Improvement of precooling supply air by way of coupled earth to air heat exchanger and solar chimney

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ABSTRACT: The performance of a passive cooling system was evaluated as part of design works for the project of an office building. The passive cooling system incorporates an array of buried pipes together with a solar chimney. The natural ventilation is enhanced with the help of the solar chimney and fresh air is cooled by circulation within the buried pipes. The array of buried pipes was used as an open loop earth-to-air heat exchanger. One of the main drawbacks identified in earth-to-air heat exchanger operation in previous studies is the drying of the soil around the pipe and consequent decreases in the soil conductivity and cooling efficiency. To overcome this problem, improving earth to air heat exchanger efficiency, it was considered a buried pipe surrounded by sand and only after the sand there was soil and a water pipe, commonly used in the drop by drop watering, was used to keep the sand and the soil wetted in the proximity of the buried pipe. The application of this system to the acclimatization of an office building was evaluated. A model was developed on this purpose, which allows foreseeing the temperature and relative humidity of the air in the building. The performance of the passive cooling system was evaluated based on the number of cooling degree hours.

Keywords: passive cooling, earth cooling, earth-to-air heat exchanger, solar chimney, thermal simulation

1. INTRODUCTION

The residential and tertiary sector, the major part of which is buildings, accounts for more than 40% of final energy consumption in the European Union and is expanding, a trend which is bound to increase its energy consumption and hence also its carbon dioxide emissions. Indeed, the use of conventional air-conditioning systems have to be considered with care due to the need of reducing the environmental impacts, which result from burning fossil fuels and from ozone-depleting CFC refrigerants used by conventional air conditioners.

The use of passive cooling techniques in the summer is advisable, either in the perspective of improving the thermal environment of non-climatised spaces as in the perspective of reducing energy consumption when the spaces are climatised. It can thus be an effective tool for attenuating the growth of energy consumption for air conditioning.

In the south part of Portugal the climate is hot and dry during the summer. Moreover, daily thermal amplitude is high. So, traditionally, people use nocturnal ventilation as the main strategy of natural acclimatization. During the daytime, windows are closed and are protected from direct solar radiation. However, if internal gains are important this strategy is not suitable. Such is the case of an office building where people density is relatively high. In this case, daytime ventilation is required to improve indoor air quality and to remove the heat generated by the people in the building. However, since outdoor air temperature often exceeds thermal comfort limit, it is advisable to precool the supply air.

Precooling of external air before entering the building can be achieved by natural means, like circulation in buried pipes [1, 2, 3]. Due to the fact that the ground exhibits high thermal inertia, temperature at a certain depth is almost constant along the year, which allows for its use either as a heat sink (in summer) or a heat source (in winter). In this study the ground will be considered as heat sink.

In the summer, in the Mediterranean region, soil temperature a few meters deep is lower than mean daily outdoor air temperature, and significantly lower than usual outdoor daytime air temperature. An array of buried pipes can thus be used as an open loop earth-to-air heat exchanger.

One of the main drawbacks identified in earth-to-air heat exchanger operation in previous studies is the drying of the soil around the pipe and consequent decreases in the soil conductivity and cooling efficiency. To overcome this problem (and thus improve the efficiency of the earth-to-air heat exchanger), the buried pipe was surrounded by a layer of sand, that stands between the pipe and the soil. External to the sand was soil and a water pipe, commonly used in the drop by drop watering, used to keep the sand and the soil wet in the proximity of the buried pipe.

Air exchange is promoted through natural ventilation due to wind and stack effects. A solar chimney is used to increment natural ventilation. In a solar chimney air is heated up in contact with a surface, which absorbs solar radiation. Heating enhances the pressure difference between the inlet and outlet of the chimney, thus increasing the rate of natural ventilation significantly [4, 5, 6, 7, 8].

2. DESCRIPTION OF THE MODEL

A model was developed as part of design works for the project of an office building. The model predicts temperature and relative humidity of the air in a room where a solar chimney enhances natural ventilation and the air entering the room is pre-cooled by circulation in an array of buried pipes. This model was adapted from an earlier one developed for livestock buildings [9]. The effect of the building mass was not considered as most of the internal surfaces of the office are covered with light insulating materials either by accustics or aesthetics reasons.

The model takes into account the variation of climatic conditions changing air flow rates.

The model comprises three sub models: one of them for predicting the behavior of the solar chimney, another for describing the earth-to-air heat exchange system (buried pipes, where the external air is circulating before entering the room) and another one for predicting the overall natural ventilation rate of the room, which includes the array of buried pipes, air within the room and the solar chimney.

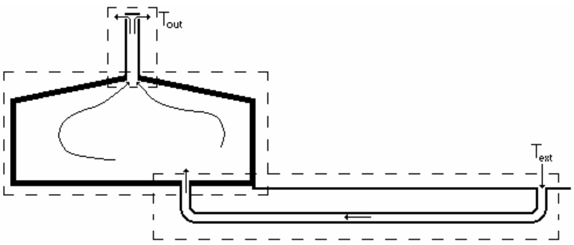

Figure 1: Building, solar chimney and buried pipes

The first model gives the temperature of the air leaving the chimney; the second one gives the temperature of the air entering the room and the third model gives the rate of ventilation which allows for the evaluation of temperature and relative humidity of the air within the room.

Ventilation flow rate results from the combined pressure effects of wind and buoyancy. The increase in pressure must be equal to the sum of all flow pressure losses between inlet and outlet. These include local losses (ζ) and friction losses (*f*).

The volumetric flow rate can be expressed as:

$$\dot{V} = S_{ch}\sqrt{\frac{2\beta g\Delta h(T_{out}-T_{ext})+(C_{p,in}-C_{p,out})v_v^2}{\zeta_{ch}+\zeta_p\left(\frac{S_{ch}}{S_p}\right)^2+\frac{f_{ch}L_{ch}}{D_{ch}}+\frac{f_pL_p}{D_p}\left(\frac{S_{ch}}{S_p}\right)^2}} \quad (1)$$

,

where the subscripts *ch*, *p*, *out*, *ext* and *in* stand for chimney, buried pipe, outlet, exterior and inlet, β is the thermal expansion coefficient, Δh is the level difference between inlet and outlet, C_p is the coefficient pressure, v_v is the wind velocity, L is the length, S is the cross section area, and D is the hydraulic diameter.

By using equation (1), ventilation flow rate can be predicted, provided ΔT is known. This implies the calculation of air temperature at solar chimney outlet. To calculate T_{out}, the heat transfer processes that occur in the solar chimney must be considered.

Temperature of the air entering the solar chimney is the temperature of the air inside the room, and results from internal heat sources, air flow rate and the temperature of the air cooled by circulation within the buried pipes.

Ground temperature at time t and depth z, $T(z,t)$ was calculated using the equation [10]:

$$T(z,t) = T_m - \frac{A_s}{2}\exp\left[-z\sqrt{\frac{\pi}{365\alpha}}\right]sen\left\{\frac{2\pi}{365}\left[t-t_0-\frac{z}{2}\sqrt{\frac{365}{\pi\alpha}}\right]\right\} \quad (2)$$

where T_m is the average annual temperature of the soil surface, A_s is the amplitude of surface temperature variation, z is the depth below surface, α is the thermal diffusivity of the ground, t is the time elapsed (in days) from beginning of calender year and t_0 is the phase constant (in days).

The interdependence among related variables compelled us to use an iterative process of calculation.

The passive system's performance evaluation is based on the number of cooling degree hours. The cooling degree hours were calculated as the sum of the positive differences between the calculated air temperature and the air temperature corresponding to the upper limit of the ASHRAE summer comfort zone [11] for the same relative humidity.

3. SIMULATION

The model was used to evaluate the influence of the main parameters of the solar chimney and of the array of buried pipes upon the thermal environment within the office with 30 adult people inside.

The dimensions of the office are: 20.0 m (length) $\times$ 8.0 m (width) $\times$ 3.0 m (height), resulting in a volume of 480.0 m^3.

The dimensions of the array of buried pipes and of the solar chimney were calculated from the model.

The array of buried pipes consists of 12 PVC pipes, 30 m long each, with an internal diameter of 0.315 m, and is placed at a depth of 2.5 m.

The solar chimney has a transparent vertical surface facing the south direction, is 4 m long, 5 m high and has a width of 0.2 m. The climate variables used in the simulations were taken from the data records of 1985 at Évora, corresponding to the hourly averaged values of temperature and relative humidity of the air, wind speed and flux intensity of solar irradiation (direct beam and diffuse) observed in a horizontal surface. This year was chosen because it corresponds to the average values of global solar radiation on a horizontal surface in a period of thirty years.

The period under study was June to September and it comprised the diurnal period, from 6h 30m to 17h 30m (solar time). The hourly values of indoor air temperature (T_{in}) and relative humidity (φ_{in}) are represented in the figure 2, together with the line that limits the thermal comfort zone.

The computation of the temperature and the relative humidity of the air was made for the inside part of the office with the solar chimney and with the array of buried pipes (earth-to-air heat exchangers). Indoor environmental conditions which represent 278 cooling degree hours, were predicted with the help of the model.

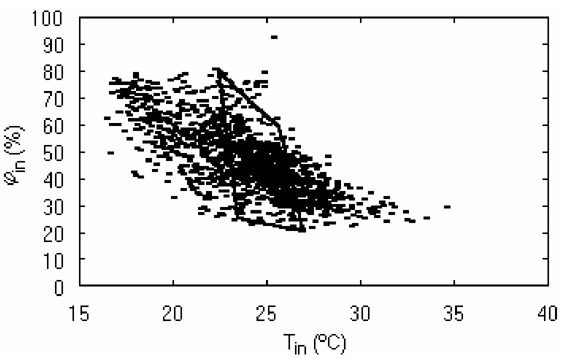

Figure 2: Thermal environment, inside the office with solar chimney and buried pipes

The number of degree-hours below the comfort range is not critical. What is considered to be critical is the control of the higher temperatures. Most of the temperatures below the summer comfort range are within the winter comfort range. In fact, in spaces with free floating temperature, variations of the temperature are much more accepted. In an ultimate case, there is always the possibility of reducing the ventilation mass flow through the pipes.

Figure 3 represents outdoor air temperature and air temperature inside the office with internal gains due to full occupancy and with the described passive cooling system, in an August week.

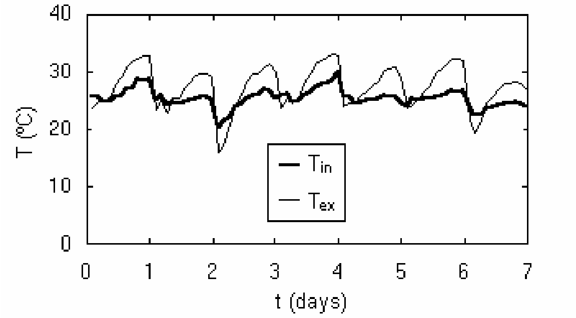

Figure 3: Outdoor air temperature (T_{ex}) and predicted indoor air temperature with the passive cooling system (T_{in}).

With the solar chimney but without the array of buried pipes (earth-to-air heat exchangers) we obtain the environmental conditions represented in figure 4. These environmental conditions exceed the upper limit of the thermal comfort zone by 3714 degree hours.

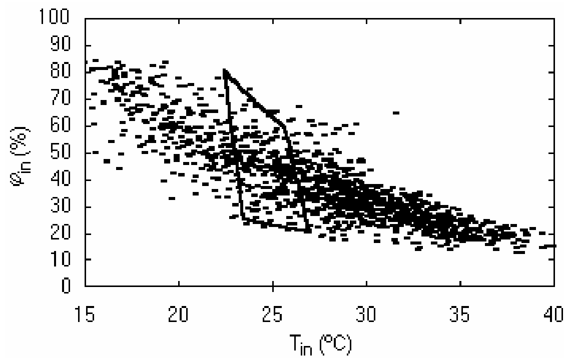

Figure 4: Thermal environment within the office with solar chimney and without buried pipes.

The influence of each one of the main parameters that characterize the array of buried pipes and the solar chimney was studied, by attributing several values to the parameter under study and maintaining the other values fixed. The indoor air temperature and relative humidity were calculated from the model. Afterwards, we calculated the number of cooling degree hours as the sum of the positive differences between the calculated air temperature and the air temperature corresponding to the upper limit of the thermal comfort zone for the same relative humidity.

To study the role of the pipe diameter, we calculated the number of cooling degree hours corresponding to the reference situation and pipe diameters ranging from 0,16 m to 0,40 m. In order to prevent the saturation of the ground temperature, it is desirable to keep the distance between pipes at least equal to four diameters. As we have a fixed ground area we took the amount of pipes that match the area of 30m×18m. The situations described in table 1 were considered:

Table 1: Number of pipes occupying 30 m land width

Number of pipes	Diameter
23	0.160 m
18	0.200 m
15	0.250 m
12	0.315 m
9	0.400 m

In figure 5 we can observe that with a diameter of 0,315 m we get the minimum value of the number of cooling degree hours, which is not far from that obtained with the diameter equal to 0,25 m. The minimum exists because the total cross section of the pipes increases with the diameter and, consequently, the ventilation flow rate increases, but, on the other hand, the efficiency of the earth-to-air heat exchanger decreases with increasing pipe diameter. So, the cooling potential of the system shows a maximum corresponding to an inlet air temperature low enough and the corresponding ventilation flow rate.

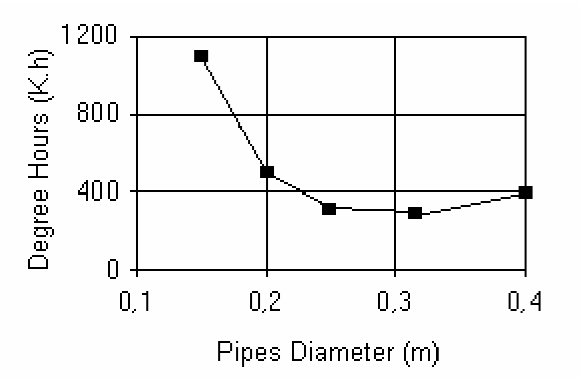

Figure 5: Number of cooling degree hours as a function of the diameter of the pipes.

We have calculated the number of cooling degree hours corresponding to several values of the length of the ducts. The influence of the length of the pipes was analyzed in two ways. The longer the pipes are, the less is the number of cooling degree hours. However, above 30 m the influence of pipes length is small. This fact can be explained by the increase in the friction losses with length and because, in a long pipe, the reduction in the air temperature is very small in the last meters.

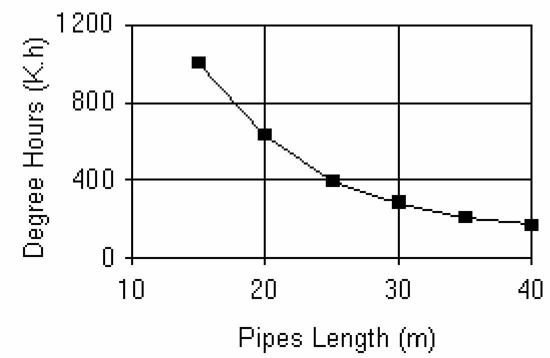

Figure 6: Number of cooling degree hours in function of the length of the pipes.

Table 2: Number and length of pipes totalizing 360 m

Number of pipes	Length
18	20 m
15	24 m
12	30 m
9	40 m

One more realistic simulation consists on keeping the sum of the length of the pipes fixed and varying the length of each one. We considered the following combinations described in table 2.

In the figure 7 we can observe that the function has a minimum corresponding to the pipes length equal to 30 m. The existence of a minimum is explained by the fact that increasing pipes length the efficiency of the earth-to-air heat exchanger is increased. On the other hand, the total cross section of the pipes decreases and so does the ventilation flow rate.

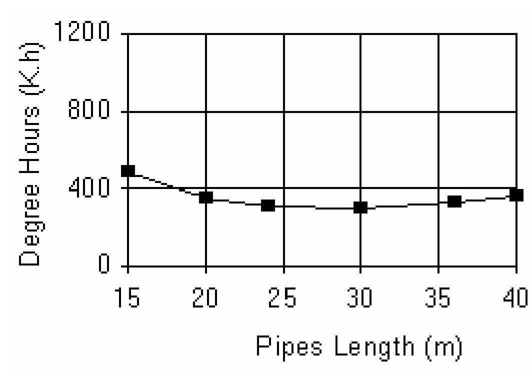

Figure 7: Number of cooling degree hours in function of the length of the pipes.

With respect to the solar chimney dimensions, we essayed several lengths from 2 to 5 m. The results obtained are represented in figure 8.

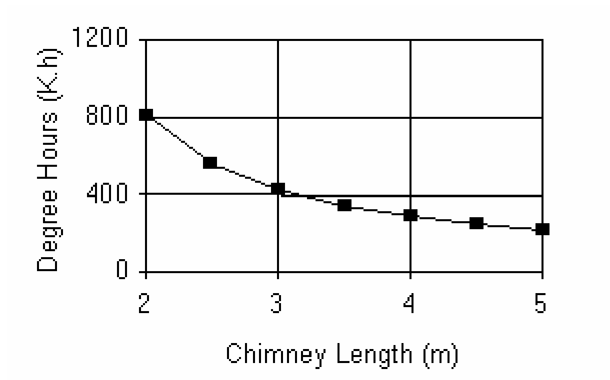

Figure 8: Number of cooling degree hours as a function of the length of the chimney.

Cross section of the solar chimney increases with chimney length and ventilation flow rate is enhanced accordingly. Therefore, the number of cooling degree hours decreases as chimney length increases, however the reduction is slight for lengths upper to 4 m.

We also have calculated indoor air temperature and relative humidity corresponding to several values of the height of the solar chimney: 1, 2, 3, 4, 5 and 6 m.

The number of cooling degree hours decreases with the height of the solar chimney because the higher the solar chimney is, the higher the air flow rate is. This is especially important for improving the efficiency of the passive cooling system at small wind velocity. Architectural reasons limit the high of solar chimney to 5 m but, as we can observe in figure 9, increasing chimney height up than 5 m has a little impact in the number of cooling degree hours.

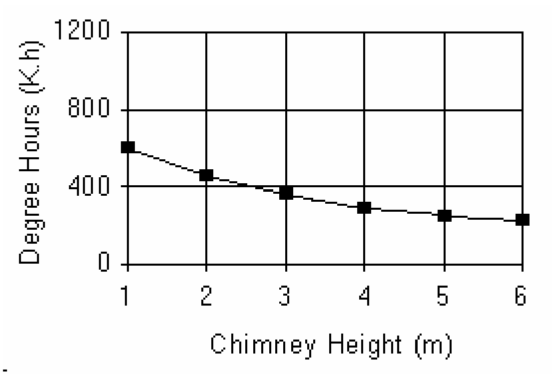

Figure 9: Number of cooling degree hours in function of the height of the chimney.

4. CONCLUSIONS

The model developed allows the dimensioning of the pipe array, namely the diameter, length and number of pipes. The model enables the dimensioning of the solar chimney as well. The model can predict the inside environmental conditions in a mono-zone building with a passive cooling system, provided that the outside climatic conditions, the geometry of the building and the internal heat gains are known.

The use of a solar chimney is quite interesting since the rate of natural ventilation induced is not dependent upon the wind speed. It is a very suitable system for regions where solar irradiation is high and wind speed is normally low.

By applying this model to an office, located in the region of Évora, it was predicted that the two passive cooling systems, the solar chimney and an array of buried pipes, yield environmental conditions which represent 278 cooling degree hours.

Future development of this model should be based on the monitoring data collected in this office after it is in operation.

The use of earth-to-air heat exchangers lowers the thermal amplitude of the air entering the building, therefore lowering the extreme values of air temperature within the building. This system is particularly suitable for regions with high annual thermal amplitude of the air, as is the case for the southern part of Portugal.

ACKNOWLEDGEMENT

The author is grateful to the Portuguese *Fundação para a Ciência e a Tecnologia* for financial support in the ambit of the project POCI/ENR/61524/2004.

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