1st International Conference on
Applications of Air Quality in Science and Engineering Purposes
10–12 February 2020, Kuwait

SOLAR TOWERS FOR A BETTER AIR QUALITY IN URBAN AREAS: ANALYSIS OF PERFORMANCES

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Abstract: A pilot solar tower has been designed and is under experimental tests in an ongoing research project in Naples Italy. In this paper the procedure to design the pilot plant and the expected performances in terms of amount of air treated and technologies for the abatement of airborne pollutants are reported. The solar tower has been designed using momentum conservation equations to evaluate volumetric flow rate, temperature, air velocity and pressure drops as function of the main geometrical parameters (height, chimney diameter and surface of the base) and solar irradiance. Mathematical calculations have been verified using a CFD model for the selected geometry of the solar tower with height of chimney of 5 m, diameter of collector 5 m and diameter of chimney 0.25 m. The CFD simulations give as results flow and temperature fields and the pressure drops. Once defined the fluid dynamic several technologies for the abatement of pollutants have been analysed. In particular: photocatalysis using TiO_2 based materials and non thermal plasma for gaseous pollutants. The very limited driving force in terms of pressure preclude the use of filters to remove particulate matter. The possibility to use appropriate impactors has been analysed. The aim is to obtain a significant reduction of main pollutants present in urban areas: NOx, PM and COV with a technology characterised by no chemicals, no or low energy inputs and very limited maintenance.

Key words: *Solar tower, pilot plant, CFD, design, performances, pollution abatement.*

INTRODUCTION

Around 55 percent of the world's population lives in an urban area or city, and in the next decades the percentage is foreseen to grow up 68 percent. WHO estimates that outdoor air pollution caused about 3 million premature deaths globally in 2012. The most noxious pollutants for public health, include particulate matter (PM), ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and VOCs.

The main strategy to mitigate air pollution in urban areas is the reduction of the emissions. Unfortunately, plans to reduce emissions are often difficult to implement and results are never as expected, due to the high non-linearity of phenomena governing the airborne pollutants concentration. In particular, the concentration of secondary pollutants (mainly O_3 but also PM and NOx) is very difficult to reduce. This depends also on the effect of background pollution due to emissions out of the area of intervention.

For all these reasons different strategies must be considered to obtain significant results in a short time. A new strategy, to mitigate the problem, is represented by the development of solar towers or solar chimneys. Solar chimneys were developed in ‘70s years to produce electrical energy and some pilot plants were realised and tested (Haaf et al., 1983). But nowadays this application is not of interest. The concept of solar towers has become again of interest as a low-cost equipment for the abatement of pollutants in urban areas. In fact, some experimental activities are in course in China, in Europe and in Arabian countries.

A solar tower uses the solar radiation to create a convective flow of air without consume of electric power. Air collected can then be treated using several kind of processes mainly photocatalytic processes. Moreover, a solar tower accelerates the dispersion of pollutants at ground level (the air that we breath) expelling them at height up to hundreds meter depending on its geometry.

In this paper the criteria adopted to design a pilot solar tower and its performances (flow of air that can be treated) together with the technologies for the abatement of pollutants are reported. The pilot solar tower has been realised in Italy and is under experimental tests in an ongoing research project.

Results and discussion

A solar tower consists mainly of a chimney and a base (collector). The collector has the function of capture the solar energy to heat the air that flows through the chimney due the difference of pressure between external air (cold and heavier) and the internal one (warm and lighter). It is a typical example of natural convective flow.

Momentum conservation equations. The fluid dynamic of solar chimney power plants was studied by several authors as: Ming et al. (2006), Koonrisuk and Chitsomboon (2007, 2009a and 2009b) and Sangi et al. (2011). Ming et al. (2006) studied the pressure distribution and the relationship between the relative static pressure and driving force with the aim to predict the power output and efficiency.
Following the approach of Ming et al. (2006) it is possible to obtain the driving force Δp (Pa) as function of the geometry of the solar tower and fluid properties:

$$\Delta p = \left(\frac{g}{\sqrt{2}c_p}\right)^{2/3} \left(\sqrt{\rho}\beta\right)^{2/3} \left(\frac{H}{r^2}\right)^{2/3} R_c^{4/3} q^{2/3} \quad (1)$$

or

$$\Delta p = \rho g H \left(\frac{\beta q}{c_p \rho \sqrt{2gH}}\right)^{2/3} \left(\frac{R_c}{r}\right)^{4/3} \quad (2)$$

where H (m) and r (m) are respectively the height and the radius of the chimney, R_c (m) the radius of the collector and q (Wm^{-2}) is the solar radiation. Other parameters are air properties (ρ, c_p, β) or gravitational constant (g).

Applying the Bernoulli equation between the entrance and exit of the air through the solar tower it is possible to evaluate the exit velocity of air and therefore the volumetric flow rate:

$$\Delta p = \frac{1}{2}\rho v^2 \quad (3)$$

An energy balance gives the temperature in the collector (T_b) assumed homogeneous and the temperature at the exit of the chimney (T_u):

$$T_b = T_o + \frac{q\alpha}{U}\left[1 - exp\left[\frac{\pi U_c}{\dot{m}c_p}\left(r^2 - {R_c}^2\right)\right]\right] \quad (4)$$

$$T_u = T_o + (T_b - T_o)exp\left(-\frac{2\pi r U H}{\dot{m}c_p}\right) \quad (5)$$

where: T_0 is the air temperature, α is the fraction of radiant energy absorbed; U and U_c are respectively the global heat transfer coefficient of the collector and of the chimney while $\dot{m}$ is the mass flow rate of air.

To design the pilot plant the ratio height of chimney/diameter of collector H/D was assumed =1 and r/R_c=20 that are typical values of solar chimneys. Then calculations were performed varying r in the range 1-7.5 m. Fig.1 shows the results in terms of volumetric flow rate Q [$m^3 h^{-1}$]; upper air velocity in the chimney v [ms^{-1}]; exit temperature T [°C] and pressure drops ΔP [atm] vs. the radius of collector.

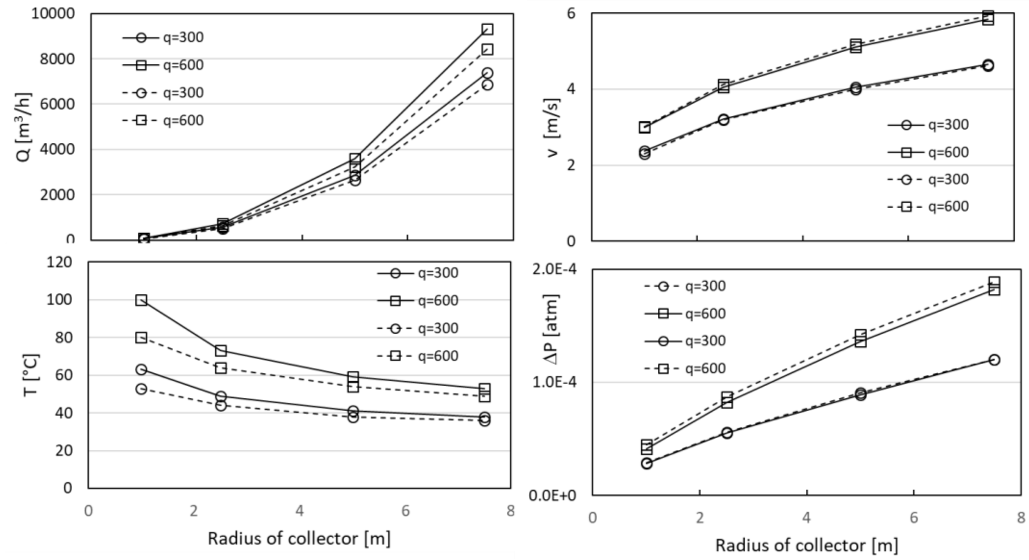

Figure 1. Volumetric flow rate (up left), air velocity in the chimney (up right), exit temperature (bottom left) and pressure drop (bottom right) against radius of collector. Curves are parametric with solar irradiance q [W m^{-2}]. Solid lines if heat exchange with ambient ($T_{ambient}$ = 15°C) is omitted and dotted lines if is considered

<u>CFD model.</u> The results reported in Fig.1 have been checked developing a CFD model of the solar tower with H= 5m (Fig. 2).

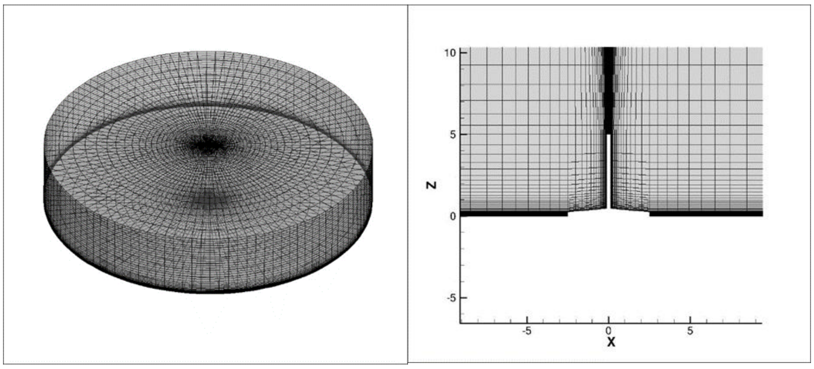

Figure 2. Mesh of the CFD model

The calculation domain has a radius of 500 m and height of 200 m. It contains 500.000 hexahedral cells respecting all the quality standards and in particular the constraint on the non dimensional length (y+) at the wall ≈ 1 by thickening the cell density near the solid walls. The model was assumed symmetric (considering an half the solar tower). Results in terms of air velocity and temperature reported in Fig. 3 confirm those obtained using momentum conservation equations and reported in Fig.1.

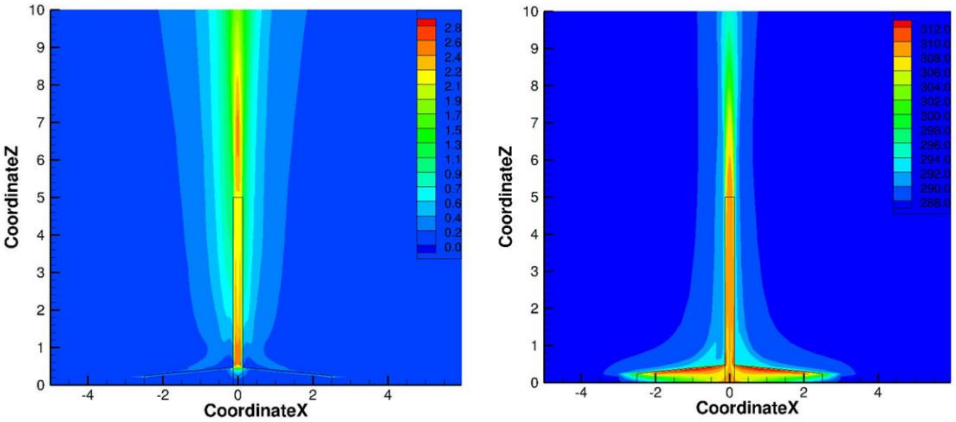

Figure 3. CFD model. Maps of air velocity [ms^{-1}] on the left and air temperature [K] on the right

Abatement of pollutants. The solar tower is developed to reduce pollution in urban areas. Therefore, main pollutants to be reduced are: NOx, PM and COV. Abatement of SOx could also be achieved but generally this pollutant is a minor concern. A positive effect would be also observed in the formation of secondary pollutants: secondary particulate and ozone. For the treatment of gaseous pollutants, the main technologies considered are: photocatalysis and low temperature plasma. The first is particularly of interest because can be developed without the need of an input of external energy, since solar irradiation can activate the photocatalysts. In this case we have considered the use of UV lamps to activate the catalysts and designed the treatment unit. Contact time has been evaluated on the basis of air velocity and length of the catalytic surface in the flow direction. In designing the treatment units, the main challenge is the very limited pressure drop that characterize the system. In fact, the difference of pressure (the driving force of the air flow) is of the order of 10^{-4} atm.

This does not create a significant limitation to the development of photocatalytic or low temperature plasma units. In fact, the pressure drops of both the units are negligible. For this technology the main limitation can be the mass transfer resistances that must be minimized. In Fig. 4 a CFD simulation shows the turbulence viscosity ratio as function of the position of UV lamps. The air flow is horizontal from left to right. The case with 3+2 lamps determines the highest turbulence and therefore is to be preferred. A similar result was obtained for the non thermal plasma treatment unit.

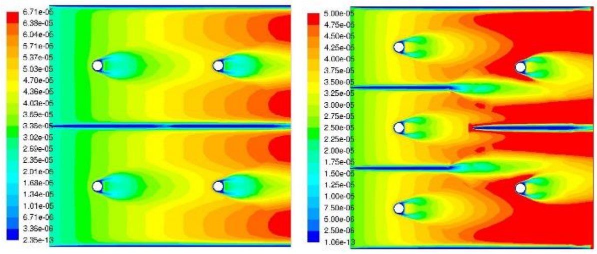

Figure 4 Turbulent viscosity ratio in case of 2+2 lamps (left) and 3+2 lamps (right)

For the abatement of particulate matter the main limitations is the very limited pressure drop available. As a consequence, normally adopted filters can not be used. In this project we have developed an impactor that it is expected would reduce the PM10 concentration in a sufficient amount (Fig. 5) with a limited pressure drop.

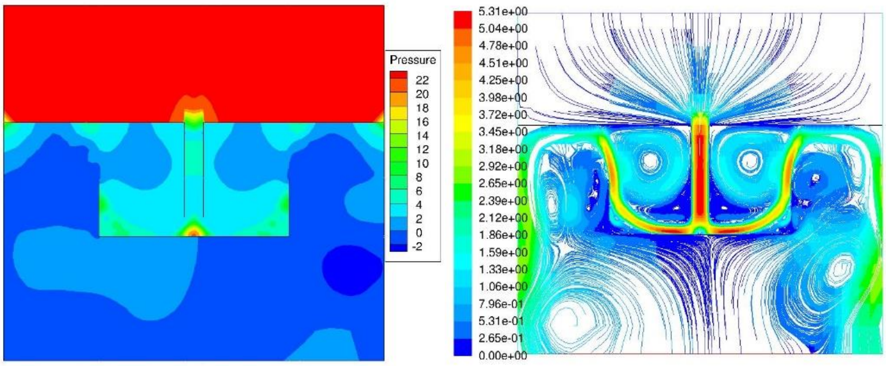

Figure 5 Pressure (left) and velocity (right) flow filed in the impactor

Finally a scheme of the pilot plant realised in Naples is reported in Fig. 6. At the moment the plant is under experimental tests to evaluate the performances.

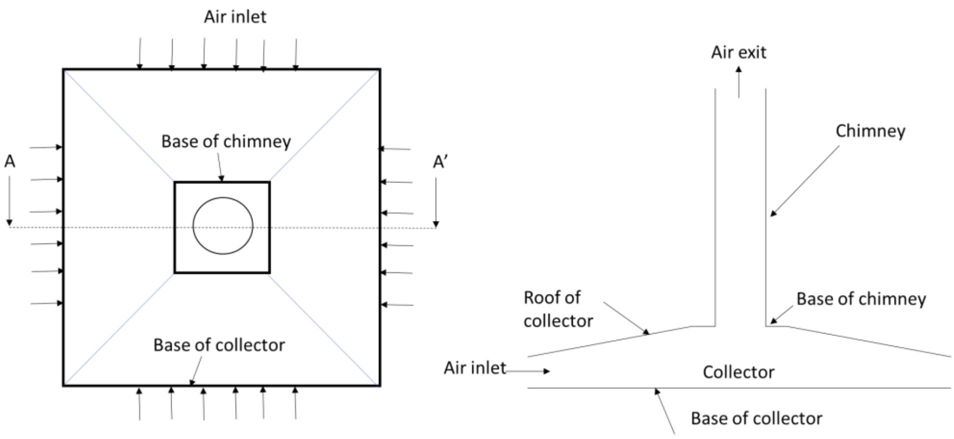

Figure 6. Bird's eye view (left) and vertical section (right) of the pilot plant realised in Naples (Italy)

CONCLUSIONS

A pilot solar tower has been designed and realised in Naples (Italy). Fluid dynamics design equations have been confirmed by CFD simulations. Dimensions of the pilot plant unit are 5 m height and 5x5 m^2 base. Photocatalytic unit treatment has been designed to maximize turbulence and minimize mass transfer resistances while particulate matter treatment unit has been designed with the constraint of the limited pressure driving force. Preliminary experimental results are promising, and research will be brought forward.

ACKNOWLODGMENTS

This research was financed by fund from POR CAMPANIA FESR 2014/2020.

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