Passive downdraught evaporative cooling applied to an auditorium

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ABSTRACT

The performance of a passive cooling system was evaluated as part of design works for the project of an auditorium. The passive cooling system uses the atmosphere as natural heat sink and incorporates a solar chimney together with an evaporative cooling tower. The natural ventilation is enhanced with the help of the solar chimney and fresh air is cooled down by passive downdraught evaporative cooling. The application of this system to the acclimatization of an auditorium was evaluated. A model was developed to this purpose, which allows to foresee the temperature and the relative humidity of the air in the auditorium. The evaluation of the performance of the passive cooling system was based on the number of cooling degree hours.

The model was also used to evaluate the influence of the main parameters characterizing the solar chimney and the evaporative cooling tower upon the thermal environment within the auditorium fully occupied. The period under study was June to September and it comprised the diurnal period, from 6h 30m to 17h 30m (solar time).

1. INTRODUCTION

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 that has been happening in the latest years in Portugal and other South-European countries. 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 (European Communities, 2003). 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 fossil fuels burning. A simulation study of retrofit proposals for 186 representative office buildings in Greece, in which conventional and solar techniques were combined, predicted energy savings for heating, lighting and cooling in the range 22 to 37% (Santamouris et al., 1994).

In the southern 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 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 auditorium where people concentration 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 auditorium. However, if outdoor air temperature exceeds the thermal comfort limit, it is necessary to pre-cool it.

In vernacular architecture there are examples of passive cooling systems, namely systems using evaporative cooling particularly in countries around the Persian Gulf (Abdulak and Pinon, 1973; Bahadori, 1978; Herdeg, 1990).

In Figure 1 we can see a passive cooling strategy that uses ventilation and evaporative cooling through a fountain.

In Figure 2 a porous water jar is used to cool down the air temperature, since evaporative cooling takes place when breezes pass over the jar surface.

Through evaporative cooling, the ambient air can potentially be cooled down to the dew point temperature simply by saturating it with moisture. This type of cooling is thus particularly efficient in relatively dry climates. But in humid climates is also possible to generate cooled air flow through evaporative cooling (Yajima and Givoni, 1997).

Evaporative cooling is a very powerful method of passive cooling that can easily compete with conventional air conditioners in consciously designed buildings (Santamouris and Asimakopolous, 1996).

Direct evaporative cooling is advisable only where and when the wet bulb temperature

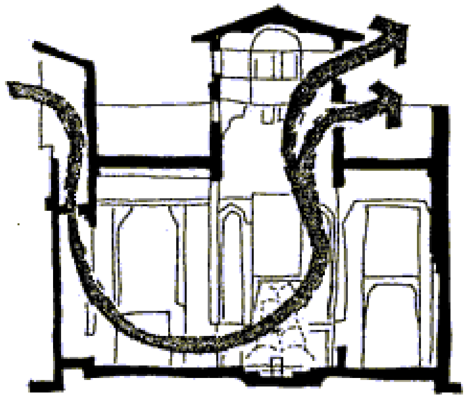

Figure 1: Passive cooling in vernacular architecture in Cairo (Abdulak and Pinon, 1973).

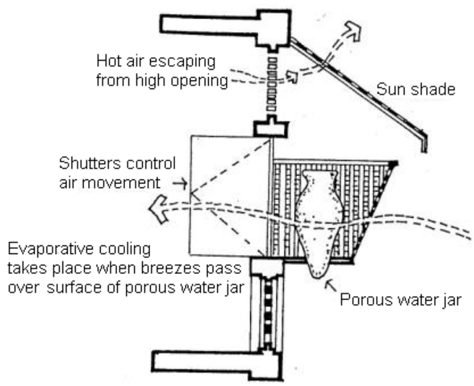

Figure 2: Passive cooling in vernacular architecture in Oman (Cain et al., 1976).

maximum in summer is not higher than about 22ºC and the dry bulb temperature is not higher than 42ºC in developed countries (Givoni, 1994). This is what happens at Évora in the major part of daytime during the summer.

Pre-cooling of external air before entering the building can be achieved by passive downdraught evaporative cooling (Cunningham and Thompson, 1986; Pearlmutter et al., 1996; Bowman et al., 1997).

The passive downdraught evaporative cooling system, as we can see in Figure 3, consists of a tower in which the ambient air enters at the top and is cooled by evaporation of water injected into the stream of ambient air. The smaller the drops the easier is water evaporation, because of the increase in the contact surface between water and air. Using compressed air it is possible to drive water as droplets with diameters of only a few microns (Lomas et al., 2004). Through a nozzle system, droplets of water are injected into ambient air stream at the top of the evaporative cooling tower. Cooled air is heavier than ambient air and falls down. The air is driven into the auditorium from the tower's bottom.

Air renewal is promoted through natural ventilation due to wind and stack effects. A solar chimney is used to increment natural ventilation. In the solar chimney air is heated up in contact with a surface kept at higher temperature by the absorption of solar radiation. Heating enhances the pressure difference between inlet and outlet of the chimney, thus increasing the rate of natural ventilation significantly (Awbi and Gan, 1992; Bansal et al., 1993; Afonso and Oliveira, 2000).

2. DESCRIPTION OF THE MODEL

A model was developed as part of design works for the project of an auditorium. The model allows the prediction of the temperature and rela-

Figure 3: Principle diagram illustrating passive downdraught evaporative cooling (adapted from Wachenfeldt and Bell, 2003).

tive humidity of the air in a room where a solar chimney enhances natural ventilation and the air entering the room is pre-cooled by evaporative cooling. This model was adapted from an earlier one developed for livestock buildings (Correia-da-Silva et al., 2001).

The model comprises three sub-models: one of them for predicting the behaviour of the solar chimney; another for predicting the temperature and relative humidity of the air leaving the evaporative cooling tower; and another one for predicting the overall natural ventilation rate of the space, taking into account the evaporative cooling tower, the air within the room and the solar chimney effect. The first model gives the temperature and relative humidity of the air leaving the chimney; the second one gives the temperature and relative humidity of the air entering the room and the third one delivers the rate of ventilation leading to the evaluation of the temperature and relative humidity of the air in the room.

As the variables of the model are strongly interdependent, calculations are made in an iterative way.

The performance of the passive cooling system was evaluated on the basis of 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 thermal comfort zone as defined by ASHRAE (2001) for the same absolute humidity.

3. SIMULATION

3.1 Solar chimney

Then, the model was used to evaluate the influence of the main parameters of the solar chimney upon the thermal environment within the auditorium with 45 adult people inside.

The dimensions of the auditorium are: 9.2 m (length) × 8.0 m (width) × 4.0 m (height) giving a volume of 220.8 m^3.

The dimensions of the solar chimney were calculated from the model.

The solar chimney has a transparent vertical surface facing the south direction, is 4m long, 5m high and 0,2 m in width. The climatic 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 typifies the climatologic normal of global solar radiation.

The period under study ranged from 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 4 together with the line that limits the thermal comfort zone.

In the Figure 4 we can see that quite often air temperature inside the auditorium with full occupation stands below the thermal comfort zone and sometimes relative humidity approaches the upper limit of thermal comfort zone. Suspending water injection when air temperature is too low can minimize the problem.

The computation of the temperature and the relative humidity of the air was made for the inside part of the auditorium with the solar chimney and with the evaporative cooling tower. Indoor environmental conditions which represent 122 cooling degree hours, were predicted with the help of the model.

Figure 5 represents outdoor air temperature and air temperature inside the auditorium with internal gains due to full occupancy and with the described passive cooling system in a week of August. The evaporative cooling efficiency was set to 0.7.

With the solar chimney but without the array of buried pipes (earth-to-air heat exchangers) we obtain the environmental conditions represented

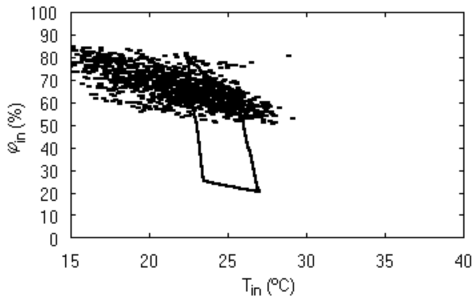

Figure 4: Thermal environment inside the auditorium with solar chimney and evaporative cooling tower.

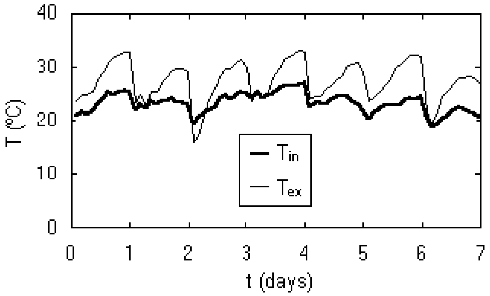

Figure 5: Outdoor air temperature (T_{ex}) and predicted indoor air temperature (T_{in}) with the passive cooling system.

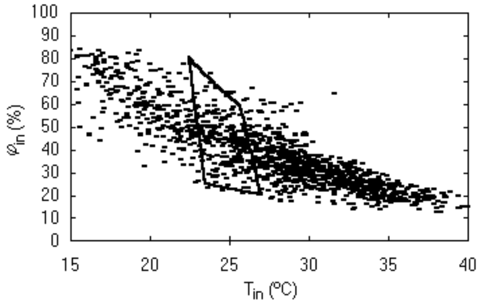

Figure 6: Thermal environment within the auditorium with solar chimney and without pre-cooling air.

in Figure 6. These environmental conditions exceed the upper limit of the thermal comfort zone by 3714 degree hours.

The influence of each of the main parameters that characterize the solar chimney was studied, by allowing several values to the parameter under study and keeping the others fixed. The indoor air temperature and relative humidity were calculated with the help of 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.

With respect to the solar chimney dimensions we essayed several lengths from 2,5 to 6 m. The results obtained are represented in Figure 7.

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 greater than 4 m.

We also have calculated indoor air tempera-

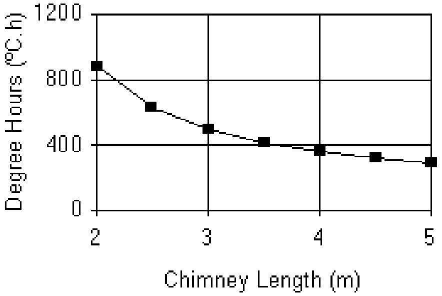

Figure 7: Number of cooling degree hours in function of the length of the chimney.

ture and relative humidity corresponding to several values of to solar chimney height: 2, 3, 4, 5 and 6 m.

The number of cooling degree hours increases with the height of the solar chimney because the higher the solar chimney is, the higher the air flow rate gets. This is especially important for improving the efficiency of the passive cooling system at small wind velocities. Architectural reasons limit the high of solar chimney to 5 m but, as we can observe in Figure 8, increasing chimney height to more than 5 m has little impact in the number of cooling degree hours.

3.2 Evaporative cooling tower

The performance of the passive cooling system in which pre-cooling of external air is achieved by passive downdraught evaporative cooling is largely dependent upon the evaporative cooling efficiency.

The number of cooling degree hours corresponding to evaporative cooling efficiencies of 0,4 and 0,8 are respectively 1053 and 81. In Figure 9 we can see that for values of evapora-

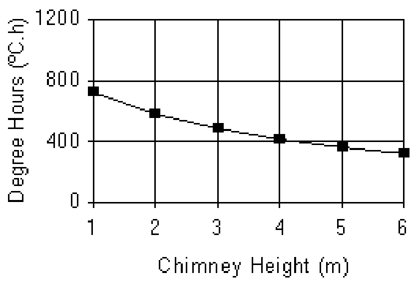

Figure 8: Number of cooling degree hours in function of the height of the chimney.

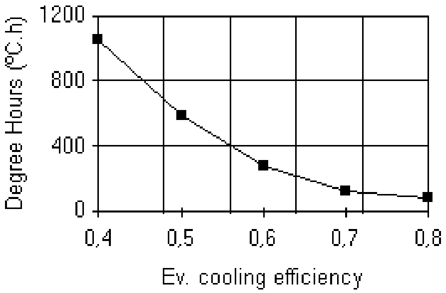

Figure 9: Number of cooling degree hours in function of the height of evaporative cooling efficiency.

tive cooling efficiency higher than 0,7 the decrease in the number of cooling degree hours is small.

Pre-cooling incoming air through an evaporative cooling tower with an efficiency of 0.7, the indoor thermal comfort conditions require 122 cooling degree hours.

4. CONCLUSIONS

The model enables the dimensioning of the solar chimney. 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 auditorium with a solar chimney and an evaporative cooling tower, located in the region of Évora, it was possible to predict environmental conditions in the auditorium which represent 122 cooling degree hours, with the evaporative cooling efficiency set to 0.7.

Direct evaporative cooling systems are adequate in the region of Évora where the summer is hot and dry.

The implementation of passive cooling strategies allows to ensure thermal comfort with a low conventional energy consumption.

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