NUMERICAL ANALYSIS OF THE CROSSWIND IN SMALL SOLAR CHIMNEY

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ABSTRACT

The solar chimney (or solar updraft tower) consists of a circular solar collector, a tower in the center of the collector, and turbines installed in the collector output or the tower entrance. The solar radiation passes through the translucent collector, reaches the ground surface and heats it. The air within the device is heated by the radiation emitted by the ground and by convection currents formed under the collector. The thermal energy is stored in the absorber layer of the ground when there is incidence of solar radiation and it is released from the ground when solar radiation is low. The density difference between the hot air inside the device and the ambient air creates convection currents that drive the air in the collector from the base to the top of the tower. Finally, the airflow in the tower drives the turbines which are coupled to electrical generators. The environmental winds influence the performance of the solar updraft towers in three main ways: heat losses by convection from the outer surface of the collector to the environment, heated air drag out of the cover and drag on the top of the chimney generating a suction effect and enhancing the upward flow in the tower. This work studied the influence of crosswinds on the system flow conditions through a numerical analysis using CFD. Results indicate that an increase on the environmental crosswinds speed from 0 to 25 m/s decreased the outlet temperature of the device in 0.3% and increased the outlet velocity in 50.26%, increasing the energetic efficiency of the device in 56.31%.

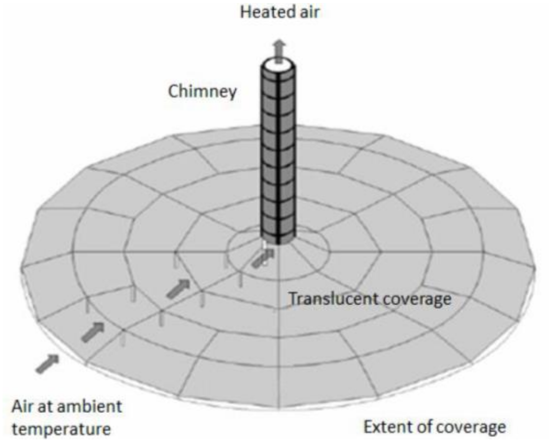

Figure 1 Geometry

NOMENCLATURE

ρ	[kg/m³]	Density
$\dot{m}$	[kg/s]	Mass flow rate
Ht	[m]	Tower height
Tao	[K]	Outflow temperature
Tai	[K]	Ambient temperature
Cp	[kJ/kg K]	Specific heat of air at constant pressure
Ac	[m²]	Collector area
Ho	[J/m²]	Extraterrestrial solar energy on a horizontal surface
μ	[Pa.s]	Absolute viscosity
t	[s]	Time
$\vec{v}$	[m/s]	Velocity vector
p	[Pa]	Pressure
E	[J]	Energy
$\vec{g}$	[m/s²]	Acceleration of gravity
$C\mu$	[-]	Empirical constant
k	[J]	Turbulent kinetic energy
ε	[J]	Dissipation of turbulent kinetic energy
$G_{b.k}$	[J]	Generation of turbulent kinetic energy due to fluctuations and mean velocity gradients
Y_M	[J]	Contribution of the fluctuating dilatation
$C_{1\varepsilon,2\varepsilon,3\varepsilon}$	[-]	Constants
$S_{k,\varepsilon}$	[-]	As defined by the user.

INTRODUCTION

The solar updraft tower (Figure 1) is a device that produces upward hot air for power generation (Schlaich, 1995). Schlaich and staff built the first prototype in Manzanares / Spain in 1982 (Haaf et al., 1983;. Haaf, 1984), which operated for seven years between 1983 and 1989, with an installed power of 50 kW (Schlaich, 1995). The results demonstrated the viability and reliability of the technology. The technology used in this device is simple, the construction materials are widely available, the collector absorbs both portions of solar radiation (direct and diffuse), it is able to operate even at night due to the heat stored in the ground, its operation and maintenance costs are low, it does not require water for cooling, its impact is low for the entire life cycle, including construction, operation and decommissioning.

The crosswinds influence the performance of solar updraft towers increasing the convective heat losses from the collector surface to the environment, dragging heated air out of the collector, and 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, convective heat losses by the first process are included in the energy equation of the most common mathematical models for solar updraft towers. Heat losses of the second process are not included in the common mathematical models, but have been investigated based on environmental wind speed profiles using CFD (Computational Fluid Dynamics) simulations.

Pretorius and Kröger (2009) investigated the effects of the wind on the environment temperature lapse rates and night temperature inversions on the performance of a large-scale solar updraft tower. The effect of environmental winds in a reference site on the plant performance was evaluated. The results indicate that the wind conditions impair the plant's performance significantly and that the night temperature change causes significant reduction in nocturnal output power. Ming et al. (2012) investigated the impact of a strong wind crossed on the power system output. The numerical analysis was performed in conditions identical to the prototype in Manzanares. A mathematical model to describe the fluid flow, heat transfer and system output power was used. The results revealed that crosswinds have an influence on the performance of solar updraft towers in two ways: when the crosswind environment is comparatively weak it will deteriorate the flow field and reduce the suction power output. On the other hand, when the crosswinds are strong enough more mass enters the system which will increase the output power flow. Zhou et al. (2012) used a model correlating atmospheric cross flow and the air flow within a solar updraft tower. The model assumes the input stream as compressible. The results showed that the crossflow air has a major influence on the input stream and on the air intake speed. The authors observed a positive environmental effect of crosswinds through the tower on the potential of the output pressure and ascending airflow speed inside the chimney. Even for a solar collector without heating the air, the environmental side winds were enough to produce an updraft with a tower velocity reaching 26% of the crosswinds speed. Ming et al. (2013) studied alternatives to overcome the negative impact of the strong wind crossed environment on the performance of a solar updraft tower with the same dimensions as the prototype in Manzanares by using a lock with 2 m high, set a few meters away from the collector inlet. A geometric model including the solar updraft tower and the outside environment was built, and mathematical models to describe the flow, heat transfer, and the output power of the whole system have been developed. The results of numerical simulation showed that, after being set a lock in front of the collector entry, the negative influence of wind shear environment on the performance of solar updraft towers was overcome.

NUMERICAL METHOD

The governing equations of the problem are the mass, linear momentum and energy conservation equations, as follows:

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

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

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

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

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

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, k , and the dissipation of the turbulent kinetic energy, ε .

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

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

(6)

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

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

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. It was assumed that the atmospheric air is a real gas. It was also taken into account the influence of a gravitational acceleration field, corresponding to an ambient temperature of 305.15 K.

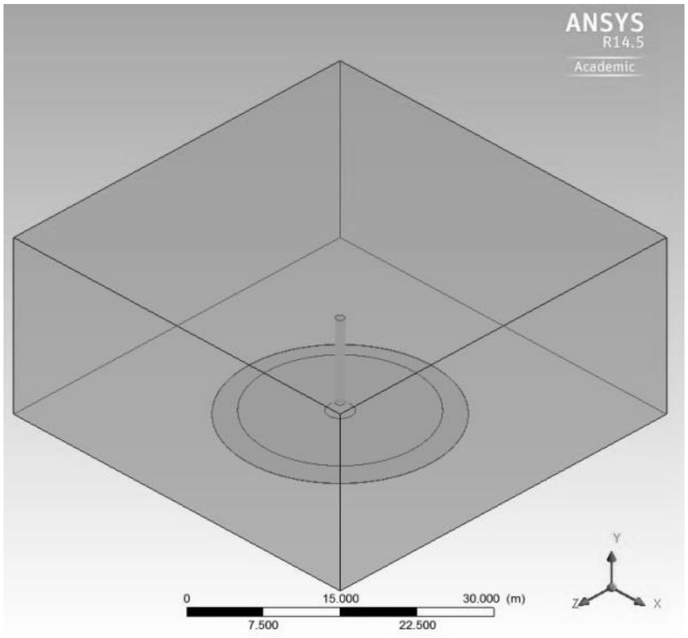

Figure 2 Geometry and boundary condition

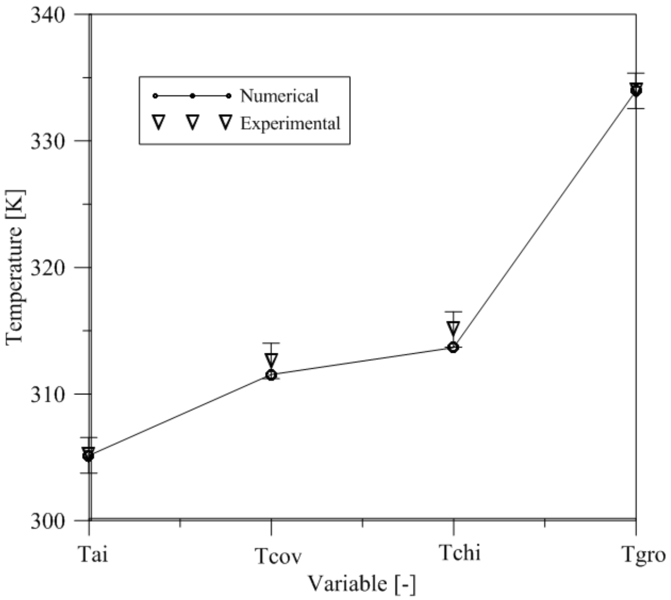

Figure 3 Validation

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. A temperature of 333.95K was prescribed for the ground surface.

The commercial software ANSYS- CFX 14.5 was used to solve the governing equations of the problem. The results obtained for the wind condition equal to 0 m/s 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.

RESULTS

Figure 4 shows the streamlines of the airflow inside the solar updraft tower. 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.

As indicated in the literature (Fasel et al, 2013), it was observed a local separation of the airflow in the tower entrance. For transient analysis, Rayleigh-Benard-Poiseuille (RBP) rollers were observed under the collector. They were attributed not only to the presence of a temperature gradient, but also to the presence of a pressure gradient, which induces the displacement of the fluid in the horizontal direction. It can be noticed the influence of the air velocity at the chimney outlet. For 0 m/s, the airflow leaving the solar updraft tower moves in a vertical direction. For 25 m/s, nevertheless, the airflow moves to the left, swept by the crosswind flow.

In Figure 5 it is possible to observe the development of the velocity along the axis of the tower. It is observed that the flow is not fully developed. Furthermore, it is possible to observe the formation of vortices affecting the tower tip region (about two top diameters) perpendicular to these vortices they are flow and chimney axis. This causes a reduction in the output speed of the flow tower, as indicated by the literature (Harte et al., 2015).

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 Figure 6, the rate of increase of environmental winds caused an increase of 50.26% on the average velocity at the tower outlet, when the speed increases from 0 to 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 7 and Fig. 8. It was observed an increase of 85.4% on the coefficient, reducing the outlet temperature in approximately 0.3%. It can be seen that the behavior of the temperature is nearly linear with the crosswind speed.

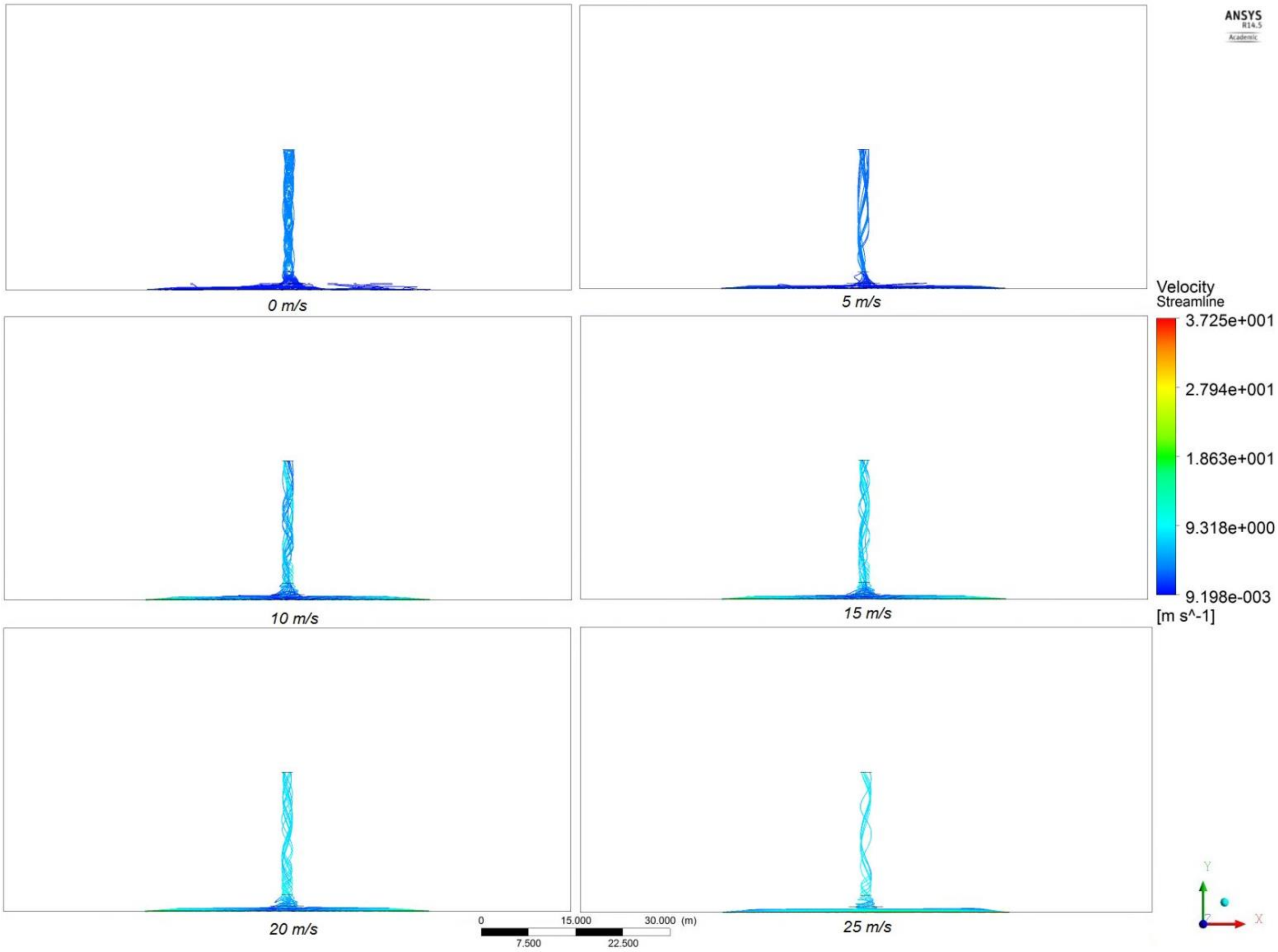

Figure 4 Streamlines of the device in a longitudinal section

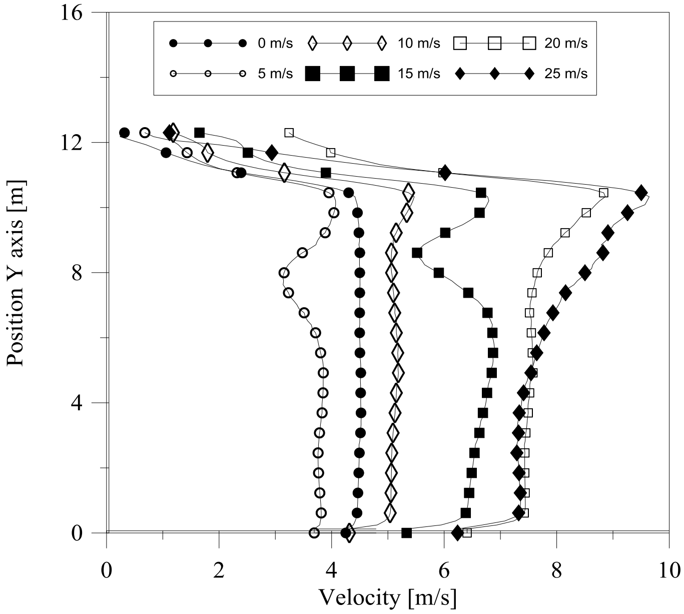

Figure 5 Distribution of the velocity vector throughout the axis chimney

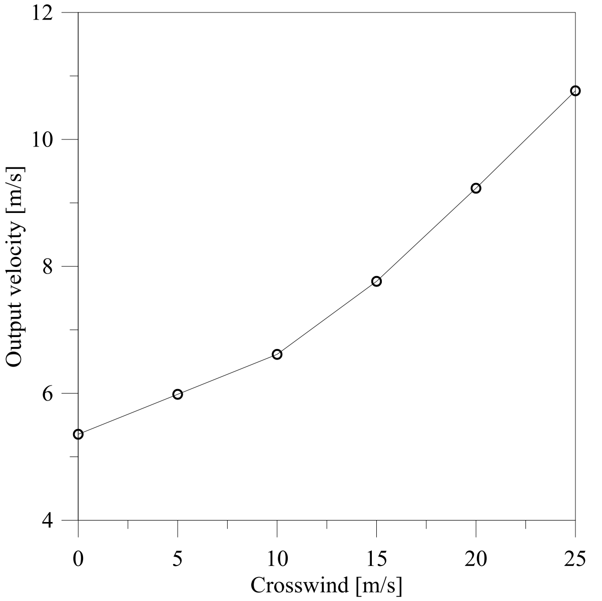

Figure 6 Influence of crosswind on the outflow velocity

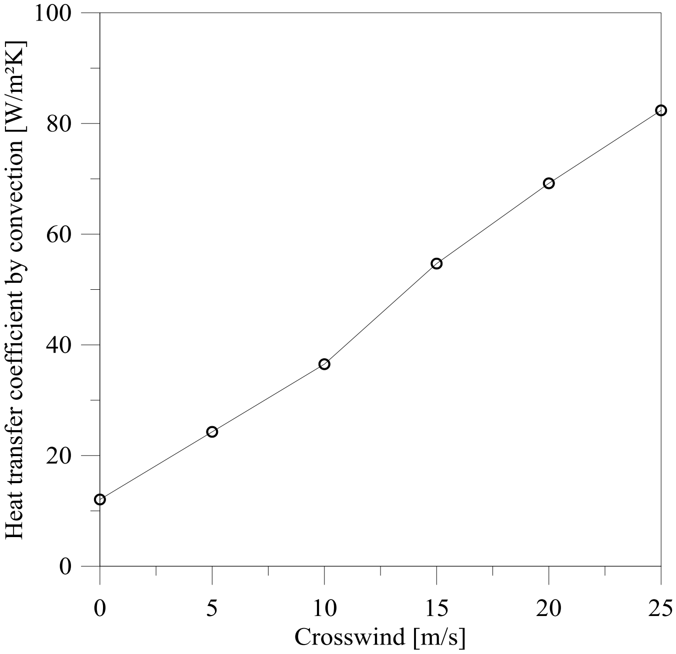

Figure 7 Influence of crosswind on the convective heat transfer coefficient

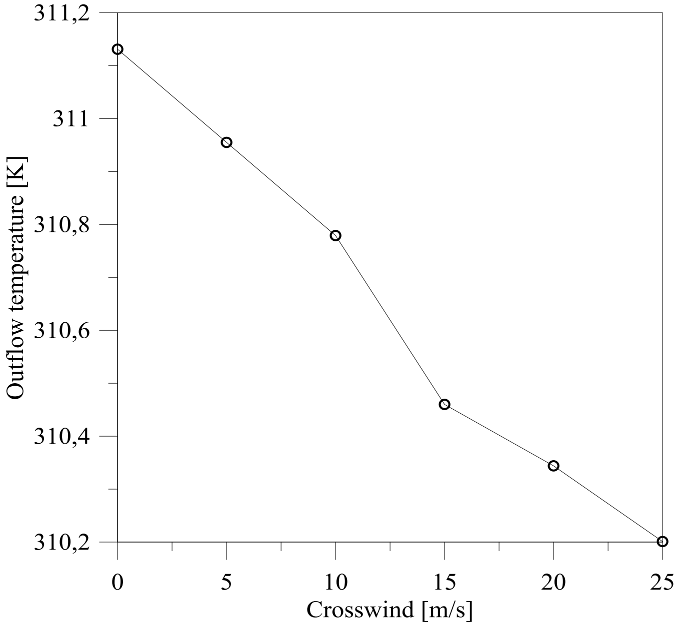

Figure 8 Influence of crosswind in outflow temperature

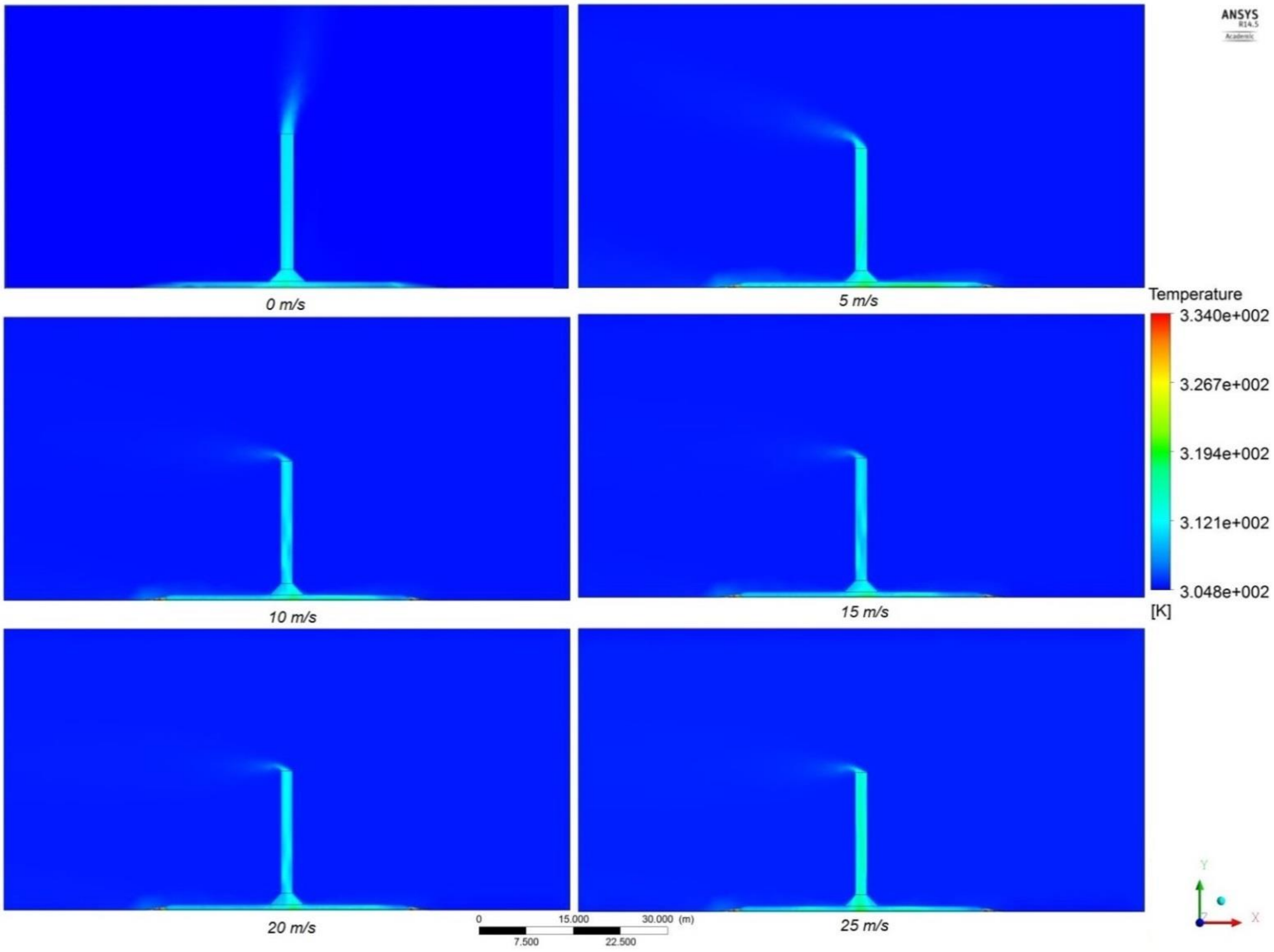

Figure 9 Temperature distributions in a longitudinal section

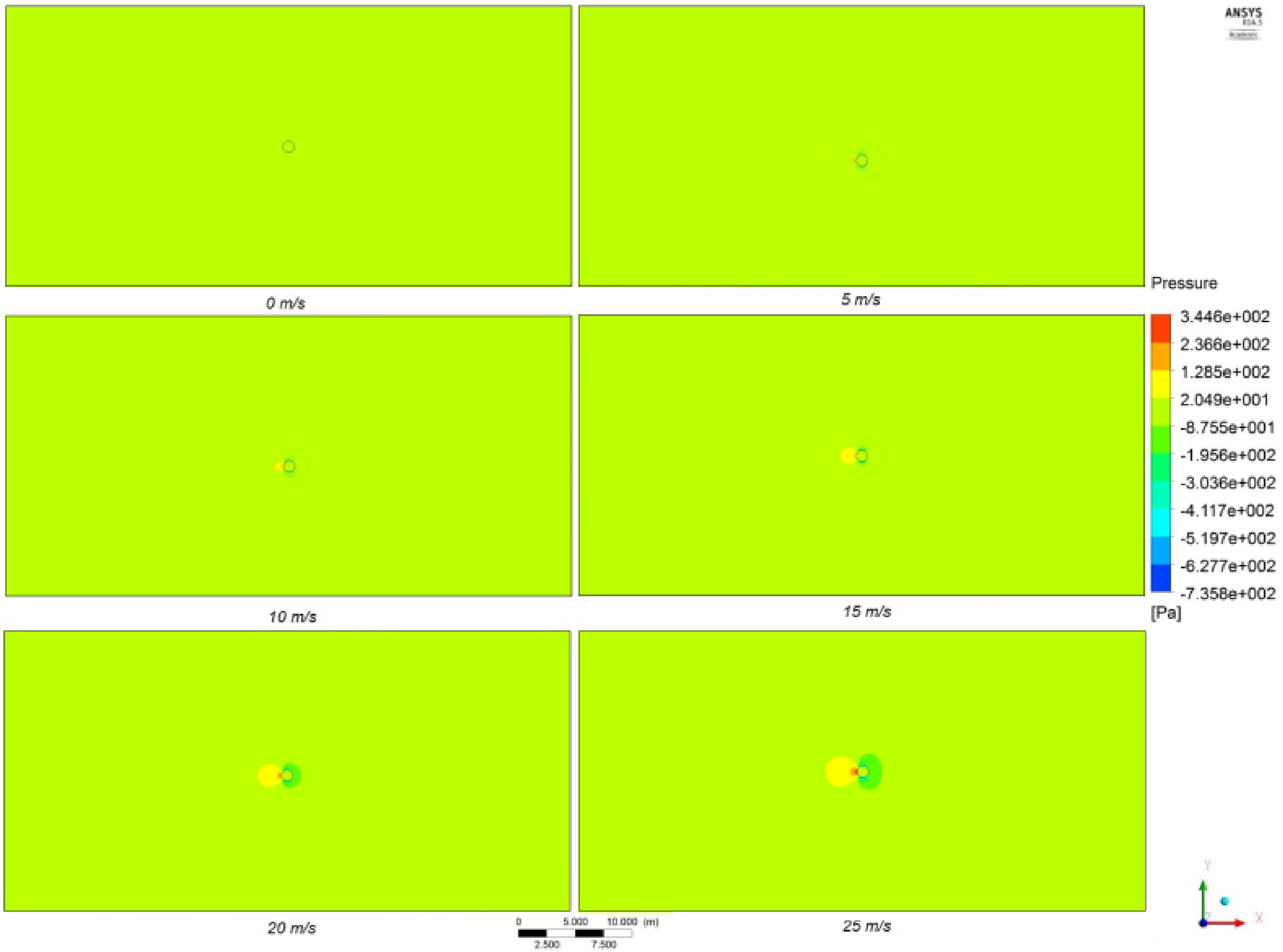

Figure 10 Pressure distributions in a transversal section

Figure 9 presents the temperature field on the computational domain. It is observed that the temperature of the atmosphere surrounding the solar updraft tower is affected by the airflow in both cases, increasing on the region close to the chimney outlet. The air is heated by the ground under the collector, and its temperature is nearly constant within the chimney. When compared the temperature values obtained for the studied crosswind speeds, the variation is not significant, lower than 1°C. For the situation analyzed the Rayleigh number was of $1x10^{12}$ order and Grashof number was of $1x10^{13}$ order, characteristics of airflow generated by natural convection.

Figures 10 show the pressure distribution on the atmosphere around the tower. It is possible to see the formation of a rosacea pressure, as evidenced in the literature (Harte et al., 2013; Lupi et al., 2015).

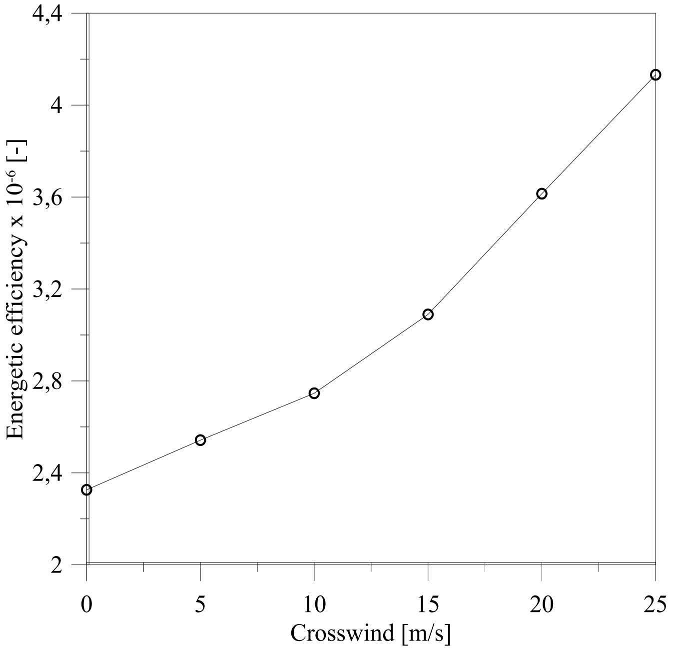

Figure 11 Influence of crosswind on the energetic efficiency

Figure 11 presents the energetic efficiency of the device, for the crosswind speeds analyzed. It can be seen that the efficiency is very low. Tingzhen et al. (2006) obtained maximum energetic efficiency of about 1% for a 300 m high solar updraft tower. Since the efficiency considerably increases with the tower height, low efficiencies were already expected. The efficiency increased about 56.31% with the crosswind speed. It was noted that an increase in the crosswind speed significantly increased the mass flow rate and slightly decreased the temperature increase inside the device. This can be explained by the fact that the effect of the mass flow rate is more expressive than the temperature increase on the efficiency.

CONCLUSIONS

It was evaluated the influence of crosswind in a small solar updraft tower. The geometric model including the solar updraft tower and the external environment were developed in conjunction with mathematical models that describe the fluid flow and heat transfer system. The results of numerical simulations have shown that environmental crosswinds 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 reduction of the effective area of the chimney outlet throttling reduces the output air flow.

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