24th COBEM - 2017

24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-1469
Long time dynamic simulation of a Solar Chimney under the Uruguayan climate

Juan Pablo Kosut
Pedro Galione
Pedro Curto-Risso
Universidad de la Republica, Instituto de Mecánica y Produccion Industrial, Montevideo, Uruguay
jkosut@fing.edu.uy;pgalione@fing.edu.uy;pcurto@fing.edu.uy

Abstract. *The present work aims to evaluate the performance of a solar chimney under Uruguayan climate. A simplified numerical model was proposed, so long time simulations can be run with adequate precision and low computational costs. Special attention has been paid to friction losses determination, due to its relevance in mass flow calculation. Different flow regimens in the solar chimney channel were analyzed, and a strategy was proposed to estimate velocity profiles. The presented model has been verified and validated using both theoretical and experimental results. Furthermore, the developed model was used to evaluate the ability of a Solar Chimney to improve comfort conditions in a building under Uruguayan climate.*

Keywords: *solar chimney, mixed convection, buoyancy forces, friction losses*

1. INTRODUCTION

Natural ventilation is known to have important advantages over mechanical ventilation in terms of economics and environmental aspects. (Khanal and Lei, 2011; Hu *et al.*, 2017; Miyazaki *et al.*, 2006).

Particularly, buoyancy driven ventilation is generated by the presence of a temperature difference between the inside and outside of a building in combination with a chimney connecting both ambients. It is of great interest since it has the ability to provide ventilation even in windless days. Also it can properly match, natural energy resources as solar radiation, with ventilation demand, that is expected to be greater in summer days.

A solar chimney, which uses solar energy to heat the air, is a great strategy to enhance buoyancy effect by providing a sufficient temperature difference an consequently an adequate flow rate.

Also a solar chimney can accumulate energy for a certain period, through the thermal capacitance provided by the solid wall, and then provide ventilation or air heating some time later, so as to match demand in a better manner.

A large number of analytical, numerical and experimental studies of solar chimneys has been made. (Bansal *et al.*, 1993; Ong, 2003; Khanal and Lei, 2015; Chen *et al.*, 2003; Arce *et al.*, 2009).

In the present work, a simplified numerical model is proposed, so long time simulations can be run. It was implemented trough a one dimensional numerical model, using heat and friction coefficient correlations. The model is intended to describe physical phenomena in the solar chimney in order to predict mass flow rate with an adequate precision but at the same time with a low computational cost. Principal aspects of the physical phenomena are: available solar radiation, heat transfer to air, glass cover and absorber wall, energy accumulation in the wall and generation of mass flow by buoyancy effect.

To obtain the mass flow induced by the chimney, buoyancy forces will be balanced by friction looses. The description of friction losses is probably the most difficult aspect in the construction of the model. Local losses are present in the inlet and outlet of the chimney, and when a change in the direction of the air flow is imposed. Also, local pressure losses must be considered in the openings of the building from where air is conducted into the chimney (e.g. windows). Inside the chimney, distributed pressure looses along the channel will depend on the flow regime. Velocity profiles in such channels are quite complicated and cannot be assumed to be the same as in forced convection (Zamora and Kaiser, 2009; Khanal and Lei, 2014; Ojofeitimi and Hattori, 2017).

A particular strategy was developed to estimate the distributed pressure looses, based in the plume method presented by He *et al.* (2016).

2. SOLAR CHIMNEY NUMERICAL MODEL

The developed model resolves transient heat transfer in the absorber wall aiming to investigate the ability of the chimney to provide ventilation or air heating in the absence of solar radiation. Wall temperature is described in a two dimensional way. An implicit finite volume method is implemented to solve wall heat transfer. Air temperature distribution in the vertical direction is solved through a one-dimensional upwind scheme. Air flow rate results from the balance of the buoyancy and friction forces.

Figure 1 shows principal components of the solar chimney and interior ambient.

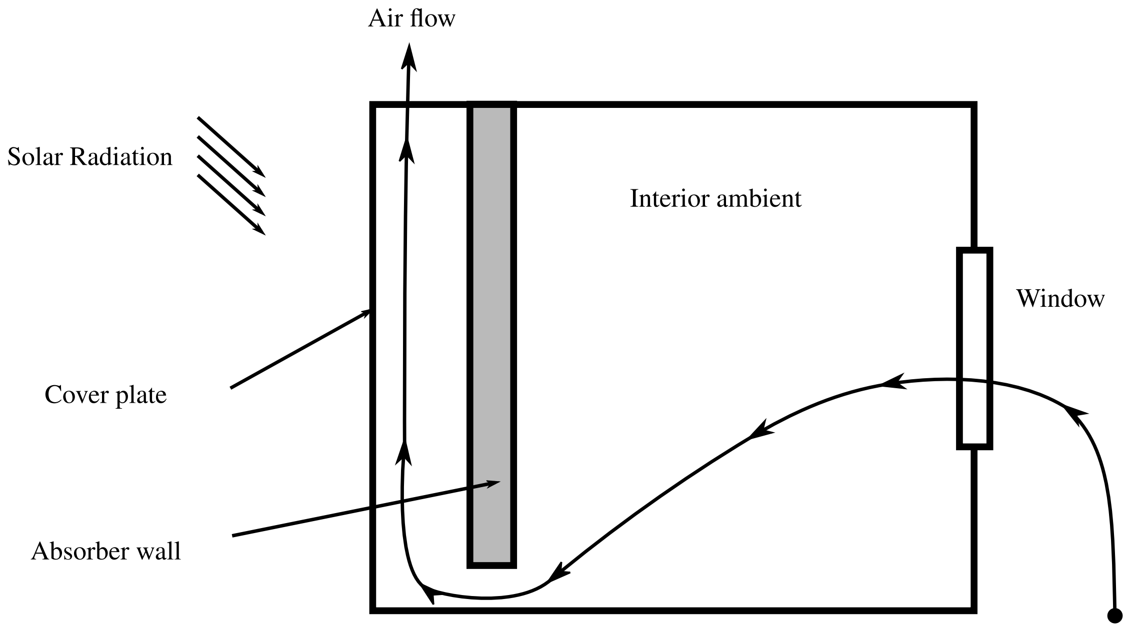

Figure 1. Solar chimney scheme

Heat transfer in the wall is resolved trough Eq. 1

$$\frac{\partial}{\partial t}(\rho T) = \frac{\partial}{\partial x}\left(\frac{k}{C_p}\frac{\partial}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{k}{C_p}\frac{\partial}{\partial y}\right) + S \tag{1}$$

The finite volume method was utilized (Maliska, 2010), and the iterative method of Gauss Seidel was implemented to solve the linear equations system. So, wall temperatures can be obtained from Eq. 2 for successive time intervals.

$$A_p T_p^{k+1} = A_s T_S^{k+1} + A_w T_W^{k+1} + A_e T_E^k + A_n T_N^k + B_p \tag{2}$$

Heat transfer to the air is calculated by Eq. 3. From the finite volume method Eq. 4 is obtained. For simplicity, transient effects and conduction in the flux direction were neglected.

$$\rho C_p\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial y}\right) = \dot{q} + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) \tag{3}$$

$$\rho u C_p D(T_{i-1} - T_i) + h_p \delta_y (T_p - T_i) + h_v \delta_y (T_v - T_i) = 0 \tag{4}$$

The cover plate is considered to have a uniform temperature, and heat capacity is neglected. So equation Eq. 5 is applied.

$$h_{rv,sky}(T_{sky} - T_v) + \alpha_v G_{solar} + h_{ext}(T_{amb} - T_v) + h_{rv,p}(T_p - T_v) + h_v(T_i - T_v) = 0 \tag{5}$$

As it was said, special attention must be paid to mass flow calculation and friction losses coefficient determination Equation 6 is obtained after balancing buoyancy forces and pressure losses.

$$(\rho_{ext} - \bar{\rho})\, gH + (\rho_{hab} - \rho_{ext})\, gH_1 = \frac{\dot{m}^2}{2} \left(\frac{k_1}{\rho_1 A_1^2} + \frac{k_2}{\rho_2 A_2^2} + \frac{k_3}{\rho_3 A_3^2} + \frac{k_4}{\rho_4 A_4^2} + \frac{fH}{D_h \rho_3 A_2^2} \right) \quad (6)$$

Considering Boussinesq approximation and ideal gas behavior, air velocity can be obtained from Eq. 7.

$$v_{ch} = \frac{1}{\sqrt{\sum R_i}} \sqrt{2 \left(\frac{\bar{T} - T_{ext}}{T_{ext}} \right) gH + 2 \left(\frac{T_{ext} - T_{hab}}{T_{ext}} \right) gH_1} \quad (7)$$

$$\sum R_i = \left(k_1 \frac{A_{ch}^2}{A_1^2} + k_2 \frac{A_{ch}^2}{A_2^2} + k_3 \frac{A_{ch}^2}{A_3^2} + k_4 \frac{A_{ch}^2}{A_4^2} + \frac{fH}{D_h} \frac{A_{ch}^2}{A_3^2} \right) \quad (8)$$

In Eqs. 6 to 8, coefficients k_i represents local losses in certain points of the air circuit and are refereed to the local velocity in each point. Values for these coefficients are obtained from the literature.

Special attention must be paid for distributed losses calculation, because different flow regimens (Zamora and Kaiser, 2009) can be found in the chimney channel. A strategy for estimating velocity profiles was implemented, based in the plume method presented by He *et al.* (2016). Plume method suggests to model air flux trough the chimney channel considering a constant velocity distributed in a certain part of the total channel width. In the present work the space occupied by the air flux was expressed in terms of turbulent boundary layer width, and adjusted by a parameter to experimental data.

2.1 Validation of numerical model

A set of verifications was carried out concluding that the model yields reasonable results. For some particular cases, it was possible to compare numerical results against analytical solutions.

The presented model has also been validated using both theoretical and experimental results.

Figure 2 shows comparison of the air flow induced by the solar chimney. It includes experimental data obtained by Chen *et al.* (2003), and analytical results reported by the same author. A comparison of both sets of data is made against the results obtained by the model developed in the present work.

The data was plotted against experimental measurement. So, model results are expected to be as close as possible to blue line . It can be observed that the proposed numerical model is able to predict air flow rate with better precision than the previous analytical model.

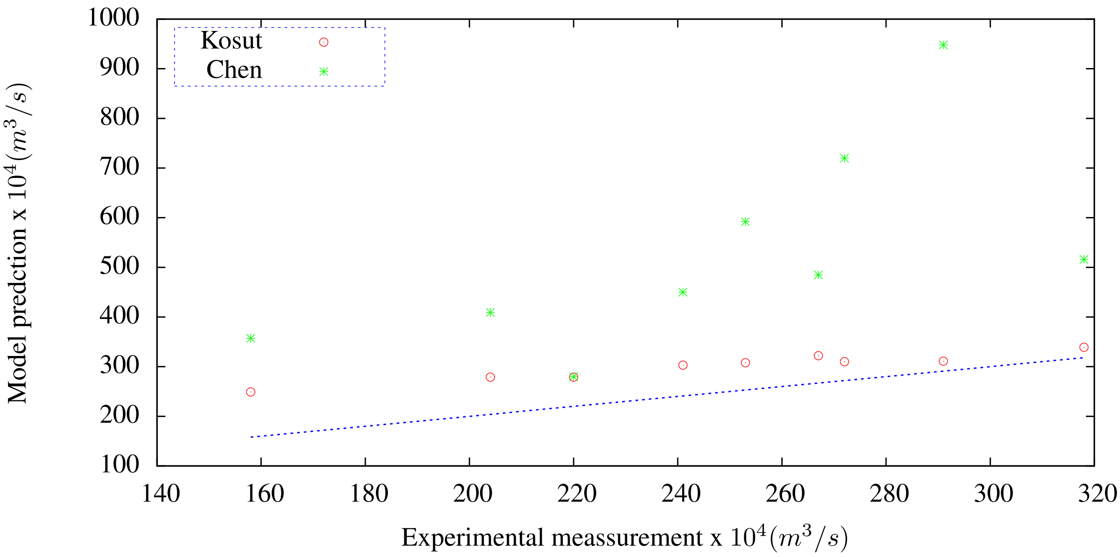

Figure 2. Comparative analysis: Experimental data-Analytical model-Proposed numerical model

3. BUILDING MODEL

In order to evaluate the ability of the solar chimney to provide comfort conditions in a building under Uruguayan climate, a very simplified model of the building was implemented, and the solar chimney was attached to the north wall. Fig. 3 shows summer and winter configurations for the solar chimney operation.

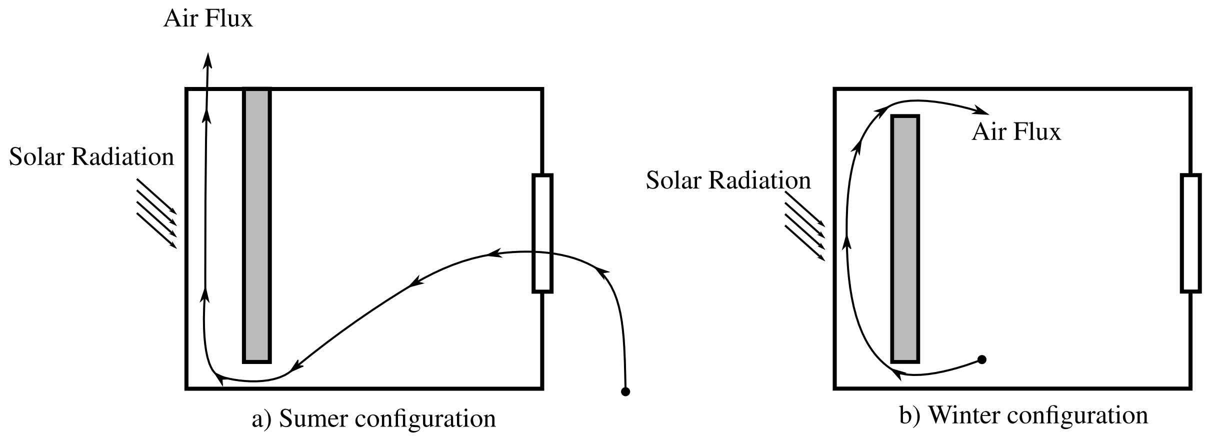

Figure 3. Solar chimney configurations

Walls, roof and floor of the room are considered to be at uniform temperature. Walls heat transfer is exclusively by convection to the room and ambient. Roof heat transfer is by convection to the room and ambient, and by radiation to the sky. Roof also receives solar radiation. Floor heat transfer is by convection to the room and by conduction to the ground. Interaction with the ground is modeled by a heat flux calculated from eq 9. (ATECYR, 2012)

$$T(z,t) = T_m - A_s e^{-z\sqrt{\frac{\pi}{365\alpha}}} cos\left[\frac{2\pi}{365\alpha}\left(t - t_0 - \frac{z}{2}\sqrt{\frac{365}{\pi\alpha}}\right)\right] \tag{9}$$

Equations 10 to 13 are walls, roof, floor and air discretized balances respectively. From this equations air room temperature can be calculated for each time interval.

$$\rho C_p \frac{\left(T^t_{wall} - T^{t-\delta t}_{wall}\right)}{\delta t} = h_{wall-ext}\left(T_{ext} - T_{wall}\right) + h_{wall-int}\left(T_{room} - T_{wall}\right) \tag{10}$$

$$\begin{aligned}\rho C_p \frac{\left(T^t_{roof} - T^{t-\delta t}_{roof}\right)}{\delta t} &= h_{roof-ext}\left(T_{ext} - T_{roof}\right) + h_{roof-int}\left(T_{room} - T_{roof}\right) \\ &\quad + \alpha G_{solar} - h_{rsky}\left(T_{roof} - T_{sky}\right)\end{aligned} \tag{11}$$

$$\rho C_p \frac{\left(T^t_{floor} - T^{t-\delta t}_{floor}\right)}{\delta t} = h_{f-ext}\left(T_{ext} - T_{floor}\right) + q^t_{ground} \tag{12}$$

$$\begin{aligned}h_{wall-int}\left(T_{wall} - T_{room}\right) + h_{roof-int}\left(T_{roof} - T_{room}\right) + h_{f-int}\left(T_{floor} - T_{room}\right) \\ + G_{air} C_p \left(T_{chim} - T_{room}\right) = 0\end{aligned} \tag{13}$$

4. METEOROLOGICAL DATA

Meteorological data used in the model was obtained from the work carried out by Alonso et al. [2016]. The authors presented a typical series of data that define the Typical Meteorological Year (TMY)

A typical meteorological series, represents statistically data from a long period of time, in terms of its mean values and variability. So, it can be used to simulate realistic human activities. For the construction of the series the authors used data from 15 years of solar irradiation obtained trough satellite photos. From that photos, they identified the presence of clouds, the main factor that affects the solar irradiation at surface level.

The typical annual series also contains some derived variables, such as direct irradiation data in normal plane or global irradiation in inclined plane. To obtain that information, it was necessary to previously separate the direct and diffuse components of the incident radiation. The authors made this separation using the Ruiz-Arias model, locally adjusted, to calculate the diffuse fraction.

Authors used the HDKR model to transport the obtained values to the sloped plane. For the horizontal plane, the model considers a non-isotropic distribution of diffuse radiation in the sky. In particular, takes into account the increase

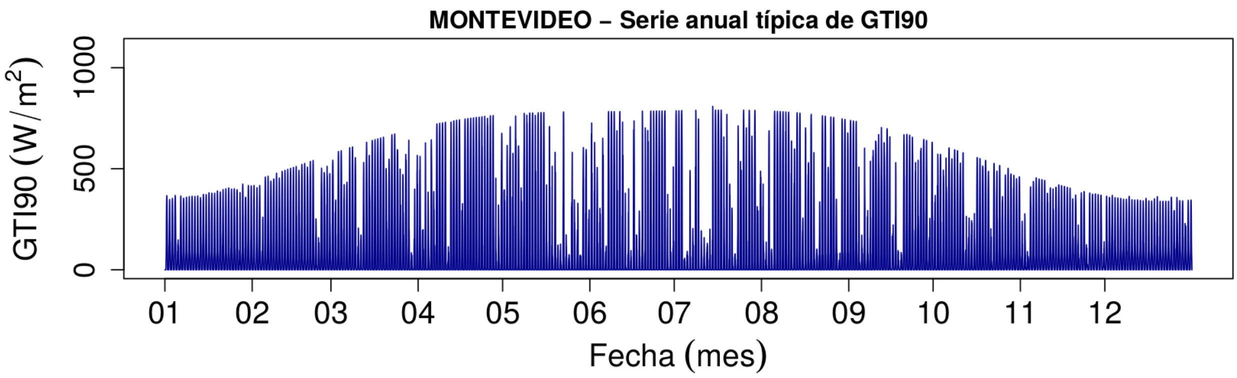

Figure 4. Typical irradiation series in vertical plane for Montevideo City

in radiation coming from the circumsolar zone. The model considers three components for incident radiation over sloped plane: the irradiation coming from the solar direction (Direct + circumsolar), the diffuse from the rest of sky, and the one reflected in the ground.

Figure 4, extracted from Alonso-Suárez *et al.* (2016) shows the daily averages of typical annual series of irradiation in the vertical plane oriented to the North, for the city of Montevideo. It is observed that maximums are greater in winter. However, in those months, cloudy days of low radiation appears very frequently. On the other hand, in summer, maximum values are lower than in winter but very few cloudy days are found.

5. RESULTS AND DISCUSSION

5.1 Winter Configuration

In winter, solar chimney should capture solar radiation and transfer it into the room, aiming to increase average interior temperature.

Simulations were carried out from June first to June 15.

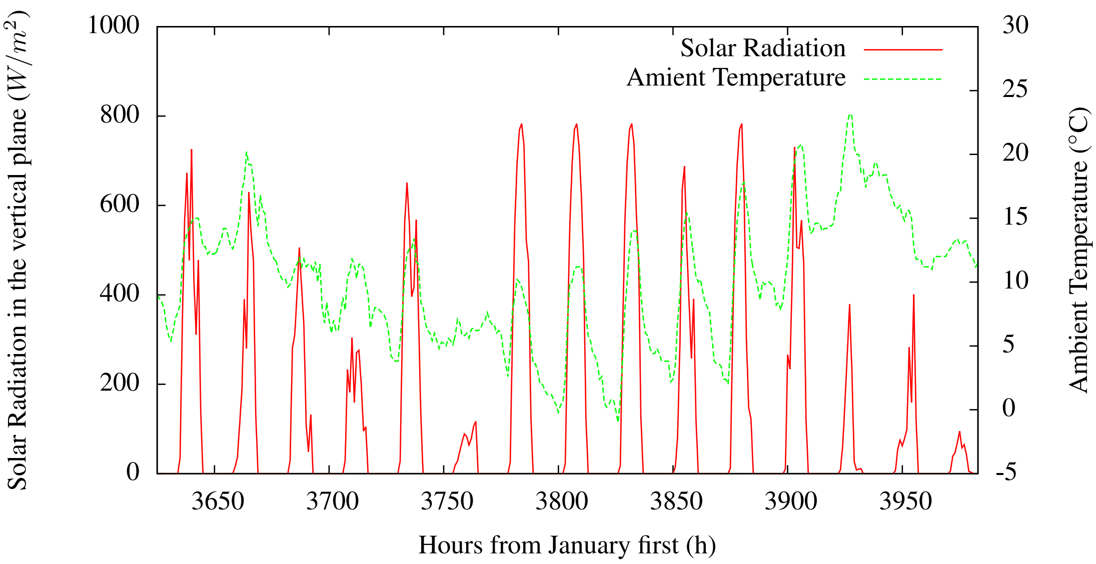

Figure 5. Winter conditions (TMY Montevideo) June First to June 15

Figure 5 shows ambient temperature and solar radiation in the vertical plane for the considered period. Solar radiation reaches a maximum of 780 W/m^2 in some days for which clear sky conditions occurred. For the majority of the days, at least some clouds are present. Also some cloudy days can be found with solar radiation being not grater than $100W/m^2$. Average ambient temperature is approximately 10°C. A maximum of 23°C and a minimum of 0°C can be found for the considered period.

Figure 6 shows the incidence of the solar chimney in the interior building temperature. The comparison is made between simulations with the single building and the building with the solar chimney attached. It can be seen that the solar chimney collaborates to increase average temperature in the interior of the building.

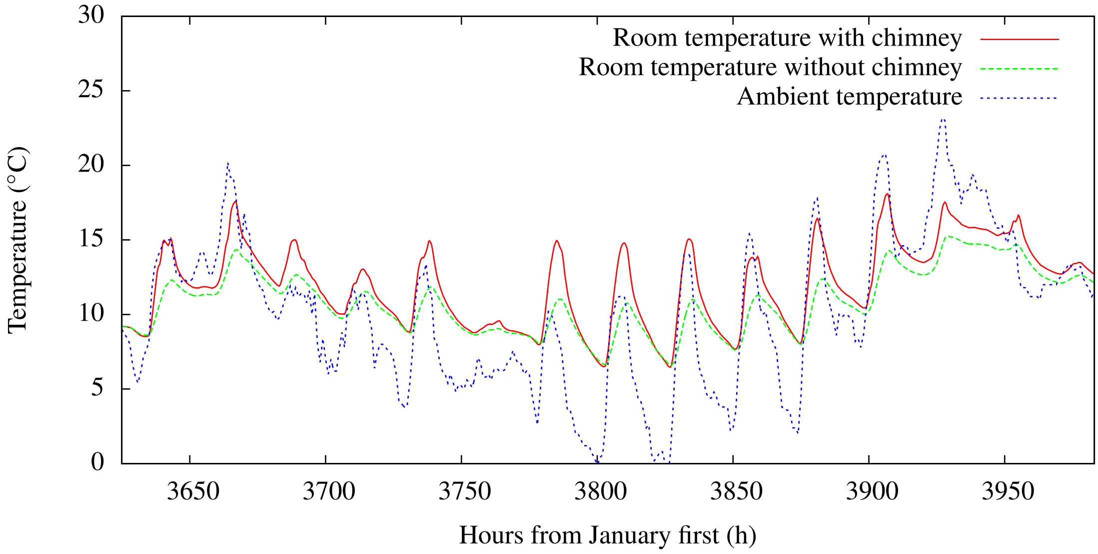

Figure 6. Comparative analysis: room winter temperature with and without solar chimney

An very simple strategy for the operation of the solar chimney was evaluated. Communication between solar chimney and the building is closed during the day, so energy is accumulated in the absorber wall. In the evening solar chimney is opened and warm air is conducted into the room. It can be seen from Fig. 7 that a better time distribution of temperature is obtained. Nevertheless, peaks appearing after chimney opening suggest that some work should be done to gradually release energy from the wall. For doing that, certain modifications should be introduced to the model, for example heat capacity of the air should be considered, and different properties of the absorber wall should be analyzed.

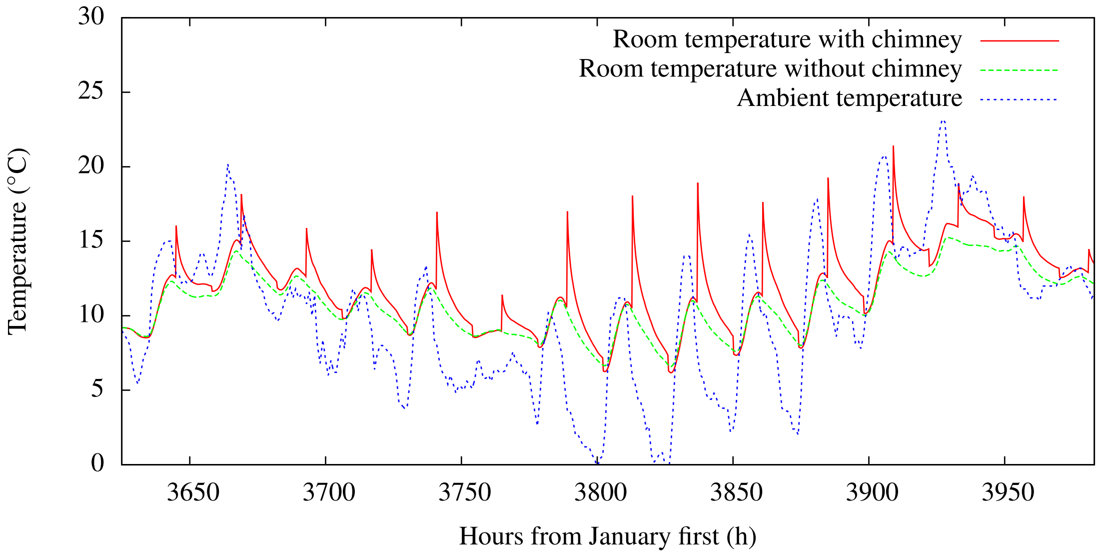

Figure 7. Comparative analysis: cumulative operation of the chimney

Figure 8 shows heat power introduced by the chimney, and heat exchanged between the room and the ambient trough wall, roof and floor. In the case of the accumulating strategy, heat generated in the chimney is better matched with heat looses. This is due to the fact that chimney is closed in periods when heat looses are generally negative. For this case, total energy generated by the chimney was calculated. It resulted to be 21,5% of the total looses of the building for this period.

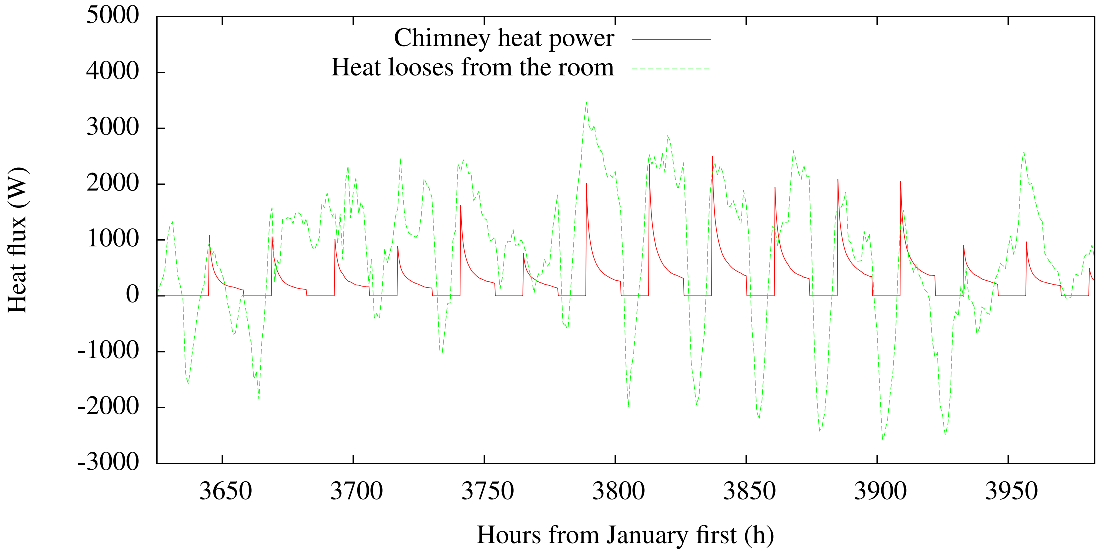

Figure 8. Heat contribution of Solar Chimney versus building losses

6. CONCLUSIONS

An analytical-numerical model has been developed for the simulation of solar chimneys integrated into buildings. The model has been verified and validated using both theoretical and experimental results. Comparison against previous similar works shows a good agreement with experimental results for various geometries of chimneys, due to the more elaborated treatment of friction losses within the chimney.

The model was used to evaluate temperature evolution of a room with an integrated solar chimney. Results show that solar chimney collaborates to improve comfort conditions, and that cumulative strategies can be applied to obtain better time distribution of temperature.

Further work should be focused in further developing and validating the calculation of friction losses, due to its relevance in air flow rate determination. Different operating strategies throughout the year should be simulated for different locations in Uruguay. In summer passive ventilation needs to be scheduled, taking into account interior and exterior temperature at any time. The model can be used also as a toll for the optimization of the chimney design.

7. ACKNOWLEDGEMENTS

The authors wish to thank the "Agencia Nacional de Investigación e Innovación (ANII)", for its support trough the project "FSE-1-2014-1-102126 SSoTeC: Simulador de aprovechamientos Solares Termoconvectivos".

8. REFERENCES

Alonso-Suárez, R., Bidegain, M., Abal, G. and Modernell, P., 2016. “Año meteorológico típico para aplicaciones de energía solar (amtues)”. Technical report, LES/UdelaR.

Arce, J., Jiménez, M., GuzmÃąn, J., Heras, M., Alvarez, G. and n, J.X., 2009. “Experimental study for natural ventilation on a solar chimney”. *Renewable Energy*, Vol. 34, pp. 2928–2934.

ATECYR, 2012. “Guía técnica de diseño de sistemas de intercambio geotérmico de circuito cerrado”. Technical report, Instituto para la Diversificación y Ahorro de la Energía (IDAE).

Bansal, N.K., R.Mathur and Bhandari, M.S., 1993. “Solar chimney for enhanced stack ventilation”. *Building and Viroment*, Vol. 28, No. 3, pp. 373–377.

Chen, Z., Bandopadhayay, P., Halldorsson, J., Byrjalsen, C. and Heiselberg, P., 2003. “An experimental investigation of a solar chimney model with uniform wall heat flux”. *Building and Environment*, Vol. 38, pp. 893–906.

He, G., Zhang, J. and Hong, S., 2016. “A new analytical model for airflow in solar chimneys based on thermal boundary layers”. *Solar Energy*, Vol. 136, pp. 614–621.

Hu, Z., He, W., Ji, J. and Zhang, S., 2017. “A review on the application of trombe wall system in buildings”. *Renewable and Sustainable Energy Reviews*, Vol. 70, pp. 976–987.

Khanal, R. and Lei, C., 2011. “Solar chimney-a passive strategy for natural ventilation”. *Energy and Buildings*, Vol. 43, pp. 1811–1819.

Khanal, R. and Lei, C., 2014. “A scaling investigation of the laminar convective flow in a solar chimney for natural

ventilation". *International Journal of Heat and Fluid Flow*, Vol. 45, pp. 98–108.
Khanal, R. and Lei, C., 2015. "A numerical investigation of buoyancy induced turbulent air flow in an inclined passive wall solar chimney for natural ventilation". *Energy and Buildings*, Vol. 93, pp. 217–226.
Maliska, C., 2010. *Transferencia de Calor e Mecanica dos Fluidos Computacional*. LTC, Rio de Janeiro.
Miyazaki, T., Akisawa, A. and Kashiwagi, T., 2006. "he effects of solar chimneys on thermal load mitigation of office buildings under the japanese climate". *Renewable Energy*, Vol. 31, pp. 987–1010.
Ojofeitimi, A. and Hattori, Y., 2017. "Wall-resolved large eddy simulation of turbulent mixed-convection heat transfer along a heated vertical flat plate". *International Journal of Heat and Mass Transfer*, Vol. 109, pp. 428–439.
Ong, K., 2003. "A mathematical model of a solar chimney". *Renewable Energy*, Vol. 28, pp. 1047–1060.
Zamora, B. and Kaiser, A., 2009. "Optimum wall-to-wall spacing in solar chimney shaped channels in natural convection by numerical investigation". *Applied Thermal Engineering*, Vol. 29, pp. 762–769.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.