POSMEC 2016 – Postgraduate Symposium in Mechanical Engineering
Department of Mechanical Engineering – Federal University of Uberlandia
December, 1st to 2nd, Uberlandia, Minas Gerais, Brazil

SOLAR CHIMNEYS

Marcus Vinicius Rezende Júnior, Federal University of Uberlândia, School of Mechanical Engineering, marcus_aluno7@yahoo.com.br
Gonzalo Cabodevila, National Engineering Institute in Mechanics and Microtechnologies, gonzalo.cabodevila@ens2m.fr
Nicolas Ratier, National Engineering Institute in Mechanics and Microtechnologies, nicolas.ratier@ens2m.fr

Abstract: *This paper aims to present the concept of solar chimneys, a possibility to produce electricity in a renewable way. Often referred to as a thermal chimney, this is a method to improve the natural ventilation of buildings by using convection of air heated by passive solar energy. In short, a solar chimney is a vertical shaft utilizing solar energy to enhance the natural stack ventilation through a building.*

Keywords*: renewable energy, solar chimneys, energy conservation*

1. INTRODUCTION

The solar updraft tower is one of the most ambitious projects in the world for generation of alternative energy. This system is a renewable energy power plant, which could provide important electric power (about 250 MW), while being safe and clean. Its main advantage is that it can operate without interruption, using the sunlight during the day and the heat of the earth's crust through the night.

A solar chimney is essentially based on two principles: warm air rises, a phenomenon explained by the force of Archimedes, and if this rising hot air is ducted, mechanical power is provided. To operate, a solar chimney must be composed of two parts:

- A heat collector transparent material occupying a large ground area
- A tower that isolates the internal rising air from external air, which allows the air located inside and at the base of the chimney to have a lower pressure than the air situated at the same altitude.

The need to duct the air has an additional purpose: it is necessary to prevent the cold air from entering the top of the chimney and down inside, that would be the case with a too broad chimney and poor ascending air flow. This risk is also an additional reason to ensure that the solar tower do not act as a flute, with the top producing oscillations, resulting in alternating upward and downward movement of the air, including ambient cold air inserted between bubbles of hot air coming out. Figure (1) illustrates the principle of operation of a solar chimney.

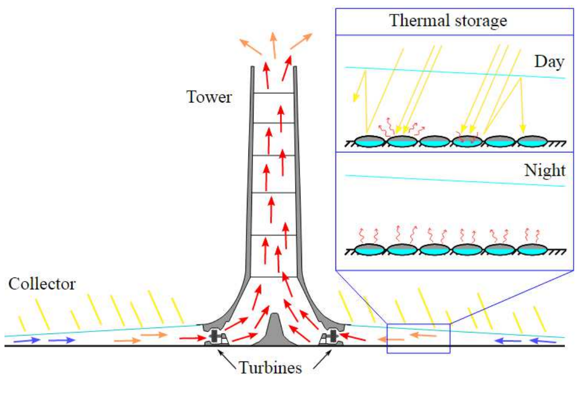

Figure 1: Schematic figure of a solar updraft tower (TAG)

This sub-pressure pulls the turbines. It is possible to calculate the hydrostatic pressure depending on the difference between the density of the internal air column and that of outside air, integrating over the entire height of the chimney (of the order of 1000 to 1500 m). This dimension was difficult to work with when the concept was defined and experienced, currently is not a problem since several residential buildings are planned to exceed 1000 m tall.

Multiplying the sub-pressure (typically of the order of 1000 Pa) by the air flow (typically 15 000 m^2 x 15 m/s), the result is the theoretical maximum power of the device: 225 MW.

2. EFFICIENCY PROPORTIONAL TO HEIGHT

The sub-pressure is proportional to the height of the chimney and therefore the efficiency of the system follows the same tendency. Its theoretical limit is the analog of a Carnot engine efficiency of which the temperature of the heat source would be that of the inside air of the chimney at its base, and the temperature of cold source is that of the same air, but at the moment when it exits the chimney through the top. Therefore, there are two conclusions about this:

- A solar chimney is a heat engine that does not need a cold reservoir: natural air cooling in the upper atmosphere plays this role spontaneously, without incurring any costs other than the collector protection against hail. If there is no heat sink, there is no need to generate a sufficient temperature difference between hot source and cold source. A temperature difference of 30 °C is commonly accepted, which is low: a solar chimney is typically a low temperature heat recovery system, which can even be a by-product of another production method, provided that there are at least 10 GW thermal (important sets of nuclear or coal power plants).
- The theoretical efficiency is 3% per km of chimney. Including the opto-thermal efficiency of the collector and various mechanical losses, that efficiency drops to 1% per km. It is not surprising that only very large devices are viable from the point of view of produced energy.

From the heat capacity of air (7R/2), of the hydrostatic pressure difference between the lightened air from the inside of the chimney and the unmodified exterior air and considering that the 1 m^3 air work that crosses a turbine is equal to this volume multiplied by the pressure difference between the upstream and downstream of the turbine, the efficiency can be written according to Eq. (1):

$$\eta = \lambda \frac{h}{T0} \tag{1}$$

T0 is the initial temperature of the air and h is the height of the tower. λ is the dry adiabatic gradient decrease of the temperature according to altitude and can be found using Eq. (2).

$$\lambda = \frac{g.M}{7\,R/2} = \frac{9{,}81\frac{m}{s^2}.29\frac{g}{mol}.2}{7.8{,}32\frac{J}{mol}.K} = 9{,}77\ °/km \tag{2}$$

For the opto-thermal efficiency of the collector, no study seems to have been made related to the cost-benefit balance of a deliberate strategy of changing the albedo of the ground to improve its performance. For example, the ground (previously leveled by bulldozers) can be covered with a layer of charcoal (black, dusky and soft material, which is not likely to sink into the ground) of about 1 cm thick. The increase value obtained is directly proportional to the decrease in the albedo. For a system of a few dozen km^2 (one or two hundred thousand tons of charcoal to spread) and a cost close to one billion Euros, a decrease on albedo of 0.2 induce an increase in value of about 200 million €, valuing the charcoal to almost 1 €/kg. Moreover, if it is produced in a region where the forest is rather expanding or stable but should be better exploited with better utilization of wood waste in the form of coal, the environmental balance will be positive: provided it does not burn, charcoal is one of the best ways to definitively sequester carbon in biomass to prevent it returns to the atmosphere as CO_2.

3. STABILITY OF THE CHIMNEY AND RESONANCE

The ideal height of the chimney is in the range of 8 km, although current projects do not exceed 1 to 1.5 km. Even with a rather small size compared to the ideal, it is necessary provide the different possible oscillations and their resonances, in so far as several phenomena are characterized by comparable frequencies, around 0.1 Hz (or periods of 10s order).

The internal air column can act as a flute, with a source of oscillation lies in the fact that hot air coming out of the chimney tends to form large bubbles successively coming out. Crosswinds generate several von Kármán Vortex Street downstream like in fig. (2) which will feed back into the chimney itself. Therefore the tower mainly consisting of a simple reinforced concrete shell will have a fundamental oscillation frequency, of the order of 0.1 Hz, liable of entering into resonance with the air vibrations.

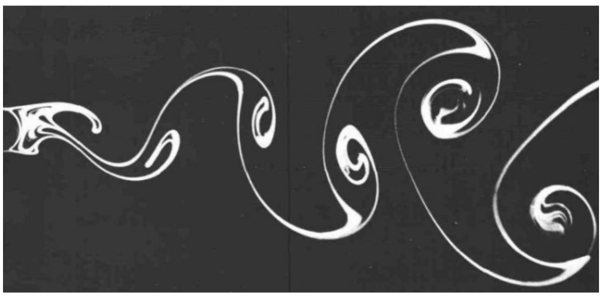

Figure 2: von Kármán Vortex street generation (LFMI)

Finding the fundamental frequency of oscillation is simple if the chosen parameters are the frequency and the amplitudes of horizontal oscillations about twenty different heights, firstly calculating the kinetic energy of the concrete and then its elastic strain energy, next calculating the minimum frequency value for which the total kinetic energy and the total elastic energy have the same amplitude, in accordance with the classical law, Eq. (3):

$$E = cst = E_p + E_c = E.cos^2\,(wt) + E.sin^2\,(wt) \tag{3}$$

In principle, the air being much lighter transmits less energy to concrete, but in the absence of damping on vibrations, this energy could accumulate and affect the chimney's structure. This is possible with the oscillations source mentioned above.

With von Kármán Vortex street generation, a transverse oscillation of the chimney can influence the downstream formation of vortices and if the natural period of occurrence of these vortices is close to the frequency of oscillation of the tower, these vortices begin to synchronize therewith. The hanging of training swirls on chimney swinging will result that the air will exert a force of the same period on the concrete, resulting in a potential increase of the amplitude of these oscillations: a classical resonance phenomenon.

4. ECONOMY OF SCALE

As presented at the beginning of this paper, the solar chimney consists of three elements: tower, collector and turbines. A virtuous circle is perfectly identifiable between the first two elements: the higher the chimney is, the higher the investment made on the collector will be easy to develop (thanks to the increase of the efficiency' system, proportional to the height of the chimney); and the big the collector is, the more the chimney will be profitable, if it is true that a 1 km chimney high and 200 m in diameter does not cost ten times more than another one 1 km high and 20 m in diameter.

5. REFERENCES

D. Bonnelle, "A fond contre le CO_2", Lyon, France: Cosmogone 2006.
D. Bonnelle, "Vent artificiel", Lyon, France: Cosmogone 2003.
D. Bonnelle; R. de Richter, "21 énergies renouvelables insolites pour le 21^e siècle", Paris, France: Ellipses 2010.
J.Schlaich, "The solar Chimney", Allemagne: Axel Menges 1994.
Laboratory of Fluid Mechanics and Instabilities (LFMI). <http://lfmi.epfl.ch/page-98810-en.html>.
Portail des énergies renouvelables et de l'écoconstruction.
<http://www.ecosources.info/dossiers/Centrale_solaire_tour_effet_cheminee>.
REZENDE JÚNIOR, M. V. Les cheminées solaires. Energies renouvelables, ETE. ENSMM, 2014.
TAG Electric inc. <http://www.tagelectricinc.com/solar-updraft-tower/>.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.