NUMERICAL ANALYSIS OF THE INFLUENCE OF ENVIRONMENTAL PARAMETERS IN SOLAR UPDRAFT TOWER

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Abstract. *Energy is essential for economic growth and social development of any country. The quality of life is directly related to energy consumption, which has grown steadily in recent decades in developing countries. The result is that energy demand is increasing and cannot be satisfied by traditional technologies. Furthermore, there is a relationship between energy consumption and environmental impact. The main source of world primary energy is based on fossil fuels. The solar updraft tower deals with the use of solar energy. Traditionally uses the air flow generated in solar updraft tower for handling wind turbine. However, large dimensions are necessary to generate electricity at competitive costs. Therefore, an alternative would be use for drying of agricultural products especially in regions without electrification, because the principle only uses solar energy as the driving force of the drying air flow. This technology has great potential for application on a large scale, especially in arid, semi-arid and remote areas, and has attracted attention from around the world. This study aims to analyse numerically the influence of environmental parameters on the performance of a solar updraft tower small.*

Keywords*: Numerical analysis, Solar updraft tower, Environmental parameters*

1. INTRODUCTION

Solar energy is the largest source of energy received by the earth. The total amount of solar energy incident on Earth is vastly superior to current energy needs and planned the world. If properly harnessed this power supply has the potential to meet all the energy needs in the future. One of the technologies used to harness solar energy is the solar updraft tower. The concept was developed by Cabanyes in 1903, but only in 1981 was built the first solar updraft tower prototype, with maximum power of 50 kW in Manzanares desert (Spain), Fig. 1. The operating principle of solar updraft tower can be described as the combination of solar collectors, chimneys and turbines technology. Part of the solar radiation that reaches the device through the manifold and heating promotes ground. The ground heat transfer by convection to the air mass inside the collector, which in turn flows upwardly toward the chimney, due to the buoyancy forces caused by temperature gradients (Schlaich, 1995).

Figure 1. Solar updraft tower in Manzanares - Spain

Maia et al. (2009) conducted a numerical analysis of transient flow in a small prototype, using the technique of finite volume in generalized coordinates. The temperature at the ground surface was used as a boundary condition, and approximated as a function of incident solar radiation and thermal properties of the ground. The results were compared with experimental data, still being investigated the influence of geometric parameters in mass flow, average temperature

output and the velocity profiles and temperature throughout the device. The analysis showed that the height and diameter of the tower are the most important parameters. Xu et al. (2011) evaluated the characteristics of air flow, heat transfer and power generated in a two-dimensional model with an energy storage layer and a turbine with similar dimensions to the prototype Manzanares. The influences of the solar radiation on pressure drop and heat transfer in the output power were analyzed. Sangi et al. (2011) described a detailed numerical analysis of a solar updraft tower, using the software FLUENT® to simulate a two-dimensional model of axial symmetry, with the turbulence model k-ε. The model was validated from Manzanares prototype data. The authors also developed a static expression for the pressure inside the collector. Tingzhen et al. (2008) performed numerical simulations using CFD techniques (Computational Fluid Dynamics). The influence of solar radiation in the turbine pressure drop, the heat transfer in the output power and the energy loss power of the solar updraft tower were evaluated. The results showed that for the solar updraft tower with a height chimney of 400m and with a collector radius of 1500m and a turbine with blades of 5m, the maximum power is about 10 MW and the turbine efficiency is 50%. Guo et al. (2015) performed a three dimensional numerical approach that incorporates the radiation model, the model solar load and an actual turbine. Variations in performance of the turbine rotation speed were studied to investigate the power control strategy for turbines in solar updraft towers. The results of the simulations with a fan and a turbine model were compared. The results indicated that the fan model is a convenient approach to investigate the turbine pressure drop and updraft speed in the design of an electrical central solar updraft tower without considering the efficiency of the turbine. Moreover, the influences of the angle of incidence of sunlight on performance was investigated for the first time, and the results revealed that, considering the time variation of zenith of the sun angle and performing shading calculation is required to predict the performance in the design and cost analysis, particularly annual performance, are required.

2. NUMERICAL MODEL

The governing equations of the problem Eq. (1) are the mass, Eq (2) refers to linear momentum and Eq (3) it represents the energy conservation equations:

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

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

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

The flow inside the solar updraft tower is turbulent. The k-ε turbulence model was used, in which the turbulent viscosity is given by Eq. (4).

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

According to Versteeg and Malalasekera (2007), $k - \varepsilon$ model allows the transport effects of turbulent properties to be assessed by transport equations for the turbulent kinetic energy, Eq. (5), and the dissipation of the turbulent kinetic energy, Eq. (6).

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

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

According to Nizetic et al (2008) the energy efficiency of solar updraft towers, disregarding the performance of the turbine is given by Eq. (7).

$$\eta = \frac{\int \dot{m} \cdot Cp \cdot (Tao - Tai)}{Ac \cdot Ho} \cdot \frac{Ht \cdot g}{Cp \cdot Tai} \tag{7}$$

3. METHODOLOGY AND BOUNDARY CONDITIONS

The geometrical dimensions of the solar updraft tower used in this study are based on a previous work, Ferreira (2004) and Maia (2005). It has a 12.30 m tower height with a diameter of 1 m, the collector diameter is 25 m and the height ranges from 0.05 m to 0.10 m.

The atmosphere around the device is represented by a parallelepiped that surrounds the entire device (Fig. 2). In the upper and lower surfaces of the parallelepiped were considered adiabatic walls. In three parallelepiped edges, an opening condition was assumed, allowing the fluid to both enter and leave the system. The bottom surface was considered as a wall, and the remaining surface belonging to the YZ plane was considered as input for wind speeds ranging between 0 and 25 m/s. In the atmosphere the ambient temperature considered ranging between 0 °C and 50 °C. It was assumed that the atmospheric air is a real gas with influence of a gravitational acceleration field. The ground is an interface with heat flux ranging between 0 and 1000 W/m². For the boundary conditions of the solar updraft tower, interface input and device output were considered. The collector was assumed as a wall, with an interface (only allowing the heat flux to leave the boundary), and the tower of the device was considered adiabatic wall.

The commercial software ANSYS- CFX 14.5 was used to solve the governing equations of the problem. The results obtained for simulation default, it is considered crosswind equal zero, ambient temperature of 32°C (305.15K) and heat flux on the ground of 565 W/m² were validated with experimental data from Ferreira (2004) and Maia (2005). The results presented correspond to a mesh with approximately 2 million elements, solved for residue of the conservation and transport equations of 10^{-6}.

Figure 3 shows the comparison of the numerical results with the experimental data for ambient temperature (Tai), coverage temperature (Tcov), outlet tower temperature (Tchi) and ground temperature (Tgro). It is observed that for all the points observed numerical values were within or very close to experimental uncertainty.
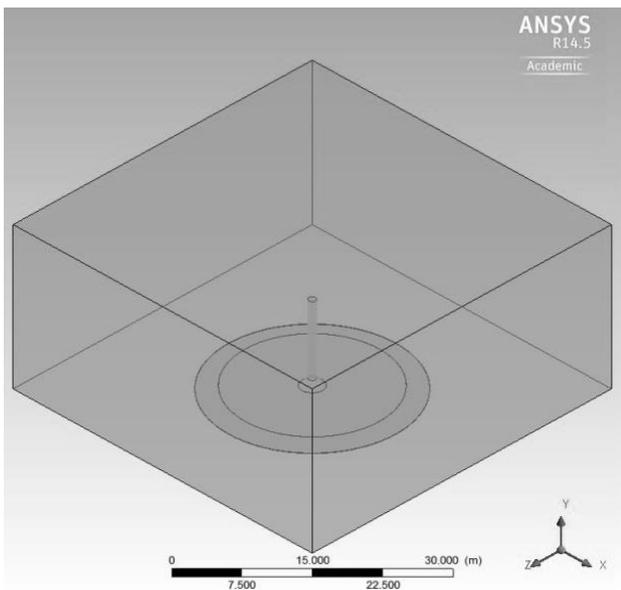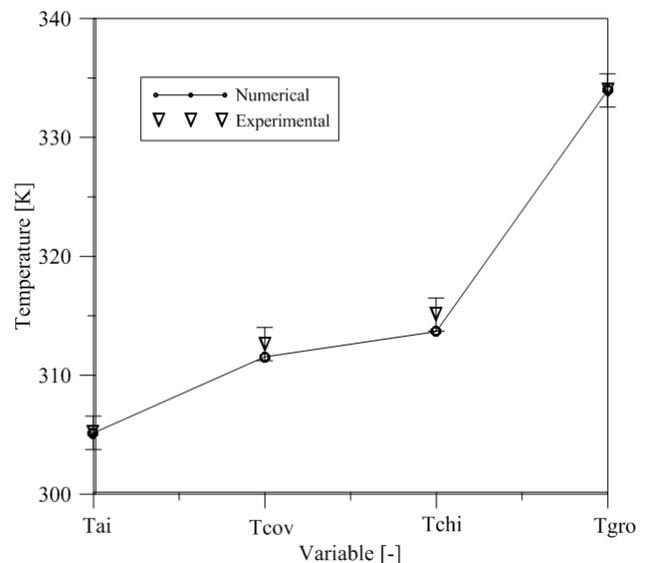

Figure 2. Geometry and boundary condition

Figure 3. Validation

4. RESULTS AND DISCUSSIONS

This study evaluated three environmental parameters (crosswinds, ambient temperature and solar irradiance absorbed) on the performance of a solar chimney prototype were evaluated ground and output flow temperatures, velocity, mass flow and energetic efficiency.

After leaving the collector, the air moves to the junction between the collector and the tower. In this region, there is a change of direction of the flow from radial to axial. Furthermore, as the flow area becomes smaller, there is an increase on the velocity at the junction. In the chimney, the flow area is constant. Therefore, the average velocity does not change; small variations are observed in the profile, since the flow is not yet fully developed. For the average speeds obtained Reynolds numbers found are the $1x10^5$ order, characteristics of turbulent flows. For the situation analyzed the Rayleigh number was the $1x10^{12}$ order and Grashof number was the $1x10^{13}$ order, characteristic of flow governed by natural convection.

The crosswinds influence the performance of solar updraft towers by heat loss through convection from the outer surface of the collector to the environment, drag heated air out of the collector, and drag generating a suction effect at the outlet of tower increasing the upward air flow in the tower. The first two processes reduce the collector efficiency,

while the latter results in increased efficiency of the tower. In general, heat loss by convection by the first process is included in the energy equation of the most common mathematical models for solar updraft towers. Heat loss of the second process is not included in the common mathematical models, but has been investigated based on environmental wind speed profiles using CFD (Computational Fluid Dynamics) simulations.
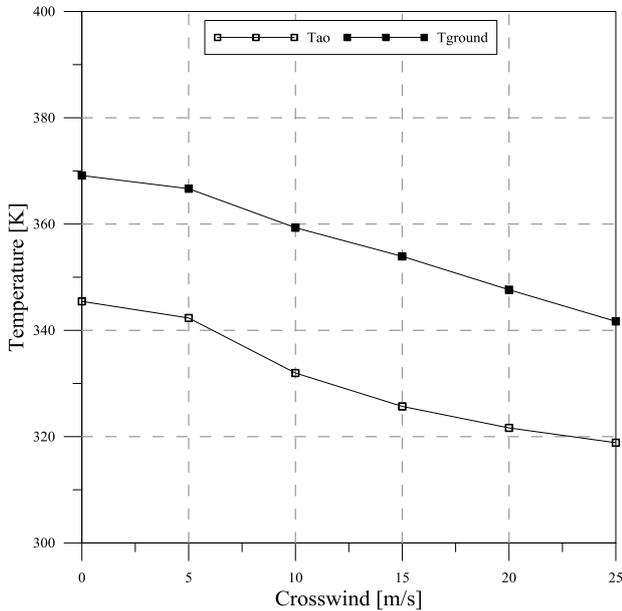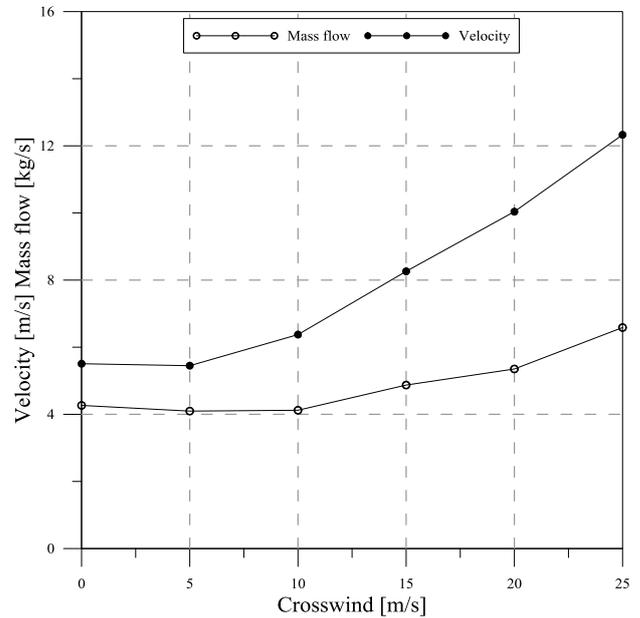

Figure 4. Influence of crosswinds at temperatures

Figure 5. Influence of crosswinds at velocity and mass flow

The crosswind influence directly on the temperatures causing a decrease in same. The ground temperature is ranging between 369.14 K and 341.69 K, since the outlet temperature of the flow ranges from 345.45 K to 318.86 K. For both reaching its minimum value for the crosswind equal of 25 m / s. The effect of the speed on the temperature is attributed to an increase on the convective heat transfer between the collector and the environment, as shown in Fig 4.

It is worth mentioning that the magnitude of the maximum velocity reached by the airflow is significantly affected by the crosswind. As the crosswind speed increases, the velocity of the airflow increases. This behavior can be explained by the increase of the mass flow entering the system. As can be seen in Fig. 5, the rate of increase of crosswinds caused an increase of 54.39% on the mass flow, when the speed increases from 0 to 25 m/s.
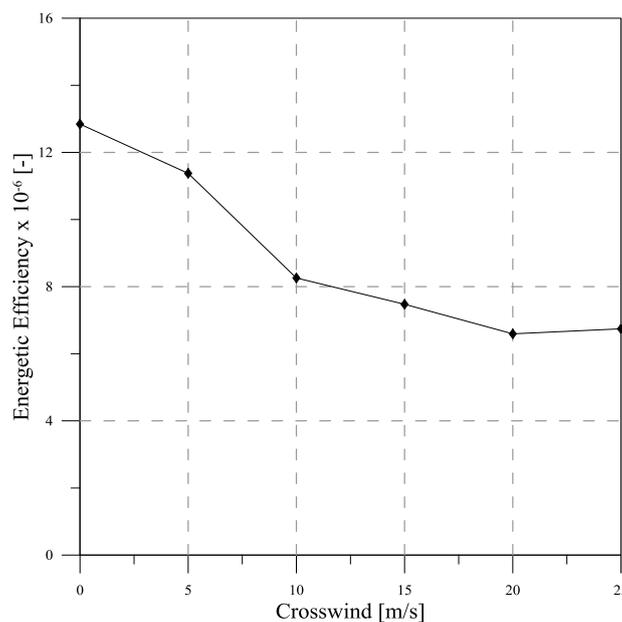

Figure 6. Influence of crosswinds at energetic efficiency

As noted in Eq. 7, the mass flow has greater influence on the efficiency than the outflow temperature difference to ambient temperature. The solar updraft tower have low energy efficiency, as affirm by Tingzhen et al. (2006), solar updraft tower with structures up to 300m high, maximum energetic efficiency is 1%. As mentioned environmental winds decreased to 7.7% the outlet temperature of the device and increase the output from velocity to 123.86 % for the range of speeds environmental analyzed (0 to 25 m / s). What favors the decrease of energy efficiency which increases 47.51%, Fig. 6.

Therefore, the effects of crosswind interfere with the effects of heat flow in the collector, increasing the convective heat losses from the collector to the environment. Furthermore, the air that enters the lower part of the tower causes distortions on the airflow and resistance on the pressure reduction or temperature difference between the interior and the exterior of the tower, the air non uniform temperature distribution inside the tower.

The influence of ambient temperature on the performance of solar updraft tower must be assessed from two points of view. The first concerns the temperature difference between the ground temperature and the ambient temperature, since this difference is related to convection and consequently the velocity and the mass flow. The second concerns the difference between the outlet temperature and ambient temperature, which is related to energetic efficiency of the device, Eq. (7).
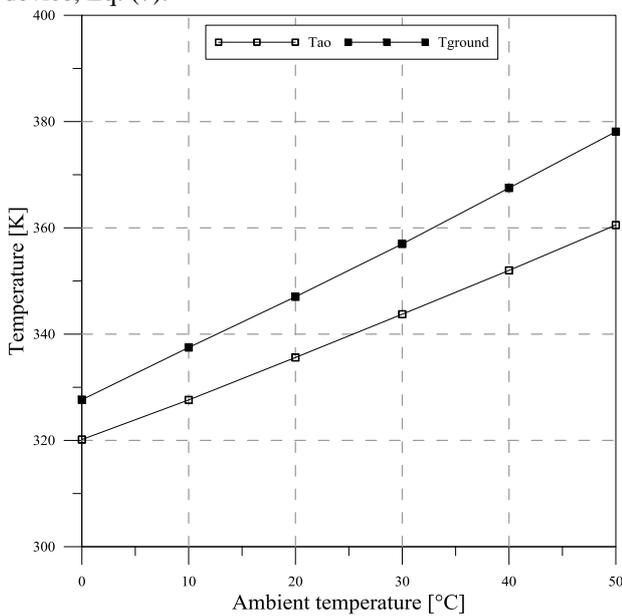

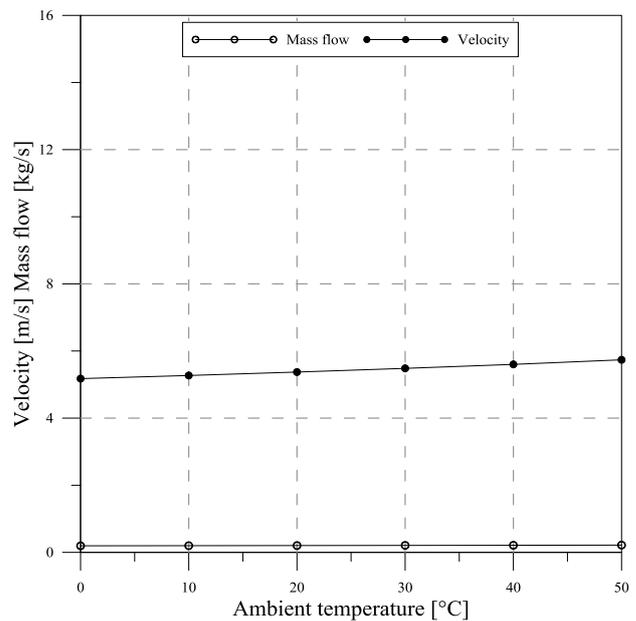**Figure 7. Influence of ambient temperature at temperatures**

Figure 8. Influence of ambient temperature at velocity and mass flow
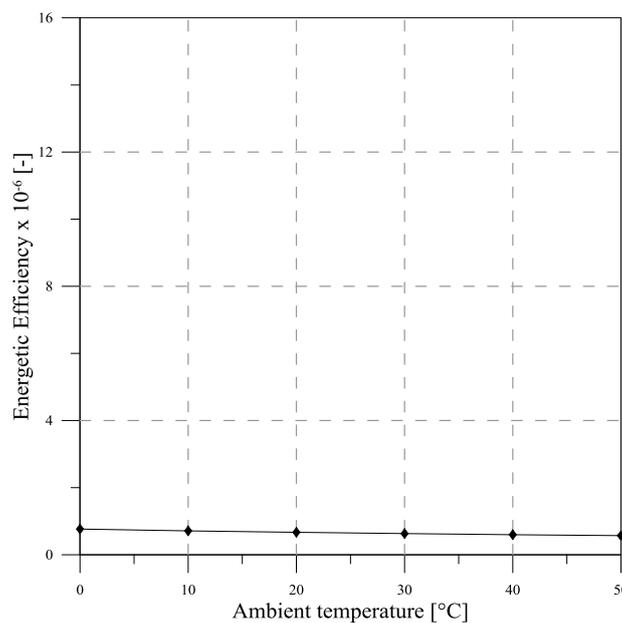

Figure 9. Influence of ambient temperature at energetic efficiency

The ambient temperature influence directly on the temperatures causing a increase in same, Fig. 7. The ground temperature is ranging between 327.66 K and 378.10 K, since the outlet temperature of the flow ranges from 320.16 K to 360.53 K. For both reaching its maximum value for the ambient temperature equal of 50 °C. The influences of the maximum temperature analyzed is about 10.82% of the velocity and mass flow (Fig. 8). What ends up generating a decreasing variation of 25.53% in the energetic efficiency of the device, Fig. 9. The exergetic efficiency reaches its maximum for the ambient temperature 0 °C with efficiency of 0.76 x 10^{-6}, and its minimum value, 0.57 x 10^{-6}, for the maximum ambient temperature analyzed. Although the temperature impact on the energy efficiency of the solar chimney, it is a secondary factor, since the temperature gradient is more important than the temperature itself.
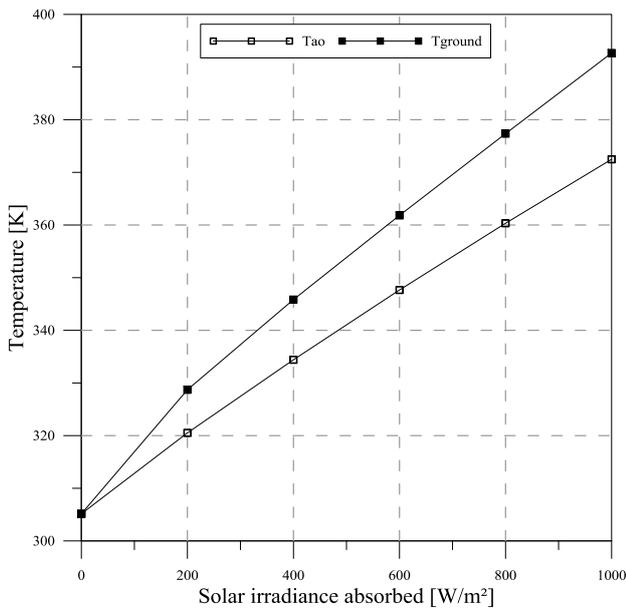

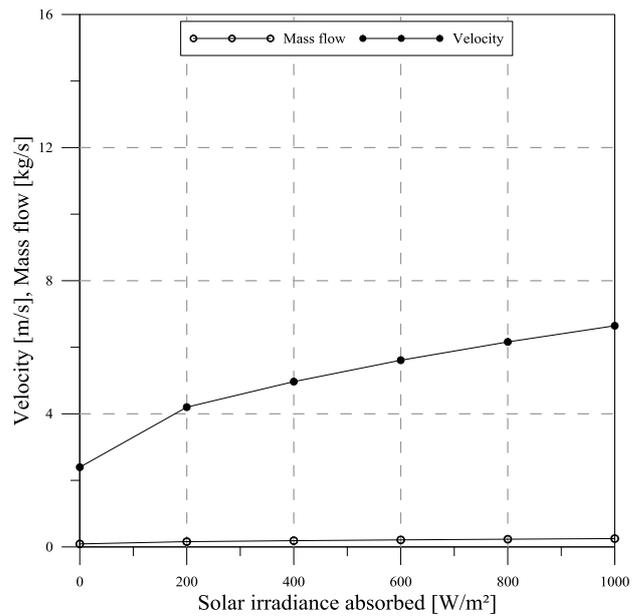**Figure 10. Influence of solar irradiance absorbed at temperatures**

Figure 11. Influence of solar irradiance absorbed at velocity and mass flow

When the influences of the solar irradiance absorbed by the ground is measured is observed that there is an exponential growth temperatures with irradiance absorbed by the ground, reaching the maximum value to the solar irradiance of 1000 W / m², Fig. 10.

The velocity and the mass flow also grow with increasing solar irradiance reaching 177.45%, Fig. 11. As a consequence there is an exponential growth of exergetic efficiency, which reaches the maximum value of 0.57 x 10^{-6} (Fig. 12).
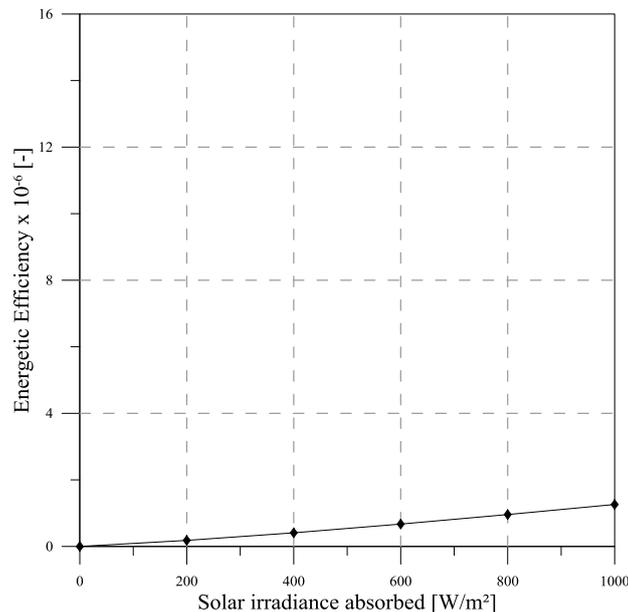

Figure 12. Influence of solar irradiance absorbed at energetic efficiency

It is worth noting that the higher the amount of energy absorbed by the ground will be greater availability of energy for flow, hence higher will be the temperature and mass flow, consequently greater energy efficiency.

Of the three parameters analyzed, the crosswinds are what most impact on device performance. Various studies have been developed to minimize the energy loss caused by crosswinds, and the use of blocking the use of screens and lowers entry.

5. CONCLUSIONS

The results of numerical simulations have shown that environmental parameters have significant influence on fluid flow and heat transfer, with both positive and negative effects.
- The effects of wind interfere with the effects of heat flow in the collector, increasing the convective heat losses from the collector to the environment;
- The air that enters the lower part of the tower causes distortions on the airflow and resistance on the pressure reduction or temperature difference between the interior and the exterior of the tower, the air non uniform temperature distribution inside the tower;
- The ambient temperature is little influence on the device performance, since the temperature gradient is more important than the temperature itself;
- The greater the solar irradiace absorbed by the ground, the greater the availability of energy to the flow.

6. ACKNOWLEDGEMENTS

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