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Development of feasibility approaches for studying the behavior of passive cooling systems in buildings

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Abstract

This study is a contribution to European projects Pascool/Joule II and Altener/Sink that deals with feasibility of passive cooling systems in Europe. The first aim of this work was to define a design methodology to evaluate natural cooling potential according to the climatic quantification criteria of the site, the cooling system performance, and comfort criteria defined by the couple of temperature and relative humidity set points. A simplified approach, based on climatic potential criteria as theoretical cooling potential index, the available potential index, the cooling need index, and the natural cooling normalized capacity, was developed. It was applied to 105 European sites for different types of evaporative cooling systems (direct and indirect), and for various temperature and relative humidity set points. During the second stage, a refined approach taking into account building characteristics and the cooling system performance, was developed. This method is based on the integration of numerical models of passive cooling systems in a thermal building software in order to consider interaction phenomena between cooling system and building. Application of this approach to one building has been done in order to assess energy consumption gain achieved by using passive cooling systems. These two complementary approaches provide helpful information dealing with the feasibility of a passive cooling technique based on comfort and energy saving criteria. They could be used by architects and building designers as helpful decision making tools during the different stages of building design. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Passive cooling technique; Evaporative system; Cooling potential; Natural cooling saving factor; Climatic atlas; Energy conservation

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Nomenclature

A Pad surface (m^2)
A_{eff} Effective exchange surface (wetted media-air) of the pad (m^2)
$C_{cond,i}$ Conductance of i surface (W K^{-1})
C_p Air specific heat (J kg^{-1} K^{-1})
COP System performance coefficient
$\varepsilon_{syst}(t)$ Efficiency of system
f_u Utilisation factor
h_i Heat transfer coefficient (W m^{-2} K^{-1})
HR Relative humidity of the air (%)
HR_{max} Maximum relative humidity level (%)
HR_{int} Indoor relative humidity of the air (%)
k Mass transfer coefficient (air-vapour) (kg m^{-2} s^{-1})
K_{ij} Radiative heat transfer conductance (W K^{-1})
L_V Latent energy of the water (J kg^{-1})
M_{evap} Evaporated water mass (kg)
M_S Water production mass (source) (kg)
m'_{jk} Mass airflow transferred from zone j to zone k (kg s^{-1})
m' Mass airflow (kg s^{-1})
$\{M_{equipement}\}$ Matrix of water mass provided by evaporative system to building (kg)
Nz Building zones number
P_k^z Source heat power provided in zone k (W)
τ_c Natural cooling normalized capacity (NCSF)r
$T_{Set\ point}$ Set point temperature (°C)
$T_{Inlet}(t)$ Inlet air temperature (°C)
$T_{Int}(t)$ Indoor air temperature (°C)
T_i^s Surface i temperature (°C)
T_j^z Air temperature of zone j (°C)
$T_{Sink}(t)$ Temperature of the sink (°C)
$\{P_{equipement}\}$ Matrix of cooling power provided by system for each zone (W)
q_i^{clo} Short wave radiation gains of the zone 1 (W)
$Q_{Available}$ Available energy of the system (kW h)
Q_{usable} Usable energy of passive cooling system (kW h)
Q_{used} Used energy provided by system (kW h)
$Q_{batiment}$ Cooling building requirement (kW h)
$\{Q_{equipement}\}$ Matrix of energy provided by cooling systems (kW h)
ρ Air density (kg m^{-3})
V'_{eq} Air flow provided by conditioning air equipment (m^3 s^{-1})
V_k^z Volume of zone k (m^3)
ω_{eq} Absolute humidity provided by cooling system
$\omega_i(t)$ Absolute humidity of air in zone i

1. Introduction

During the steps of design and building construction, multiple information, of different nature, is necessary for the participants of the project. Among this information it is found that one that allows to choose a building design type, to choose a cooling technique that ensures a sufficient comfort degree, to size air conditioning systems, and finally to evaluate the energy consumption and the energy gain due to the use of a passive cooling technique. Several methods [1,2] offer more or less precise information about the thermal building behavior and the evaluation of buildings equipped with passive cooling systems. These approaches, based on the use of a psychometric chart, provide a useful qualitative information for architects and building designers on the feasibility of a passive cooling technique based on comfort aspects.

Nevertheless, they allow neither quantification of the potential of each cooling technique nor calculation of the energy gain achieved by using a passive cooling system. In the European projects Pascool/Joule II [3] and Altener/Sink [4] we developed two complementary approaches of thermal building evaluation.

The first approach is a simplified method based on an analysis of cooling potential of climates and on the estimation of evaluator factors, presented in the form of an atlas for each passive cooling technique. This approach provides helpful information for architects and building designers. It deals with the interest and the feasibility of each passive cooling technique according to the comfort criteria and energy conservation aspects [5].

The second approach is a detailed method of the thermal building behavior, obtained by the coupling of passive cooling systems and thermal building models [6]. It can be used for sizing passive air conditioning systems and for evaluating the energy gain achieved by using passive cooling systems.

2. Method of evaluation of the cooling potential

The analysis of natural cooling systems behavior shows that it is possible to establish a common general equation for all natural techniques concerned [7,8]. For each studied passive cooling system, it is possible to define evaluator factors which characterize the climate conditions, the nature of the technique, potential of the sink and the building type. These factors allow comparison of the different passive cooling techniques potential. Knowing the characteristics of the used fluid properties and of the natural source of cooling, called the sink, evaluator indexes dealing with the cooling potential of passive systems could be defined. During the cooling process and according to heat and mass transfer with the sink (Fig. 1), the fluid (air) will have an evolution from an initial state characterized by inlet temperature, $T_{Inlet}(t)$, and inlet absolute humidity, $\omega_{Inlet}(t)$, to a final state characterized by outlet temperature, $T_{Outlet}(t)$, and outlet absolute humidity, $\omega_{Outlet}(t)$. In an ideal process, outlet conditions of the system coincide with those of the sink, $T_{Outlet}(t)=T_{Sink}(t)$ and

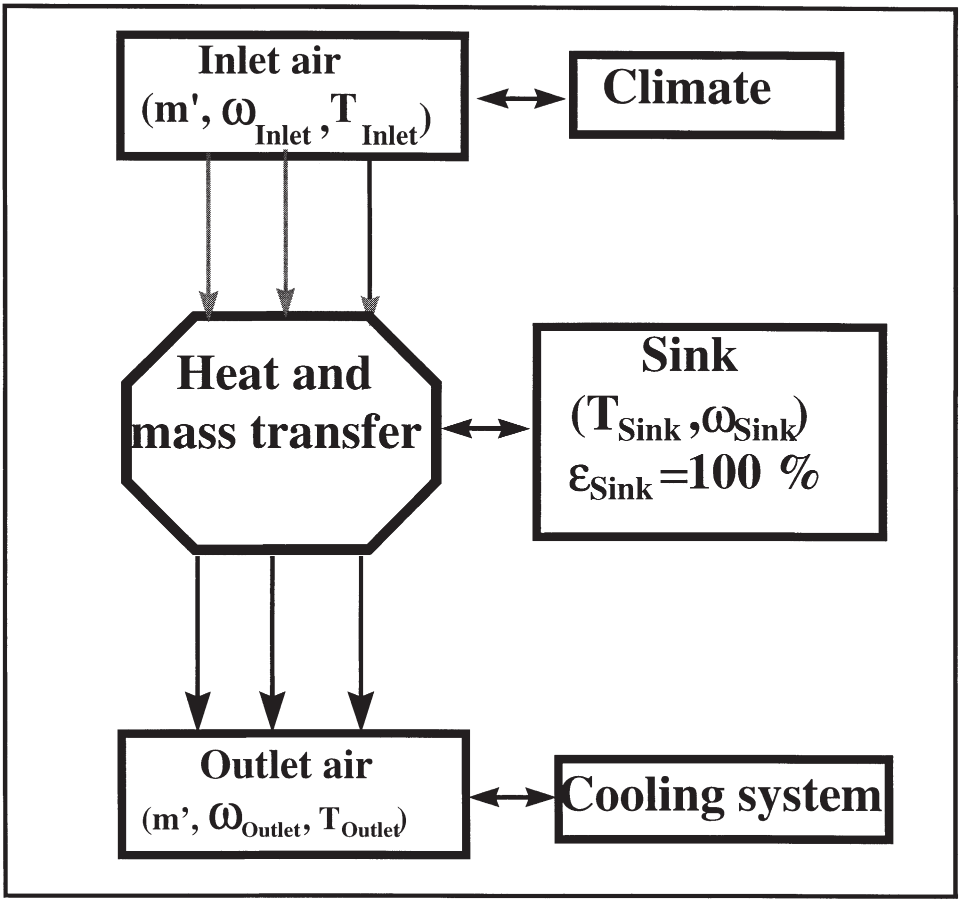

Fig. 1. Diagram of heat and mass transfer.

$\omega_{Outlet}(t)=\omega_{Sink}(t)$. The sensible energy theoretically available from the sink can be written as:

$$Q_{Theoretical}=m'(t)C_p[T_{Inlet}(t)-T_{Sink}(t)]\,dt \tag{1}$$

For the passive cooling systems which operate with the same air massflow rate and the same fluid (air), the value $[T_{Inlet}(t)-T_{Sink}(t)]$, integrated on the period of study τ, constitutes an index, $IP_{Theoretical}$, of comparison of the theoretical potential that depends only on the sink by $T_{Sink}(t)$ and the climate of the site by $T_{Inlet}(t)$,

$$IP_{Theoretical}=[T_{Inlet}(t)-T_{sink}(t)]\,dt \tag{2}$$

measured in degree-hours (°h).

The theoretical cooling potential index, $IP_{Theoretical}$, is obtained assuming an ideal cooling system (system efficiency=1). This index is particularly of interest to establish a comparative potential map of the different passive cooling techniques [9]. An example of evaluating the cooling potential indexes is given in Fig. 2.

Unfortunately, the theoretical cooling potential index does not take into account the system efficiency and the cooling requirement of the building. For more precise comparisons, we have defined three other indexes:

- The available cooling potential index $\left(IP_{available}=\frac{Q_{Available}}{m'_{air}C_{P,air}}\right)$ is defined according to the climatic conditions of the site, to the nature of the technique and some comfort criteria of the building defined by a temperature set point and a relative humidity set point (Fig. 2). It is given by:

$$IP_{Available}=[T_{Set\ point}(t)-T_{Sink}(t)]\delta(t)\ \mathrm{d}t \qquad (3)$$

  where $\delta(t)=1$ if $T_{Sink}<T_{Set\ point}$, and $\delta(t)=0$ if $T_{Sink}>\mathrm{T}_{Set\ point}$.
- The useful cooling potential index $\left(IP_{Useful}=\frac{Q_{Useful}}{m'_{air}C_{P,air}}\right)$ which depends not only on climatic conditions of the site and the required comfort level but also on the performance of the passive cooling system itself. It is given by:

$$IP_{Useful}=[T_{Set\ point}(t)-T_{Inlet}(t)]\delta_1(t)\ \mathrm{d}t \qquad (4)$$

  with $\delta_1(t)=1$ if $T_{Outlet}<T_{Set\ point}$, and $\delta_1(t)=0$ if $T_{Outlet}>T_{Set\ point}$.
- The building cooling requirement index $\left(IB_{Requirement}=\frac{Q_{Requirement}}{K_{Building}}\right)$ represents the cooling needs to be provided by the system to ensure the suitable comfort conditions in the building (Fig. 2). It is given by:

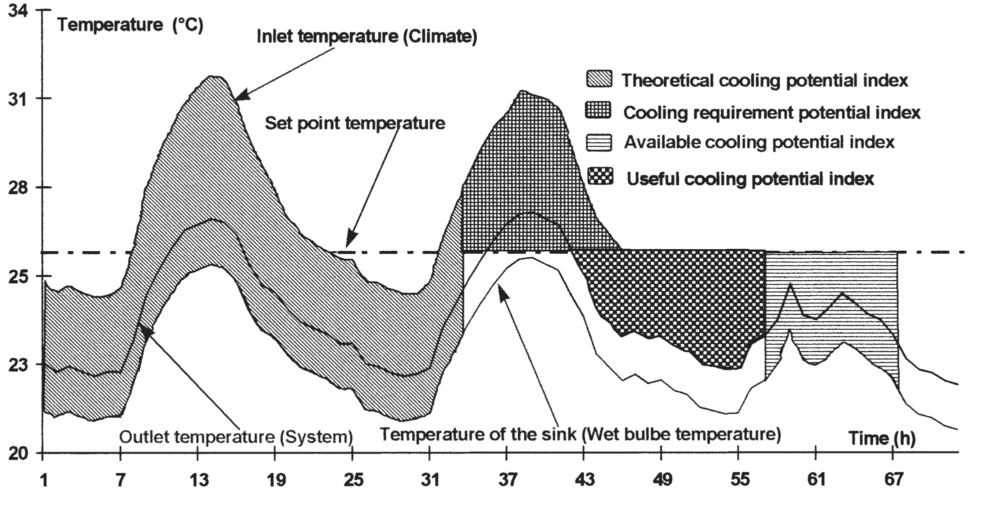

Fig. 2. Evaluation of cooling potential index.

$$IB_{Requirement}=[T_{Inlet}(t)-T_{Set\ point}(t)]\delta_2(t)\ \mathrm{d}t \tag{5}$$

where $\delta_2(t)$=1 if $T_{Inlet}<T_{Set\ point}$, and $\delta_2(t)$=0 if $T_{Inlet}>T_{Set\ point}$.

According to these previous assessment factors it is possible to deduce the natural cooling normalized capacity, the utilisation factor and the coefficient of performance.

- The natural cooling normalized capacity, τ_c, represents the ratio between the energy that may be delivered by the natural cooling system and the summer needs in air conditioning of the building. It is defined by:

$$\tau_c=\frac{Q_{Useful}}{Q_{Requirement}} \tag{6}$$

It can be used to assess the economical advantage of the combined passive and conventional solution compared with a classical cooling system. When $\tau_c\geq 1$, all the cooling load can be covered by the passive system. When $\tau_c<1$, it suffices to study the diminution of the energy consumption, $1-\tau_c$, and the size of the conventional system in function of the passive system investment cost to estimate the economical advantage of the combined passive–classical solution. For example, if τ_c=0.7, i.e. 70% of the cooling requirements is provided by the passive system, and 30% should be provided by a classical system, which size was reduced. The designer may compare the economic advantage, due to the reduction in energy cost, with the investment cost. This index is therefore a determining parameter for the choice of cooling techniques to be used.

- The utilisation factor, $f_u(t)$, represents the part of energy used by the system among all available energy. It is defined by:

$$f_u(t)=\frac{Q_{Useful}(t)}{Q_{Available}(t)} \tag{7}$$

This factor allows to evaluate the available power fraction that will be really used by the system during the period of study. For example, $f_u(t)$=1 means that the system operates on full power during all the period of study; $f_u(t)$=0.3 means that the cooling system operates on the average to 30% of its maximum power. The value of $f_u(t)$ translates a good or bad exploitation of potentialities of the system and allows consequently to judge the pertinence of the passive system sizing.

- The coefficient of performance (*COP*) of the system is defined by the ratio between energy brought by the system and the total consumption of the system. It is defined by:

$$COP(t)=\frac{Q_{Useful}(t)}{Q_{Consumption}(t)} \tag{8}$$

This common parameter to conventional and passive systems can be used as economic criterion to choose a system.

3. Integration of evaporative cooling systems in a thermal building model

3.1. Presentation of PASSPORT+ software

PASSPORT+ is a thermal building software which was developed in the framework of the European research project Pascool/Joule II [10]. This software is developed on a modular structure and designed to facilitate the coupling of the various passive cooling system models to the thermal building behavior. This software was validated by comparing its results with the other codes such that TRNSYS, BLAST, DOE2.1D, SUNCODE, ESP, S3PAS, VUB/BRE and SER1-RES [10].

The thermal behavior modeling of a building consists in establishing the mass and heat transfer balance equations for each face of the building surfaces. If the building is constituted by N_Z zones and N_S surfaces, a system of (N_Z+N_S) linear equations will be obtained.

The energy balance equation applied on a surface i of the zone j of the building is:

$$C_{cond,i}T_i^s+h_iS_i(T_i^s-T_i^z)+q_i^{'clo}+\sum_{j=1}^{N_z}K_{ij}(T_i^s-T_j^s)=P_i^s \tag{9}$$

Air balance equation applied on each zone is represented by the following system of equations:

$$V_k^ZC_p\frac{d(\rho T_k^z)}{dt}=P_k^z+\sum_{j=1}^{NS}h_jS_j(T_j^s-T_k^z)+\sum_{j=0}^{Nz}m_{jk}^{'}C_pT_j^z-\sum_{j=0}^{N_z}m_{kj}^{'}C_pT_k^z \tag{10}$$

The mass conservation equation for the water expressed in each zone allows us to evaluate the humidity transfer in the building:

$$V_i\rho\left(\frac{d\omega_i}{dt}\right)=V_{\inf}^{'}\rho[\omega_{ext}-\omega_i(t)]+\sum_{j=1}^{N_Z}V_{jl}^{'}\rho[\omega_j(t)-\omega_i(t)]+V_{eq}^{'}\rho[\omega_{eq}-\omega_i(t)] \tag{11}$$
$$+M_S^{'}+M_{evap}^{'}$$

Balance equations (9) and (10) can be put under the form of a matrix where surface temperature and temperatures of zones represent the system variables (Eq. (12)), where [T], [B] and [C] are matrix of constants and [D] depends on multizones air transfer. The right hand member of this equation is a column of powers of (N_S+N_Z) elements. In the first N_S columns represent power terms due to surface heat transfer (Eq. (9)) and N_Z represent other column power terms due to the multizone aeraulic transfer and sources of heat present in these zones (Eq. (10)).

$$\begin{bmatrix} \mathrm{A} & \mathrm{B} \\ \mathrm{C} & \mathrm{D} \end{bmatrix}\times\begin{bmatrix} \mathrm{T}_{surfaces} \\ \mathrm{T}_{zones} \end{bmatrix}=\begin{bmatrix} \mathrm{P}_{surfaces} \\ \mathrm{P}_{zones} \end{bmatrix} \tag{12}$$

The expression of surface temperatures in function of zone temperatures allows us to simplify the problem, to reduce the size of the linear system to solve (Eqs. (13), (14), (15) and (16)) and to obtain eventually a classical linear system (Eq. (16)).

$$\{T_{surfaces}\}=[A^{-1}](\{P_{surfaces}\}-[B]\{T_{zones}\}) \tag{13}$$

$$\{[D]-[C][A^{-1}][B]\}\cdot\{T_{zones}\}=\{P_{zones}\}-[C]\{P_{surfaces}\} \tag{14}$$

$$\{[D]-[C][A^{-1}][B]\}=[M] \tag{15}$$

$$\{P_{zones}\}-[C]\{P_{surfaces}\}=\{P\} \tag{16}$$

$$[M]\{T_{zones}\}=\{P\} \tag{17}$$

where the brackets denote matrixes and the curly braces denote vectors.

The development in implicit finite differences of the water mass balance equation transferred in the building allows us to deduce the expression:

$$\left[\frac{V_i\rho}{\Delta t}+V'_{\inf}\rho+\sum_{j=1}^{N_Z}V'_{jl}(1-\delta_{ij})\rho\right]\omega_i-\sum_{j=1}^{N_Z}V'_{jl}(1-\delta_{ij})\rho\omega_j=V'_{\inf}\rho\omega_{ext}+M'_S+M'_{evap} \tag{18}$$

which may be rewritten in matrix form:

$$[R]\{\omega_{zones}\}=\{S\} \tag{19}$$

where [R] and {S} are matrices constituted of constant terms.

3.2. Integration of evaporative system models in PASSPORT+

The integration of conventional or passive cooling systems consists in integration of additional terms in Eqs. (17) and (19) which represent, respectively, the power brought by the system (available power of the system), and mass of vapour brought by the direct evaporative system [11]. Eqs. (17) and (19) become:

$$[M]\{T_{zones}\}=\{P\}+\{P_{equipement}\} \tag{20}$$

$$[R]\{\omega_{zones}\}=\{S\}+\{M_{equipement}\} \tag{21}$$

3.3. Direct evaporative system description

The construction of the direct evaporative cooling consists, in principle, of an air supply duct incorporating a wetted porous pad (Fig. 3). In such a system, an adiabatic

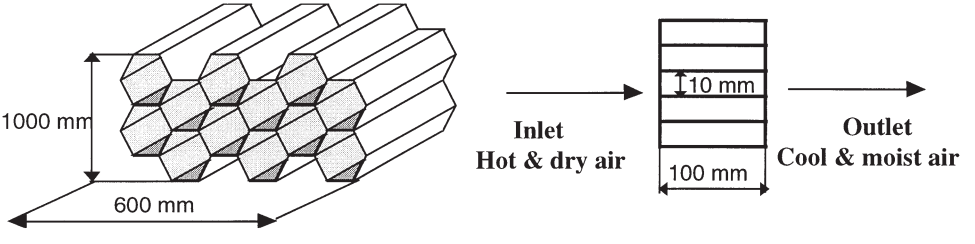

Fig. 3. Pad cooling diagram.

process takes place resulting in cooling and humidifying the air. The use of this system is recommended in very low humidity areas.

The modeled system is made from cellulose. According to Allard and Belarbi model [9], the performance of such a system depends on the size of the wetted surface, thermal and physical conditions of the inlet air and the moisture of the system surface. Experimental and numerical studies of direct evaporative cooling systems [6] show that efficiency value is in the range 0.5 and 0.8. It is defined by the following relationship:

$$\varepsilon_{syst}^{Direct}=1-\exp\left(-\frac{kA_{eff}}{m_a^{'}}\right) \tag{22}$$

For a unity pad cooling surface (A=1 m^2), electrical consumption of the system does not exceed 0.05 Watt for a unit airflow rate (1 l s^{-1}), and the consumption of water does not exceed 0.4 l day^{-1} and by unit airflow rate (1 l s^{-1}) [12].

3.4. Indirect evaporative system description

The modeled indirect evaporative system is made up of a pad coupled to a heat exchanger. The diagram shown in Fig. 6 presents two possible configurations of such a passive system. In the first case, it is a full new air (continuous line in Fig. 4). In the second case, it is a mixed air system (dashed line in Fig. 4). Note that in both cases, the air cooled by adiabatic evaporation is not in contact with the air injected

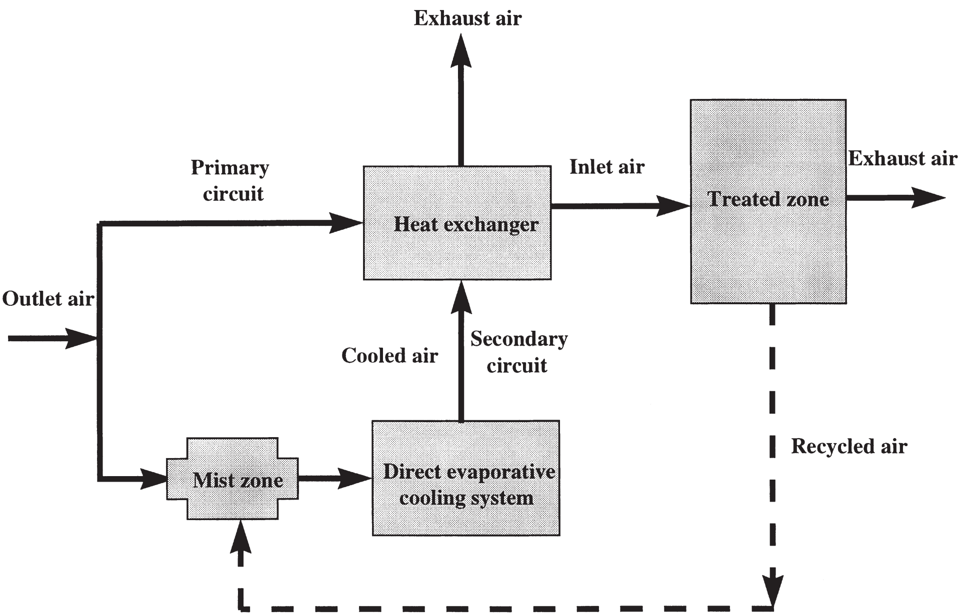

Fig. 4. Indirect evaporative cooling scheme.

in the air conditioned zone since it passes through a heat exchanger; consequently, the absolute humidity of the air remains unchanged.

According to experimental and theoretical results [11], the efficiency of this system is generally between 0.3 and 0.7. It is defined according to Belarbi [6] by the relationship:

$$\varepsilon_{syst}^{indirect}=\varepsilon_{syst}^{direct}.\varepsilon_{exchanger} \tag{23}$$

Its electrical consumption, evaluated for a unit air volume flow rate (1 l s^{-1}), does not exceed 1 W. Its consumption of water calculated for a unitary volume flow rate (1 l s^{-1}), does not exceed 0.3 l day^{-1} [13].

3.5. Cooling protocol for buildings

The developed model supposes that each zone of the building can be equipped with independent cooling systems. When the indoor air temperature is lower than the heating set point temperature, this zone has to be equipped with a heating system to ensure the comfort of the occupants; needs of air conditioning are positive ($Q_{Requirement}>0$) and will be evaluated for heating.

When the value of indoor air temperature is between the heat and the cooling set point temperatures, then the building needs in air conditioning of summer are nil, the building operates in free floating mode, the ventilation suffices to ensure the comfort of the occupants.

When the indoor air temperature is higher than the cooling set point temperature, cooling is necessary. It will be ensured by passive and/or the conventional cooling system. In this case, three modes of operative conditions are possible, according to the need of air conditioning of the building and available energy provided by the passive system:

3.5.1. Full cooling by passive system

The passive evaporative systems should provide alone the cooling of the building in the case where its outlet temperature is inferior or equal to the cooling set point temperature, $T_{Outlet}<T_{Set\ point}$, and where the outlet relative humidity is less than the set point relative humidity ($HR_{Outlet}<HR_{Set\ point}$).

3.5.2. Full cooling by conventional system

The conventional system provides alone the cooling of the building in the case where the outlet temperature of the evaporative system is higher than the set point temperature, $T_{Outlet}>T_{Set\ point}$ and/or where the set point relative humidity is less than the outlet relative humidity ($HR_{Outlet}>HR_{Set\ point}$).

3.5.3. Cooling by combined systems

When energy provided by passive cooling system is not sufficient to ensure comfort conditions in building, both systems, passive and conventional, will operate simultaneously.

3.6. Definition of the outlet parameters

According to the evaluation method previously described by Belarbi [6], based on the interaction between the system and the building models, one can evaluate the building performance indexes: indoor temperature and relative humidity distribution, building requirement energy, theoretical cooling energy of the sink, total available energy brought by the evaporative system, energy used by the system to cool the building, natural cooling normalized capacity, utilisation factor and the system *COP*.

4. Application of the cooling potential approach

Evaluators indexes have been defined for different climatic conditions of 105 south European sites. For the two evaporative cooling techniques, and for different levels of temperature and hygrometry set points (providing the wished comfort degree), assessment of air conditioning requirement index have been undertaken. Evaluation of available and useful cooling potentials index and the rate of energy provided by the evaporative cooling system (natural cooling normalized factor) has been done. This part constitutes a preliminary assistance stage for the choice of the natural cooling technique which will provide a suitable comfort in the building. From real meteorological data of studied sites, we evaluated, during this phase, the climatic potential of each site by considering also their respective cooling needs. This study was achieved during the five months of summer (May to September). Fig. 5a presents values of the theoretical cooling potential index for seven European sites (La Rochelle, Crotone, Carpentras, Roma, Sevilla, Athens, and Lisbon). We can observe very high value of theoretical potential index for Carpentras and Athens, about 18 000 degree-hours (°h), high values of the theoretical index for Sevilla and Crotone, about 13 000°h, average values for Lisbon and Roma, about 9000°h and finally a small value of the theoretical cooling potential index for the site of La Rochelle (2080°h).

Fig. 5b presents the evolution of the useful cooling potential index of the direct evaporative system according to the levels of temperature set points. This index takes into account the efficiency of the evaporative system. For a system with a constant efficiency, it behaves: $IP_{Useful}=\varepsilon_{System}IP_{Available}$.

Fig. 5c presents the evolution of the cooling requirement index according to the temperature set point levels.

These results show that, taken independently, the theoretical cooling potential index does not represent the aptitude of the system to cover the cooling needs. So it is necessary to couple this theoretical potential to the cooling needs of air conditioning (defined from the building and climate characteristics) considering the system performance. From these considerations we have introduced the natural cooling normalized factor [9] defined as the rate between the useful cooling potential index and the cooling requirement index during a given cooling period, τ, and for each temperature set point. Representation of the natural cooling normalized factor, given by Fig. 5d, shows that we can have a theoretical cooling potential index in one location, Sevilla, highest that an other site, La Rochelle, while the natural cooling

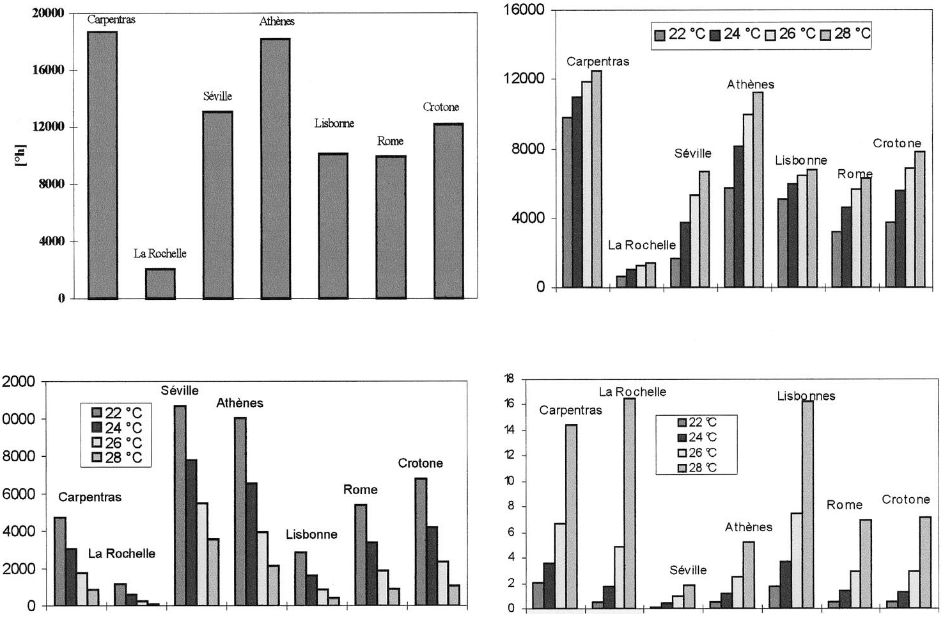

Fig. 5. Cooling potential indexes for seven locations in southern Europe. (a) Theoretical cooling potential index for evaporative cooling system for $T_{Set\ point}$=25°C and HR_{max}=70%. (b) Useful cooling potential index for evaporative cooling system (°h). (c) Cooling requirement index (°h). (d) Natural cooling normalized capacity for evaporative cooling system.

normalized factor in the first site is less than in the second site (Figs. 5a and 5d). Consequently, the natural cooling normalized factor appears to be a more relevant index for passive cooling systems evaluation.

5. Atlas of evaporative cooling system potential

The generalisation of the study to the other sites of southern Europe has enabled us to represent, for each country, a map of the cooling potential indexes which were defined previously. An atlas of available cooling potential index of southern European countries, for the evaporative cooling system, is presented in Figs. 6 and 7. We note that the available cooling potential index of La Rochelle is 35% less than of Sevilla (respectively 4500°h and 7000°h).

For each type of building and for each level of indoor set point temperature, a chart of cooling requirement for an evaporative system was elaborated [6]. Figs. 7a–7d represent the variation of cooling needs of the same type of building in different southern European climates for set point temperature $T_{Set\ point}$=25°C. We can observe, for the same building, that the cooling needs of La Rochelle is 75% less than at Sevilla (respectively 6 kW h/m^2 and 25 kW h/m^2). From these results, we deduce

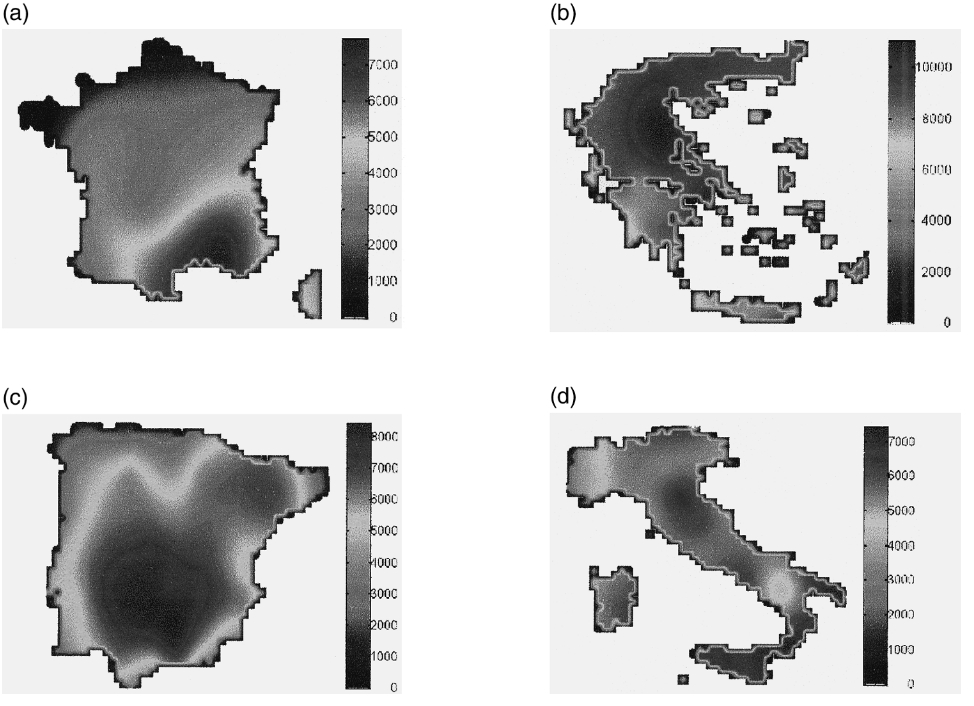

Fig. 6. Atlas of available cooling potential index in southern Europe (°h): (a) France; (b) Greece; (c) Iberia; (d) Italy.

that the site of La Rochelle is far more propitious that Sevilla for the evaporative cooling technique use. Consequently, comparative studies of the European atlas of the different passive cooling techniques could have been used during the first stages of building project, by architects, as helpful decision making tools for the choice of the most adapted passive technique.

6. Application of the global approach

6.1. Building description

The studied building is a three level office and classroom building of La Rochelle (University Institute of Technology), built in 1968. The structure is made of heavy concrete and polystyrene insulating material inside the walls. The concrete thickness is 20 cm and the polystyrene thickness is 3 cm. The average mass of the building is about 420 kg/m^2, its volume heat transmission losses are 0.55 W/m^3 K. The studied zones are located at the second floor. They are made of two active zones.

Zone 1 ($7.10\times25.85\times3.16$ m^3) is oriented to the south and equipped with passive and conventional cooling systems, zone 2 ($9.65\times25.85\times3.16$ m^3) is oriented to the

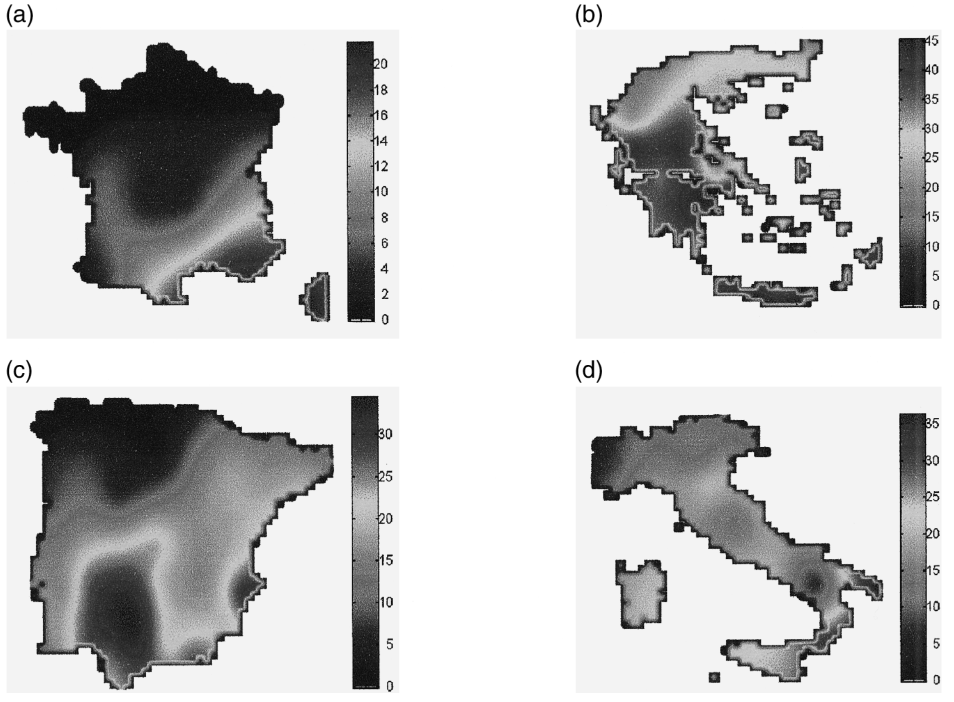

Fig. 7. Atlas of cooling needs in southern Europe (kW h/m^2): (a) France; (b) Greece; (c) Iberia; (d) Italy.

north, without any cooling system and zone 3 regroups the totality of the other ones adjacent to zones 1 and 2 (Fig. 8). Zone 2 was not been equipped with a cooling system because of the orientation of its facade (to the north) and for energy saving aspects.

The internal gains due to the occupant, light and mechanical are considered in two operative periods (20:00–08:00 h and 08:00–20:00 h); they are assessed to 93.8 W/m^2 during the occupied period. The ventilation airflow rate is assumed to be constant and equal to one air change per hour. The operative conditions, considered in the following studies, are defined by set point temperatures fixed to 25°C for cooling and 20°C for heating and maximum relative humidity set point fixed to 70%.

6.2. Simulation result analysis

Preliminary simulations were made in La Rochelle case study building assuming free floating building. The results show the comfort (defined by the two following conditions: $20°C<T_{indoor}<25°C$ and $40\%\leq HR_{indoor}\leq 70\%$) and discomfort conditions in the building during the cooling period. According to Fig. 9, zone 1 is in discomfort conditions during 80% of occupancy period. Consequently, cooling is necessary to ensure comfort for the occupants.

Simulations were performed assuming zone 1 of the building equipped by evapor-

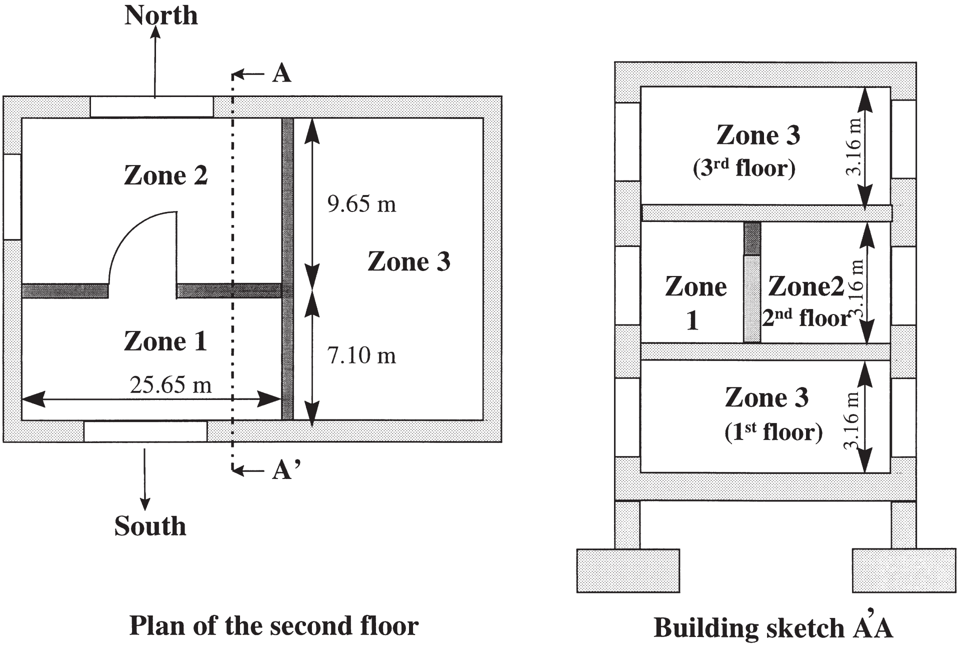

Fig. 8. Case study building description.

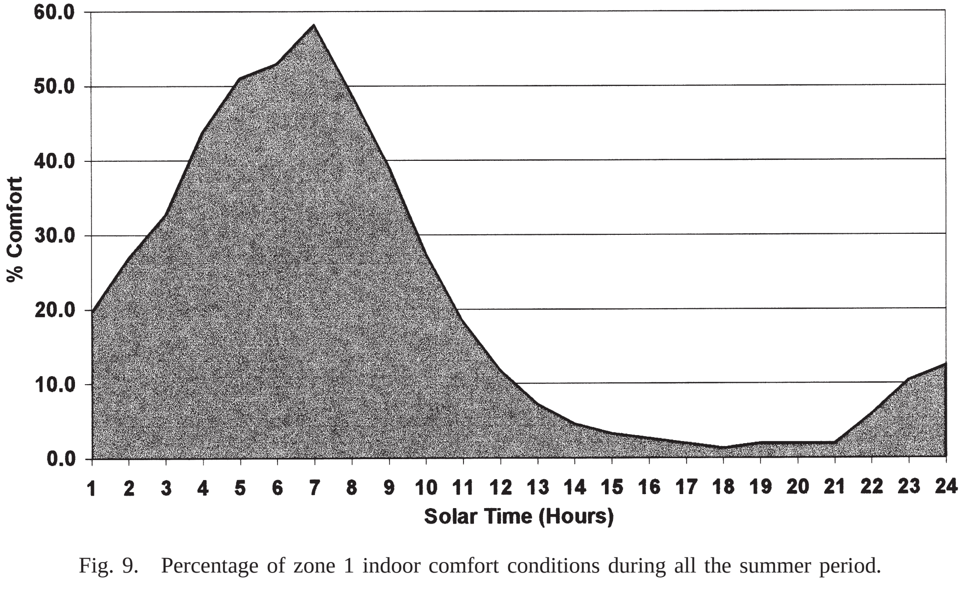

Fig. 9. Percentage of zone 1 indoor comfort conditions during all the summer period.

ative cooling systems previously described and if necessary by conventional system. These systems working period was defined by the cooling protocol which was previously described. Simulation results are represented in Figs. 10a–10d. Fig. 10a presents monthly distribution of theoretical and available energies of direct and indirect evaporative cooling systems. According to Fig. 10a, climatic potential, given by $Q_{Theoretical}$, of direct evaporative cooling system is 8% less than the indirect one ($Q^{Indirect}_{Theoretical}$=195 kW h/m^2 and $Q^{Direct}_{Theoretical}$=180 kW h/m^2) and cooling potential provided by direct evaporative systems, given by $Q_{available}$, is about 20% less than the indirect one ($Q^{Indirect}_{Available}$=80 kW h/m^2 and $Q_{Available}$=65 kW h/m^2).

Fig. 10b illustrates the monthly distribution of useful cooling energy of direct and indirect systems as well as the monthly distribution of cooling requirement of the case study building. According to these results it can be noticed that the direct evaporative system provides 73% of cooling requirement of building. The indirect system provides 90% of cooling requirement of building. Consequently, the indirect cooling system seems more suitable than the direct one for ensuring comfort conditions.

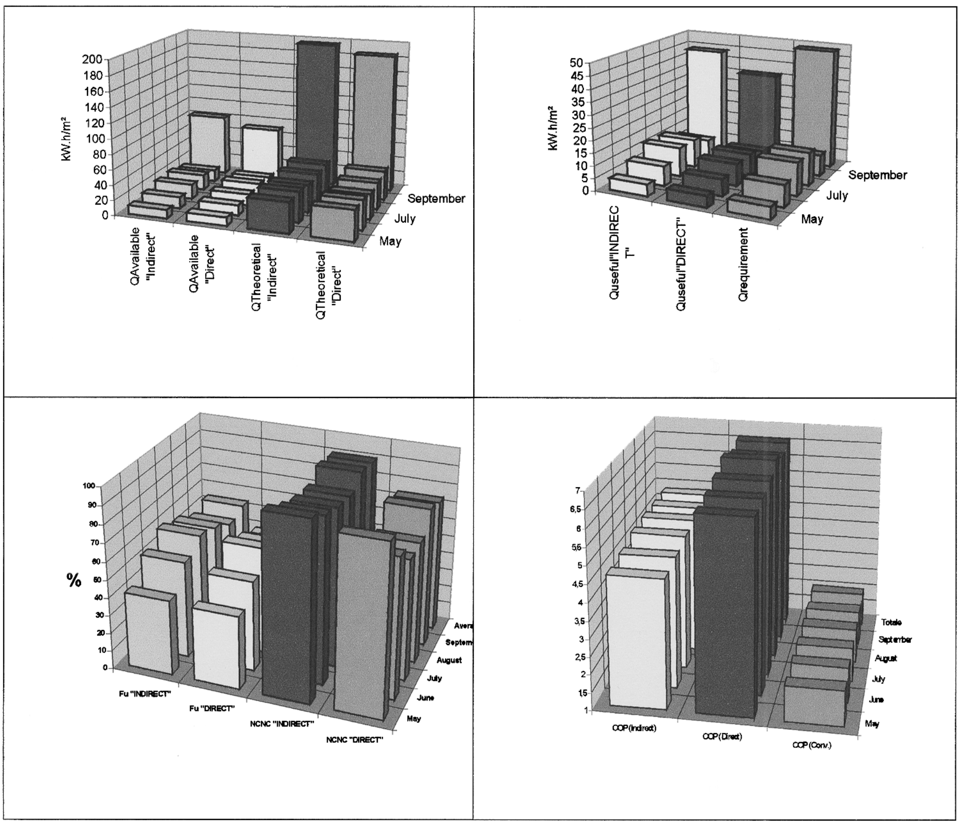

Fig. 10. Monthly distribution during the cooling period: (a) theoretical and available energy; (b) useful energy and building requirements; (c) natural cooling normalized capacity (NCNC) and utilization factor; (d) *COP*.

Fig. 10c presents monthly distribution of natural cooling saving factor and utilisation factor of direct and indirect evaporative cooling systems. As shown in Fig. 10b direct evaporative cooling system ensures building comfort conditions during 72% of cooling period ($\tau_{C,\ direct}$=0.72) and indirect evaporative cooling system provides building comfort conditions during 90% of cooling period ($\tau_{C,\ indirect}$=0.90).

According to Fig. 10c the utilisation factors, f_u, of these systems are about 35% for the direct system and about 52% for the indirect system. These results mean that the direct system operates at an average of 35% of peak power (52% for indirect system). These values can be used to judge the quality of sizing of the cooling systems.

Fig. 10d presents monthly distribution of passive (direct and indirect evaporative system) and active (conventional) systems' *COP*. According to the simulation results it can be shown that the direct evaporative system provides a high energy saving gain (COP_{Direct}=6) relative to the indirect one ($COP_{Indirect}$=4.7). These values can be used to evaluate the energy conservation of the building.

According to the previous simulation results, it is possible to make decisions related to the chosen cooling system which will be used in this building according to the indoor comfort criteria and the energy saving consideration.

7. Conclusions

The simplified approach which was presented in this paper provides information which could be used to contribute to a bioclimatic analysis of European sites and to study the performances of different cooling systems according to the climate characteristics and comfort criteria. An evaluator, called natural cooling normalized capacity, was defined in order to make comparison studies of passive cooling system potential. It allows to select, for each location and for each building type, the adapted passive technique which provides a predefined degree of comfort with less energy consumption. Simulation results, obtained for the evaporative system, show that this technique offers a good cooling potential level for the most of the sites located in the south of Europe. By extending this study to other cooling techniques, we will be able to locate southern sites of Europe suitable for each passive cooling technique. The generalisation of this approach on other European sites allowed to build a decision making tool, in the form of an atlas, that could be used by architects and building offices during the first phases of a project. However, this first approach does not consider internal heat gains contributions, the type of the building and the interaction building–cooling system. In order to get the overall evaluation of a proposed solution, it was improved a refined approach based on integration of passive cooling system and thermal building models. This approach provides accurate results dealing with the thermal building behavior, following the use of passive cooling system.

Application of this approach to a typical French office building located at La Rochelle, in a temperate and humid climate, shows the advantage of using evaporative cooling techniques (direct and indirect) to provide desired indoor comfort conditions and to reduce the building summer air conditioning cost.

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