PREHEATING OF SUPPLY AIR THROUGH AN EARTH TO AIR HEAT EXCHANGER COUPLED WITH A SOLAR CHIMNEY

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ABSTRACT

The performance of a passive heating system was evaluated as part of design works for the project of an office building. The passive heating system incorporates an array of buried pipes together with a solar chimney. The solar chimney collects solar energy, heating fresh air and pulling it from an array of buried pipes. The array of buried pipes was used as an open loop earth-to-air heat exchanger and air circulation inside pipes is due to the action of the solar chimney. We studied the heating fractions due to the solar chimney and to the buried pipes. 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 heating system was evaluated based on the energy absorbed by the ventilation air.

KEYWORDS

Earth-to-air heat exchanger, Solar chimney, Thermal simulation, Sustainable buildings, Passive heating.

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. The current trend is towards an increase of energy consumption and hence also of carbon dioxide emissions associated with the climatisation of buildings. Conventional heating systems have to be considered with care due to the need of reducing the environmental impacts, which result from burning fossil fuels.

The use of passive heating techniques in the winter is advisable, with the objective of reducing energy consumption with the climatisation of spaces. It can thus be an effective tool for attenuating the growth of energy consumption for air conditioning. Through solar collectors it is possible to heat indoor spaces in regions with a quite high solar radiation during the winter.

To ensure indoor air quality, buildings need adequate ventilation rates. Many commercial and industrial buildings need to have high ventilation rates. The supply of fresh air during the winter could represent a very high amount of energy spent to heat it. Preheating of external air before entering the building can be achieved by natural means, like circulation in buried pipes (Givoni 1994, Santamouris and Asimakopolous 1996, Trombe and Serres 1994). 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 source.

In Portugal, during the winter, soil temperature a few meters deep is higher than mean daily outdoor air temperature. An array of buried pipes can thus be used as an open loop earth-to-air heat exchanger.

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 (Awbi and Gan 1992, Bansal et al. 1993, Bansal et al. 1994, Awbi 1994, Afonso and Oliveira 2000).

In the south of Portugal, even in winter, there is a high number of sunny days and in these days solar radiation incident on the vertical surface of the solar chimney is adequate to provide the air circulation inside the buried pipes.

We can save a significant amount of energy through the circulation of the air in buried pipes before the air enters in the building.

The system studied consists on an array of buried pipes and a solar chimney that collects solar heat and enhances natural ventilation, pulling the fresh air to circulate through the array of buried pipes. With this system we can save an important amount of energy.

DESCRIPTION OF THE MODEL

A model was developed that predicts temperature and relative humidity of the air in a monozone building where fresh air is introduced after its circulation in an array of buried pipes and in a solar chimney. In the array of buried pipes the air is preheated and in the solar chimney air is heated by the greenhouse effect. The circulation in the buried pipes is due to the action of the solar chimney. This model was adapted from an earlier one developed for livestock buildings (Correia-da-Silva et al. 2001).

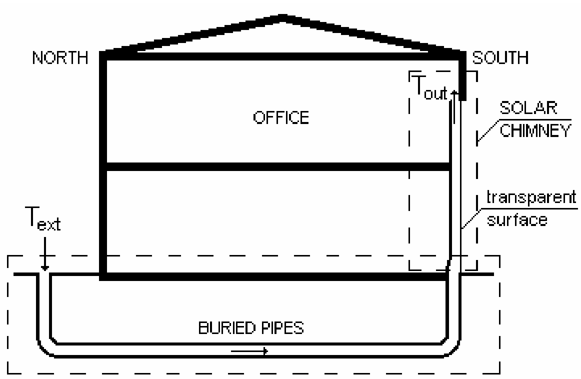

Figure 1: Office with passive heating system (buried pipes and solar chimney).

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 solar chimney) and another one for predicting the overall natural ventilation rate of the room, which includes the array of buried pipes and the solar chimney.

The first model gives the temperature of the air leaving the chimney; the second one gives the temperature of the air leaving the buried pipes 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.

The ventilation flow rate depends on the buoyancy pressure increase, due to the increase in air temperature between T_{ext} and T_{out}. The increase in buoyancy 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) on the chimney walls and on the internal surfaces of the pipes. So, we have the equation (Afonso and Oliveira 2000):

$$\rho\beta g\Delta h\left(T_{out}-T_{ext}\right)=\sum_i \rho\zeta_i \frac{v_i^2}{2}+\sum_i \rho f_j \frac{L_j v_j^2}{2D_j} \qquad (1)$$

where the subscripts *out* and *ext* stand for outlet and exterior, β is the thermal expansion coefficient, Δh is the level difference between inlet and outlet, L is the length and D is the hydraulic diameter.

From equation (1) we can calculate the volumetric flow rate, expressed as:

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

where the subscripts *ch* and *p* stand for chimney and buried pipe and *S* is the cross section area.

By using equation (2), ventilation flow rate can be predicted, provided ($T_{out}-T_{ext}$) 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.

In the solar chimney, convective heat transfer coefficients, between vertical surfaces and air were calculated from forced end free convection coefficients, through the equation (Incropera and DeWitt, 1996):

$$h=\sqrt[3]{h_{forc}^3+h_{free}^3} \qquad (3)$$

Temperature of the air entering the solar chimney is the temperature of the air leaving the buried pipes after to have been heated by circulation within the buried pipes. This heating effect occurs when air temperature is inferior than ground temperature, situation that normally occurs during the heating season.

Ground temperature at time *t* and depth *z*, $T(z,t)$ was calculated using the equation (Labs 1989):

$$T(z,t)=T_m-\frac{A_s}{2}exp\left[-z\sqrt{\frac{\pi}{365\alpha}}\right]sen\left\{\frac{2\pi}{365}\left[t-t_0-\frac{z}{2}\sqrt{\frac{365}{\pi\alpha}}\right]\right\} \qquad (4)$$

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 calendar 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 heat gains of the ventilation air.

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 supply air heating potential of the system.

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

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 array of buried pipes consists of 12 PVC pipes, 30 m long each, with an outer diameter of 0.315 m, and is placed at a depth of 3 m.

The climate variables used in the simulations were taken from the "Test Reference Year" (TRY) of Lisbon, corresponding to the hourly averaged values of temperature and relative humidity of the air and flux intensity of solar irradiation (direct beam and diffuse) observed in a horizontal surface.

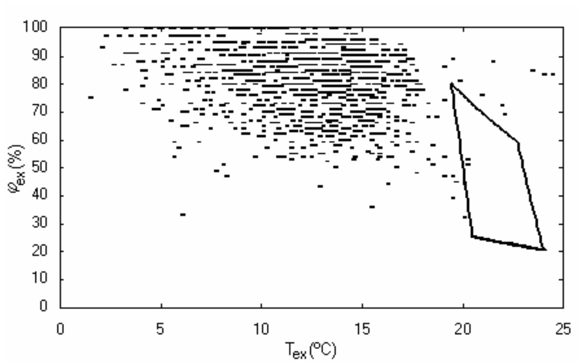

Figure 2: Daytime outdoor air temperature (T_{ex}) and relative humidity (φ_{ex}) in the heating season.

The period under study was the diurnal period, from 7h 30m to 16h 30m (solar time) of all the heating season that covers 5,3 months of the year. The hourly values of outdoor air temperature (T_{ex}) and relative humidity (φ_{ex}) are represented in the figure 2, together with the line that limits the thermal comfort zone (ASHRAE 1997).

Figure 3 represents inlet air temperature and relative humidity in consequence of preheating fresh air by the passive system. Comparing figures 2 and 3, we can see that with the heating system we have an important air heating. Sometimes the inlet air temperature belongs to the thermal comfort zone, but most of time is lower than comfort temperature but not too much.

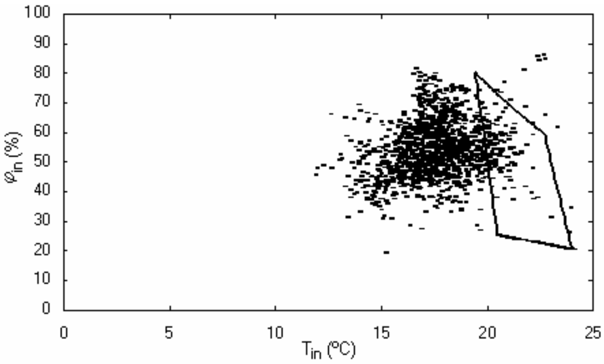

Figure 3: Predicted inlet air temperature (T_{in}) and relative humidity (φ_{in}) with the passive heating system.

The influence 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 inlet air temperature and relative humidity were calculated from the model. In figures 4, 5, 6, 7 and 8, the upper and the lower lines represent the performance of the system and the performance of the air-to-earth heat exchanger alone, respectively. These performances were evaluated based on the energy absorbed by the ventilation air.

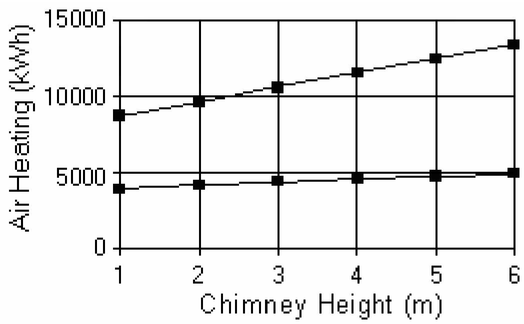

Figure 4: Thermal performance of the system in function of chimney height (here and in the figures below the upper and the lower lines represent the performance of the system and the performance of the buried pipes alone, respectively).

With respect to the solar chimney dimensions, we have calculated inlet air temperature and relative humidity corresponding to several values of the height of the solar chimney: 1, 2, 3, 4, 5 and 6 m.

Heat gain of air in the passive heating system increases with the height of the solar chimney. The fraction which is due to the air-to-earth heat exchanger also increases but less clearly. In fact, the higher the solar chimney is, the higher the air flow rate is. In the case of the solar chimney there is also an increase of the solar collector area but in the air-to-earth heat exchanger the contact surface between air and pipes maintains the same.

We also have essayed several lengths from 2 to 5 m. The results obtained are represented in figure 5.

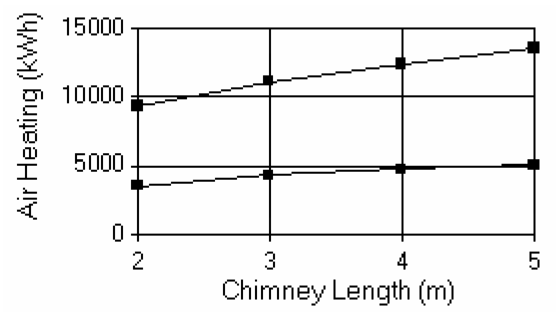

Figure 5: Thermal performance of the system in function of chimney length.

Air heat gain increases with the increase of chimney length because solar collector area becomes bigger. Also the cross section of the solar chimney increases with chimney length and ventilation flow rate is enhanced accordingly. For values of chimney length between 3 m and 5 m, air heat gain due to the air-to-earth heat exchanger suffers a slight increase.

We have calculated the heating potential corresponding to several values of the length of the ducts. In figure 6 we can observe that the longer the pipes are, the more is the energy absorbed by the supply air. 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 increase in the air temperature is very small in the last meters.

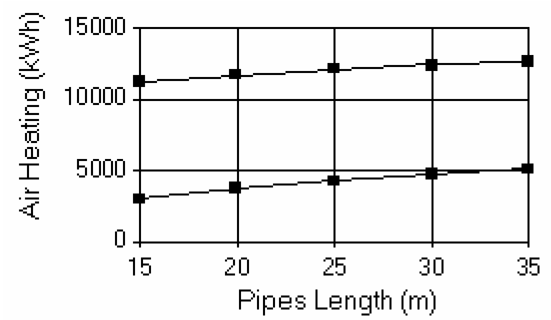

Figure 6: Thermal performance of the system in function of buried pipes length.

To study the role of the pipe diameter, we calculated the heat gains corresponding to the reference situation and pipe outer 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 outer 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	OUTER DIAMETER
23	0.160 m
18	0.200 m
15	0.250 m
12	0.315 m
9	0.400 m

In figure 7 we can observe that with an outer diameter of 0.315 m we get the maximum heat gain from the air-to-earth heat exchanger, which is not far from that obtained with the outer diameter equal to 0.250 m. The maximum exists because the efficiency of the earth-to-air heat exchanger decreases with increasing pipe diameter but, on the other hand, the total cross section of the pipes increases with the diameter and, consequently, the ventilation flow rate increases. Thermal performance of the system is almost constant when pipe outer diameter passes from 0,315 m to 0,400 m.

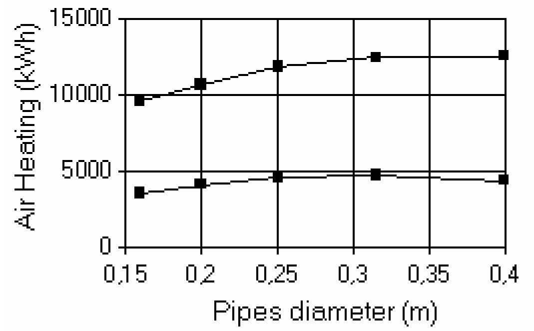

Figure 7: Thermal performance of the system in function of buried pipes outer diameter.

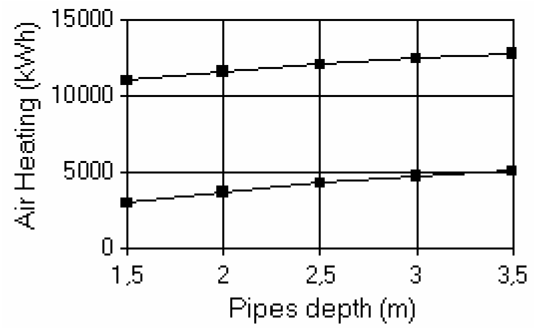

Figure 8: Thermal performance of the system in function of buried pipes depth.

We essayed several pipe depths: 1.5, 2, 2.5, 3 and 3.5. In the figure 8 we can see that the two lines corresponding to total heating and the heating fraction due to the earth to air heat exchanger are quite parallel. That is consequence of the fact that only this fraction depends of the pipe depth.

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 monozone building with a passive heating 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 very powerful namely in the south of Portugal where the solar irradiation is high during all the year. The solar chimney accomplishes two important roles: the air heated in its interior can be used to heat indoor space and it promotes natural ventilation. In office buildings which have mainly a diurnal occupation it is a very interesting passive solar heating system to use.

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

By applying this model to an office, located in the region of Lisbon, it was predicted that the two passive heating systems, the solar chimney and an array of buried pipes, yield environmental conditions not far of the thermal comfort zone. The air heating by the system represents, during the heating season, 12500 kWh.

Future development of this model should be based on the monitoring data collected in a test facility whose construction finished recently.

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