural convection heat transfer between the wall and the semi-transparent cover (hg) is given by DeWitt [13], where for a laminar flow ($Ra<10^9$):

$$Nu = \frac{0.68 + (0.67\, Ra^{\frac{1}{4}})}{\left[1 + \left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right]^{4/9}} \quad (9)$$

And for a turbulent flow ($10^9<Ra$):

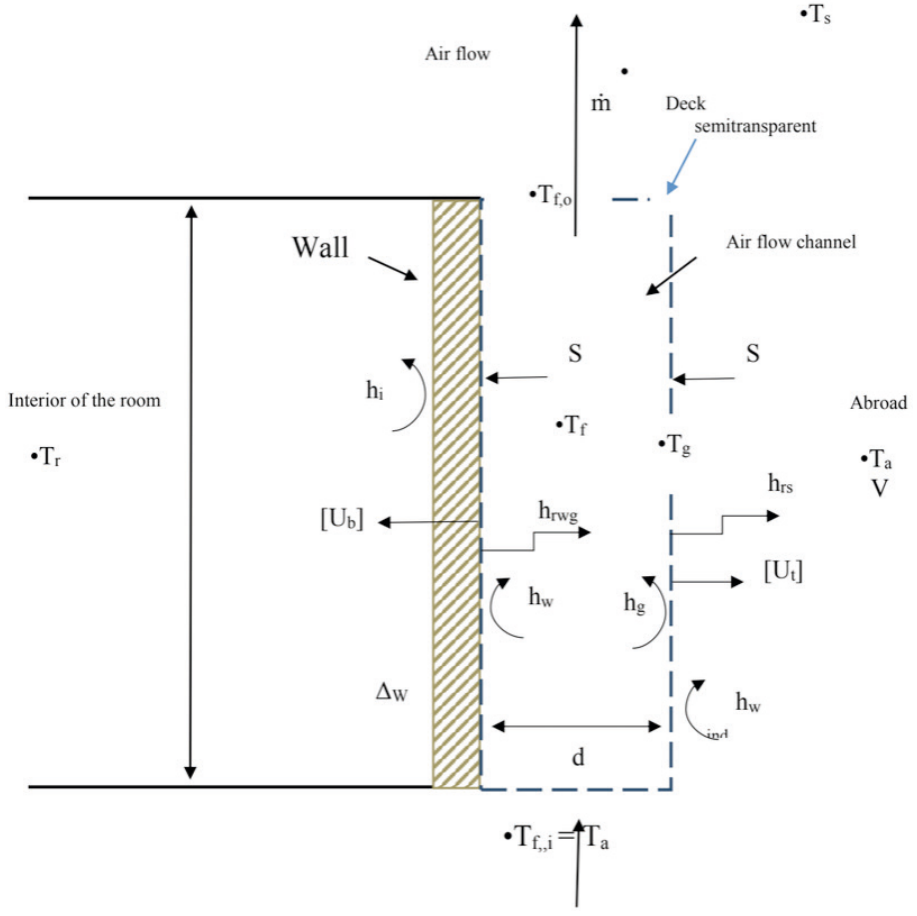

Figure 1. Physical model of the solar chimney. Ong, 2003 [11].

$$Nu = \left\{ \frac{0.825 + \left(0.387 Ra^{\frac{1}{6}}\right)}{\left[1 + \left(\frac{0.492}{Pr}\right)^{9/16}\right]^{8/27}} \right\}^2 \tag{10}$$

From experimental observations, an optimal value of γ=0.75 is reported. The useful heat transfer for the air stream is then written in terms of mean and indoor air temperature.

$$\dot{q}'' = \frac{\dot{m} c_f \left(T_f - T_{f,i}\right)}{\gamma W L} \tag{11}$$

Defining:

$$M = \frac{\dot{m} c_f}{\gamma W L} \tag{12}$$

The useful heat transfer is expressed as:

$$\dot{q}'' = M\left(T_f - T_{f,i}\right) \tag{13}$$

The volumetric air flow is calculated with the following equation:

$$\dot{V}_o = C_d \frac{A_o}{\sqrt{1 + A_r}} \sqrt{\frac{2gL\left(T_f - T_r\right)}{T_r}} \tag{14}$$

$$\dot{m} = C_d \frac{\rho_{f,o} A_o}{\sqrt{1 + A_r}} \sqrt{\frac{2gL\left(T_f - T_r\right)}{T_r}} \tag{15}$$

The recommended value for the discharge coefficient C_d is 0.6 [14].

RESULTS

Figure 3 qualitatively compares the results obtained from the temperatures with the simulation code implemented in Scilab with the results reported by Ong, 2003, [11]. It is observed that the results agree satisfactorily with the data reported by the author. In the same way, Figure 4 compares the efficiency and mass flows in different positions of the chimney, it is concluded that the results also agree with those of the author Ong.

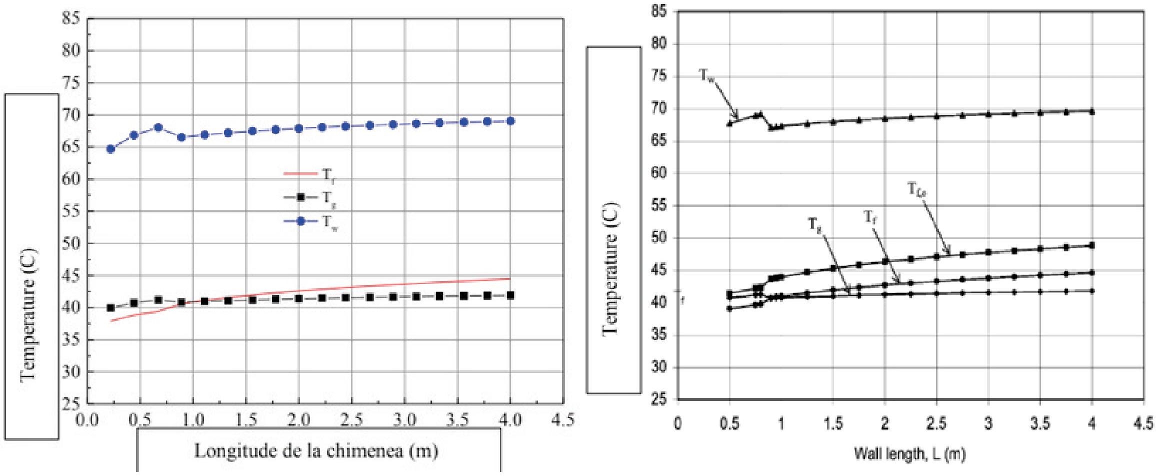

Figure 3: Comparison of temperatures with those reported by Ong, 2003.

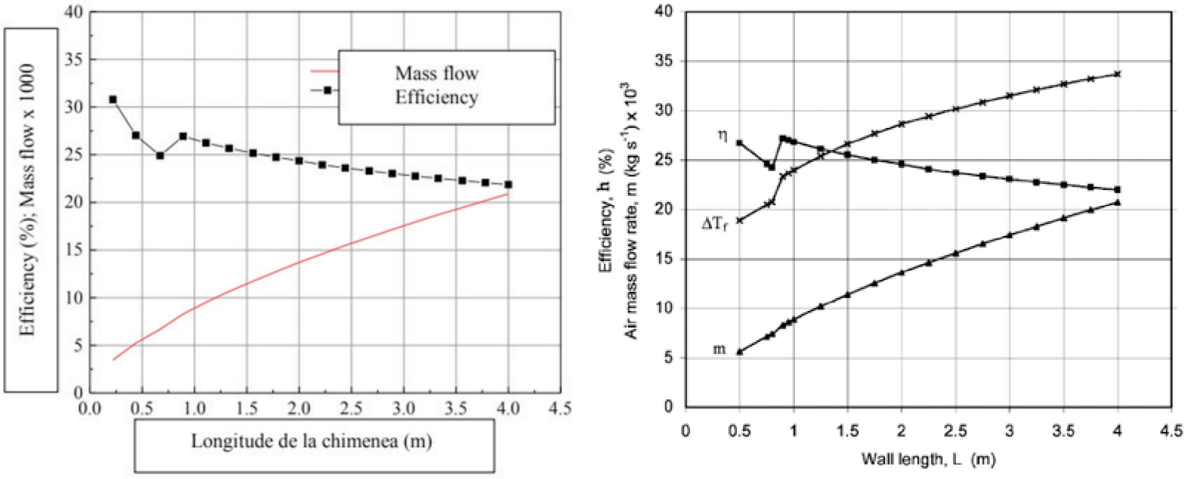

Figure 4: Comparison of efficiency and mass flow with those reported by Ong, 2003.

CONCLUSIONS

In the present work, the physical and mathematical model of a solar chimney for its application as passive ventilation in buildings was described, all the energy balances in the glass cover, in the absorber plate and in the air confined between them were presented in detail. these, from which the equations are obtained to determine the one-dimensional temperature profile in the permanent state of these elements. These equations were expressed in terms of heat transfer coefficients by convection and radiation, and the equations necessary for their calculation were described. Because the equations are nonlinear, it was necessary to implement the solution in a numerical code, which was carried out in the Scilab numerical calculation software. The results obtained from the developed code were verified with the results reported in the literature, obtaining satisfactory results.

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