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# EXPERIMENTAL ANALYSIS OF A MODULAR SOLAR CHIMNEY

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***Abstract.*** *Solar chimneys are devices that use the incident solar energy to generate a hot airflow. These devices were originally designed for power generation, but it has been proven that large structures are required to generate electricity at competitive prices. Small-scale devices can be used for other purposes, such as food drying and ventilation. A solar chimney power plant consists mainly of two components: solar collector and tower. The geometry of the components plays an important role in the performance of the solar chimney, characterized mainly by the airflow temperature and velocity. The influence of these parameters in the airflow was numerically studied by several researchers. To investigate experimentally this influence, an experimental prototype was designed and built in Belo Horizonte, Brazil. The device is modular, which allows the diameter of the solar collector and the diameter and height of the tower to be changed. The collector diameter was varied between 3.0 m, 4.0 m, and 5.0 m. The tower diameter was varied between 0.10 m, 0.15 m, and 0.20 m, and the tower height, between 1.0 m, 1.5 m, and 2.5 m. The mass flow rate and the airflow temperatures were evaluated. For maximum solar radiation of 800 W/m$^2$ and maximum ambient temperature of 27°C, the maximum outlet airflow temperature and mass flow rate obtained were approximately 53°C and 0.053 kg/s, respectively. Results showed that the tower diameter and height have more impact on the mass flow rate and that the collector diameter has more impact on the outlet airflow temperature.*

***Keywords:*** *Solar chimney, modular solar chimney, experimental analysis, parametric analysis*

## 1. INTRODUCTION

The solar chimney, or solar updraft tower, is a device that combines the concepts of solar collector and chimney to induce a hot airflow that can be used to run wind turbines and generate electricity or to dry agricultural products. A portion of the solar radiation incident on the solar collector crosses the translucid cover and reaches the ground. There is a convective heat transfer to the air. The density difference between the hot air inside the solar chimney and the ambient air produces a buoyancy force that acts as a driving force. The buoyancy force generates a hot airflow towards the tower. Fresh air enters the device by its periphery, generating a continuous airflow. The energy carried by the airflow can be converted into mechanical energy in wind turbines and subsequently, in electrical power in conventional generators. A portion of the energy absorbed by the ground surface is accumulated during the day and released to the air under the collector at night, ensuring a continuous functioning of the system (Schlaich, 2002; Zhou et al., 2015).

The solar chimney uses both direct and diffuse components of solar radiation. It also uses simple technology and the materials are widely available. The maintenance costs are low, and its operation is simple and it has high durability. The power generated increases with the dimensions, and the production costs decrease (Zhou et al., 2015). Nevertheless, the installation costs are high, due to the high dimensions required. One of the major disadvantages of the solar chimney is the low efficiency of conversion of solar energy into electricity.

The first operational solar chimney power plant was built in Manzanares, Spain, with a maximum output of 50 kW (Muhammed and Atrooshi, 2019). The plant operated for seven years, in which several tests were performed to evaluate its performance. The prototype operated successfully. The results are described by (Haaf, 1984; Haaf et al., 1983), who demonstrated the viability and reliability of the project.

Since the construction of the Manzanares power plant, several other studies have been performed on this subject. According to (Cristiana B. Maia et al., 2019), several solar chimney projects have been released this century, but they have not yet been realized. Nevertheless, the projects promise to provide the needed demonstrations of scale and improved performance. The solar energy conversion is very low, ranging from 0.5% to 10% of the solar energy input, according to (Fathi et al., 2018). For this reason, several studies are been performed as an attempt to increase the efficiency of the use of solar energy. Innovative technologies have been incorporated by combining geothermal sources (Cao et al., 2014; Habibollahzade et al., 2021) or cooling towers (Ghorbani et al., 2015) to increase the thermal efficiency of a Rankine cycle. Hybridization with photovoltaic panels (Cao et al., 2021; Pratap Singh et al., 2020) and desalination systems (Cristiana B Maia et al., 2019; Ming et al., 2017; Zuo et al., 2019) are also been studied.

Large areas are required to generate power at competitive prices (Maia et al., 2009). Small-scale prototypes can be used for other purposes, such as food drying (Balijepalli et al., 2020; Ferreira et al., 2008; Maia et al., 2017; Yapıcı et al., 2020). Most of the studies in literature concern large structures, and only a few studies are found on small-scale solar chimneys. Of these papers, only a small percentage work with modular prototypes, and none in Brazil. The novelty of the present paper is the design and construction of a small-scale modular prototype of a solar chimney in Belo Horizonte, Brazil. The main geometric parameters were varied, allowing the assessment of their influence on the airflow.

## 2. MATERIALS AND METHODS

In this work, a prototype of a solar chimney was designed and built in the city of Belo Horizonte, Brazil (20°S latitude and 44°W longitude). The experiments were performed at GREEN PUC Minas, a laboratory of the Pontifical Catholic University of Minas Gerais. The dimensions of the prototype were defined with an approximated scale of 1:50 from the Manzanares prototype. The standard geometry has a tower 2.5 m high and a diameter of 0.2 m and a collector with 5.0 m of diameter and 0.1 m of height. The main parameters are allowed to be varied in 3 different dimensions each. The collector diameter was varied between 3.0 m, 4.0 m, and 5.0 m. The tower diameter was varied between 0.10 m, 0.15 m, and 0.20 m, and the tower height, between 1.0 m, 1.5 m, and 2.5 m.

The tower was made with PVC tubes, to ensure a light and resistant structure. To avoid thermal losses for the environment, it was covered by an insulating material. The collector is horizontal, and it was made using polygons of a thermodiffuser film, normally used in greenhouses. The plastic film is protected against infrared radiation and can stabilize the action of ultraviolet radiation. The transmittance of the film is 71% (Ferreira et al., 2008). The collector was kept elevated using steel rods. Figure 1 presents a photograph of the device, without the insulation of the tower.

Figure 1. Experimental prototype.

The prototype was positioned on a blackened surface, to increase the energy absorbed and increase the air temperature. The ground surface was treated to avoid the migration of humidity from the ground to the airflow. It was applied a concrete layer over the ground, and after 25 days, it was applied a solution of HCl to make the surface rough. After that, the surface was washed and two layers of a waterproofing acrylic compound, mixed with two layers of a matte black water waterproofing compound, were applied over the surface.

The ambient conditions were monitored using data from a meteorological station of GREEN PUC Minas. The parameters used in this work are the horizontal global radiation, humidity, and ambient temperature, using a Campbell datalogger, CR1000 model, a Kipp & Zonen pyranometer CM 6B model, an Eppley pyrheliometer Nip model, and a Vaisala thermohygrometer, HMP45AC model.

The airflow temperature was measured with a K-type thermopile, with an accuracy of 0.58°C. It was inserted into a plastic hole, to increase the conductive thermal resistance and minimize the heat losses for fin effects. It was placed inside an aluminum-coated PVC tube to minimize the effect of solar radiation. The thermopile was positioned at the tower outlet, in a position corresponding to the centerline. The relative humidity was measured with two thermo hygrometers model HTR-157 (Instrutherm), with an accuracy of 0.1%. The first was positioned at the system inlet and the other, at the system outlet, to ensure that the airflow was not absorbing humidity from the ground. An uncertainty analysis was performed using the methodology recommended by (Moffat, 1988).

## 3. MATHEMATICAL MODEL

The velocity at the system outlet was measured using a hotwire anemometer. Nevertheless, the sensor presented instabilities during its operation and the results were not reliable. The mass flow rate was estimated using a correlation based on the correlations from the literature. (Koonsrisuk et al., 2010) proposed an expression for the mass flow rate based on geometric parameters. It was observed, nevertheless, that the expression was only suitable for higher dimensions of solar chimneys since one assumption was that the tower diameter was much smaller than the collector diameter. (Castro Silva, 2014) adapted the expression to small-scale solar chimneys. The mass flow rate $\dot{m}$ is the estimated by:

$$\dot{m} = \sqrt[3]{\frac{\frac{\rho^2 \beta' g q"_{disp} \pi^3}{8 Cp_{ao}} H_t \left[ R_c^2 - \left(\frac{D_t}{2}\right)^2 \right]}{\frac{4 F_y H_t}{D_t^5} + \frac{\frac{F_x}{64}}{R_c h_c^3} + \frac{1}{D_t^4}}}, \quad (1)$$

ρ and $Cp_{ao}$ represent the density and specific heat of the air. $H_t$ and $D_t$ represent the tower height and diameter, $R_c$ and $h_c$ represent the collector radius and height. β' is the volumetric expansion coefficient, g is the gravity acceleration. $F_x$ and $F_y$ represent the friction factors in the collector and tower, proposed by (Koonsrisuk et al., 2010) and (KRÖGER and BURGER, 2004), respectively. $q"_{disp}$ is the available energy for the airflow, represented by the convective heat transfer between the ground surface and the airflow. The convective coefficient is evaluated according to (Pretorius, 2007).

## 4. RESULTS AND DISCUSSION

The influence of the geometric parameters was evaluated by comparison of the results to those obtained with the standard geometry. The airflow parameters evaluated were the outlet temperature and mass flow rate. In a solar chimney power plant, it is important to increase the mass flow rate because the turbine power increases with the airflow velocity. An increase in the airflow temperature increases the buoyancy forces, increasing the airflow driving force and consequently increasing the velocity. In small-scale solar chimneys used to dry agricultural products, the airflow temperature plays a more important role. Since the remotion of humidity from the products depends on the difference between the relative humidity of the airflow and the products, a higher airflow temperature results in lower relative humidity and higher drying rates.

The outlet temperature was measured and the mass flow rate was estimated according to Eq. (1). The results are presented for a 24 hours test, on an hourly basis. The incident solar radiation and the ambient temperature are also presented since these values varied between the experimental tests.

The first parameter evaluated was the collector diameter. Values of 3.0 m, 4.0 m, and 5.0 m (standard geometry) were assessed. Figures 2 and 3 present horizontal global solar radiation and ambient temperature measured on the test days. The average incident solar radiation levels when the tests of 3.0 m and 4.0 m were close, with a peak of approximately 800 W/m². When the standard geometry test was performed, the maximum solar radiation was 600 W/m². The ambient temperature follows the same behavior of solar radiation, with lower values for the standard geometry test (24.0°C, while the other tests had an average ambient temperature of 27.8°C).

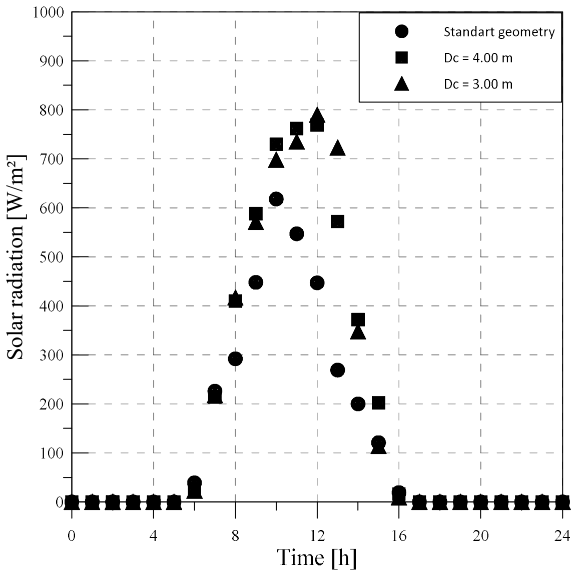


Figure 2 – Solar radiation for the tests evaluating the collector diameter

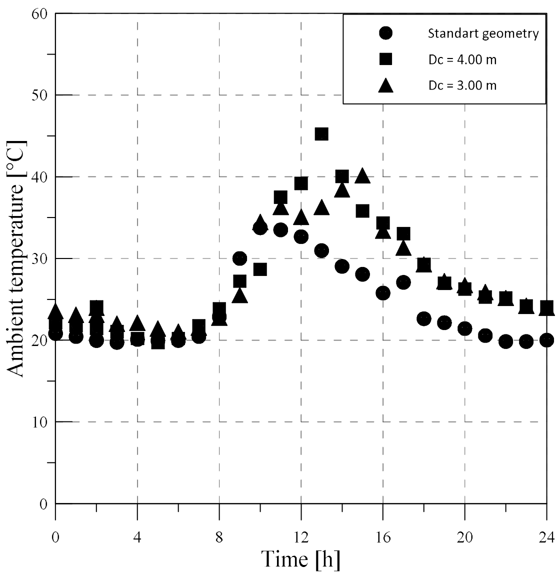


Figure 3 – Ambient temperature for the tests evaluating the collector diameter

Figure 4 presents the outlet airflow temperature and Fig. 5 presents the estimated mass flow rate of the airflow. The standard geometry presented lower values of the outlet temperature, due to the lower incident solar radiation. When compared the other values of the diameter, a slight increase of the temperature is observed with the increase of the collector diameter. The maximum temperature was 53.0°C for a diameter of 4.0 m and 51.6°C for a diameter of 3.0 m. The mass flow rate also increased with the increase of the collector diameter. It can be explained with the increase of the heated area, increasing the driving force of the airflow.

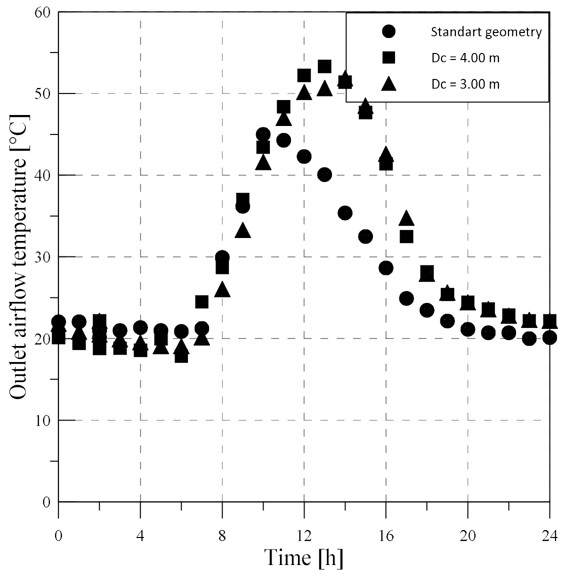


Figure 4 – Outlet airflow temperature for the tests evaluating the collector diameter

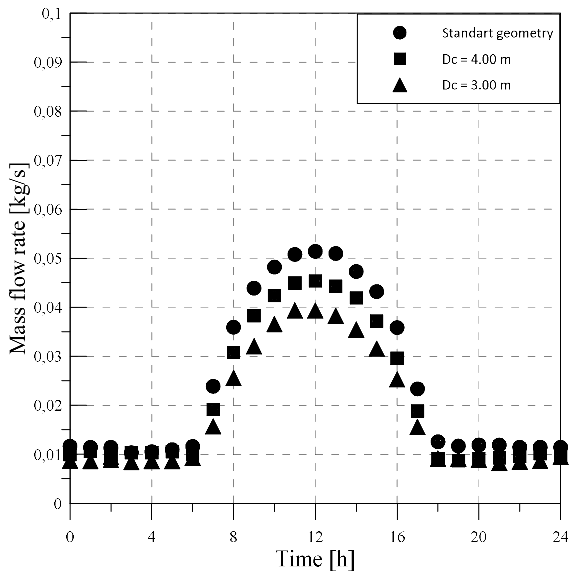


Figure 5 – Mass flow rate for the tests evaluating the collector diameter

The second parameter evaluated was the tower diameter, with values of 0.10 m, 0.15 m, and 0.20 m (standard geometry). Figures 6 and 7 present the ambient conditions for the days of the tests. For the standard configuration, the maximum incident solar radiation was approximately 600 W/m$^2$, with an average ambient temperature of 24.0°C. For the test of 0.10 m, the maximum solar radiation and average temperatures were 720 W/m$^2$ and 27.0°C, and for the test of 0.15 m, the maximum solar radiation, and average temperatures were 600 W/m$^2$ and 25.0°C.

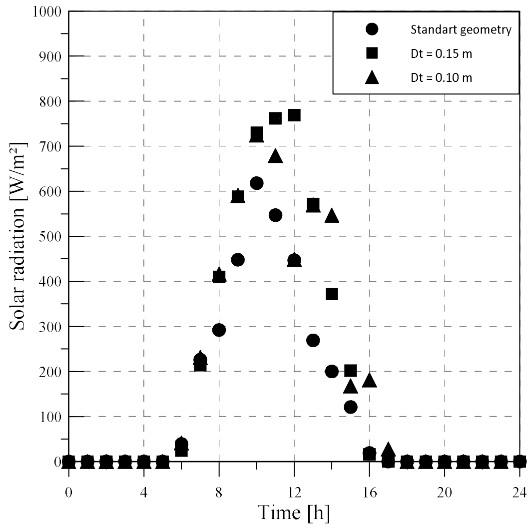


Figure 6 – Solar radiation for the tests evaluating the tower diameter

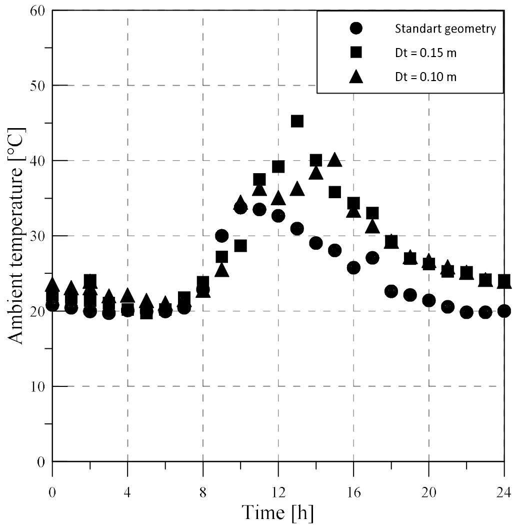


Figure 7 – Ambient temperature for the tests evaluating the tower diameter

The airflow parameters can be seen in Figs. 8 and 9. The increase in the tower diameter decreases the outlet temperature and the mass flow rate.

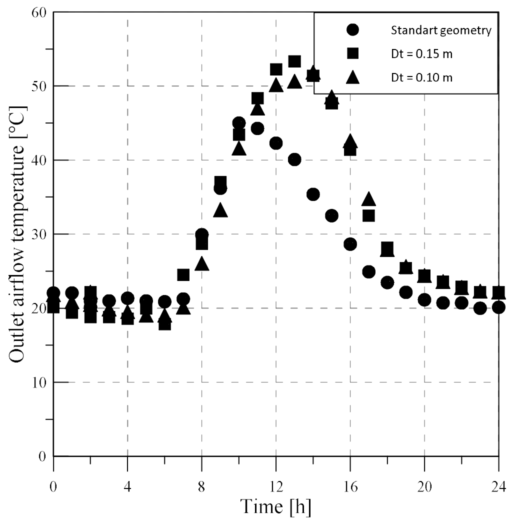


Figure 8 – Outlet airflow temperature for the tests evaluating the tower diameter

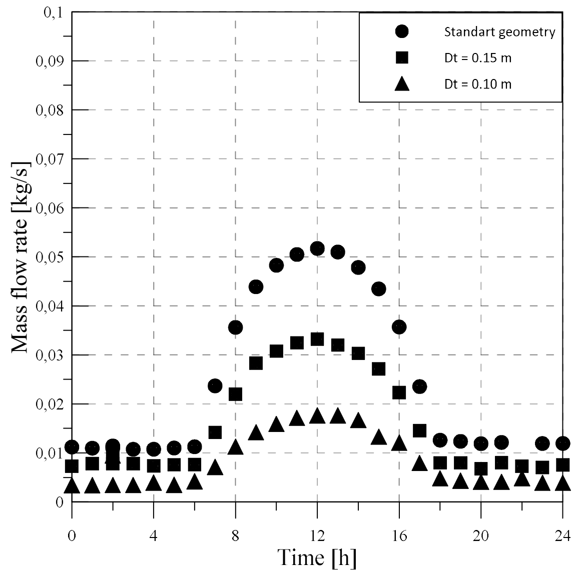


Figure 9 – Mass flow rate for the tests evaluating the tower diameter

The tower height was varied between the values of 1.0 m, 1.5 m, and 2.5 m (standard geometry). Figures 10 and 11 present the solar radiation and ambient temperature for the days of the tests. For the standard configuration, the maximum incident solar radiation was approximately 600 W/m$^2$, with an average ambient temperature of 24.0°C. For the test of 1.0 m, the maximum solar radiation and average temperatures were 660 W/m$^2$ and 23.9°C and for the test of 1.5 m, the maximum solar radiation, and average temperatures were 680 W/m$^2$ and 22.6°C. An increase in the incident solar radiation is followed by an increase in the ambient temperature.

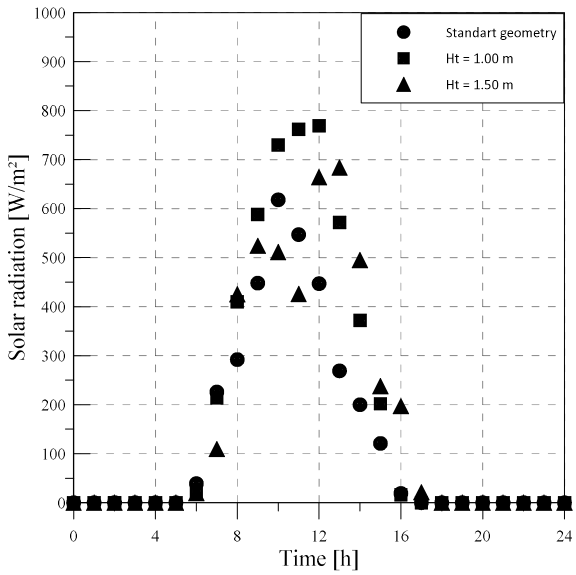


Figure 10 – Solar radiation for the tests evaluating the tower height

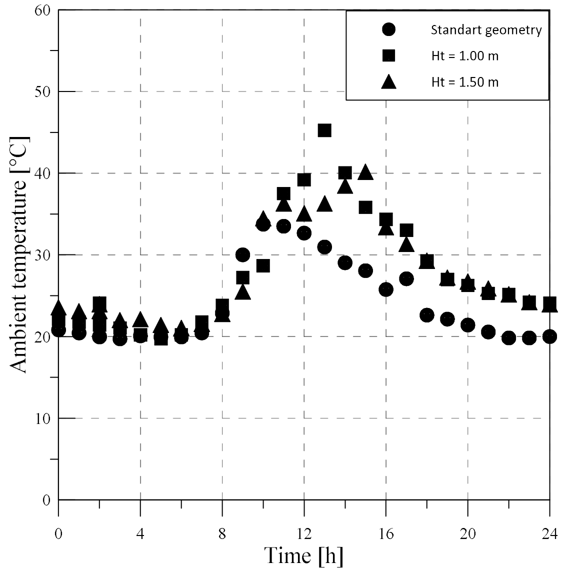


Figure 11 – Ambient temperature for the tests evaluating the tower height

The airflow parameters can be seen in Figs. 12 and 13. An increase in the tower height increases the pressure difference between the bottom and top of the tower, increasing the driving force for the airflow, increasing the mass flow rate. The increase in the tower diameter decreases the outlet temperature and the mass flow rate. The outlet temperature decreased with the tower height.

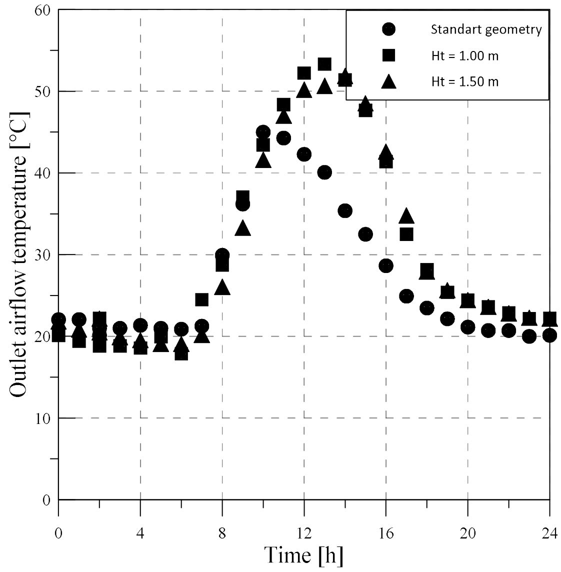


Figure 12 – Outlet airflow temperature for the tests evaluating the tower height

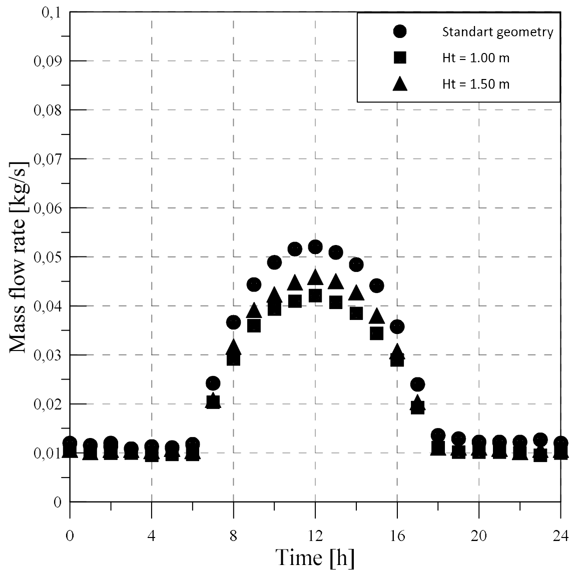


Figure 13 – Mass flow rate for the tests evaluating the tower height

The results presented are following the literature (Maia et al., 2009; Yapıcı et al., 2020), indicating the general behavior of the airflow parameters with geometric variables. Studies of similar dimensions were not found in literature, not allowing the comparison of particular values.

## 5. CONCLUSIONS

In this paper, it was developed an experimental analysis of the influence of the main geometric parameters on the airflow inside a small prototype of a solar chimney. According to the literature, the parameters that most influence the airflow are the tower diameter and height, and the collector diameter.

A prototype was designed and built in the city of Belo Horizonte, on an approximate scale of 1:50 of the Manzanares pilot plant. The results showed that, for the values assessed, the mass flow rate is more affected by the tower diameter and height. An increase in the tower dimensions increases the mass flow rate. The outlet airflow temperature is more affected by the collector diameter. When the collector diameter is increased, it is possible to heat a greater portion of air, increasing the airflow temperature. These results are consistent with the results presented by the literature.

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