h_t overall heat transfer coefficient from the water column 1 to the water column 2 through the trap material, W/m^2 °C
h_o, h_o' convective heat transfer coefficient from an absorber to the water and air respectively, W/m^2 °C
$I(t)$ solar intensity on south wall, W/m^2
K_g thermal conductivity of the glass cover, W/m °C
K_t thermal conductivity of the trap material, W/m °C
L_g thickness of the glass cover, m
L height of the south wall, m
M_w mass of the water in the water wall, kg
M_{w1} mass of water column 1 per unit area, kg/m^2
M_{w2} mass of water column 2 per unit area, kg/m^2
$\dot{m}_f$ airflow velocity, kg/s
$\dot{Q}_G$ net thermal flux gain/loss, W/m^2
$\dot{Q}_{G1}$ direct thermal flux gain, W/m^2
$\dot{Q}_{G2}$ indirect thermal flux gain, W/m^2
T_a ambient air temperature, °C
T_b blackened surface temperature, °C
T_f flowing air temperature, °C
T_R room air temperature, °C
T_{RF} blackened surface temperature of an air heater, °C
T_w temperature of the water wall, °C
T_{w1} temperature of water column 1, °C
T_{w2} temperature of water column 2, °C
t time
u flow velocity of air, m/s
U_L heat transfer coefficient from enclosed room air to ambient, W/m^2 °C
V wind velocity, m/s

Greek symbols

α absorptivity
τ transmittivity of glass cover
$(\alpha\tau)$ product of absorptivity and transmittivity
ρ_a density of air, kg/m^3
δL_w total thickness of the water column, m
δL_{w1} thickness of water column 1, m
δL_{w2} thickness of water column 2, m
δL_t thickness of the trap material, m
$\dfrac{\Delta E_{bj}}{E_b}$ emissive power
η_j extinction coefficient for the water, m^{-1}
μ_j extinction coefficient for the trap material, m^{-1}
δ_j fraction of solar radiation having extinction coefficient, η_j

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On the use of the atmospheric heat sinks for heat dissipation

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Abstract

During recent years, energy consumption of buildings for cooling purposes has significantly increased. In order to reduce the energy consumption while maintaining high levels of thermal comfort, building research has been oriented towards the appropriate use of the natural heat sinks.

The present paper provides comparative information regarding the performance of the more important passive and hybrid cooling techniques involving the use of a natural heat sink. Ground cooling by earth-to-air heat exchangers, direct and indirect evaporative coolers as well as night ventilation techniques are considered. The impact of the systems and techniques on the thermal behaviour of a typical building is investigated by means of a sensitivity analysis of the main parameters determining their performance.

1. Introduction

Overheating problems occurring during the warm period have a direct impact on thermal comfort as well as on energy consumption of buildings for air-conditioning purposes. A review of the recent market data, 1976–1985, concerning sales of air-conditioning units has shown a relative increase of about 300% representing today a market turnover of $20 billion [1].

Penetration of air-conditioning units is extremely important in selective countries having a serious impact on the peak electricity load. It is reported that, due to the serious heat waves observed during recent years, sales of air-conditioning units in Greece have increased by about 800% [2], while 38% of the non-coincident peak demand in the USA is induced by air-conditioning [3]. Therefore, reduction of the air-conditioning induced load is a major concern for utilities and energy experts.

Use of passive cooling techniques like appropriate microclimate, shading and thermal capacitance, can contribute significantly to prevent overheating, to increase thermal comfort and to decrease the cooling load [4].

Techniques and systems involving dissipation of the remaining excess heat of the building to a natural heat sink, like convective, evaporative, radiative and ground cooling, have gained an increasing acceptance during recent years [2]. Real-scale applications in Europe, reported in ref. 5, confirm a high potential of those systems and techniques. However, especially in Europe, very little information is available on the performance of the various natural cooling techniques as well as on the comparative advantages and disadvantages of the systems.

The aim of this paper is to provide comparative information regarding the influence and the performance of the most important natural cooling techniques on a building. Night ventilation techniques as well as ground cooling

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via earth-to-air heat exchangers and direct and indirect evaporative cooling systems are examined. For each technique, the relative influence on the thermal behaviour of the building was investigated by means of a sensitivity analysis of the main parameters determining their performance.

2. The reference building

The building used in this study is a typical dwelling, defined as the reference Greek building [6]. It is a 80 m^2 one-storey house situated in the Athens region, designed by A. Tombazis. The floor plan of this building is illustrated in Fig. 1. This house consists of two bedrooms, a living room together with a kitchen and a bathroom.

The building is well insulated. The U-values of the walls, floor and ceiling are 0.53, 0.31 and 0.89 W m^{-2} °C, respectively. All windows are single-glazed and well shaded during the summer period. More details on this building are given in ref. 6.

3. The climatic data

The building was assumed to be located in the Athens region (latitude 37°58′ N). The climate in Athens is characterized as 'warm Mediterranean', with mild and relatively wet winters and warm dry summers. An analysis of the summer climatic data of Athens for cooling purposes is given in refs. 7 and 8.

During the simulation procedure, the test reference summer weather data are used [6]. Test reference summer weather data are created in order to provide hourly values of all the necessary climatic data used for cooling purposes, i.e., ground temperature at various depths, sky temperature, wet bulb temperature, etc. Primary data are taken from the National Observatory of Athens [9].

4. Description of the simulation procedure

The thermal behaviour of the building was simulated using as a basic software the code CASAMO-CLIM, developed by the Ecole Nationale des Mines de Paris, France [10]. This program is developed especially for cooling purposes and is validated against real buildings.

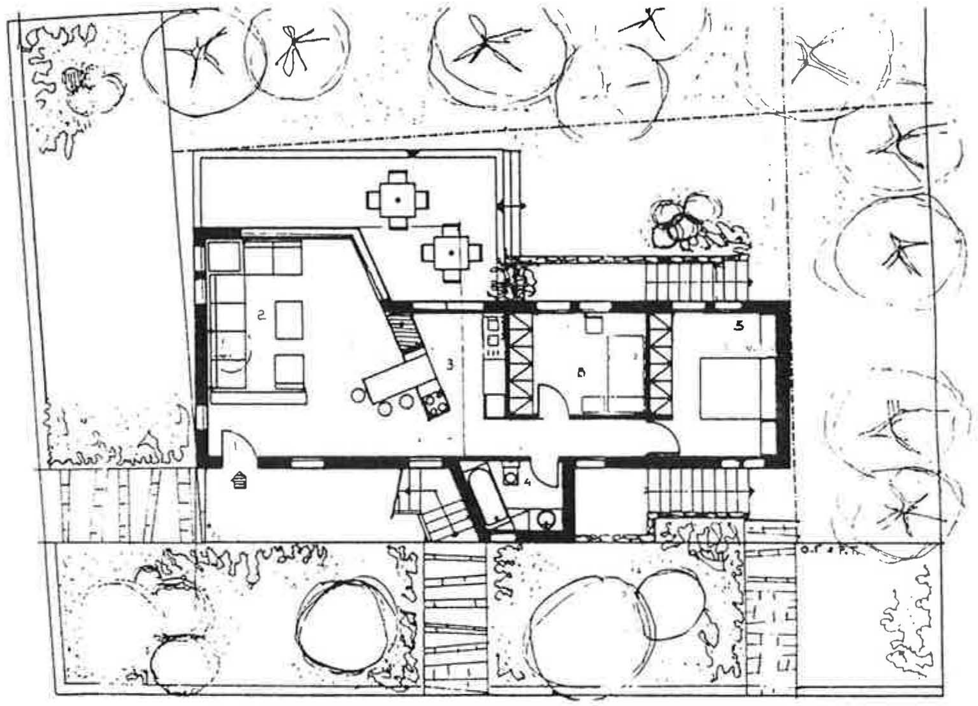

Fig. 1. Floor section of the reference Greek building. 1, entrance; 2, dining room; 3, kitchen; 4, WC; 5, bedrooms.

The code allows a detailed description of the simulated building, and provides a dynamic calculation of the shading levels. The program calculates the hourly variation of the indoor air temperature and of the relative humidity of the building. The necessary cooling load to obtain a defined setpoint temperature can also be calculated.

In order to simulate the performance of the passive and hybrid cooling components integrated into the building, special algorithms describing the performance of these systems have been developed and integrated into the basic code.

Four different types of passive and hybrid cooling systems and techniques have been simulated:

(a) earth-to-air heat exchangers (buried pipes);

(b) direct evaporative cooling components;

(c) indirect evaporative cooling components;

(d) night ventilation techniques.

In the following Sections, the algorithms used for the description of each system are described and the results are presented.

5. Ground cooling

The simulated system consists of an underground horizontal PVC pipe, whose inlet sucks in air from the environment using an electric fan. The air is cooled by being circulated underground and is then injected in the building.

The basic configuration of the system consists of a pipe 50 m long having an internal diameter of 0.2 m, placed at a depth of 4 m. The thickness of the pipe wall is 0.005 m. The air velocity inside the pipe is 5 m/s.

In order to calculate the impact of the ground cooling system on the building, a subroutine providing the thermal performance of the buried pipes has been developed and integrated into the code. For this purpose the algorithms proposed in ref. 11 have been used. Comparative analysis of 13 different algorithms proposed to calculate the efficiency of such systems, reported in ref. 12 has shown that the algorithm used is more complete and it is characterized by high accuracy.

A major question associated with the use of an earth-to-air heat exchanger is the choice of the optimal depth at which the exchanger has to be burried. In order to investigate the influence of this parameter on the thermal behaviour of the building, a series of simulations have been performed with the depth of the exchanger varying from 1.5 m to 6.5 m. The choice of this range was based on the ground temperature variation curves as a function of the depth. Such curves for Athens are given in ref. 13. As observed, the ground temperature at depths up to 1.5 m is not low enough to allow an efficient performance of a heat exchanger. Also, at depths greater than 6.5 m the ground temperature stops decreasing and remains almost steady, or in some cases, it increases slightly.

The variation of the indoor temperature of the building obtained when no earth-to-air exchangers are used, as well as when the exchanger is place at various depths, is reported for the summer months in Fig. 2. The daily variation of the ambient air temperature has also been reported. As shown, a 2–5 °C reduction of the peak indoor temperature can be obtained as the depth of the earth-to-air heat exchanger ranges between 1.5 to 6.5 m, respectively.

The most important air temperature decrease is obtained for depths ranging between 3 m and 6.5 m. More precisely, the maximum indoor temperature decrease observed in June occurs when the exchanger is placed at a depth of 4 m. For July and August this maximum value occurs for a depth of 5 m. Consequently, the optimal contribution of the heat exchangers to the indoor temperature decrease of the reference building occurs at depths between 4 and 5 m.

The results are consistent with the ground temperature variation as a function of depth from where it can be observed that the minimum values occur within the range 3.5–5 m.

Use of lower depths involves problems of inverse operation of the system. It is possible under some circumstances that the ambient air will be heated by circulating through the heat exchanger. Such a case is illustrated in Fig. 3.

In this Figure the daily variation of the ambient air temperature and of the air temperature at the outlet of the heat exchanger, placed at a depth of 1.5 m, are compared.

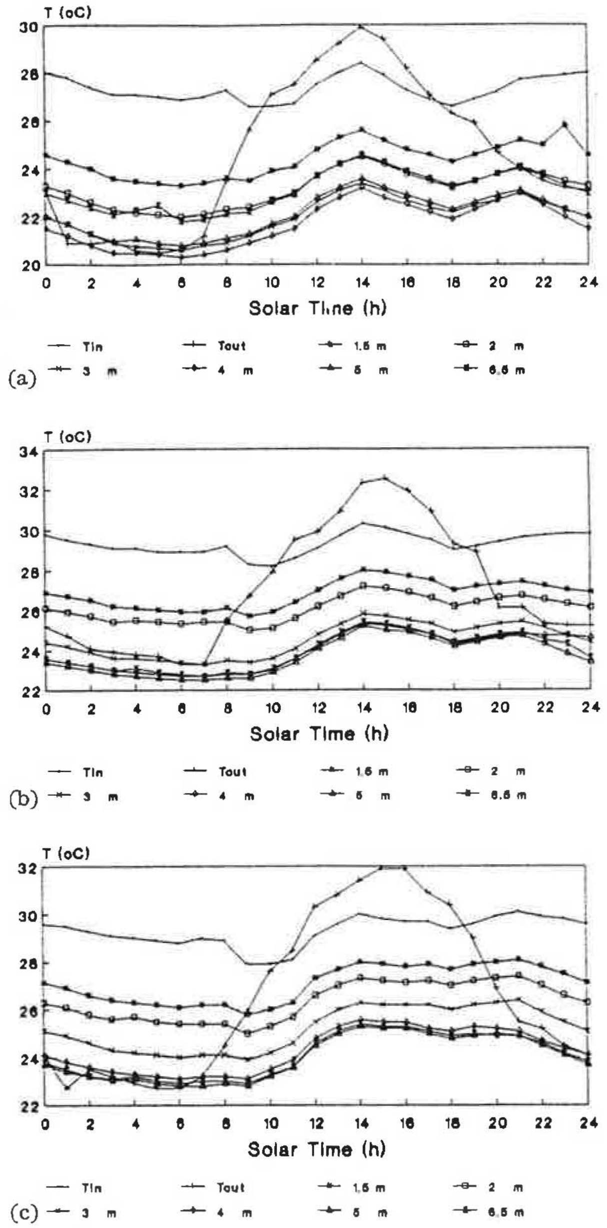

Fig. 2. Influence of the depth of the earth-to-air heat exchanger on the indoor air temperature. (a) June. (b) July. (c) August. Tin = indoor temperature without earth-to-air heat exchangers. Tout = ambient temperature. –*–, –□–, –×–, –◆–, –▲–, –X– = indoor temperatures using an earth-to-air heat exchanger buried at 1.5, 2, 3, 4, 5 and 6.5 m respectively.

Between 21:00 and 08:00 the ambient temperature is lower than the air temperature at the outlet of the exchanger, which shows that in this case the ambient air is heated by passing through the heat exchanger. This is due to the fact that the outdoor temperature at night is lower than the ground temperature at low depths. In that case, a control system is required. Control algorithms regulating the operation of an earth-to-air heat exchanger linked to a building are described in detail in ref. 14.

The effect of changing the length, the internal diameter and the air velocity inside the exchanger, on the indoor temperature of the reference building has also been investigated. During these simulations the depth of the exchanger has been fixed at 4 m. The length has been increased from 50 m to 70 m, the diameter from 0.20 m to 0.22 m and the air velocity has been decreased from 5 m/s to 3 m/s. The impact of these variations on the indoor temperature of the building is illustrated in Fig. 4 for the summer months.

Referring to Fig. 4, it can be observed that when the length of the exchanger increases from 50 m to 70 m, the corresponding indoor temperature drop is about 0.5 °C. This is because the temperature decrease of the air during the last 20 m in the exchanger is not very important compared to the temperature decrease at the first 50 m.

The increase of the diameter of the exchanger from 0.20 m to 0.22 m leads to a more important decrease of the indoor temperature of the building, which is of about 1.5 °C. This is because increasing the diameter, and maintaining constant the air velocity in the exchanger, increases the cooled airflow rate and consequently the cooling energy injected into the building.

On the contrary, when the air velocity is reduced, the cooling energy offered to the building is also reduced, resulting in higher indoor temperatures.

6. Direct evaporative cooling

The direct evaporative cooling device considered in this study is a parallel-plate-pad evaporative cooler. This cooler consists of a centrifugal fan (diameter 25 cm). The parallel plate matrix has a 50 m wetted area and is composed of 38 plates. The dimensions of each plate are 1.20 m × 0.60 m × 0.0035 m and the gap between each one of the plates in the matrix is 4.4 10^{-3} m. The pump of the water distribution system has a capacity of 250 m^3/h of water under a head of 3 m.

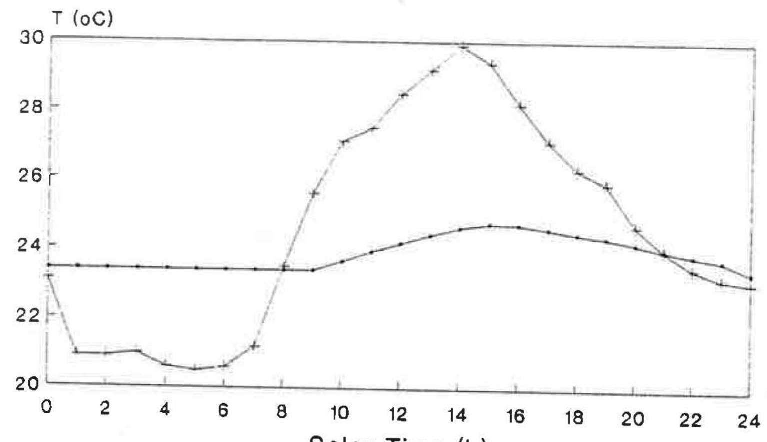

Fig. 3. Comparison between the ambient air temperature and the air temperature at the outlet of the earth-to-air heat exchanger placed at a depth of 1.5 m. –■– exchanger outlet. –+– ambient air.

In order to predict the performance of the direct evaporative system the algorithms presented in ref. 15 were used and linked to the overall calculation program. These algorithms, created using identification procedures, are of sufficient accuracy and are compared successfully against experimental data.

Using as input data the ambient dry and wet bulb temperature, the fan rate (in r.p.m.) and the water mass flow rate, the temperature and the relative humidity at the outlet of the cooler are calculated.

In order to analyse the impact of the parameters regulating the performance of the system to the building, a sensitivity analysis has been performed. Therefore the influence of the fan speed as well as of the flow rate of the water humidifying the parallel plate matrix has been investigated.

The results are presented in Fig. 5, for a typical day of each month. It is observed that a maximum reduction of the peak indoor air temperature of about 4–6 °C is possible. An increase of the water flow rate has an almost negligible variation on the indoor temperature of the reference building. In most of the cases examined, the corresponding temperature variation curves practically coincide. Their difference becomes about 0.5 °C when the high fan rate 3500 r.p.m. is used. It is deduced also that the effect of the fan rate change on the indoor temperature of the reference building is important. The mean temperature decrease is about 1.5 °C when the fan rate is increased from 800 r.p.m. to 1500 r.p.m.

7. Indirect evaporative cooling

Indirect evaporative cooling systems can provide efficient cooling of buildings without increasing the moisture content of the indoor air. Various types of indirect evaporative cooling systems have been proposed [16], however plate-type indirect evaporative coolers have given very encouraging results and have already seriously penetrated into the marked [17]. The type of cooler considered in the present research consists of a plastic heat exchanger with dimpled sheets of a hydrolic polymer, two fans, a water pump and simple water sprays [19].

In order to calculate the efficiency of the system, the saturation efficiency algorithm for that cooler, proposed in ref. 18, is used. The air temperature at the outlet of the cooler is then calculated using as inputs the outdoor dry and wet bulb temperatures. An analysis is performed of the impact on the building of the velocity with which the cooler air circulates through the primary circuit of the heat exchanger of the cooler (the evaporation takes place in the secondary circuit). Two air velocities have been considered, 0.3 m/s and 0.1 m/s. The results showing the effect of the air velocity variation on the indoor temperature of the reference building are illustrated in Fig. 6.

It is deduced that the increase of the air velocity is inversely proportional to the indoor temperature. In all cases, a temperature decrease of at least 1.5 °C is obtained, compared with the indoor temperature when no cooling

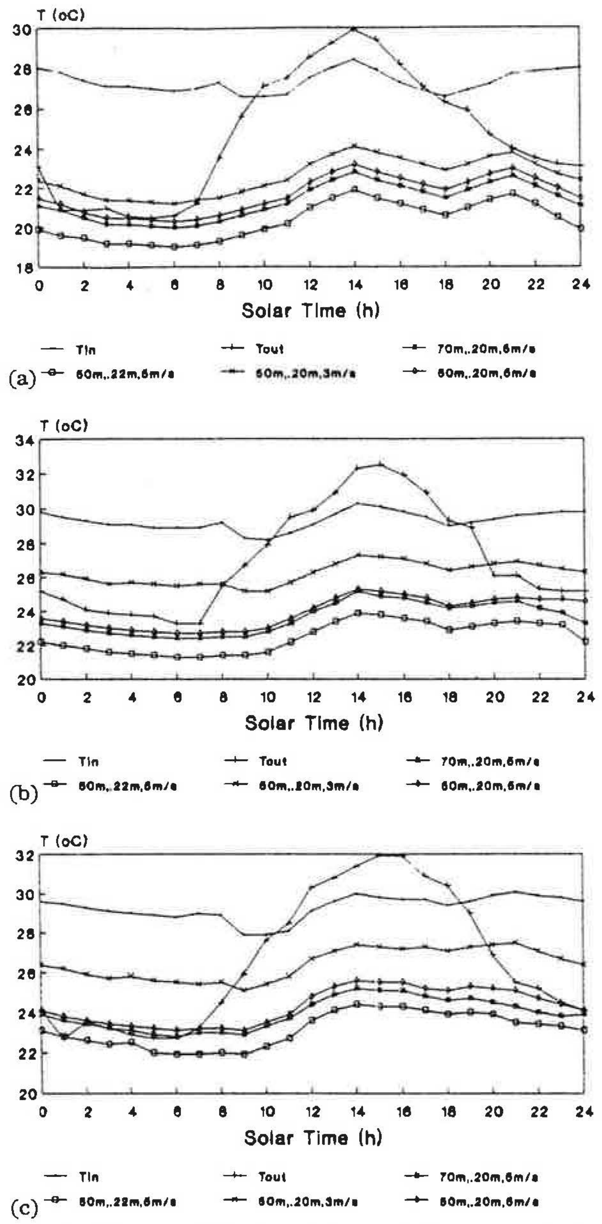

Fig. 4. Influence of the length, internal diameter and air velocity changes on the indoor air temperature. (a) June. (b) July. (c) August. Tin = indoor temperature without earth-to-air heat exchangers. Tout = ambient temperature. -□-, -×-, -◇-, -*- = Indoor Temperatures using earth-to-air heat exchangers of length L (m) diameter D (m) and an air speed V (m/s) as indicated.

load is provided to the building. During June, acceptable indoor temperature levels are obtained even with the low air velocity. However, in order to create comfortable indoor conditions during daytime in July and August, the high air velocity has to be chosen.

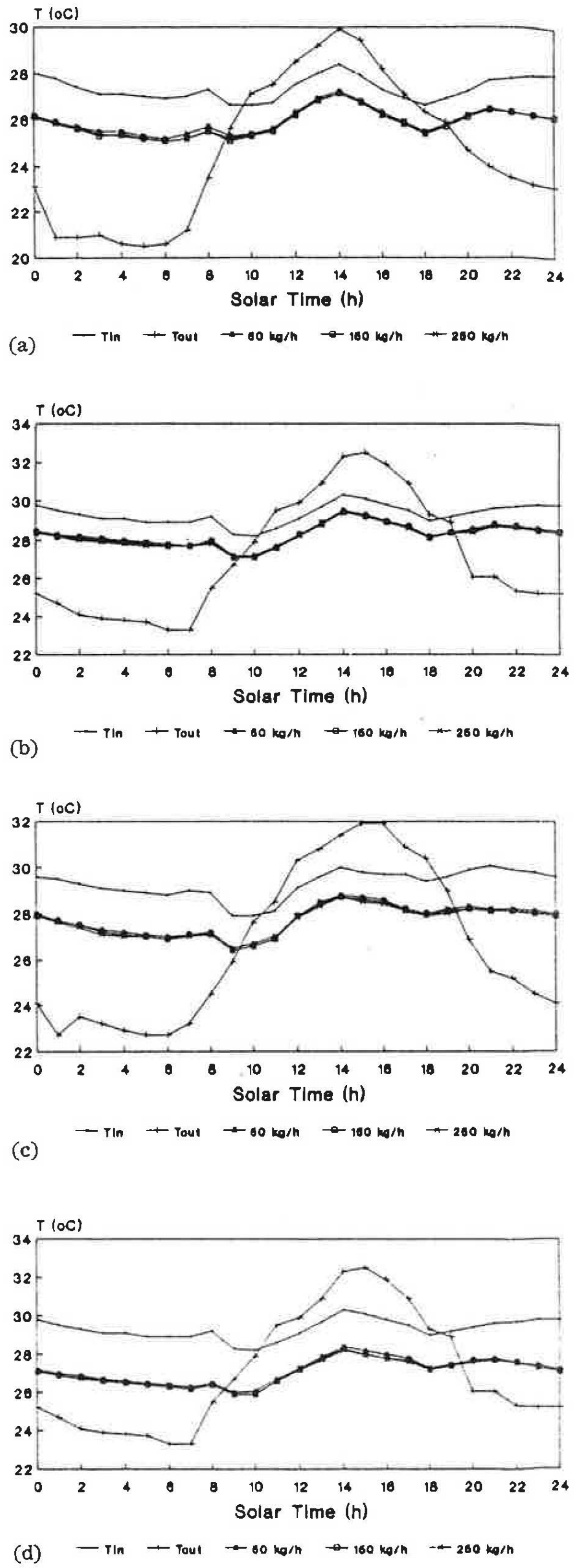

Fig. 5. Influence of the direct evaporative cooler on the indoor air temperature. (a) June, 800 rpm. (b) July, 800 rpm. (c) August, 800 rpm. (d) July 1500 rpm.

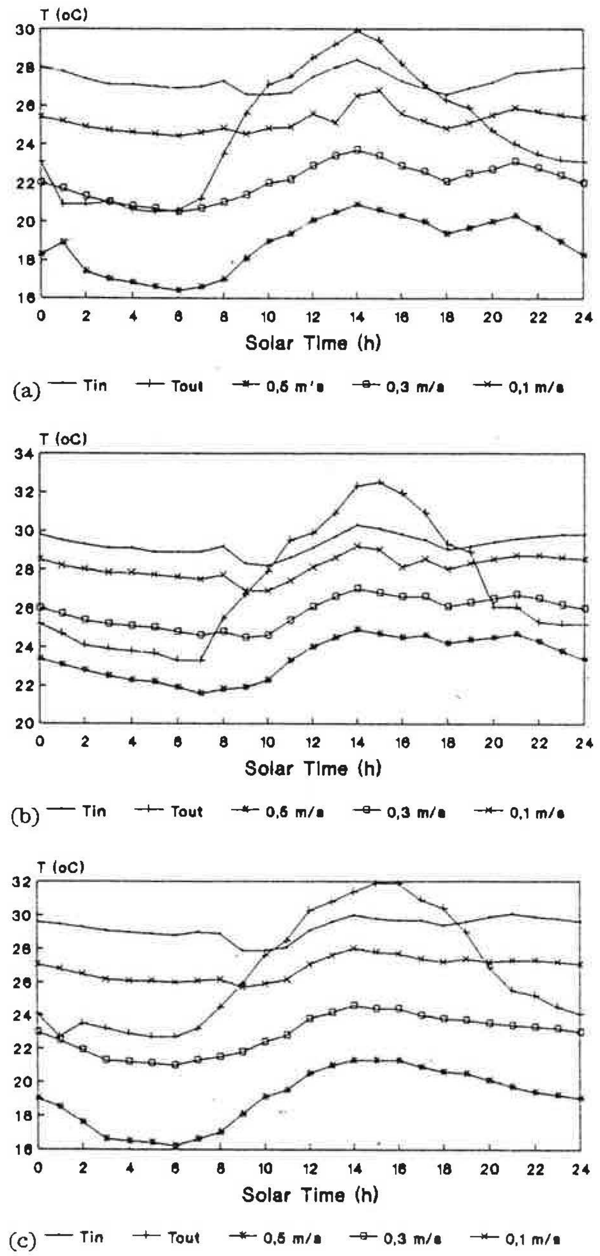

Fig. 6. Influence of the indirect evaporative cooler on the indoor air temperature. (a) June. (b) July. (c) August. Tin = indoor temperature without indirect evaporative coolers. Tout = ambient temperature. -*-, -□-, -×- = indoor temperatures when indirect evaporative coolers with air speeds equal to 0.5, 0.3 and 0.1, respectively, m/s are used.

8. Night ventilation

Night ventilation can provide effective cooling of buildings while contributing to increased indoor comfort during daytime [20]. Successive applications of night cooling techniques for buildings are described in refs. 21 and 22.

We have considered that the building was ventilated from 21:00 until 07:00, using various ventilation rates ranging between 2 ach and 8 ach with a step of 2 ach. The indoor air temperature profiles obtained were compared with the reference case in which a ventilation rate of 1 ach has been assumed to apply all day.

The results are illustrated in Fig. 7. As expected, the indoor temperature is decreased by increasing the ventilation rate. However the maximum depression of the peak indoor temperature does not exceed 1 °C.

The decrease of the indoor temperature during the daytime is more important in June and August and less in July, due to the high night ambient temperature occurring during this month. However, simulations have shown that while the use of night ventilation can contribute to the cooling of the building, it is not sufficient to produce acceptable temperature levels during the day and for this reason a complementary cooling system is required.

9. Conclusions

The impact of a number of passive and hybrid cooling techniques on the thermal performance of a reference building has been investigated. Night ventilation, ground cooling, by means of an earth-to-air heat exchanger, as well as direct and indirect evaporative cooling systems and techniques, have been studied.

The results have shown that:

(a) The use of night ventilation techniques can provide a part of the cooling load required for the building, however the use of additional cooling systems is necessary.

(b) When earth-to-air heat exchangers are used, the pipe has to be buried at a depth ranging between 3.5 and 5 m. Regarding the sensitivity of other parameters of the system, it has been discovered that the diameter and air velocity variations affect significantly the indoor temperature of the building. The increase of the length of the exchanger over a certain value does not have a significant impact on the building temperature.

(c) The most important parameter affecting the indoor temperature of the building, when

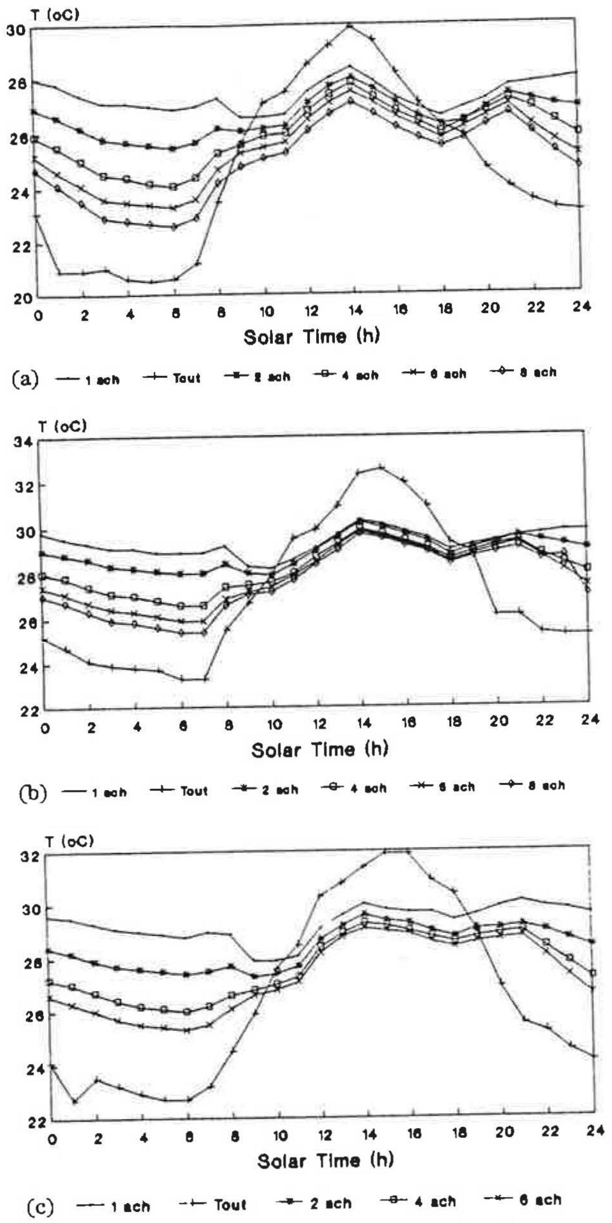

Fig. 7. Influence of night ventilation on the indoor air temperature. (a) June. (b) July. (c) August. Tout = ambient temperature. –•–, –□–, –×– = indoor air temperatures when night ventilation is equal to 2, 4 and 6 air changes per hour, respectively. Daytime ventilation is always equal to 1 ach.

a specific direct evaporative cooler is used, is the fan rate of the cooler, rather than the flow rate of the water humidifying the pad of the cooler. The indoor temperature decrease is satisfactory for a fan rate higher than 1500 r.p.m.

(d) The use of indirect evaporative coolers can lead to acceptable indoor temperature levels during June and August for an air speed though the cooler of 0.1 m/s, but during July an air speed of 0.3 m/s is required.

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