Passive ventilation through a solar chimney

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Abstract: the aim of the current thesis is to present a physical model with the purpose of describing the performance of a solar chimney. It has to be in contact with an enclosure allowing the airflow with the outside. This effect would be the result of the natural convection caused by the incidence of the solar radiation throughout the day. Consequently, the hypothetical cooling of the enclosure itself in summer will be studied. To do so, the dependency of the chimney's instantaneous efficiency on different structural parameters as the length or the tilt with respect to the horizontal plane will be analysed. The model is based on the energy balance between the different parts of the chimney; a few equations which will be solved iteratively. Therefore, several magnitudes involved in the process will be determined, such as the different uniform temperatures or the air mass flow rate through the chimney.

I. INTRODUCTION

A perfectly appropriate case for this study is the air ventilation that has to be present in the farms belonging to the swine sector. Throughout the last decades, farmers have been investing big sums of money to provide huge amounts of energy from electricity or the burning of fossil fuels to the complex ventilation systems installed in the farms. The only intention for this is keeping a suitable room temperature so that the different stages as the gestation, lactation or weaning are satisfactorily completed.

For this reason, the ventilation which doesn't require a consumption of artificial energy is known as *passive*, and it is mainly aimed for cooling. In this case, the chimney will allow the air stream to passively ventilate the farm: the solar energy will be absorbed in order to heat up the air of the chimney channel. In this way, it will raise by a difference of pressure and density with the outside, where the temperature is lower; this phenomenon is known as natural convection.

Therefore, the objective of this thesis isn't only to determine the physical magnitudes involved in it. Other purposes include knowing the most adequate way to pose and solve the problem and also finding out in which circumstances the efficiency of the ventilation by the chimney is maximum.

II. PHYSICAL MODEL

Tackling a convective problem is not an easy task. Thus, the mathematical model that will be developed here must be as simple as possible, and only in this way we will able to find a solution to all of the parameters of the problem.

A. The solar chimney

First of all, before analysing the physical scenario, this has to be well defined. In this way, we will start by presenting the chimney's structure. The part that is directly exposed to the outside is a translucent glass cover (L1), which would allow the transfer of the solar radiation. Consecutively, the solar heat absorbing wall (L2) is found, consisting of a blackened surface with the objective of capturing all possible radiation. The space that is between these two is the flow channel, that is to say where the air will flow from the bottom to the top. This is due to the heat captured by the wall that is transferred to the air channel. Therefore, in this order, the room air will enter into the chimney, raise up, and finally leave the channel.

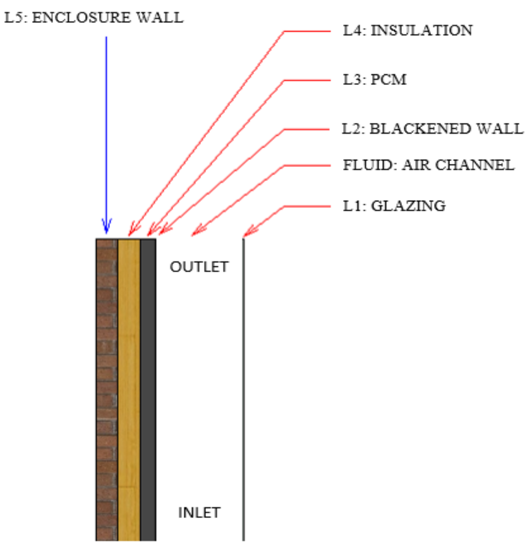

FIG. 1: The built-in solar chimney's structural distribution.

The next wall is another issue that must be analysed apart from this study. Liu and Li [5] were pioneers in the experimental study of a solar chimney PCM-based (L3). The phase-change material has the function of absorbing the heat radiated from the sun during the daytime, storing it to release it at night-time. After the sunset, without radiation the temperature of the air channel won't be high enough to cause natural convection. For this reason, the integration of a PCM unit into the solar chimney could improve and optimise the utilization of the solar energy with the aim of lengthening the night ventilation of the enclosure, in this case the farm.

The chimney position is also a primary factor that completely modifies the resolution of the physical problem. In this study we will consider two alternatives of this: built-in or on the roof. In both cases, the presence of an insulation is essential, and thus the next part will be an insulator (L4) that prevents heat losses. Lastly, only in the built-in chimney, the farm's own wall (L5) will cover the insulation, while for a chimney on the roof, the latter will be in contact with the outside.

B. Overall thermal energy balance

Ong [7] was one of the first to propose a thermal network in the form of algebraic equations describing the heat exchange across the different parts of the chimney. In this study, we'll work with four equations:

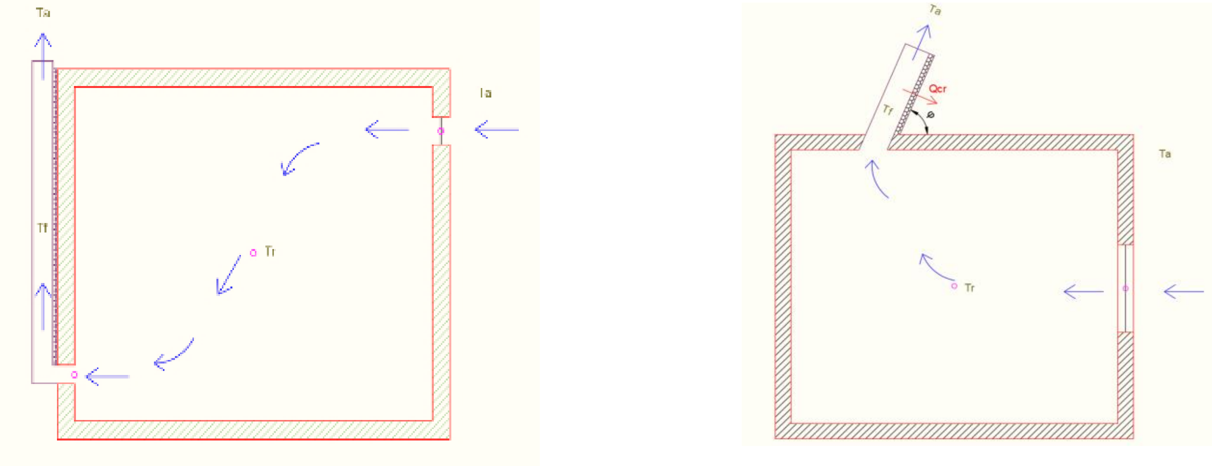

FIG. 2 & 3: Representative schemes of built-in chimney (left) and tilted on the roof (right).

glazing $\quad S_1 + Q_{f\to 1} + K_{2\to 1} = K_{1\to s} + Q_{1\to a} \quad (1)$

air $\quad Q_{2\to f} = \dot{q} + Q_{f\to 1} \quad (2)$

wall $\quad S_2 = Q_{2\to f} + C_{2\to 4} + K_{2\to 1} \quad (3)$

and depending on the position of the chimney

built-in $\quad C_{2\to 4} = C_{4\to r} \quad (4)$

roof $\quad C_{2\to 4} = K_{4\to s} + Q_{4\to a} \quad (5)$

where the numbers in subscript refer to the different parts of the chimney (L1, L2…) and the letters are:

Subscript	Meaning
f	fluid (air channel)
s	sky
a	environment (outside)
r	room (farm)

TABLE 1: Nomenclature of the system of thermal equations.

On the other hand, if H refers to the global solar irradiation on a fixed plane $\left[\frac{W}{m^2}\right]$ that hits the surface of the chimney, S is the one that is absorbed, with the distinction of:

$$S_1 = \alpha_1 H \tag{6}$$

$$S_2 = \tau_1 \alpha_2 H \tag{7}$$

where the different coefficients are specified in the appendix. Moreover, the heat exchanges are:

Latin symbol	Transfer mechanism
Q	Convection
K	Radiation
C	Conduction

TABLE 2: Nomenclature of the transferred energy.

Each of these is always defined in the same way:

$$Q_{i\to j} = h\left(T_i - T_j\right) \tag{8}$$

$$K_{i\to j} = \varepsilon_{i\to j}\sigma\left(T_i^4 - T_j^4\right) \tag{9}$$

$$C_{i\to j} = U\left(T_i - T_j\right) \tag{10}$$

where $\sigma = 5{,}6704 \cdot 10^{-8}\ \frac{W}{m^2 K^4}$ is the Stefan-Boltzmann constant. h could be h_{wind} (from McAdams [6], when one of the exchangers is the environment) or h_{conv} (when this is the fluid), and thus the heat transfer coefficients are:

$$h_{wind} = 5{,}7 + 3{,}8V \tag{11}$$

$$h_{conv} = \frac{Nu\ k_f}{D_H} \tag{12}$$

$$\varepsilon_{i\to j} = \left(\frac{1}{\varepsilon_i} + \frac{1}{\varepsilon_j} - 1\right)^{-1} \tag{13}$$

$$U = \frac{1}{\sum_{L_i} R_i} \tag{14}$$

with $V = 1\ m/s$ the wind velocity, Nu the Nusselt number, k the air thermal conductivity, ε the emissivity, R the thermal resistance of the heat exchanger and $D_H \equiv \frac{L}{10}$ the hydraulic diameter, where L is the length of the chimney. All of these coefficients are also specified in the appendix.

In this way, the thermal network is based on four equations with four unknown variables: T_1, T_f, T_2 and T_4, which are considered to be uniform. Finally, the term $\dot{q}$ is analysed in the following subsection.

C. Air mass flow rate

The heat transferred to the air flowing in the chimney channel is given by:

$$\dot{q} = \frac{\dot{m}c_f}{W}\left(T_{f_o} - T_{f_i}\right) = \frac{\dot{m}c_f}{\gamma W}\left(T_f - T_r\right) \tag{15}$$

We consider a square chimney gap; then, $W \equiv \frac{L^2}{10}$ is the area of the wall, while c is the air specific heat that depends on the temperature. $T_{f_i} = T_r$ is the inlet temperature at the bottom of the chimney and T_{f_o} is the outlet temperature at the top of it; the latter is specified in the appendix, as well as the factor γ.

There are some ways of computing the air mass flow rate $\dot{m}$. We choose the one that uses pressure difference between a point above and one below the top of the chimney, calculated from Bernoulli's principle. It was proposed by Alemu [1]:

$$\dot{m} = \delta A \sqrt{2\rho_r (P_{out} - P_{in})} \tag{16}$$

where $A \equiv \frac{L^2}{100}$ is the area of the channel and ρ the air density depending on the temperature. Moreover, δ is a discharge coefficient that adjusts the air velocity for the friction losses along the channel:

$$\delta = \left[1 + \frac{\rho_r}{\rho_{f_o}} + \frac{L}{D_H} f\right]^{-\frac{1}{2}} \tag{17}$$

an expression extracted from Syrios [10]. The term f is the Darcy-Weisbach friction factor that depends on the air mass flow rate itself, as it is showed in the appendix. The equation is implicit, and then, it will be solved by the secant method.

In a real case, the wind velocity can be $V > 1\ m/s$, and due to Bernoulli's principle, $v_{air} = \frac{\dot{m}}{\rho_f A}$ would take off. This fact is evidenced in the following figure:

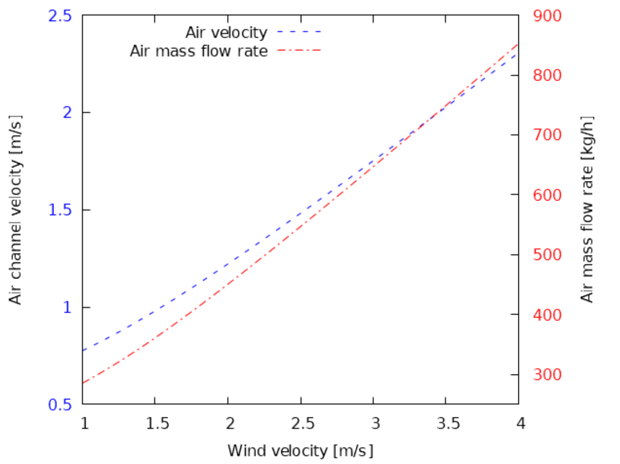

FIG. 4: Air channel velocity and mass flow rate depending on wind velocity.

If not stated otherwise, the physical conditions are always $L = 3\ m$, $H = 428\ \frac{W}{m^2}$, $T_a = 25{,}8\ °C$ and $T_r = 31{,}8\ °C$.

D. Resolution and results

After all, the thermal network is a system of nonlinear equations. For solving it, it will be used a modified Newton-Kantorowich iterative method using a FORTRAN programming. Then, in each iteration, $\dot{m}$ must be computed because it depends not only on wind velocity but also on unknown air temperature.

An interesting study is also the instantaneous efficiency of the chimney. Ong proposed the following:

$$\eta = \frac{\dot{q}}{H} \tag{18}$$

This efficiency gives us an idea of heat collection by the blackened wall of the chimney from the solar irradiation H.

Using the daily solar radiation database and temperature profile from PVGIS [8], we can represent the solutions of the system of equations throughout a day of August:

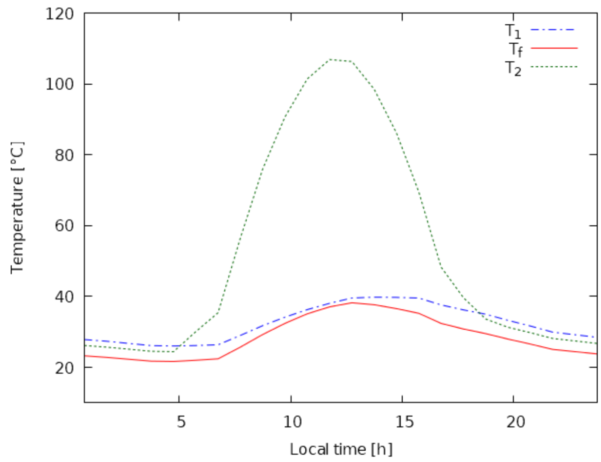

FIG. 5: The daily distribution of glass, air and wall temperatures for built-in chimney as well as on the roof.

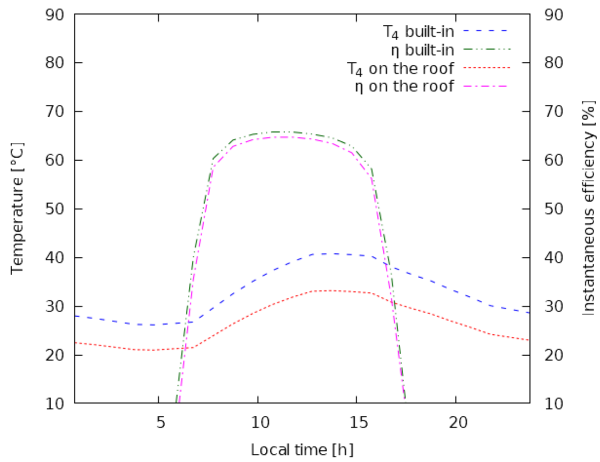

FIG. 6: The insulator temperature and the instantaneous efficiency depending on the position of the chimney.

Greater efficiency means greater ventilation, which drastically reduces the thermal stress of the animal:

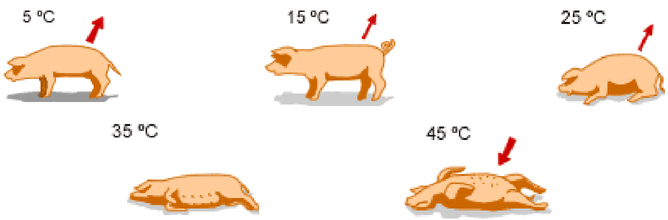

FIG. 7: The animal health and welfare get worse with temperature.

Thereby, the instantaneous efficiency has also interesting behaviours in dependence on structural parameters of the chimney itself that have to be studied:

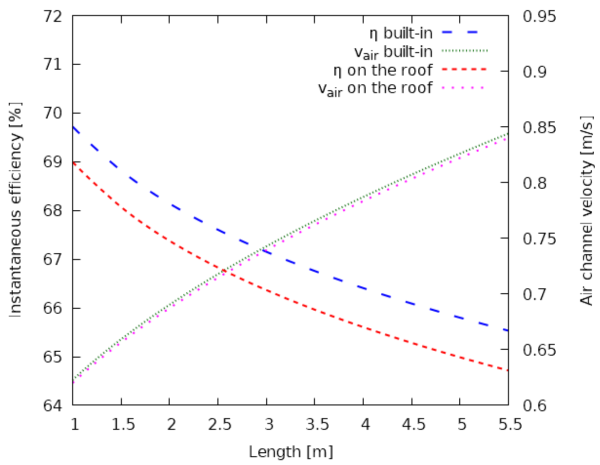

FIG. 8: The length is a factor to take into account regardless of the position of the chimney.

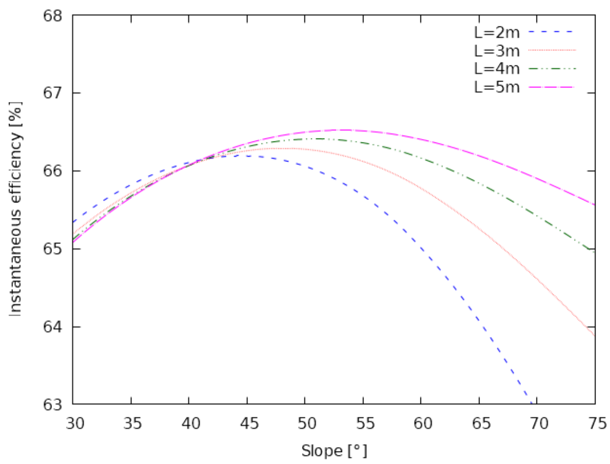

FIG. 9: The efficiency varies in relation to the tilt of the chimney on the roof according to the length.

III. CONCLUSIONS

- With other methods of computing $\dot{m}$, this remains almost constant whereas V increases. Then, the Alemu's method represents the most realistic scenario.
- At daytime, the wall temperature is clearly the highest, but without irradiation, at night-time, the temperature of the glazing is higher.
- The insulator temperature is the only that depends on the position of the chimney; if the latter is built-in, this temperature and the instantaneous efficiency are higher than if the chimney is on the roof.
- The air channel velocity increases with the length of the chimney, but surprisingly the efficiency decreases.
- For normal lengths, the optimal slope of a solar chimney on the roof is between 40° and 55° with respect to the horizontal plane. However, if it is built-in the maximum efficiency can be achieved with a length as short as possible.

IV. APPENDIX

The different terms that have been appearing throughout the text are:

A. Characteristic coefficients

The following coefficients of the different parts of the chimney are extracted from Duffie [2] and Garg [3].

Glazing (L1):

Coefficient	Meaning	Value
α	absorbance	0,05
τ	transmittance	0,93
ε	emissivity	0,10
e	roughness $[\mu m]$	1,50

TABLE 3: Characteristic coefficients of L1.

Wall (L2):

Coefficient	Meaning	Value
α	absorbance	0,90
ε	emissivity	0,95
e	roughness $[\mu m]$	90,00

TABLE 4: Characteristic coefficients of L2.

Moreover, the emissivity of the enclosure wall (L5) is $\varepsilon_5 = 0{,}05$.

By last, the different thermal resistances $[\frac{m^2K}{W}]$ of the heat exchangers by conduction are:

Coefficient	Value
R_2	$1{,}43 \cdot 10^{-5}$
R_3	0,07
R_4	2,00
R_5	2,17
R_r	0,13

TABLE 5: Different thermal resistances for each energy transferor by conduction.

B. Physical properties

The different physical properties of the air channel, such as the density ρ, the thermal conductivity k, the specific heat c and the dynamic and cinematic viscosity μ and ν respectively, depend on the temperature. Therefore, several value tables have been used to build an interpolator polynomial for each property that varies linearly with air temperature. These tables are extracted from Çengel [11]. The nomenclature is

$$\rho(T_i) \equiv \rho_i$$

C. Nusselt number

The Nusselt number can be computed with the Churchill and Chu correlation:

$$Ra < 10^9 \qquad Nu = 0,68 + \frac{0,67[Ra\sin(\varphi)]^{\frac{1}{4}}}{\left[1+\left(\frac{0,492}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{4}{9}}} \tag{19}$$

$$Ra \geq 10^9 \qquad Nu = 0,825 + \frac{0,387[Ra\sin(\varphi)]^{\frac{1}{6}}}{\left[1+\left(\frac{0,492}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}} \tag{20}$$

where the Prandtl and Rayleigh numbers are, respectively:

$$Pr = \frac{c_f \mu_f}{k_f} \tag{21}$$

$$Ra = Pr \cdot \frac{g D_H^3}{\nu_f^2} \frac{\left(T_i - T_f\right)}{T_f} \tag{22}$$

with $g = 9{,}81\, m/s^2$ the acceleration of gravity and T_i the temperature of the glazing or the wall, depending on where the convection exchange occurs.

D. Hydraulic diameter

Considering a square chimney gap, the width and the depth of the channel are $w = d \equiv \frac{L}{10}$, respectively. Then, the hydraulic diameter, by definition, is given by:

$$D_H \equiv \frac{2wd}{w+d} = \frac{L}{10} \tag{23}$$

E. Temperature correlations

The sky is assumed to be a black body. Then, Swinbank [9] proposes the following equivalent temperature:

$$T_s = 0{,}0552 T_a^{\frac{3}{2}} \tag{24}$$

Moreover, the outlet temperature at the top of the chimney is proposed by Hirunlabh [4] by means of this experimental correlation:

$$T_f = \gamma T_{f_o} + (1-\gamma) T_r \tag{25}$$

with $\gamma = 0{,}75$.

F. Darcy-Weisbach friction factor

Ong proved that for $L \leq 0{,}8\, m$ the natural convection in a solar chimney is developed by a laminar flow. Therefore, for higher lengths the Alemu's method must be considered in a rough-pipe turbulent air regime. Its friction factor is given by the Swamee-Jain equation:

$$f = \frac{1}{4}\left[\log\left(\frac{e_1 + e_2}{7{,}4 D_H} + \frac{5{,}74}{Re^{0{,}9}}\right)\right]^{-2} \tag{26}$$

where $Re = \frac{\dot{m} D_H}{A \mu_f}$ is the Reynolds number.

Acknowledgments

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