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THERMODYNAMIC ANALYSIS OF A REDUCED PROTOTYPE OF A SOLAR CHIMNEY

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Abstract. *In the past decades, the world is facing an increasing average world per capita demand for energy combined with a growing population. Fossil fuels are the primarily world energy, a cheap energy source, but associated with a great number of environmental problems. Solar energy is a clean, abundant and renewable source of energy. There is a wide variety of technologies developed to take advantage of solar energy. Solar chimneys are devices that use the atmospheric air as working fluid and the solar energy to generate a hot airflow. In most of the prototypes, the airflow is used to drive a turbine. However, tall structures are required to provide a reasonable amount of energy. Solar chimneys with reduced dimensions can be used to other goals, like the drying of agricultural products. In this study, it is presented an analysis of a small prototype of a solar chimney. Experimental data were used in conjunction with the first and second laws of thermodynamics to estimate the amounts of energy and exergy lost to the surroundings and the exergetic efficiency of the process. The results show that the solar radiation plays an important role on the behavior of temperatures, mass flow rates and specific humidities. The heat transfer rates are higher for higher solar radiation and temperatures. An analysis of the second law of thermodynamics indicates that the higher exergy rates are due to heat transfer. Due to the dimensions of the prototype, the hot airflow generated was not used to drive a turbine, leading to very significant exergetic losses. Therefore, there is a great potential of exergy to be harnessed.*

Keywords: *Solar chimney, Thermodynamic analysis, Exergy.*

1. INTRODUCTION

Recent decades have been marked with an increase of the average demand per capita energy combined with a growing world population. The world energy supply is mainly based on fossil fuels. Coal, oil and natural gas accounted for approximately 86.6% of the total world supply of primary energy (corresponding to 5292 Mtoe) in 1973. In 2009, these fuels were responsible for the supply of 9829 Mtoe (IEA, 2011). Although cheaper than renewable energy, there are a number of problems associated with fossil fuels, such as greenhouse gases. Beyond addition, the depletion of these energy sources is occurring at a rapid pace. A viable solution to this problem is to replace fossil fuels with renewable energy sources.

Hermann (2006) awakens a reflection to quantify the global resources of exergy, and allows us to examine the use of resources that can guide the efforts for technological research. Particularly, the author highlights the enormous potential of solar energy, which has a low conversion efficiency and low usage. The available reservoirs and exergy fluxes are more than sufficient to provide energy services to the increasing population and activity of mankind. Therefore, it is important to identify and evaluate a variety of energy resources in order to provide enough power options for a sustainable energy future.

Off all the renewable sources of energy available, solar thermal energy is the most abundant one and is available in both direct as well as indirect forms. The total annual solar radiation falling on the earth is more than 7500 times the world's total annual primary energy consumption. The annual solar radiation reaching the earth's surface is an order of magnitude greater than all the estimated (discovered and undiscovered) non-renewable energy resources, including fossil fuels and nuclear (Thirugnanasambandam *et al*, 2011). Solar energy can be divided into passive and active applications. Passive solar heating is characterized by the use of natural lighting and heat for space heating. Active solar energy is the direct use of solar radiation as a source of thermal energy to heat fluids and environments and to generate mechanical power or electricity. It can also be converted directly into electricity, through effects on certain materials, among which stand out the thermoelectric and photovoltaic systems.

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The solar chimney is a power plant that uses solar radiation to raise the temperature of the air and the buoyancy of warm air to accelerate the air stream flowing through the system. The device was described by Schlaich in 1995. The solar chimney combines the technologies of solar collectors, chimneys and turbines. Solar radiation that reaches and passes through the coverage heats the soil beneath, which in turn heats the air, as a greenhouse (Fig. 1). The buoyancy forces caused by temperature gradients promote airflow into the chimney located at the center of the coverage. In the solar collector, the solar energy is converted in thermal energy, and the generated thermal energy is converted into kinetic energy in the chimney. Using a combination of a wind turbine and a generator, it is able to generate electricity. (Xu *et al.*, 2011, Dai *et al.*, 2003, Schlaich, 1995). An experimental plant with a peak output of 50 kW was established in 1981/82 in Manzanares desert (Spain), about 150 km south of Madrid. The plant produced electricity for eight years, proving the feasibility and reliability of this novel technology (Bernardes *et al*, 2003). Economic evaluations based on experience and knowledge accumulated during the design and operation of the facility of Manzanares, demonstrated that solar chimneys with power greater than or equal to 100 MW are capable of generate electricity at costs comparable to those of conventional plants. (Schlaich and Schiel, 2000).

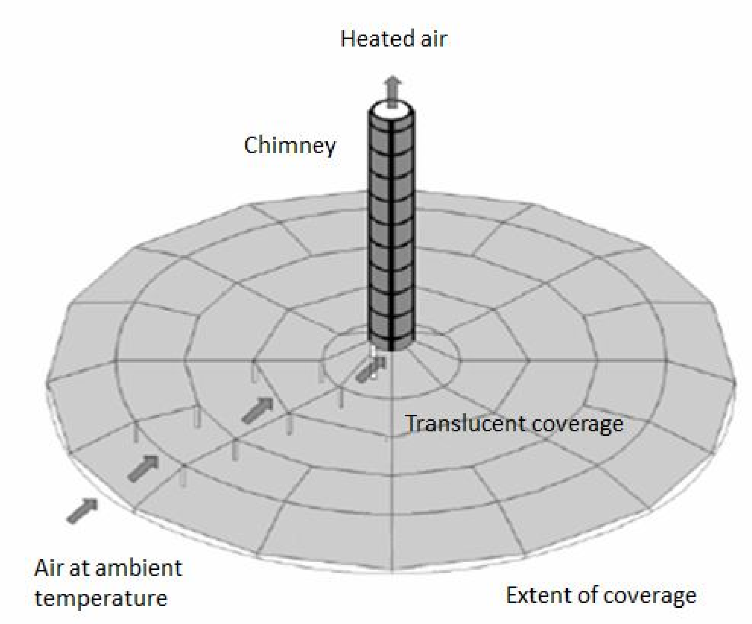

Figure 1. Schematics of the prototype

There is also an ongoing project to build a facility that uses this technology. The installation will be built in Australia and is expected to generate 200 MW, enough to power 200 thousand homes, with a tower about 1 km height and coverage of 5 km in diameter (Hamdan, 2011). In order to get a reasonable amount of energy at competitive prices is necessary to use very tall structures, since the efficiency of converting solar energy into electrical energy is very low. An alternative would be to use solar chimneys with reduced dimensions for drying of agricultural products. These structures would be about the size of storage silos. (Maia, 2005; Ferreira, 2004).

Among the experimental studies, several highlighted the work of Dai *et al.* (2003), which evaluated the performance of a solar chimney that can provide 110-190 kW of electricity to remote villages in northwest China. The device has a chimney of 200 m and 10 m in diameter. The influence of temperature, solar radiation, the diameter of the collector and chimney height in the performance of the installation was evaluated. Larbi *et al.* (2010) performed a performance analysis of the influence of physical and geometrical parameters of the output power of a chimney to be installed in Algeria. The authors provided a differential equation of fluid temperature as a function of radius and the oscillations caused by conduction, convection and radiation. Global equations were defined for the pressure drop and the power output, following the model equations proposed by Schlaich. Ferreira et al. (2008) conducted a feasibility analysis of a solar chimney for drying agricultural products. Velocity, temperature and humidity were monitored as a function of the incident solar radiation. Drying tests were performed and the results were compared with results for natural drying in the sun, showing better results. Maia *et al.* (2009a) performed an experimental analysis of the airflow inside a prototype of a solar chimney. Temperature, velocity, humidity and solar radiation were measured inside and outside the device, as well as the temperature at several depths of the ground. It was observed that the higher values of velocity and temperature were obtained to higher values of solar radiation. Airflow temperature under the cover increases toward its center. In the tower, the airflow was roughly adiabatic, indicating that the fiberglass used to cover the tower minimized thermal losses to the external environment. A portion of solar radiation reaching the ground surface was transferred to the deeper layers of the ground, being stored as heat. At night when ground surface temperature is lower than the

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temperature of the deeper layers, heat flux went in the opposite direction, insuring the uninterrupted functioning of the solar chimney.

Maia *et al*. (2009b) carried out a transient analysis of the axi-symmetric flow in a solar chimney of small proportions, using the method of finite volume in generalized coordinates. The conservation equations of momentum, mass and linear equations for energy and transport quantities of turbulence were solved. The analysis showed that the height and diameter of the tower are the most important parameters in the temperature and velocity of the airflow. Koonsrisuk and Chitsomboon (2009) evaluated five simple theoretical models proposed in the literature to evaluate solar chimneys. The influence of the dimensions of the collector and tower and the solar radiation on the performance was evaluated.

Zhou *et al*. (2009) determined a differential expression of the maximum height of the chimney to minimize convection and the maximum height of the chimney to maximize the power output. The theoretical model was validated with measurements of the prototype in Manzanares. In Hamdan (2011) a simplified model for thermodynamic analysis of airflow within a solar chimney is presented. The simplified Bernoulli equation combined with static fluid and ideal gas equation was implemented and solved to predict plant performance. The model showed that increasing the second law efficiency and power is related to the height and diameter of the chimney. Most studies presented in literature deal only with analysis based on the first law of thermodynamics. To the best knowledge of the authors, Petela (2009) is the only author who presented a thermodynamic analysis of energy distribution across the system, with an exergetic approach. In this work, a simplified mathematical model of the chimney was developed. However, the results are theoretical and based on several assumptions, not in experimental data.

In this work, experimental data obtained in a prototype of a solar chimney were used to perform an analysis based on the First and Second Laws of Thermodynamics. The energy transferred to the airflow, the exergetic efficiency and the losses of exergy were determined. The Engineering Equation Solver (ESS) software was used to determine the moist air properties.

2. MATERIALS AND METHODS

The experimental setup consists of a prototype of a solar chimney, with tower height and diameter of 12.3 m e 1m, respectively, and collector diameter of 25 m and height varying from 0.05 m to 0.5 m in the tower, Fig.2. The prototype was built in Belo Horizonte, Brazil. Although many authors present results for a period of one day, this work presented results for a period of four days, in order to improve the understanding of the influence of climatic parameters in the airflow. The experiments were conducted in late autumn in Brazil, with maximum and minimum temperatures around 27.3° C and 8.4° C, respectively. Relative humidity ranged between 25.6% and 90.6% and the maximum solar radiation was 1065 W/m^2.

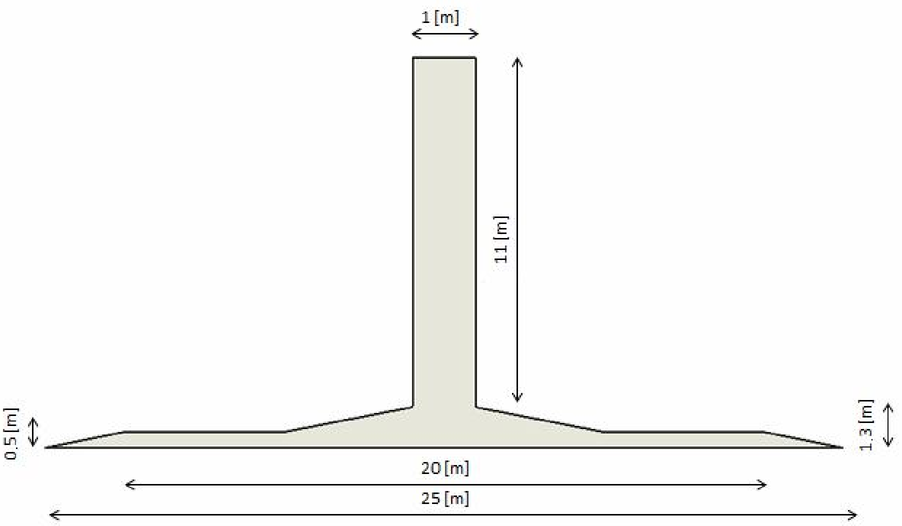

Figure 2. Dimensions of the prototype

Airflow and ambient temperatures were measured with K thermocouples (uncertainty of 1°C). Eppley Black and White Pyranometers Model 8-48 were used to determine the total and diffuse components of the incident solar radiation (global uncertainty of 5%). Propeller Homis anemometers were used to measure the velocity in the tower (global uncertainty of 6%). A numeric integration was performed to determine the mass flow rate of the airflow. Capacitive psychrometers were used to measure the ambient relative humidity and the relative humidity of the airflow (uncertainty of 6%).

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3. MATHEMATICAL EQUATIONS

The equations set presented in the mathematical model were developed according to Hepbasli (2008) and Celma and Cuadros (2009) models. The four balance equations of mass, energy, entropy and exergy were applied to find the work and heat interactions, rate of exergy decrease, rate of irreversibility and efficiency exergetic. It can be noticed that in all the balance equations the cumulative terms are neglected, considering that even if the thermodynamics properties change with time, its temporal derivatives are null.

The general equation of conservation of mass can be expressed as:

$$\dot{m}_{ai} = \dot{m}_{ao} \tag{1}$$

Where $\dot{m}_{ai}$ and $\dot{m}_{ao}$ represent the inlet and outlet of mass flows of air, respectively.

The mass conservation for the moisture can also be written in terms of specific humidity of inlet and outlet, respectively, ω_{in} and ω_{out}, as:

$$\dot{m}_{ai}\omega_{in} + \dot{m}_{mp} = \dot{m}_{ao}\omega_{out} \tag{2}$$

The heat transfer rate is obtained by the energy conservation equation:

$$\dot{Q} = \dot{m}_{ao}(h_{ao} + \frac{V_{ao}{}^2}{2}) - \dot{m}_{ai}(h_{ai} + \frac{V_{ai}{}^2}{2}) \tag{3}$$

The energy utilization rate was neglected, since there is no turbine in the system. V_{ai} and V_{ao} represent the air velocity in the inlet and outlet of the system, respectively. The specific enthalpies of the air in the inlet and outlet, h_{ai} and h_{ao}, were determined using the correlations available in the EES.

The general exergy balance can be written as follows:

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{lost} \tag{4}$$

In the previous equation, $\dot{E}x_{in}$, $\dot{E}x_{out}$ and $\dot{E}x_{lost}$ represent the exergy inflow, outflow, and the exergy loss.

$$\sum \dot{E}x_{in} = \dot{E}x_{mass,in} + \dot{E}x_{heat} \tag{5}$$

$$\sum \dot{E}x_{out} = \dot{E}x_{mass,out} + \dot{E}x_{work} \tag{6}$$

The exergy flow rate due to the heat transfer is given as:

$$\dot{E}x_{heat} = \left(1 - \frac{T_o}{T_k}\right)\dot{Q} \tag{7}$$

$\dot{Q}$ is the heat transfer rate through the boundary at temperature T_k at location k, considered as the ground temperature. T_o represents the dead state temperature. To the system considered, the exergy rate due to work interactions $\dot{E}x_{work}$ can be neglected.

The exergy inflow $\dot{E}x_{mass,in}$ is due only to the airflow entering the system, and the exergy outflow $\dot{E}x_{mass,out}$ is due to the airflow leaving the system and to the water removed from the ground.

$$\dot{E}x_{mass,in} = \dot{m}_{ai}\psi_{ai} \tag{8}$$

$$\dot{E}x_{mass,out} = \dot{m}_{ao}\psi_{ao} + \dot{m}_{mp}\psi_{wo} \tag{9}$$

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Assuming air as real gas, the flow of exergy specific entrance and exit is calculated (ALPUCHE *et al*., 2005):

$$\psi_{ai} = \left(C_{p,ai} + \omega_{ai} C_{p,v}\right) T_o \left(\frac{T_{ai}}{T_o} - 1 - \ln\frac{T_{ai}}{T_o}\right) + \left(1 + 1.6078\omega_{ai}\right) R_a T_o \ln\frac{P_{ai}}{P_o} + \\ + R_a T_o \left[\left(1 + 1.6078\omega_{ai}\right) \ln\left(\frac{1 + 1.6078\omega_0}{1 + 1.6078\omega_{ai}}\right) + 1.6078\omega_{ai} \ln\left(\frac{\omega_{ai}}{\omega_0}\right)\right] \quad (10)$$

$$\psi_{ao} = \left(C_{p,ao} + \omega_{ao} C_{p,v}\right) T_o \left(\frac{T_{ao}}{T_o} - 1 - \ln\frac{T_{ao}}{T_o}\right) + \left(1 + 1.6078\omega_{ao}\right) R_a T_o \ln\frac{P_{ao}}{P_o} + \\ + R_a T_o \left[\left(1 + 1.6078\omega_{ao}\right) \ln\left(\frac{1 + 1.6078\omega_0}{1 + 1.6078\omega_{ao}}\right) + 1.6078\omega_{ao} \ln\left(\frac{\omega_{ao}}{\omega_0}\right)\right] \quad (11)$$

Where R_a is the ideal air constant, P_o is the dead state pressure, and P_{ai} and P_{ao} are the air pressure in the inlet and outlet, respectively.

The outlet specific flow exergy of the water, considered as an incompressible substance, is given by

$$\psi_{wo} = C\left(T_{ao} - T_o - T_o \ln\frac{T_{ao}}{T_o}\right) \quad (12)$$

It is assumed that the air and water leave the system at the same temperature T_{ao}. In the previous equation, C is the specific heat of water.

The exergy efficiency ε is defined as the ratio of the total exergy output to the total exergy input:

$$\varepsilon = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} \quad (13)$$

Exergy is always measured relative to a reference environment, the dead state. When the system is in equilibrium with the environment, the system state is called the dead state due to the fact that the exergy is zero. According Hepbasli (2008), dead state is arbitrary. Typically, the results are presented in literature for steady state conditions. In this document, non-steady state conditions were evaluated. The reference temperature for dead state is the minimum inlet temperature measured (about 8.5°C), with zero velocity and elevation coordinates in relation to the environment, with the local ambient atmospheric pressure (91.5 kPa).

4. RESULTS AND DISCUSSION

Figure 3 presents the total and diffuse components of solar radiation measured during the four days of tests. The average clearness index (the ratio of the daily radiation to the extraterrestrial radiation of the day, Duffie and Beckman, 2006) was determined for each day, obtaining 0.68, 0.63, 0.72 and 0.53, respectively, for the first, second, third and fourth day of tests. It can be seen that higher clearness indexes correspond to clearer days.

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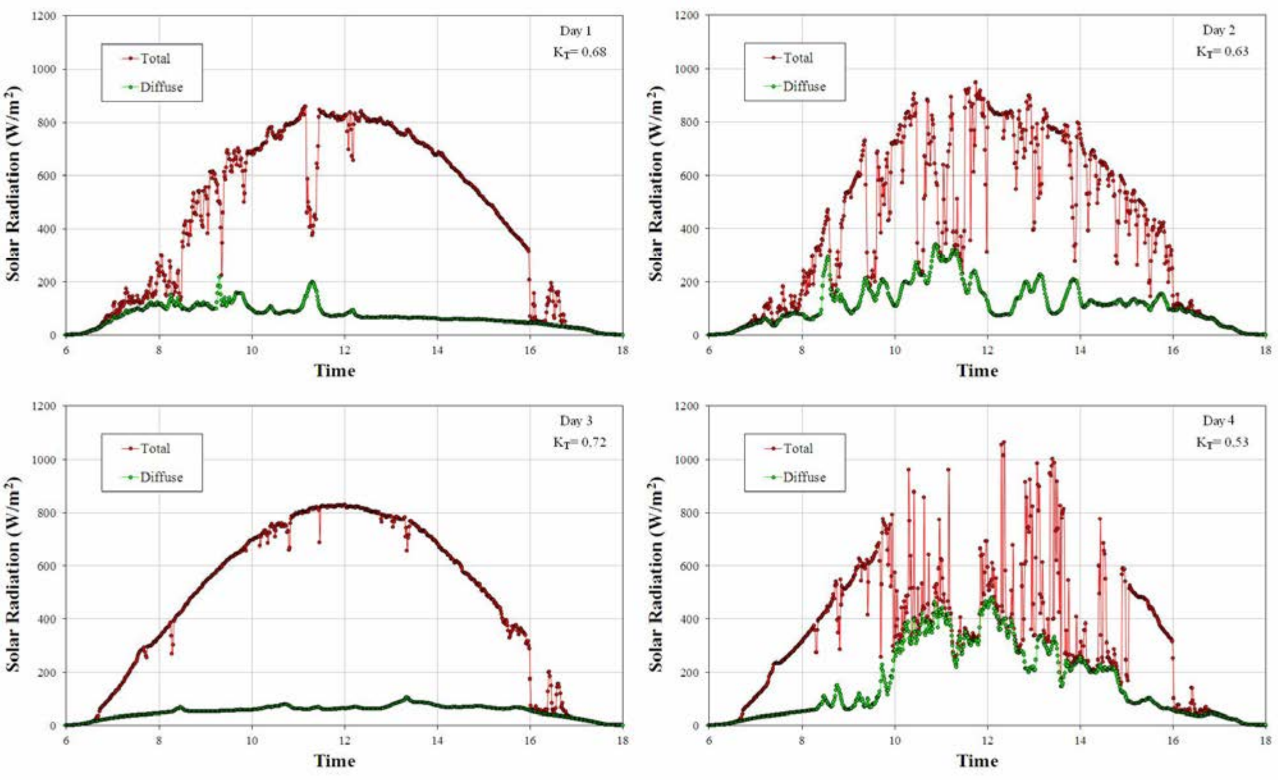

Figure 3. Total and diffuse components of solar radiation

Figure 4 shows the temperatures of the inlet and outlet airflow, and the ground temperature. As expected, the total solar radiation and temperature profiles show a similar behavior. It can be seen that the solar chimney is capable of operating at night, when no sunlight is present, since a portion of the heat stored during the day is conducted to the ground surface and transferred to the air stream overnight (Maia *et al.*, 2009a). It is important to note that the temperatures reached near maximum values at noon and minimum values near midnight.

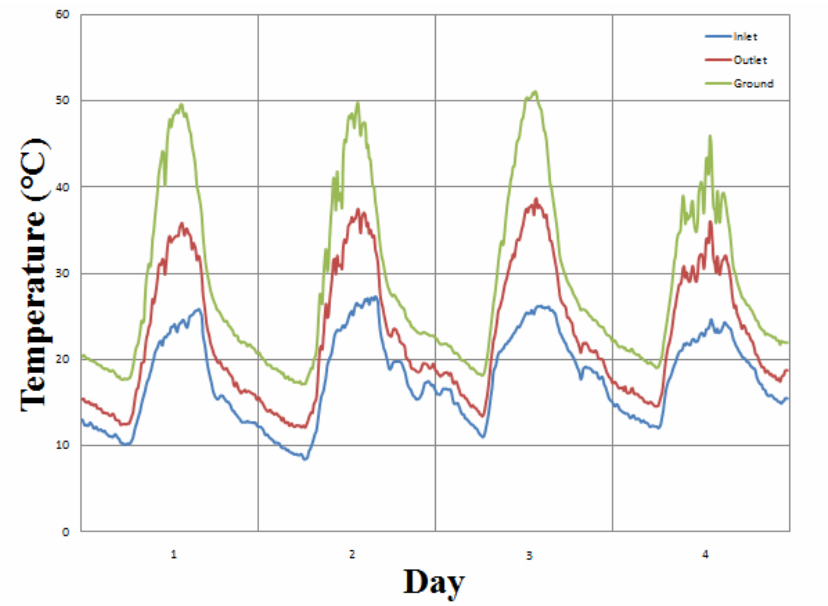

Figure 4. Temperature distribution

Figure 5 shows the specific moisture of the inlet and outlet airflow, as well as the difference between them. It can be seen that the output humidity is higher than the inlet moisture. Since the prototype soil was not sealed, the difference may be explained by the removal of water from the soil by the airflow. During the day, ambient temperatures are higher, causing a decrease of the input specific humidity. Therefore, it was easier to remove water from the soil, increasing the specific humidity difference at the inlet and outlet. At night, an opposite behavior was found.

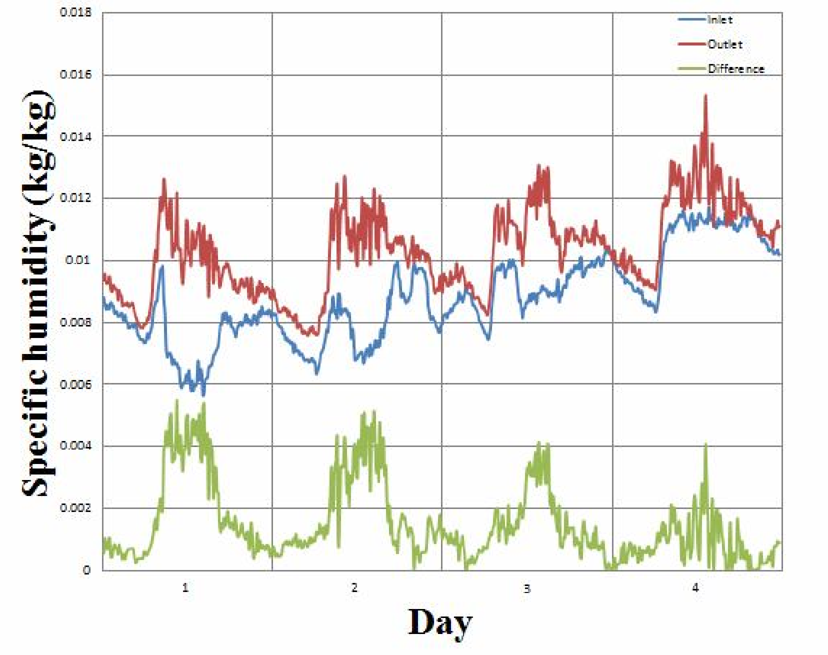

Figure 5. Specific humidity

The airflow is generated by natural convection. Therefore, the velocity depends on the difference between the ground and the air flow temperatures, which depends on the incident solar radiation. Figure 6 shows the mass flow rate during the entire test. The higher mass flow rates were obtained when the solar radiation and the temperature was higher, but it can be noticed that there is a flow of air overnight, due to the temperature difference observed in Fig. 3. The velocity in the tower varied from 1.1 m/s to 2.7m/s, corresponding to Reynolds numbers from 6.4×10^4 to 1.5×10^5, characteristics of turbulent airflows.

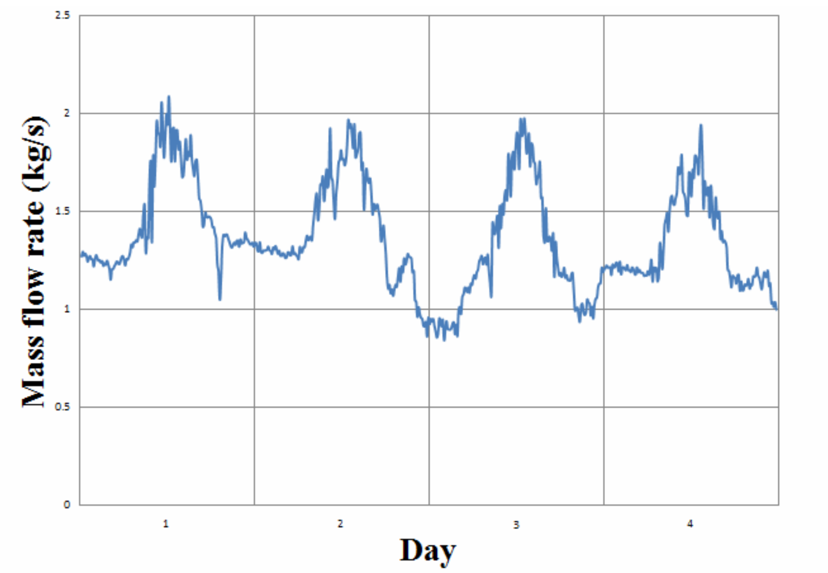

Figure 5. Mass flow rate

Figure 6 shows the heat transfer rates from the ground to the airflow. As expected, the heat transfer rate exhibits a behavior similar of other results, higher when the solar radiation is higher. There is a small portion of heat transferred during the night, when there is no incidence of solar radiation.

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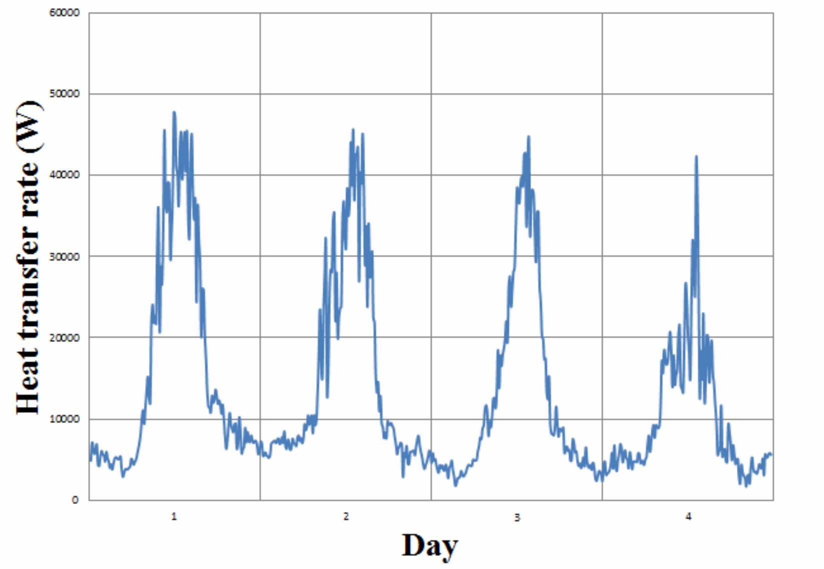

Figure 6. Heat transfer rates

As previously discussed, the dead state is a reference state arbitrary. In this paper, the minimum temperature obtained during the tests was chosen as the reference for the dead state, being defined as a temperature of 8.4° C and a pressure of 91.5 kPa. Figure 7 shows the rates of exergy as a function of time. The general behavior of the exergy rates is similar to the behavior of the temperature. The exergy output is comprised of two portions, one due to the exergy of exhaust air and the other exergy due to removal of water from the soil (whereby this represents 0.45% of the total exergy output).The higher exergy rates were found for the exergy rates due to the heat transfer, and the lower exergy rates were found for the exergy of the water removed from the ground.

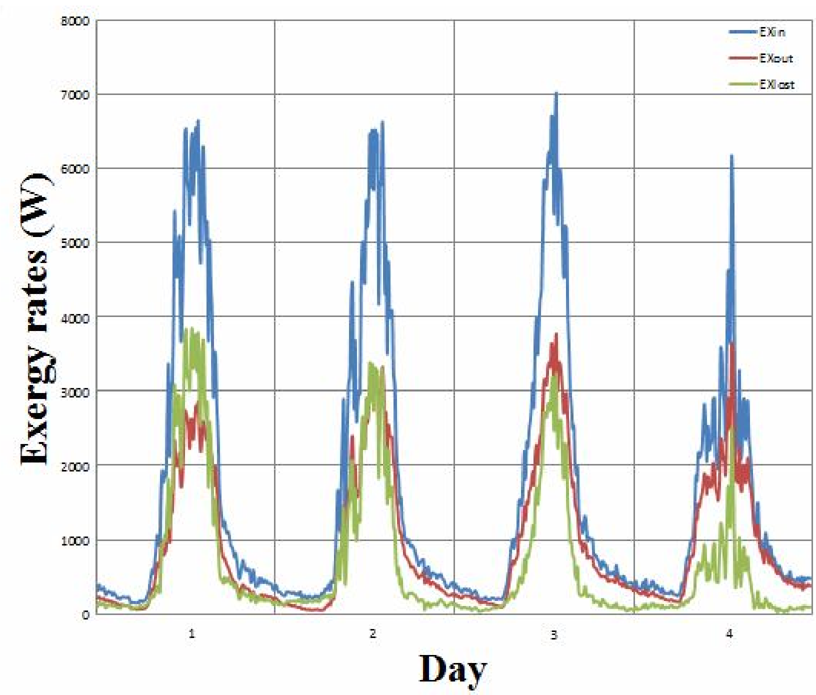

Figure 7. Exergy as a function of time for the dead state selected

Figure 8 shows the exergetic efficiency. The maximum exergetic efficiency (95.1%) was reached on the fourth day and the minimum efficiency (19.80%) was achieved on the second day.

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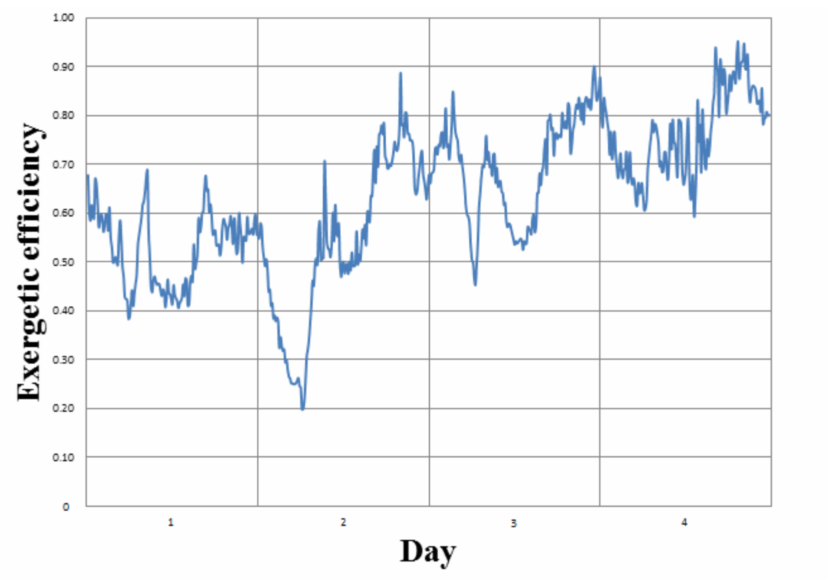

Figure 8. Exergy efficiency

The exergetic losses were significant due to the fact that the hot airflow was only used to remove water from the ground; nevertheless, the main goal of this paper was to analyze the behavior of the airflow inside the solar chimney with no products inside. It is important to note that, in spite of this, the hot airflow generated in a solar chimney can be used to drive a turbine in solar chimney power plants or to dry agricultural products in a smaller prototype. In a solar chimney power plant, it is shown that higher solar radiation levels increase the power output and the energetic efficiency of the system. In a drying process, the most important parameter of the drying efficiency is the difference between the relative humidities of the airflow and the products to be dried. An increase of the source of energy (in this case, the solar energy) increases the airflow temperature, which decreases the relative humidity of the air, improving the drying characteristics.

5. CONCLUSIONS

It was performed an analysis of the energy and exergy rates in a prototype of a solar chimney built in Belo Horizonte, Brazil. Experimental tests were performed over a period of four days during the autumn, which were used to determine the behavior of the airflow temperature, mass flow rates, heat transfer and exergy rates related to the incident solar radiation and ambient temperature. The main points of the conclusion are:

- The mass flow rate and temperature are closely related with the solar radiation incident on the device;
- The highest exergy rates were found for the exergy rates due to the heat transfer;
- Higher levels of solar radiation provide higher rates of heat transfer to the airflow. Since this heat was not used in this prototype, the exergy losses were higher, and the exergetic efficiencies were lower. It is important to note that the exergy losses were high because the hot airflow was only used to remove water from the ground. In a solar chimney power plant, the airflow generated is used to drive a turbine and in a solar chimney to dry agricultural products, the hot airflow is used to remove water from the products, therefore, it is expected that the exergy losses will be reduced.

6. ACKNOWLEDGEMENTS

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