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DEVELOPMENT OF COMPUTATIONAL MODELING OF A SOLAR CHIMNEY ATTACHED TO A ROOM FOR NATURAL VENTILATION

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Abstract. *The present work aims to develop a computational model for the analysis of turbulent flow in an inclined passive wall solar chimney attached to a room, where solar radiation affects this wall, heating the air and generating its movement inside the chimney and consequently in the attached room. The flow is admitted turbulent, incompressible, with heat transfer by natural convection and it is analyzed in the transient regime in a two dimensional domain. The conservation equations of mass, momentum and energy equations are numerically solved by the finite volume method using the FLUENT software. The standard k-ε turbulence model was used to reproduce the airflow turbulence in the chimney. The simulations were carried out using a constant heat flux of 1000 W/m², absorber wall height H_a = 2.5 m and chimney inclination of 4º with the vertical direction. An investigation of grid and time-step sensibility was performed and independent grid and time-step were used to obtain results of mass flow rate in the attached room. Results obtained with the present numerical model were in close agreement with those obtained in the literature. This problem was also analyzed in the steady state, but without obtaining results close to those already published.*

Keywords: Solar Chimney, Numerical Investigation, FLUENT Software, Natural Ventilation.

1. INTRODUCTION

Global warming is a widespread issue and it is known that the temperatures on the planet are increasing every year. The 1990s and 2000s were the warmest of the last 1,000 years, according to the website of the National Institute for Space Research - INPE (2019). According to the same website, the projections of the Intergovernmental Panel on Climate Change - IPCC indicate that in the next 100 years there may be an increase in the global average temperature between 1.8° C and 4.0° C. The use of air conditioning has become essential in hot regions as the Middle East, despite the fact that conventional air conditioning units consume most of the energy required by buildings and generate harmful gas emissions (Reda et al., 2015; Peixoto et al., 2005). This is also a reality in Brazil, where there is an increase in demand and air conditioning installations every year, generating more environmental impacts and greater consumption of energy, i.e., leading to great expense for the consumer.

Added to this, the concern with a sustainable building until a few years ago was practically null. In general, most residential buildings are designed and constructed considering only economic and functional issues, without a comprehensive awareness of the environmental and energy consumption implications (Abdeen et al., 2019). Gradually, this has been changed in Brazil, through legislation and a greater awareness of engineers and architects when designing homes and buildings. Within the aspects considered in sustainable building, it is the

demand for naturally ventilated environments, seeking a reduction in the dependence on the use of air conditioning and consequently a lower power consumption and less expense to the consumer. Therefore, solar chimneys show a promise technique for the enhancement of air movement in naturally ventilated buildings using renewable and clean sun energy (Abdeen et al., 2019).

Several studies concerning solar chimneys have been carried out over the years in order to find a way to improve the mass flow rate in the room attached to the chimney. For instance, Abdeen et al. (2019) carried out an experimental and numerical study in the hot season of Egypt with the objective of enhance thermal comfort in the attached room and found as the best configuration a solar chimney with 1.85 m high, 2.65 m wide, 75° inclination angle and 0.28 m air inlet opening. In addition, authors verified, through sensitivity analyses, that the chimney width is the most influential parameter and the chimney height has a negligible effect. They also proved the effectiveness of the configuration found by applying average values of solar radiation of 500 W/m², 750 W/m² and 850 W/m², obtaining 0.28 m/s, 0.47 m/s and 0.52 m/s of air velocity in the internal environment, which guarantees the gain of thermal comfort for the occupants.

In another study carried out in winter in Egypt, Serageldin et al. (2018), proposed an optimization of the solar chimney coupled to an earth-to-air heat exchanger (EAHE) in order to heat the internal environment. Results found showed that the ideal angle of inclination is in the range of 30º to 35º. Moreover, the height in the range of 1.94 m and 1.97 m, the width between 0.92 m and 0.97 m and the air gap between 0.19 m and 0.23 m were recommended. Authors also performed sensitivity analyses where it was found that the EAHE exchanger pipe diameter is the most sensitive parameter, followed by chimney height and EAHE inlet height and position. Khanal and Lei (2012) found that a reverse flow occurs at the exit of the solar chimney when the thermal boundary layer thickness is smaller than the air gap width at the chimney exit, resulting in a reduction in mass flow rate. As a solution to suppress this reverse flow and increase the mass flow rate, they proposed a new concept of solar chimney, named Inclined Passive Wall Solar Chimney (IPWSC).

Khanal and Lei (2014) studied experimentally the IPWSC type of solar chimney, where its effectiveness was verified through the application of heat flux from 100 W/m² to 500 W/m² in an absorber height of 0.7 m, base air gap width of 0.1 m and inclination variation from 0º to 6º. The experimental results are supported by shadowgraph and smoke flow visualizations. In this study, the authors were able to verify that the flow velocity is strongly affected by the angle of inclination of the wall while the temperature field was insensitive as this angular variation occurred. They also visualized an unusual behavior for the temperature data at the chimney exit, due to the presence of a reverse flow or a transition to turbulence. In addition, they demonstrated that the IPWSC has significant improvements in the ventilation rate compared to conventional chimneys, since the air flow rate increases as the angle of the wall increases, reaching a maximum value on a certain inclination angle. This increase in air flow is attributed to the reduction in the reverse flow that appears at the chimney exit.

Afterwards, Khanal and Lei (2015) carried out a numerical investigation of turbulent flow with natural convection using the IPWSC. Results proved the efficiency of this model in gaining natural ventilation with heights greater than 1 m for the absorber wall. In addition, the study showed that the standalone solar chimney model, which is often adopted in solar chimneys studies, over-predicts the mass flow rate in comparison to the attached model. Therefore, the authors recommended the adoption of the latter model to evaluating the system performance since it led to results closest to the reality by the fact that the chimneys is part of the building envelope. The study also showed that for different heat flux the angle of inclination of 4º is the one that best ventilates the environment.

The purpose of the following work is to develop a computational modeling for the analysis of turbulent flow in an IPWSC attached to a room, allowing future investigation about its design. The sensibility of mesh and time-step is performed and the independent results for the mass flow rate in the chimney are compared with those predicted in the work of Khanal and Lei (2015). In addition, simulations considering the convective flow at the steady state are compared with transient solutions for the flow at the steady state. This comparison allowed the achievement of recommendations about the validity of this simplification for the problem studied here.

2. MATHEMATICAL MODELING

For the present problem, the following simplification hypotheses are assumed: the flow is admitted incompressible, turbulent, transient, with natural convection, without thermal radiation and the domain is two-dimensional. The thermophysical properties are kept constant, except for the density which is varied according to Boussinesq approximation to driven the flow into the domain. The standard k-ε turbulence model was adopted to reproduce the airflow turbulence in the chimney. In this way, the time-averaged conservation equations of mass, momentum in x and y directions and energy are given, respectively, by (Bejan, 2013):

$$\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} = 0 \tag{1}$$

$$\rho\left[\frac{\partial \bar{u}}{\partial t} + \bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial y}\right] = -\frac{\partial \bar{p}}{\partial x} + (\mu + \mu_t)\left(\frac{\partial^2 \bar{u}}{\partial x^2} + \frac{\partial^2 \bar{u}}{\partial y^2}\right) \tag{2}$$

$$\rho\left[\frac{\partial \bar{v}}{\partial t} + \bar{u}\frac{\partial \bar{v}}{\partial x} + \bar{v}\frac{\partial \bar{v}}{\partial y}\right] = -\frac{\partial \bar{p}}{\partial y} + (\mu + \mu_t)\left(\frac{\partial^2 \bar{v}}{\partial x^2} + \frac{\partial^2 \bar{v}}{\partial y^2}\right) + \rho g \beta (T - T_0) \tag{3}$$

$$\left[\frac{\partial \bar{T}}{\partial t} + \bar{u}\frac{\partial \bar{T}}{\partial x} + \bar{v}\frac{\partial \bar{T}}{\partial y}\right] = (\alpha + \alpha_t)\left(\frac{\partial^2 \bar{T}}{\partial x^2} + \frac{\partial^2 \bar{T}}{\partial y^2}\right) \tag{4}$$

The equations for turbulent viscosity and thermal diffusivity, are given by (Launder and Spalding, 1972):

$$\mu_t = \frac{\rho C_\mu k^2}{\varepsilon} \tag{5}$$

$$\alpha_t = \frac{\mu_t}{\rho \operatorname{Pr}_t} \tag{6}$$

In Eqs. (1) to (6), (¯) represents the time average operator, x and y represent the horizontal and vertical coordinates, respectively; $\bar{u}$ is the average velocity in the x direction (m/s); $\bar{v}$ is the average velocity in the y direction (m/s); ρ is the density of the fluid (kg/m³); t is the time (s); p is the pressure (Pa); μ is the dynamic viscosity (kg/m s); μ_t is the turbulent viscosity (kg/m s); g is the gravitational acceleration (m/s²); β coefficient of thermal expansion (1/K); T is the temperature (K); α is the thermal diffusivity (m²/s) given by $\kappa/\rho c_p$; κ is thermal conductivity of air; c_p is the specific heat capacity (J/kg K); α_t is the turbulent thermal diffusivity (m²/s); C_μ is a constant ($C_\mu = 0.09$); ε is the dissipation rate of turbulent kinetic energy (m²/s³); k is the turbulent kinetic energy (m²/s²); Pr_t is the turbulent Prandtl number given by ν_t/α_t and ν_t is the turbulent kinematic viscosity given by μ_t/ρ (m²/s).

The equations for the standard k-ε turbulence model, are given by :

$$\frac{\partial k}{\partial t} + \frac{\partial (\bar{u}k)}{\partial x} + \frac{\partial (\bar{v}k)}{\partial y} = \frac{1}{\rho}\frac{\partial}{\partial x}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right] + \frac{1}{\rho}\frac{\partial}{\partial y}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right] + \frac{1}{\rho}\frac{\partial}{\partial x}[G_k + G_b] - \varepsilon \tag{7}$$

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial (\bar{u}\varepsilon)}{\partial x} + \frac{\partial (\bar{v}\varepsilon)}{\partial y} = \frac{1}{\rho}\frac{\partial}{\partial x}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x}\right] + \frac{1}{\rho}\frac{\partial}{\partial y}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial y}\right] + C_{1\varepsilon}\frac{\varepsilon}{\rho k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\frac{\varepsilon}{k} \tag{8}$$

In Eqs. (7) and (8), G_b and G_k represent the production of the turbulent kinetic energy due to buoyancy and the mean velocity gradients, respectively and are calculated as follows:

$$G_b = \beta g_i \frac{\mu_t}{\sigma_t}\frac{\partial \bar{T}}{\partial x_i} \tag{9}$$

$$G_k = \mu_t\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_j}\right)\frac{\partial \bar{u}_i}{\partial x_j} - \frac{2}{3}\rho k \delta_{ij}\frac{\partial \bar{u}_i}{\partial x_j} \tag{10}$$

In addition to the variables previously presented, in Eqs. (7) to (10), δ_{ij} is the Kronecker delta; $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{3\varepsilon}$ are constants with empirical values of 1.44, 1.92 and 0.09, respectively and σ_k and σ_ε are the turbulent Prandtl numbers for k and ε with empirical values of 1.0 and 1.3, respectively.

3. PROBLEM FORMULATION

The configuration of the system is shown in Fig. 1, where there is an inclined passive wall solar chimney, composed of an inclined glass wall (transparent to solar irradiation) and an absorber wall, being attached to a room (ventilated space). It is admitted H_a the height of the absorber wall, W_t the thickness of the absorber wall, W_i the size of the inlet window, H_i the size of the inlet opening to the chimney, H and L the height and length,

respectively, of the ventilated space, W_e the exit air gap width and W_g the base air gap width. The solar radiation passes through the glass wall and reaches the absorber wall, which absorbs the energy. Consequently, the air inside the chimney is heated, becoming lighter and leaving the chimney through its top opening. This process inside the IPWSC generates an airflow movement in the attached space, causing the external air to enter the room through the window, maintaining the air circulation in the attached room.
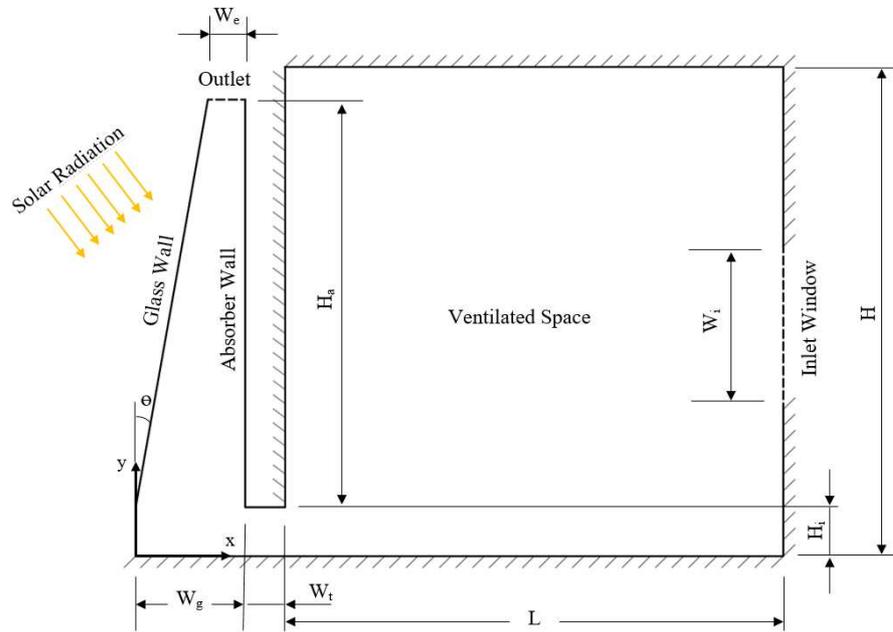

Figure 1. Configuration of a two-dimensional solar chimney (IPWSC) attached to a room.

As showed in Fig. 2, the following boundary conditions for the computational domain are considered: the walls have non-slip and impermeability condition and an adiabatic profile, except the absorber wall which is submitted to a constant heat flow of 1000 W/m² (mimicking the effect of absorber of solar energy). For the entrance of the room (window) and exit (chimney mouth), the pressure gauge is admitted equal to zero and the temperature is at 300 K.
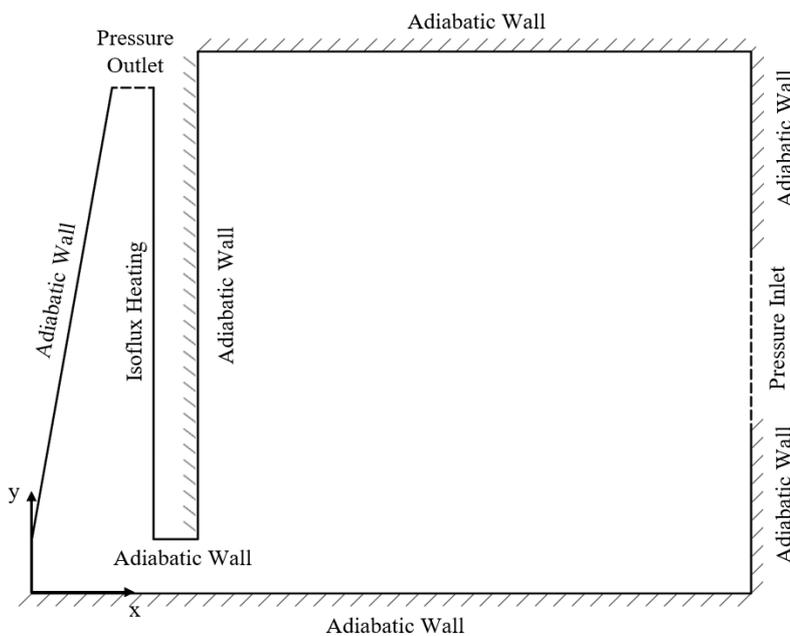

Figure 2. Boundary conditions for the computational domain.

To reproduce the numerical methodology, simulations are carried out using the following geometric parameters: a passive solar chimney with a 4° inclination, an absorber height constant and equal to 2.5 m and the

ratios of $H_a/W_g = 6.25$; $H/H_a = 1.20$; $H_a/W_i = 2.5$ and $L/W_t = 12.5$. This geometry configuration is the same used in the work of Khanal and Lei (2015), allowing the verification of the present computational model. The Table 1 present the thermophysical properties used in the simulations.

Table 1. Thermophysical properties used in the simulations.

c_p (specific heat capacity)	1007 J/kg K
α (thermal diffusivity)	2.249×10^{-5} m²/s
ρ (density at T_0)	1.1614 kg/m³ (Boussinesq)
β (coefficient of thermal expansion)	0.0033 K^{-1}
κ (thermal conductivity)	0.0263 W/m K
μ (viscosity)	1.85×10^{-5} kg/m s

4. NUMERICAL MODELING

The conservation equations and those used in closure of turbulence, Eqs. (1) – (8), are numerically solved with the finite volume method (FVM) using the FLUENT software (Patankar, 1980; Versteeg and Malalasekera, 2007; ANSYS, 2011; Maliska, 2004). For this study, a total period of time of $t = 10.0$ s is investigated considering a time step of 0.01 s and 300 iterations per time step. The SIMPLE scheme is adopted for the coupling between continuity and momentum equations through pressure and second order upwind are employed for treatment of advective terms of momentum and energy. The simulations are considered converged when the residuals for mass, velocities and for the turbulence model equations are less than 10^{-6}. For energy equation, the simulations are converged when the residuals are less than 10^{-8}. In addition, sub-relaxation factors of 0.7 are imposed on the conservation equations.

In the present study, a grid independence test is carried out in order to make a comparison with the study of Khanal and Lei (2015). The parameter used to check the independent mesh was the mass flow rate at the chimney exit, which is directly proportional to the mass flow rate in the attached room. To measure the effectiveness of the system, Khanal and Lei (2015) previously used this parameter. Respecting the geometry specifications previous mentioned, the GMSH software was used to generate 8 meshes with different refinements, as shown in Tab 2.

The criterion that the variation in mass flow between the meshes is $|(\dot{m}_j - \dot{m}_{j+1})/ \dot{m}_j| < 1\%$ is established for determining the independent grid, where the mesh with 42,482 volumes could be considered as the independent mesh. However, considering the increase of the stablished criterion for the next mesh, with 50,864 volumes, this more refined grid is used since the variation for the last three meshes seems more stable than that obtained in the range between 42,482 and 59,512. It is worth mentioning that the subscript "i" refers to the course mesh, while "i + 1" refers to the next refined mesh.

Table 2. Grid independence test considering the criteria for mesh independence $|(\dot{m}_j - \dot{m}_{j+1})/ \dot{m}_j| < 1.0 \times 10^{-2}$.

Number of Elements	$\dot{m}$ (outlet)	$|(\dot{m}_j - \dot{m}_{j+1})/ \dot{m}_j|$
7,213	0.1677918	5.27×10^{-2}
14,182	0.1589552	8.49×10^{-2}
29,561	0.1454553	1.15×10^{-2}
35,232	0.1437806	1.75×10^{-2}
42,482	0.1412623	6.02×10^{-3}
50,864	0.1404116	8.81×10^{-3}
59,512	0.1391742	6.26×10^{-3}
68,247	0.1383036	

In addition to the mesh independence, a time-step independence study is also carried out in order to investigate the time-step which not affect the results, as well as, to verify if the $\Delta t = 0.01$ s used in the grid independence test can be used for future use of the computational model. For all investigated time-steps it is considered a final physical time of $t = 10.0$ s of operation of the solar chimney. Therefore, for simulations with different time steps (Δt), different numbers of time step are used in order to obtain the results always referring to

10.0 s of physical time. The results obtained in this study are shown in Tab. 3, where the same criterion for the mass flow variation between the different Δt to be less than 1% was used and it can be seen that the time step, adopted until then, satisfies the established criterion.

Table 3. Time-step independence test considering the criteria for time step independence of $|(\dot{m}_j - \dot{m}_{j+1})/\dot{m}_j| < 1.0 \times 10^{-2}$.

Number of Time Steps	Δt (s)	$\dot{m}$ (outlet)	$|(\dot{m}_j - \dot{m}_{j+1})/\dot{m}_j|$
10	1.0000	0.1877974	2.65×10^{-1}
100	0.1000	0.1380868	1.68×10^{-2}
1,000	0.0100	0.1404116	1.21×10^{-3}
10,000	0.0010	0.1405815	7.05×10^{-5}
100,000	0.0001	0.1405716	

5. RESULTS AND DISCUSSION

To verify the computational model, the results obtained from the simulation with the independent mesh and time step previously reported for the physical time of $t = 10.0$ s are analyzed. These results required about 8 h of processing time in a computer with two dual-core Intel processors i7-4960X 3.60 GHz and 32 GB of RAM. The data analyzed are the behavior of the mass flow rate, velocity and the contour of the turbulent intensity in an IPWSC type solar chimney attached to a room, composed of an inclined glass wall, an absorber wall, an entrance of the room (window) and an exit (chimney mouth).

The chimney geometry is designed according to parameters already mentioned in the formulation of the problem and the angle of 4° is used since it was the one that produced the best mass flow rate in the system in the study carried out by Khanal and Lei (2015). Using the previously reported boundary conditions, a constant heat flow equal to 1000 W/m² is imposed on the absorber wall. It is considered a transient model with $\Delta t = 0.01$ s and a steady state model.

The data of grid independence test and time step independence test presented above have been performed in the transient regime. However, a study of the results in the steady state has also been carried out to verify the availability of solving the equations in this regime. This investigation is performed since Khanal and Lei (2015) does not clearly recommended the solution of the problem considering a modeling in the steady state or transient regime until the achievement of the steady state. Thus, to verify the computational model of this study, some qualitative and quantitative parameters obtained here are confronted with the results presented in the work of Khanal and Lei (2015).

Figure 3 shows the contour of the turbulent intensity published by Khanal and Lei (2015) and Fig. 4 the contours of the turbulent intensity of the present study, being the Fig. 4a the field obtained at the steady state and Fig. 4b in the transient regime (time-averaged condition when the flow reaches the steady state). Figures 3 and 4 show that there is a similar tendency between the study of the referred author and the present work. However, results seem more similar when the steady state is considered (Fig. 4a). In order to investigate quantitatively the differences, mass flow rate and averaged velocities in the chimney are investigated.
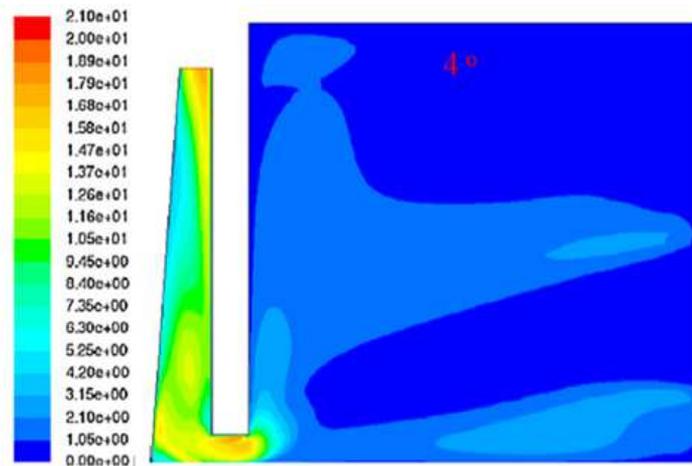

Figure 3. Contour of the turbulent intensity published by Khanal and Lei (2015).
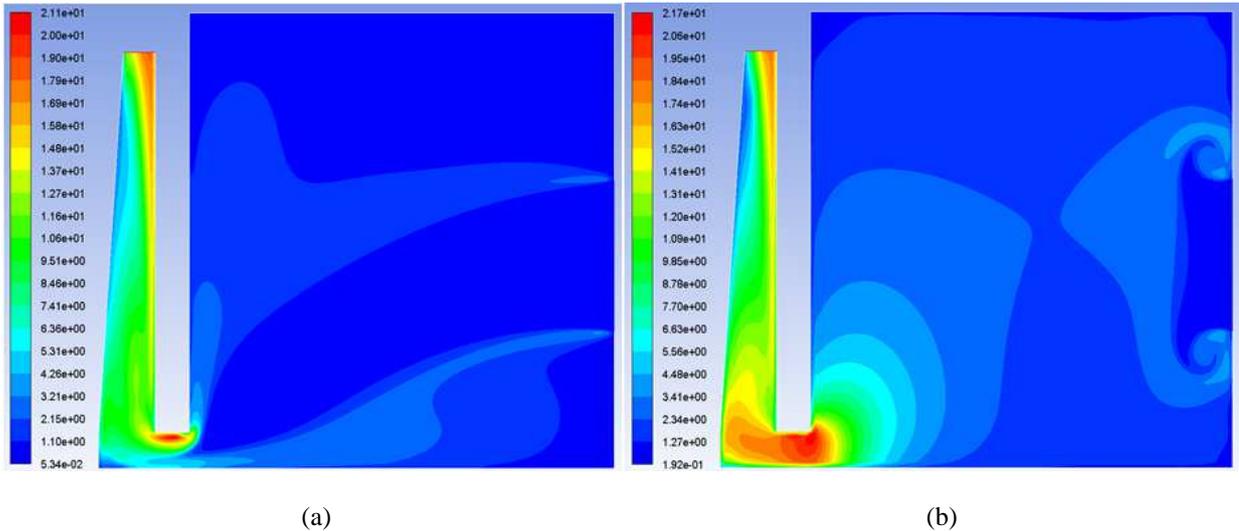
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<tr><td>(a)</td><td>(b)</td></tr>
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Figure 4. Contours of the turbulent intensity of the present study (%) – (a) Steady state (b) Transient regime.

Another analyzed data that is important for verifying the efficiency of the system is the mass flow rate per unit length at the chimney exit, calculated by the product of the density (kg/m³), the exit air gap width (m) and average velocity at the chimney exit (m/s), as the equation:

$$\dot{m} = \rho w_e \bar{v}_e \qquad (11)$$

The dimensionless variable $\dot{M}$ is presented by Khanal and Lei (2015) for comparative evaluation of the performance of the solar chimney, given by:

$$\dot{M} = \frac{\dot{m}}{\rho \alpha} \qquad (12)$$

In the study published by Khanal and Lei (2015), it can be seen that the optimum $\dot{M}$ value of 5,100 is achieved with a constant heat flux of 1000 W/m² with an angular inclination of 4º to the vertical direction. With this data and Eqs. (11) and (12) it is possible to find the mass flow rate and the average velocity at the chimney exit. In turn, with the simulations performed in this work, it is possible to obtain the mass flow rate and the average velocity at the chimney exit and therefore calculate the value of the dimensionless $\dot{M}$ in order to make it possible to compare the results. A summary of the obtained results can be seen in Tab. 4:

Table 4. Comparison of results between the present work and the one published by Khanal and Lei (2015).

	Heat Flux (W/m²)	$\dot{M}$	$\dot{m}$ (kg/s m)	$\bar{v}_e$ (m/s)
Khanal and Lei (2015)	1000	5100.0	0.1332	0.510
Present Work (Steady)	1000	5926.3	0.1548	0.593
Present Work (Transient)	1000	5375.7	0.1404	0.538

As can be seen, in comparison with Khanal and Lei (2015), the variables $\dot{M}$, $\dot{m}$ and $\bar{v}_e$ in the steady state showed a difference of 826.3, 0.0216 kg/s m and 0.083 m/s respectively, i.e., a magnitude difference of 16.2% in the first two variables and 16.4% in the average velocity. Making this same comparison with the results obtained in the transient regime, this difference drops to 5.4% for the dimensionless variable and for the mass flow rate and to 5.5% for the average velocity. Once the quantitative results obtained with the solution at the steady state led to considerable differences to the results reached in Khanal and Lei (2015), while the transient solution conducted to similar results, it is recommended the use of transient solution in the present model.

6. CONCLUSIONS

This work aimed to develop a computational model for the analysis of turbulent flow in an IPWSC type solar chimney attached to a room using the best chimney geometry configuration obtained in the study by Khanal and Lei (2015). Grid independence and time step independence tests were carried out, as well as simulations in the

steady and transient regimes and the results obtained regarding the contour of turbulet intensity, mass flow rate and average velocity at the chimney exit were analyzed and compared with the work of Khanal and Lei (2015).

Although the contour of turbulent intensity in the steady state visually presents a better proximity than the contour in the transient regime to those obtained by Khanal and Lei (2015), the numerical results for mass flow rate, average velocity and the dimensionless variable in this last mentioned regime show a greater agreement. Differences of 5.5% for velocity and 5.4% for the other variables were obtained when the transient solution is taken into account, while in the steady state solution this divergence is in the range of 16%. Therefore, it can be concluded that the computational model developed in the transient regime reproduces better the behavior of turbulent flow in an IPWSC type solar chimney attached to a ventilated space, being recommended its use for future investigation about its design. The simulations carried out in the steady state did not find satisfactory quantitative results, so modeling in this state is not recommended to reproduce the behavior of the fluid inside the chimney.

7. ACKNOWLEDGEMENTS

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