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EVALUATION OF THE BOUNDARY CONDITIONS FOR THE GROUND IN THE NUMERICAL ANALYSIS OF A SOLAR CHIMNEY

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Abstract. *A solar chimney is a renewable-energy, combining three essential elements – solar air collector, chimney, and wind turbine. The airflow generated is typically used to drive wind turbines. In small solar chimneys, the power generated is not economically competitive; therefore, the airflow can be used to other purposes, such as drying of agricultural products. In this paper a numerical analysis of the airflow inside a small solar chimney is performed, using CFD techniques. The main focus of the paper is the assessment of the boundary conditions used for the ground, and the influence of the use of the soil as an energy storage layer and how it affects the airflow parameters. The results are compared with experimental data from the literature. The results show that the use of energy storage layer has greater influence on the distribution of temperatures than about the velocity distribution and that yours absence underestimates the heat losses. So their use is essential for consistent description of the flow behavior within the solar chimney.*

Keywords: *Solar Chimney, Numerical Analysis, Boundary conditions, ANSYS-CFX.*

1. INTRODUCTION

Nowadays, increased demand for energy and the use of fossil fuels on a large scale have raised serious concerns about the environmental impacts caused by them. According to Akella (2009), conventional sources of energy based on fossil fuels have proven to be effective for energy production and for economic progress. However, these sources affect the environment and human life, and are being depleted at an accelerated rate. This motivated the search for alternative energy sources, intended to minimize these impacts.

Renewable energy sources currently provide between 15 and 20% of total worldwide energy demand. According to ANEEL (2014), in Brazil 83% of the energy generated is from renewable sources, with 79% from hydro and 4% from other sources. The lack of diversification of the Brazilian energy matrix resulted in dependence on rainfall precipitation regime, showing that the diversification of energy sources in the energy matrix is an alternative to energy independence.

Seeking to obtain energy resources less harmful to the environment, solar chimneys appear as an interesting alternative, capable of generating electric power from solar radiation. These devices combine the technologies of solar collector, chimney or tower and wind turbine. The solar chimney consists of a tubular central tower, a coverage made of a translucent material, and a wind turbine. During the insolation period, part of the incident solar radiation is absorbed by the ground. The air mass inside the device is heated and flows to the tower due to the buoyancy forces caused by temperature gradients. At night, when there is no solar radiation, part of the thermal energy stored in the deeper layers of the ground is transferred to the airflow, allowing continuous operation of the system (Ferreira et al, 2006). The airflow generated by natural convection and chimney effect drives a wind turbine, generating electric power (Hurtado et al, 2012).

The first pilot plant was built in Manzanares (Spain) and started its operation in June 1982 (Haaf, 1984). The prototype consisted of a tower with 195 m high and 10 m of diameter, with a coverage with diameter of 240 m and a height variable (2m in the entrance and 6 m in the center of the coverage) (Schlaich, 2000). The prototype proved that large structures are necessary to be economically competitive to conventional power plants. Ferreira (2004) and Maia (2005) proposed a new feature for small devices, using the heated airflow to dry agricultural products.

Several numerical studies have been developed to predict the behavior of the airflow within a solar chimney. Ferreira et al (2000) presented a numerical study of the turbulent airflow inside a solar chimney, using the incident solar radiation and ambient temperature as boundary conditions. Maia (2005) refined the model proposed by Ferreira et al (2000), evaluating the numerical results with experimental data obtained from a prototype built in the city of Belo Horizonte. Castro Silva (2014) evaluated the influence of geometric parameters in energy and exergy efficiency, based on the experimental data obtained by Ferreira (2004) and Maia (2005). It stands out even the work done by Sangi et al (2001) conducted a detailed numerical analysis of a solar chimney, using Fluent software and k-ε turbulence model. The model was validated with data from Manzanares prototype. Xu et al (2011) evaluated the characteristics of air flow, heat transfer and power in a two-dimensional model with energy storage layer and a turbine with similar dimensions to the prototype Manzanares. Tingzhen et al (2008b) used the CFD (Computational Fluid Dynamics) techniques to evaluate the influence of solar radiation in the turbine pressure drop and losses of the solar chimney power.

The ground plays an important role in the energy balance due to its behavior as a heat storage system (Hurtado, 2012). An accurate assessment of the ground directly affects the flow conditions in a numerical analysis. The present work evaluates the influence of the ground in the numerical analysis of a small solar chimney. The dimensions used were based on an experimental prototype. The governing equations were solved using the commercial software ANSYS - CFX. The boundary conditions adopted, mass flow rate and temperatures, were prescribed and temperatures, were prescribed and obtained experimentally by Maia (2005) and heat transfer coefficient for the coverage was suggested by Castro Silva(2014).

2. MODELLING

In this work, the conservation equations of mass (1), momentum (2), and energy (3) for the airflow are described as below.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \cdot \vec{v}) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \cdot \vec{v}) + \nabla \cdot (\rho \cdot \vec{v} \cdot \vec{v}) = -\nabla p + \nabla \cdot \left(\mu \left[\left(\nabla \vec{v} + \nabla \vec{v}^T \right) - \frac{2}{3} \nabla \cdot \vec{v} I \right] \right) + \rho \{\vec{g}\} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\vec{v}(\rho E + p)) = \nabla \cdot \left(k_{eff} \nabla T - h\vec{J} + \left(\mu \left[\left(\nabla \vec{v} + \nabla \vec{v}^T \right) - \frac{2}{3} \nabla \cdot \vec{v} I \right] \cdot \vec{v} \right) \right) \tag{3}$$

Three-dimensional, transient and random fluctuations of the properties, characteristic of turbulent flows, do not allow a strictly analytical approach to the problem. In this work the k - ε turbulence model was used. This model uses the concept of turbulent viscosity, defined as:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{4}$$

Where ρ, C_μ, k and ε, represent the density, an empirical constant, the turbulent kinetic energy and the dissipation of turbulent kinetic energy, respectively.

The transport equations for k and ε are, respectively (Versteeg and Malalasekera, 2007):

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{5}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k}(G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon \tag{6}$$

Where G_k is the generation of turbulent kinetic energy due to mean velocity gradients, G_b the generation of turbulent kinetic energy due to fluctuations, Y_M the contribution of the fluctuating dilatation in compressible turbulence $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{3\varepsilon}$ are constant, S_k and S_ε terms are set by the user.

3. METHODOLOGY

The geometric dimensions of the solar chimney used in this analysis were based on previous works from literature (Ferreira, 2004; Maia, 2005; and Castro Silva, 2014). It was used a solar chimney with tower 12.3 m high and 1 m in diameter and a collector with a diameter of 25 m and variable height relative to the ground at the entrance of 0.05 m to 0.5 m in the rest of the coverage.

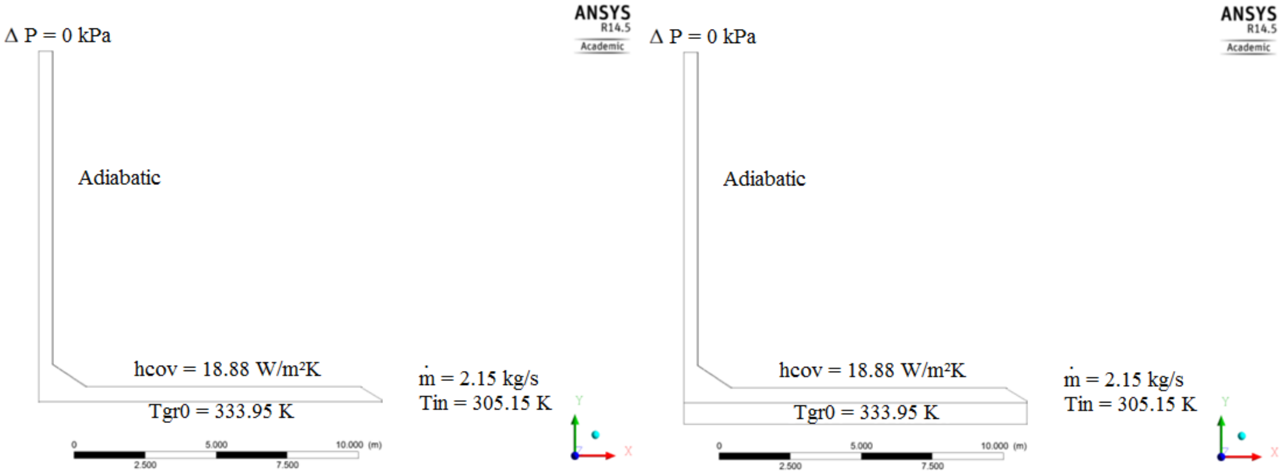

Figure 1. Boundary conditions of physical model

Figure 1 presents the boundary conditions adopted. It was used a prescribed temperature in the ground (333.95 K), instead of the actual solar radiation. The tower was assumed adiabatic, and a convection heat transfer coefficient of 18.88 W/m²K (Castro Silva, 2014) was set for the coverage. Is was also assumed that the air at the inlet is ambient temperature (305.15 K), with a mass flow rate of 0.18 kg/s. Numerical values were obtained from literature, based on experimental data (Ferreira, 2004 and Maia, 2005).

The commercial software ANSYS - CFX 14.5 was used to solve the governing equations. In order to evaluate the influence of the ground in the numerical analysis, the geometry was first defined as only the solar chimney (coverage and tower) and then also including the ground under the coverage (Fig. 1). The results obtained for each situation were compared with experimental data from literature.

4. RESULTS AND DISCUSSION

The ground under the coverage plays a fundamental role in the heat transfer processes, operating as an energy storage layer. A portion of the solar radiation absorbed by the ground during the day is transferred to deeper layers of the ground. At night, when there is no incidence of solar radiation, the heat stored in the ground is transferred to the surface layer. This mechanism is responsible for the continuous operation of the solar chimney, even when there is no incidence of solar radiation. Nevertheless, often the ground influence is neglected in numerical analysis. In this paper, a numerical analysis of the airflow was performed, taking into account the influence of the ground. Two simulations were run, the first assuming a constant value for the surface ground and the second assuming the ground as a semi-infinite solid.

Figure 2 shows the current lines for both simulations, with and without the energy storage layer. The air entering the device is accelerated towards the tower, due to the reduction of the cross sectional area. In the junction between the coverage and the tower, there is a change of direction of the airflow, from radial to axial. It can be noticed the presence of local separation under the coverage, as indicated in the literature (Fasel et al, 2013). When compared the results for the simulations with and without the ground, it is observed that the recirculation appears downstream when the ground is taken into account.

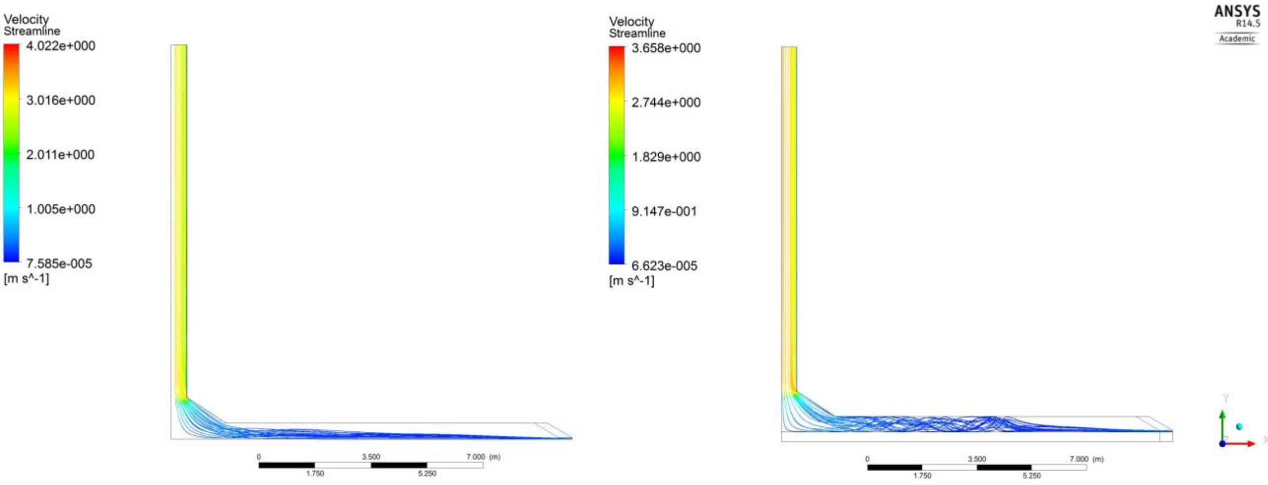

Figure 2. Streamlines of the airflow

When the airflow leaves the coverage and reaches the junction between the coverage and the tower, it is observed an increase of the velocity due to the reduction of the area. In the tower, small variations of the velocity profile are observed, since the airflow is not fully developed. However, the average velocity in the tower remains constant, since the cross sectional area does not vary. Figure 3 shows the velocity profile in the tower, evaluated at a height corresponding to half the tower height. It is observed an average velocity of around 2.5 m/s, corresponding to a Reynolds number of about $1x10^5$. It can be concluded, therefore, that the airflow in the tower is turbulent, and that the flat profile obtained was already expected. Since the mass flow rate is equal for both simulations (established by the boundary conditions), only small variations were observed for the simulations with and without the ground.

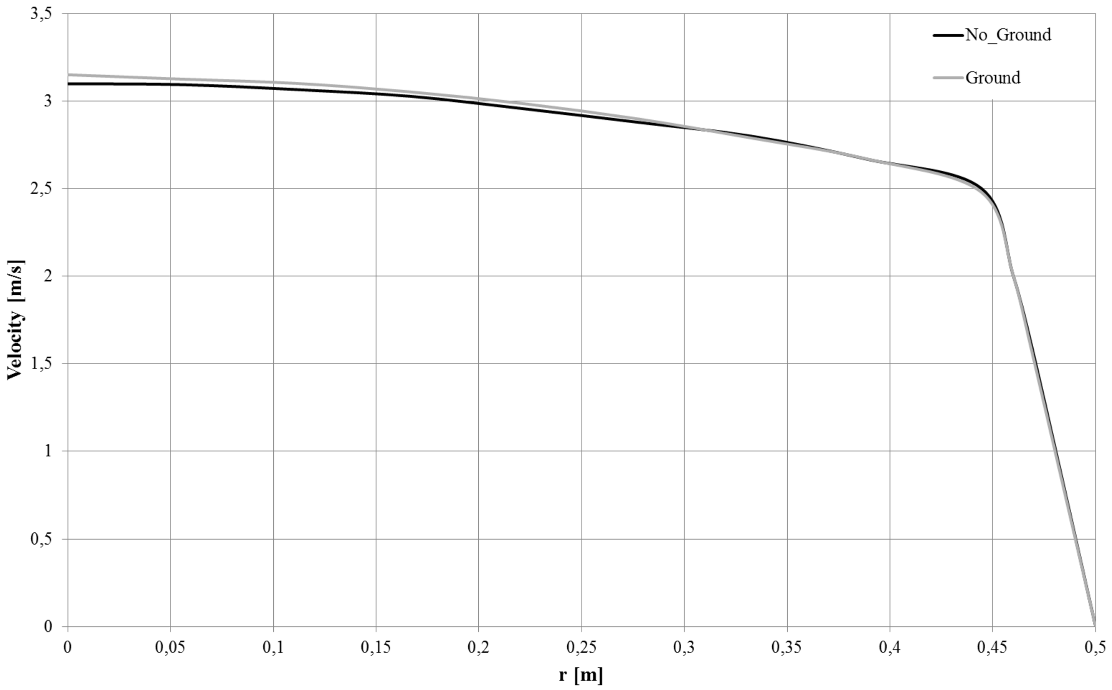

Figure 3. Velocity profile in the chimney

Figure 4 shows the temperature fields inside the solar chimney and the ground (when applicable). Higher temperatures were obtained when the ground was not considered, since heat losses for the deeper layers of the ground were not taken into account. For the simulation without the ground, with a prescribed value for the ground surface temperature, the maximum temperature difference was 23 K, while for the simulation with the ground; the maximum temperature difference was 17 K. In both cases, the greater changes of temperature occurred under the coverage, due to thermal insulation imposed on the tower by the boundary conditions.

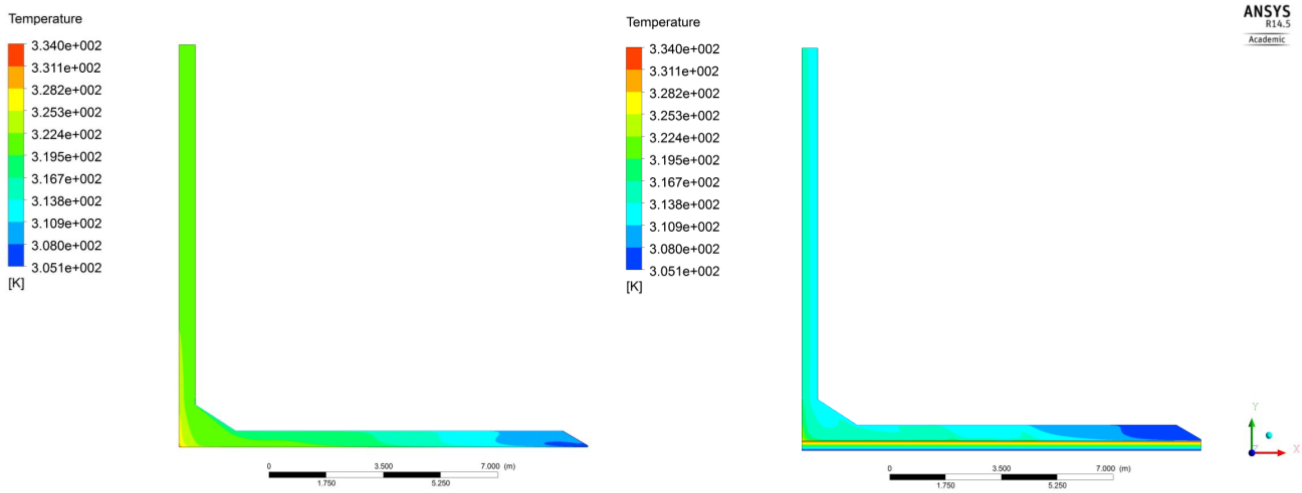

Figure 4. Temperature fields

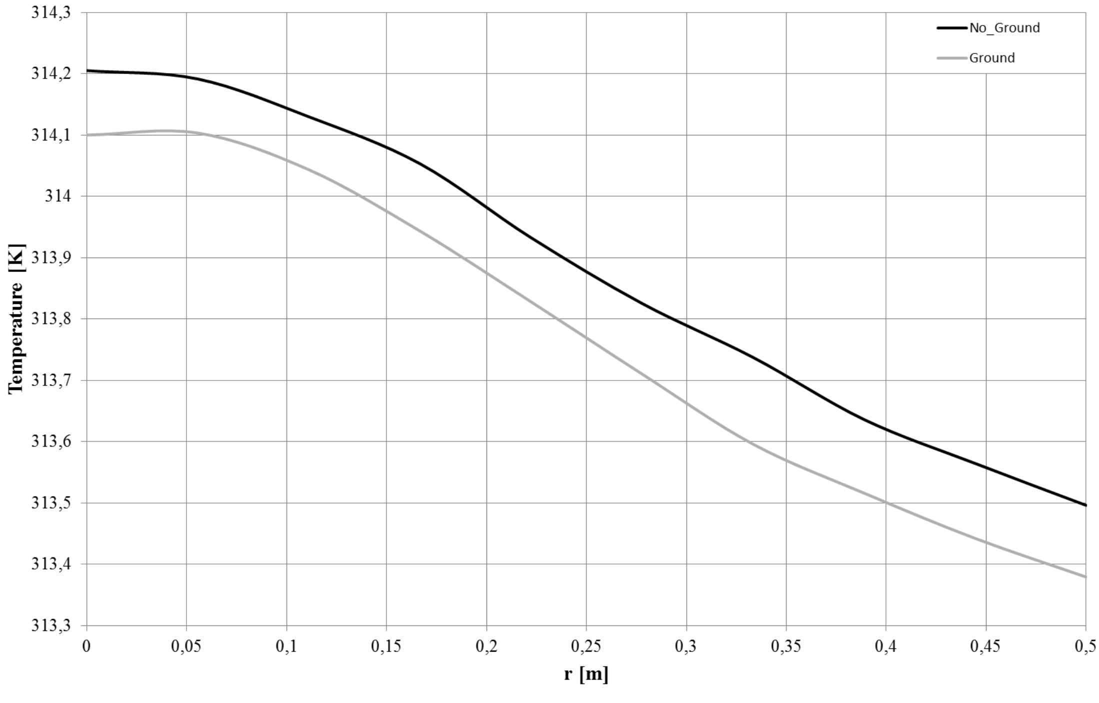

Figure 5. Temperature profile in the chimney

Figure 5 shows the temperature profile found in the chimney at a height corresponding to half the total height of the tower. As expected, the highest temperatures were found in the center (r = 0). The boundary condition used in the tower was thermal insulation, which justifies the small temperature differences found at a given cross section, of about 0.7 K. The simulation without the ground provided higher temperatures, as already observed in Fig. 4.

Figure 6 shows the temperature profile in the coverage, in an axial position corresponding to half the coverage radius. The temperature is highest in the region close to the ground (y = 0), reducing towards y = 0.5 m. In the regions close to the walls (ground surface and coverage), higher temperature gradients are observed. In the central region, the temperature differences showed a range of approximately 5 K.

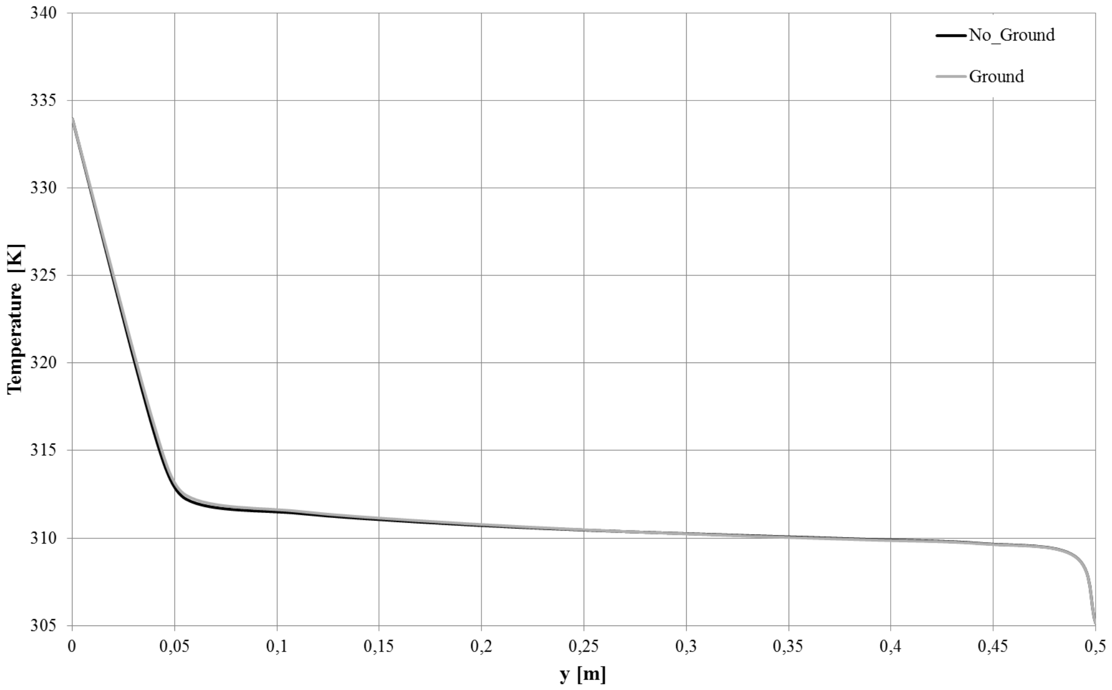

Figure 6. Temperature profile in the coverage

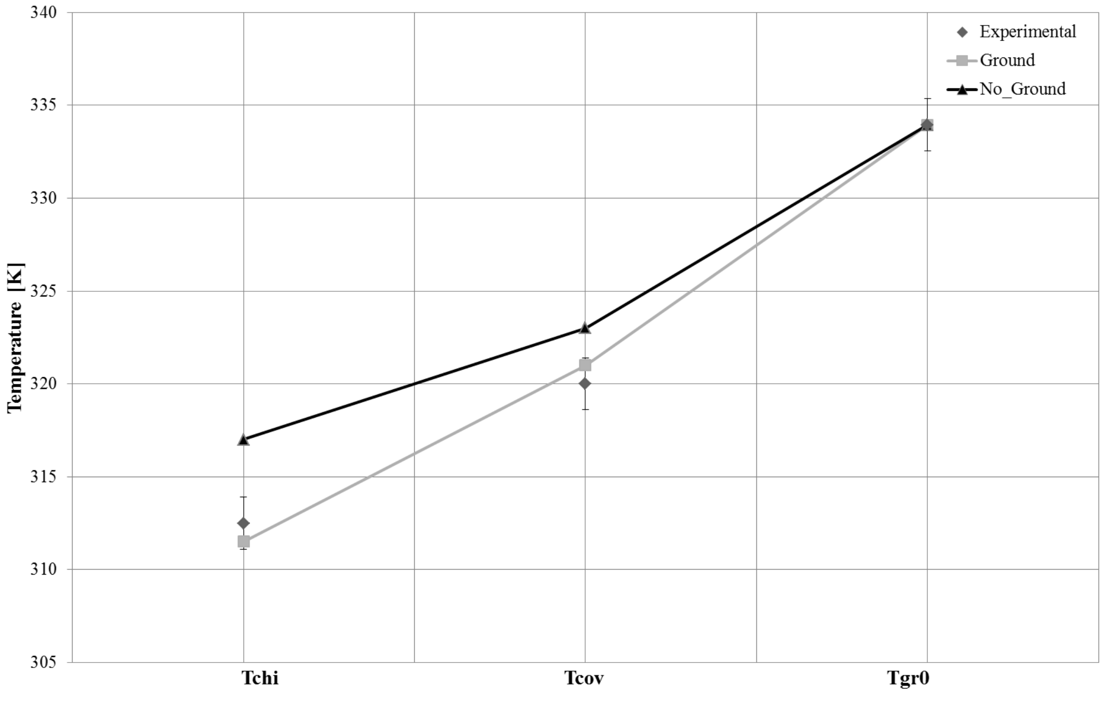

Figure 7. Comparison between the numerical and experimental data

Figure 7 presents a comparison between, numerical and experimental values of temperature. Experimental data was available in the literature (Ferreira, 2004 and Maia, 2005). Tchi corresponds to the temperature in the outlet of the chimney, Tcov, the temperature in the coverage surface and Tgr0, the ground surface temperature. It can be noticed that the ground surface temperature obtained in the numerical analysis is equal to experimental data, since this value was prescribed as boundary condition. In both simulations, the ground temperature was higher than the coverage surface, which was higher than the outlet temperature, as expected. The simulation with the ground provided more accurate results for the temperatures, always inside the uncertainty range of experimental data, which did not occur for the simulation without the ground.

5. CONCLUSIONS

It was performed a numerical simulation of the airflow inside a small-scale solar chimney. The influence of the ground under the coverage was evaluated by the comparison of the results of two geometric configurations: the first considering a ground layer under the coverage, and the second with only the solar chimney. Numerical results were compared to experimental data of a prototype built in Belo Horizonte / Brazil (data from literature). The main conclusions drawn are listed below:

(1) The analysis without a storage layer provided lower velocities and higher temperatures;
(2) Since the mass flow rate was imposed in both simulations, the influence of the ground is more important on the temperature distribution than on the velocity distribution;
(3) The analysis without storage layer was not able to accurately predict the temperature distribution along the device, while the analysis with energy storage layer gave values within the experimental uncertainty range analysis;
(4) The use of the ground as energy storage layer in the simulation is an important factor in the heat transfer process and should be considered in the numerical simulation. Otherwise, heat losses can be underestimated.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE