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The cooling potential of a metallic nocturnal radiator

G. Mihalakakou [a,*], A. Ferrante [b], J.O. Lewis [c]

[a] University of Athens, Physics Department, Division of Applied Physics, Laboratory of Meteorology, Building Physics 5, University Campus, 157 84 Athens, Greece

[b] University of Bologna, Institute of Architecture and Urban Studies, Bologna, Italy

[c] Energy Research Group, University College Dublin, Richview, Clonskeagh Drive, Dublin, Ireland

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Abstract

The dynamic performance of a radiative cooling system for buildings is calculated and presented in the present paper. The cooling system consists of a lightweight metallic radiator covered by a single polyethylene wind screen and used for cooling the ambient air below its designed initial temperature. The cooler air is directed and eventually mixed with the indoor air of the building to provide primarily instantaneous thermal comfort during the night and secondly to cool the interior mass of the building by convection, thus creating a cold storage for the following day. The present system analysis was performed for one among a large number of rehabilitated historical industrial buildings located in Legnano—a city close to Milano. The dynamic thermal performance of the system during the summer period has been calculated using an accurate mathematical model. Temporal variations of the radiator performance have been developed as a function of all the input parameters. © 1998 Elsevier Science S.A. All rights reserved.

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1. Introduction

The energy consumption of buildings for cooling purposes has increased considerably during the last decade. Especially in hot climate countries, the penetration of conventional air conditioning units is extremely important, having a serious impact on the peak electricity load.

The use of passive and hybrid cooling techniques involving dissipation of the remaining excess heat of the building to a natural heat sink, like the sky or the ground have gained increasing acceptance in recent years [1,2].

Radiative cooling techniques are based on the principle of heat loss by long-wave radiation emissions, from a body towards another body of lower temperature, which is regarded as the heat sink. In the case of buildings the cooled body is the building and the heat sink is the sky, since the sky temperature is lower than the temperatures of most of the objects upon the earth [3].

Long-wave radiation emissions is a continuous day and nighttime phenomenon. However, during the daytime the long-wave radiation emitters are exposed to solar radiation. The objects absorbing solar radiation are heated and that in most cases outweighs the cooling effect produced by the emission of long-wave radiation [4]. For this reason, the net cooling effect of the radiators can be obtained only during the nighttime (nocturnal radiation).

There are two methods of applying radiative cooling in buildings. The first method is called direct, or passive, radiative cooling. In this case the building envelope radiates towards the sky and gets cooler. The second method is called hybrid radiative cooling. In this case the radiator is not the building envelope but usually a metal plate [3].

There are several design options for applying passive radiative cooling in buildings which involve three basic types of nocturnal radiators: (1) a movable insulation system which can be moved over the high mass roof of the building, (2) a lightweight, usually metallic radiator which cools the ambient air below its initial temperature and (3) an unglazed water-type solar collectors.

A lightweight metallic radiator with an air space and ambient air flow underneath was used in this research (Fig. 1). The operation of such a radiator is the opposite of an air flat plate solar collector. Air is cooled by circulating under the metallic surface of the radiator before being directed into the building to provide instantaneous cooling during the night and to cool the interior mass of the building by convection, creating a cold storage for the following day. The main two differences between a lightweight metallic radiator and an air

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[*] Corresponding author. Tel.: +30 1 7284934; fax: +30 1 7295282.

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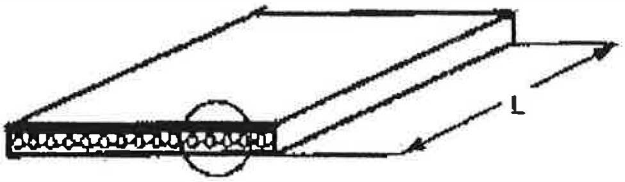

Fig. 1. A lightweight metallic radiator.

flat plate solar collector are firstly the different operating period during the day and secondly the radiator is not equipped with glazing material since ordinary glazing used in solar systems is not transparent to long-wave radiation.

In the present study, the nocturnal radiator is covered with a thin polyethylene wind-screen which reduces the convective heat gains from the warmer ambient air to the radiator, thus improving the efficiency of the system. Taking into account that wind-screens have to be transparent to long-wave radiation, thin polyethylene films (60–100 μm) can be used in these radiators.

The main objective of this paper is to investigate the energy potential of a nocturnal lightweight wind-screened radiator under real climatic conditions, used for cooling a restored historical building in Italy and, in this respect, to determine the feasibility of the whole system. The effectiveness and the cooling potential of the cooling system is investigated and presented in a format suitable for designers' use.

2. Modeling of the nocturnal radiator

The mathematical formulation of radiant cooling techniques can be described as follows:

- Calculation of the climatic potential for the net radiant heat loss as a function of the ambient air temperature, relative humidity and cloudiness.
- Calculation of the 'stagnation' temperature, as well of the outlet temperature of the heat transfer fluid flowing through a one-dimensional path in a radiator.
- Calculation of the cooling energy delivered to the building, as a function of the design details of the radiator and the air flow.

The climatic potential for radiant cooling techniques was taken into consideration by various researchers [5–7,4,8]. The mathematical formulation expressing the emissivity of clear sky, as a function of the ambient dew point temperature, can be written as follows [7]:

$$E_s = 0.787 + 0.764\ln[(T_{dp}+273)/273] \quad (1)$$

Cloudiness has an effect on the atmospheric radiation which can be expressed by the factor C [9]:

$$C = 1 + 0.0224n - 0.0035n^2 + 0.00028n^3 \quad (2)$$

Therefore, the sky emissivity is given by:

$$E_c = E_s(1 + 0.0224n + 0.0035n^2 + 0.00028n^3) \quad (3)$$

where n is the total opaque cloud amount (0 for clear sky and 1 for overcast sky).

The convective heat exchange between the radiator and the ambient air, which can express the cooling energy delivered to the building, can be written as [4]:

$$Q_r = h(T_r - T_a) \quad (4)$$

where h is the convective heat transfer coefficient which is a function of wind velocity. Different formulations have been expressed for evaluating the above mentioned coefficient [10–13]. The convective heat transfer coefficients, used in the present study are calculated using the following expressions.

- For a radiator without wind-screen

$h = 5.7 + 3.8V$ if $V < 4$ m/s

$h = 7.3V^{0.8}$ if $V > 4$ m/s

- For a radiator covered by a single Polyethylene layer wind-screen

$$h = 0.5 + 1.2V^{0.5} \quad (5)$$

The stagnation temperature of a metallic wind screened radiator is the minimum temperature that the radiator can attain and can be calculated as a function of the air and sky temperatures, cloudiness and the transmittance of the wind-screen. Thus, it can be expressed as follows [13]:

$$T_{st} = (0.544C_n t_w E_r T_{cs} + hT_a)/(0.544C_n t_w E_r + h) \quad (6)$$

where C_n is the formulation presented in Ref. [7] for the cloudiness coefficient:

$$C_n = 1 - 0.56n$$

The exit air temperature of the heat transfer fluid flowing through a one-dimensional path in a radiator is presented by the following expression [3]:

$$T_{out} - T_{st} = (T_{in} - T_{st})\exp(-U_p A/mc_p) \quad (7)$$

where A is the surface of the radiator and U_p the overall heat transfer coefficient between the air circulating under the radiator and the ambient air, and can be calculated by the following expression:

$$U_p = 1/[(1/h_f) + (1/h) + (D_r/K_r)] \quad (8)$$

where D_r is the thickness and K_r the thermal conductivity of the radiator and h_f is the effective heat transfer coefficient defined by the following expression:

$$h_f = h + 4\sigma T_a^3 \quad (9)$$

where h is the convective heat transfer coefficient between the wind screened covered radiator and the ambient air and is given by Eq. (5) for a wind-screen covered radiator.

3. The rehabilitation process of the urban area of Legnano

The urban area of Legnano is characterised by a strong combination of natural and artificial, man-made urban factors. The restoration procedure is based on the combination of the individual buildings' design and of the urban-bioclimatic architecture. In order to combine effectively the individual building design method and the urban planning several different analysis processes were followed. For this reason, all the natural–environmental and artificial man-made systems were analysed. The various climatic factors of the present urban area were studied in order to investigate the effectiveness and the energy potential of a passive cooling or heating system such as the radiative coolers or an earth-to-air heat exchangers system as well as the contribution of natural and night ventilation techniques and of daylighting to the energy efficiency of buildings. The environmental characteristics of the urban area were divided into the following three groups:

(a) Natural systems
(b) Climatic elements and measurements
(c) Anthropological, artificial and infrastructure systems

For the rehabilitation, the area 'Cantoni', which is a significant sample area in the city of Legnano, was selected primarily for its intermediate scale and secondly for its very large number of natural–artificial components in a relatively restricted space. These components, which cross the heart of the city, give the area the feature of complexity and of interrelation between the natural–environmental and anthropological systems.

The area 'Cantoni' divides the city of Legnano in two different historical urban centres—Legnano and Legnanello. The whole area consists of complex water and natural green systems, such as the river Olona, and of a very large number of historical industrial buildings. The rehabilitation project of the urban area Cantoni was based primarily on a water systems investigation and secondly on the energy efficiency investigation of the existing urban forms such as the industrial buildings.

The water systems were selected as the most representative among natural–environmental factors of the area for a large scale investigation. An extensive and integrated analysis of the water flowing system was developed and presented in Ref. [14].

The significance of urban re-planning at this scale is regarded as necessary, considering that the rehabilitation process of buildings cannot exist separately from the restoring process of the whole area, especially because buildings should be examined also from outside, [15].

The construction of the Cantoni buildings started in 1870 and it continued until 1949. The buildings were industrial and used for velvet weaving. The rehabilitation process of the historical buildings was mainly based on the following methodological approaches: (i) analysis and description of the urban infrastructure and especially of existing connections; (ii) analysis and description of all existing buildings in relation to their orientations; (iii) analysis and description of all the existing buildings as well as of the urban open spaces between buildings in relation to various climatic indicators; (iv) analysis and description of all the existing buildings and of the urban open spaces between buildings in relation to the direction and velocity of the prevailing winds.

The step by step restoration methodological analysis and its results were presented in Ref. [16].

4. Assessment of the energy potential of the radiator

4.1. Calculation of the radiator cooling effectiveness

In order to assess the thermal performance of the metallic radiator under real climatic data, comprehensive basic parametric studies have been performed. The thermal model described in Section 2 was used to simulate the performance and the feasibility of a typical nocturnal horizontal radiator 14 m in length and 7 m in width.

The spacing between radiator and insulation was 3 cm. The radiator was considered to be a stainless steel plate, having an emissivity of 0.9 in the IR band-width. The radiator was used only during the nighttime. Fan power is necessary in the radiator to draw outside air through the radiator. For the simulations the air velocity was set at 3 m/s.

The mathematical model was used primarily to calculate the sky temperature depression and the stagnation temperature of the radiator as well as the potential rate of cooling power transferred to the building by this radiator.

The Meteorological Station of Castellanza in Legnano and of Milano provided the real climatic data used in the present study. The following climatic data were used in this research:

- Ambient air temperature (°C)
- Global solar radiation (W/m^2)
- Diffuse solar radiation (W/m^2)
- Relative humidity (%)
- Wind speed (m/s)
- Cloud cover

Calculations extend over the time period 1983–1993 for the months July and August using hourly values of the air temperature and from 1800 to 0700 LST.

For the calculations four different wind speeds were used: 1, 1.5, 2 and 2.5 m/s. The temporal variation of the ambient air temperature as well of the radiator's stagnation temperature for different wind speeds, for a clear night (cloud cover, $n=0$) as well as for a cloudy night (cloud cover, $n=4$) of July are given in Figs. 2 and 3, respectively. As shown, the stagnation temperature depression of the radiator for a clear and dry day was about 7.5°C for 1 m/s wind-speed, about 6°C for wind-speed 1.5 m/s, 4.2°C for 2 m/s and 2.9°C for 2.5 m/s wind-speed. The ambient air temperature fluctuated between 23.1 and 16°C. Accordingly, for a cloudy day the stagnation temperature of the radiator fluctuated in the range of 17.7 to 10.6°C for 1 m/s wind-speed, 16.8 to 9.7°C for 1.5 m/s, 15.7 to 8.5°C for 2 m/s and 14.5 to 7.2°C for 2.5 m/s.

Fig. 4 shows the mean daily useful cooling energy delivered to the building by the radiator for a clear and for a cloudy day and for various wind speeds. As shown, the useful cooling

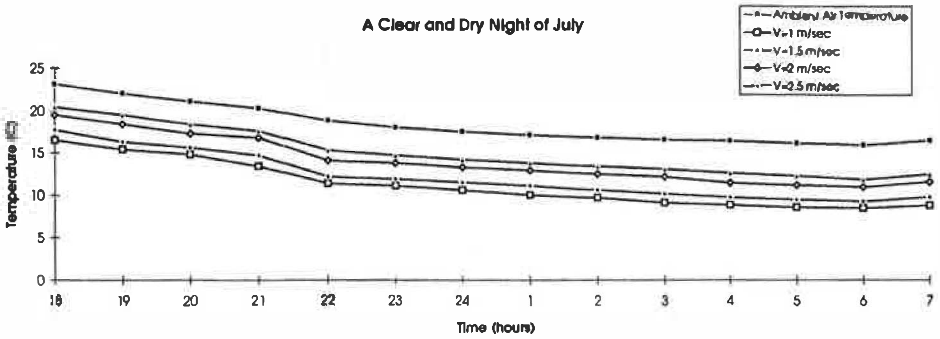

Fig. 2. Temporal variation of the ambient air temperature and of the radiator's stagnation temperature for different wind-speeds and for a clear night of July.

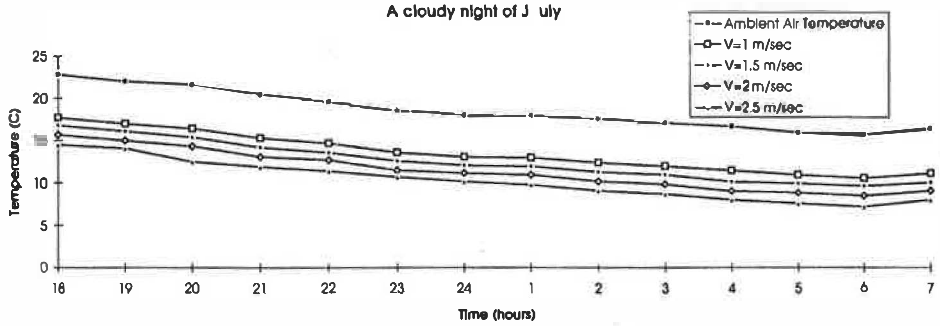

Fig. 3. Temporal variation of the ambient air temperature and of the radiator's stagnation temperature for different wind-speeds and for a cloudy night of July.

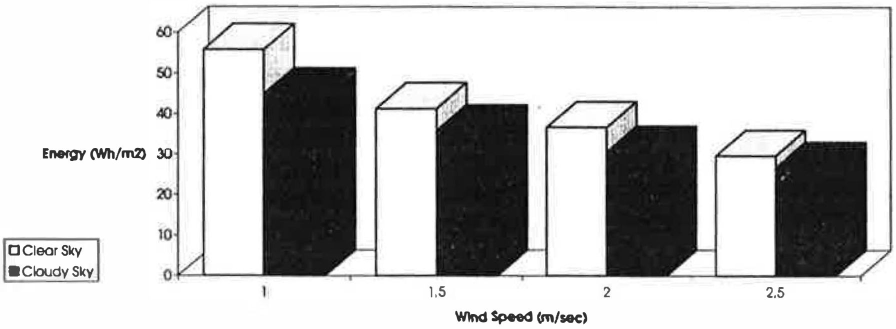

Fig. 4. Mean daily useful cooling energy transferred to the building by the radiator for a clear and a cloudy day of July.

energy varied between 29.7 to 55.8 W h/m^2 for a clear sky and between 26.7 to 44.9 W h/m^2 for a cloudy sky.

4.2. *Calculation of the building thermal performance using the radiative cooler*

The thermal behaviour of one industrial building in the Cantoni area, was calculated using TRNSYS environment [17]. TRNSYS is a transient system simulation programme with a modular structure which facilitates the addition to the programme of mathematical models not included in the standard TRNSYS library. For the analysis the building 13–14 of Fig. 5 was selected. The whole building was regarded as one thermal zone, ($20 \times 20 \times 3.2$), with floor on the ground and with internal partitions. Hourly values of the climatic measurements were used in order to calculate the indoor air temperature values for a representative day of July. The city of Legnano was selected as station. The ventilation rate was taken equal to 8 air changes per hour.

Furthermore, the building was equipped with a lightweight stainless steel radiative cooler covered with a single layer polyethylene wind-screen. The radiator was 15 m in length and 10 m in width and the air velocity through the radiator was fixed at 2.5 m/s. The radiator was used during the night for passive cooling purposes. Fig. 6 shows the air temperature values inside the building's thermal zone without the use of the cooler as well as the indoor air temperature when the building is equipped with the cooler, for a representative clear-sky night of July. As it can be seen the indoor air temperature fluctuated between 17.9 to 28.5°C without the use of radiator and between 11.8 to 24.2°C using the nocturnal radiator.

Fig. 7 shows the building indoor air temperature for a representative cloudy night of July. As shown, the indoor temperature varied in the range of 15.8 to 24.3°C without the use of the cooler and in the range of 12.4 to 22.1°C with the air flow from the radiative cooler.

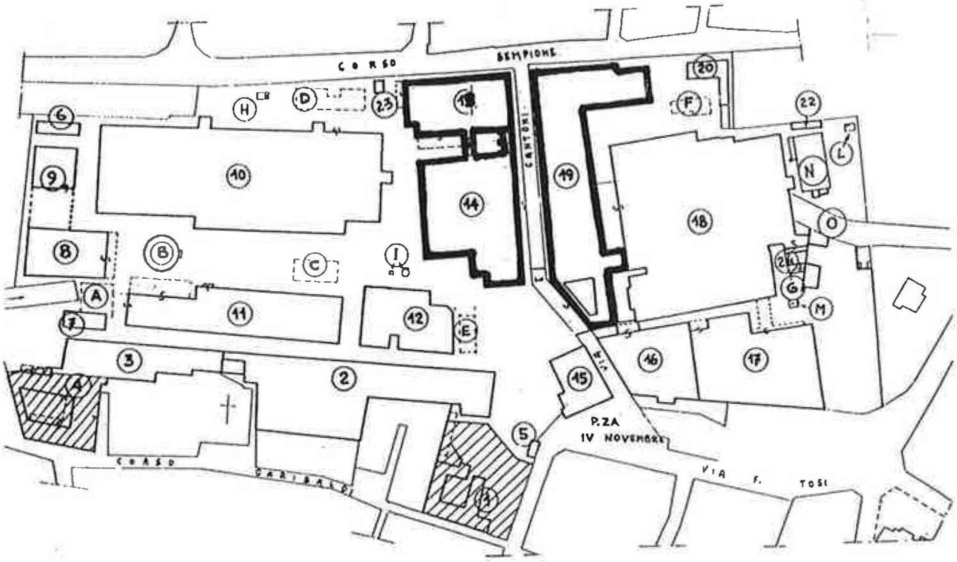

Fig. 5 . The Cantoni area and the buildings.

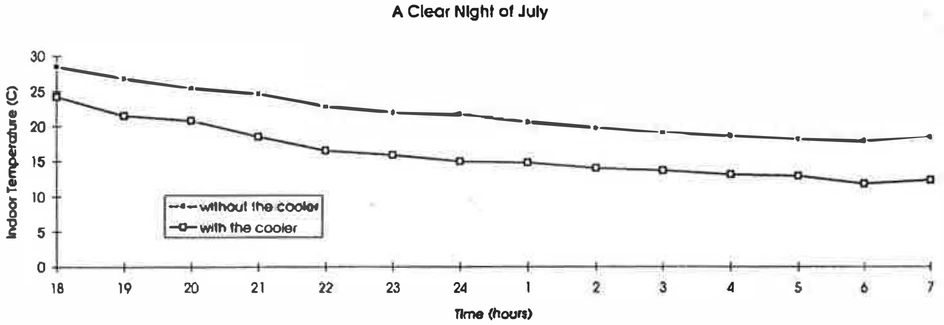

Fig. 6. The temporal variation of the indoor air temperature without and with the radiator and for a clear-sky night.

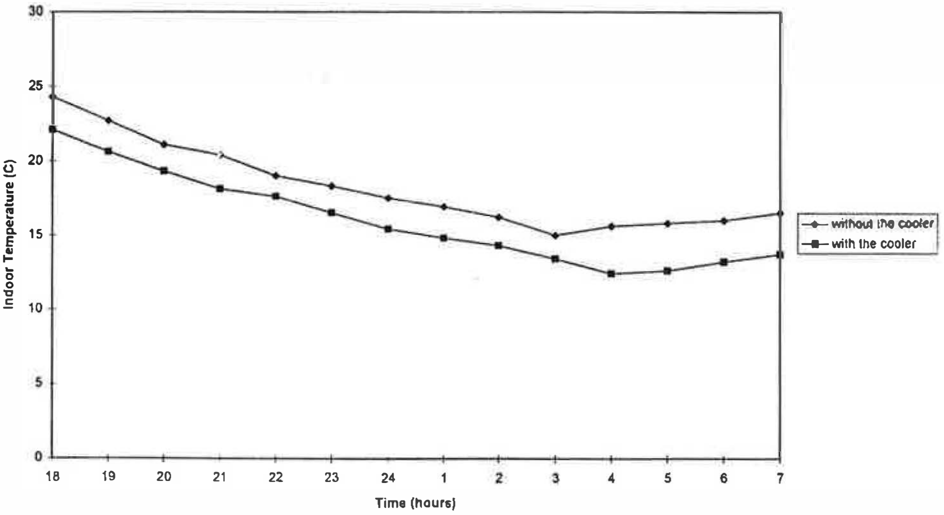

Fig. 7 . The temporal variation of the indoor air temperature without and with the radiator and for a cloudy night.

5. Conclusion

The dynamic thermal performance of a lightweight metallic radiator covered by a single polyethylene wind screen was calculated using accurate mathematical model. The metallic radiator was designed for one among a large number of rehabilitated historical buildings in Italy. Finally, the thermal behaviour of the above mentioned building equipped with a lightweight radiative cooler was calculated using a transient system simulation programme.

6. Nomenclature

A	Surface of the radiator (m^2)
C_n	Cloudiness coefficient
C_p	Specific heat capacity of the air (J/kg °C)
D_r	Thickness of the radiator (m)
E_c	Emissivity of the cloudy sky
E_r	Emissivity of the radiator
E_s	Emissivity of clear sky
h	Convective heat transfer coefficient (W/m^2 °C)
h_f	Effective heat transfer coefficient (W/m^2 °C)
K_r	Thermal conductivity of the radiator (W/m^2 °C)
m	Mass flow rate of the air flowing through the radiator (kg/s)
n	Total opaque cloud amount
Q_r	Convective heat exchange between the radiator and the ambient air (W)
T_a	Ambient air temperature (°C)
T_{cs}	Clear sky temperature (°C)
T_{db}	Ambient dew point temperature (°C)
T_{in}	Inlet temperature of the heat transfer fluid flowing through the radiator
T_{out}	Exit temperature of the heat transfer fluid flowing through the radiator (°C)
T_{st}	Stagnation temperature of the radiator (°C)
t_w	Long wave transmittance of the wind-screen
U_p	Overall heat transfer coefficient between the air circulating under the radiator and the ambient air (W/m^2 °C)
V	Wind speed (m/s)

Greek characters

σ	Stefan–Boltzmann constant

References

[1] J. Cook, Passive Cooling, MIT Press, 1989.
[2] G. Mihalakakou, On the Use of Ground for Heat Dissipation, PhD Dissertation, University of Athens, 1994.
[3] A. Argiriou, Radiative Cooling, in: Santamouris, D. Asimakopoulos (Eds.), in the project-book, Passive Cooling of Buildings, James & James edn., UK, 1995.
[4] G. Givoni, Passive and Low Energy Cooling of Buildings, Van Nostrand Reinhold, an International Thomson Publishing, USA, 1994.
[5] P. Berdahl, R. Fromberg, The thermal radiance of clear skies, J. Solar Energy 29 (1982) 229–314.
[6] P. Berdahl, M. Martin, Emissivity of clear sky, J. Solar Energy 33 (1984) 663–664.
[7] E. Clark, C. Allen, The estimation of atmospheric radiation for clear and cloud skies, in: Proceedings of the Second Nat. Passive Solar Conference, Vol. 2, 1978, pp. 675–678.
[8] M. Martin, Radiative cooling, in: J. Cook (Ed.), Passive Cooling, MIT Press, 1989.
[9] E. Clark, Passive/hybrid comfort cooling by thermal radiation, in: Proc. Int. Passive Cooling Conf. Miami Beach, FL, 1981, pp. 682–714.
[10] E. Clark, P. Berdahl, Radiative cooling: resource and applications, in: Proc. of the 5th Nat. Passive Solar Conf., Amherst, MA, Passive Cooling Handbook, US Department of Energy Publication 375, 1980, pp. 167–201.
[11] J. Duffie, W. Beckmann, Solar Energy Thermal Processes, Wiley, New York, 1974.
[12] D.G. Hansen, J.I. Yellot, A study of natural cooling processes in a hot arid region, in: Proc. of 2nd Nat. Passive Solar Conf., Philadelphia, USA, 1978, pp. 653–657.
[13] M. Mostrel, B. Givoni, Windscreen in Radiant Cooling, J. Passive Solar, 1982, pp. 229–238.
[14] A. Ferrante, G. Mihalakakou, J.O. Lewis, The energy efficiency investigation of historical industrial buildings, in: Proceedings of Int. Conf. Healthy Buildings '95, Milano, Italy, 1995.
[15] A. Bitan, The high climatic quality of the future, J. Atmos. Environ. 26B (1992) 313–329.
[16] A. Ferrante, G. Mihalakakou, C. Odolini, The rehabilitation investigation of a historical urban area, J. Renewable Energy 10 (1997) 577–584.
[17] TRNSYS 13.1, A transient system simulation programme developed from Solar Energy Laboratory, University of Wisconsin-Madison, Madison, WI, 1990.