ANALYSIS OF A VENTILATED RESIDENTIAL BUILDING BY MEANS OF AN AIR BASED RADIATIVE COOLING SYSTEM

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ABSTRACT

The thermal performance of a monozone building located in Lisbon is studied when night ventilation combined with radiative cooling is used in order to remove the heat from indoors. For simulating the thermal behaviour of the building, a commercial energy building software is used. The potential for radiative cooling in Lisbon, as well as the efficiency of the radiative cooling system were investigated previously. A validated numerical model is used in order to predict the temperature of the air at the outlet of the radiative system. The outdoor night air cooled by the radiative system is then used to cool the building by ventilation. Various simulations are performed using, as weather source, averaged values derived from the typical reference year of Lisbon. It is concluded that when properly designed, a radiative cooling system such as described here, may enhance the effectiveness of night cooling.

KEYWORDS

Night ventilation, radiative cooling, thermal simulation.

INTRODUCTION

The recent statistics regarding the large amount of energy consumed in buildings and the environmental concerns over greenhouse gas emissions and ozone depletion, have determined the today's specialists involved in the construction process to move toward more passive and hybrid approaches to cooling. Among most often-proposed solutions for reducing the cooling loads in buildings there is nocturnal radiative cooling technique. The performance of this technique depends mainly on the strategies adopted in order to "produce" and to make use of the radiative cooling, and on the local climatic conditions. Radiative cooling has received wide attention in recent years, various authors aiming to study in detail the physical processes influencing its performance. Among most recent reviews on radiative cooling we mention here those performed by Santamouris et al (1996) and Givoni (1994). Most of the studies, however, have focused more on performance of the radiative cooling systems and less on the strategies meant in order to make greater use of this phenomenon.

The present study represents the last part of a more general one that had as objective the assessment of the applicability of radiant cooling as a mode of heat dissipation from a typical low-rise building located in Lisbon. The radiative cooling system chosen circulates air underneath a metal deck (flat plate) exposed to sky, lowering in such a way the outdoor air temperature. The cool air is then directed into the building to provide instantaneous cooling. The building is to be cooled during the night when the outdoor air temperature is low enough to allow the use of night ventilation alone. Therefore, this approach might be seen as a hybrid technique. The research is aimed focusing on the cooling capacity and on the decrease of the peak temperature that can be reached by a radiative cooling system. These values are compared against similar values obtained in the case when the night ventilation is used alone. The simulations were carried out for a monozone building (5 by 5 by 3 m) with a single window facing south.

DESCRIPTION OF THE RESEARCH

In order to accomplish the aim stated above, two steps had to be performed:

1. determining the temperature of the fluid at the outlet of the radiative cooling system
2. simulating the thermal behavior of the building

The temperature of the air at the outlet of the radiative panel has been calculated using a CFD code. The geometrical configuration of the radiative cooling system is shown in Figure 1.

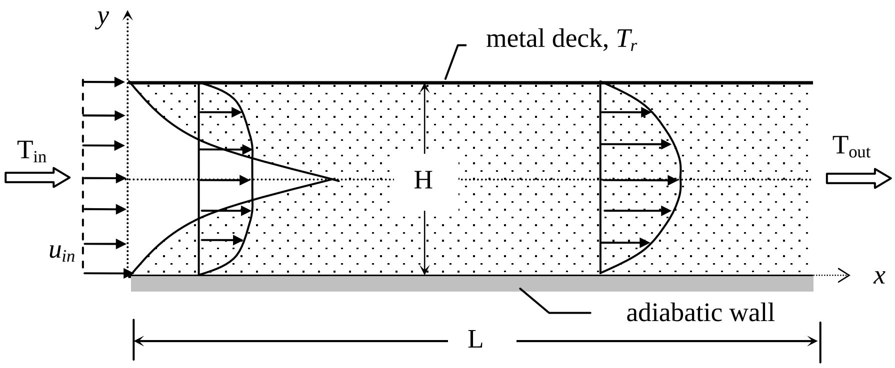

Figure 1: Schematic of the radiative system

The numerical model (CFD code) is mainly based on the model whose brief description is given in Aelenei et al (2002). The presently employed numerical model, however, has been updated in the sense that the temperature of the metal deck is not longer considered as known, but is calculated. Another major difference comes from the fact that this new version does not account for turbulence. The program solves the transport equations for momentum and enthalpy and assumes the flow to be nearly compressible, steady, laminar and two-dimensional. These equations can be written in a generalized form for the dimensionless variable Φ, as in Patankar (1980):

$$\frac{\partial}{\partial x}(\rho u \phi) + \frac{\partial}{\partial y}(\rho v \phi) = \frac{\partial}{\partial x}\left(\Gamma_\phi \frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma_\phi \frac{\partial \phi}{\partial y}\right) + S_\phi \qquad (1)$$

The boundary conditions were stated as follows:

- At inlet ($x = 0$): $\dot{m}$ = constant; v = 0; $T_{in} = T_a$ (ambient air temperature)
- At the top wall (y = H): u = 0; v = 0; k_f dT/dy = h (T_a- T_r)
- At the bottom wall (y = 0): u = 0; v = 0; $\partial T / \partial y = 0$ (adiabatic wall).

- At outlet (x = L): p = 0; $\partial[u, v, T]/\partial x = 0$

The description of the algorithm used for solving the non-linear second order partial differential equations on form given by Eqn. 1 is also given in Aelenei (2002).

The dimensions chosen for the channel shown in Figure 1 are 4 x 2 x 0.02 m. The metal plate is supposed to be made of steel 0.003 m thick, painted on the exterior side with ordinary white paint. The climatic data required to run the numerical model have been introduced on the basis of the "Test Reference Year" correspondent for Lisbon. The analysis has been carried out for August, that is the hottest month. The average values of data input, as a function of the hour of the day are given in Table 1.

TABLE 1
Climatic data of Lisbon for August

Time	Dry bulb temp. (ºC)	Relative humidity (%)	Wind speed (m/s)	Time	Dry bulb temp. (ºC)	Relative humidity (%)	Wind speed (m/s)
1	19.2	0.68	3.63	13	26.2	0.53	3.57
2	18.8	0.69	3.43	14	27.4	0.51	3.92
3	18.4	0.7	3.38	15	28	0.5	4.82
4	18.3	0.7	3.9	16	28.2	0.5	5.43
5	17.9	0.71	3.51	17	27.5	0.5	5.64
6	17.8	0.71	3.3	18	26.6	0.51	6.16
7	17.7	0.72	3.09	19	24.7	0.56	6.8
8	18.2	0.72	3.4	20	22.7	0.61	6.64
9	19.8	0.7	3.6	21	20.9	0.64	6.42
10	21.4	0.64	4	22	20.3	0.65	5.9
11	23.3	0.6	3.9	23	19.8	0.66	4.87
12	24.9	0.56	3.6	24	19.6	0.68	4.24

The temperature of the air at the outlet of the panel, T_{out}, has been estimated accounting for five different fluid flow rates. These were calculated so that to obtain ventilation rates for the building under investigation ranging from one to twelve air changes per hour (ACH). The values of T_{out} resulted for the hours when the building is to be ventilated are given in Table 2.

TABLE 2
Outlet radiator temperature for different flow rates

Time	T_{in}	T_{out}				
		ACH 1	ACH 2	ACH 4	ACH 8	ACH 12
21:00	20,9	19,25	19,73	20,1	20,36	20,47
22:00	20,3	18,58	19	19,47	19,74	19,85
23:00	19,8	17,88	18,45	18,88	19,18	19,31
0:00	19,6	17,55	18,16	18,6	18,95	19,08
1:00	19,2	16,97	17,6	18,14	18,5	18,64
2:00	18,8	16,52	17,2	17,72	18,08	18,25
3:00	18,4	16,1	16,8	17,3	17,68	17,83
4:00	18,3	16,16	16,8	17,3	17,62	17,76
5:00	17,9	15,65	16,3	16,83	17,2	17,34
6:00	17,8	15,48	16,1	16,7	17,07	17,22
Average	19,1	17,014	17,614	18,104	18,438	18,575
DT = T_{in} - T_{out}	-	2,086	1,486	0,996	0,662	0,525

As shown in Table 2, the values of T_{out} correspondent for each flow rate were averaged and the resulted values were then subtracted from the inlet correspondent averaged temperature. The reduction of the temperature of the fluid DT has been obtained in this way. One may notice the effect of altering the air flow rate on the temperature difference between radiator inlet and outlet in Figure 2.

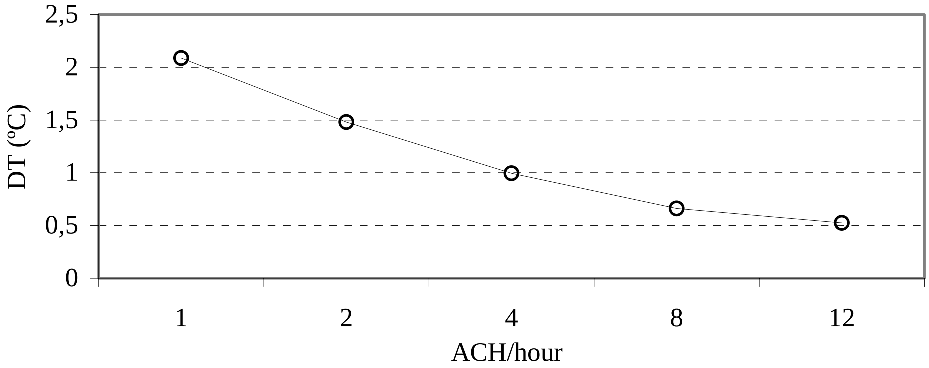

Figure 2: Air flow rate versus DT

For simulating the thermal behavior of the building, the software NewQUICK* has been employed. The program is based on the airflow-networking model as described in Joubert et al (1989) and Mathews et al (1997). It can predict hourly air temperatures and relative humidities as well as heating and cooling loads. Complete load and energy analysis of a building can further be executed in order to design an efficient air-conditioning system (HVAC). The simulation tool executes dynamic thermal calculations for realistic 'real life' temperature and load predictions and accounts for the thermal mass. External shading devices, interior mass, direct solar heat gains and ground contact surfaces can be modeled. The program proved its usefulness in the present investigation mainly because of its ability to simulate various ventilation strategies.

The simulations were carried out for a monozone building (5 by 5 by 3 m) designed with traditional building materials: 0.21m brickwork wall as external envelope, and a 0.07m brickwork wall as internal partition. In addition to the data regarding building size, construction materials, thermal characteristics, etc., climatic data concerning temperatures, relative humidities, global radiation and diffuse radiation have also been introduced. The thermal behavior of the building has been simulated for various air changes rates during the night, adopting two ventilation strategies. The first approach consisted in introducing outdoor fresh air into the building interior (night cooling), whereas in the second approach, the outdoor air meant to remove the heat from interior has been circulated first through the radiative cooling system. In this way, the night cooling effect has been enhanced. In both cases the ventilation has been achieved by mechanical means. Furthermore, this analysis has been performed for two building external envelope configurations. One for which the building is not thermally insulated, and the other one for which the external walls are thermally insulated with expanded polystyrene of 0.04m. Before viewing the results, few other relevant facts should be pointed out first:

- The window is assumed to stay closed throughout the day.
- The building is a standard type allowing for minimum ventilation due to infiltrations.
- Neither internal loads nor occupancy factors were accounted in the simulation.

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* NewQUICK Version 1.01 – developed by E.H. Mathews

- The energy consumption has been calculated assuming that the air conditioning equipment is working from 12:00 a.m. to 6:00 p.m. having as setpoint an indoor temperature equal to 23 ºC.
- The format of climatic data required to run the simulation is similar to that given in Table 1, which means that all the calculations are performed for a design day.

The peak and averaged temperatures correspondent to the design day of August, and the monthly cooling loads calculated for each case emerged in this analysis, are given in Table 3.

TABLE 3
Cooling loads (kWh) with maximum and average temperatures (ºC) resulted from various simulations

	Non insulated building						Insulated building					
	Night Cooling			Radiative cooling			Night Cooling			Radiative cooling		
	T_{max}	T_{med}	Cooling Load	T_{max}	T_{med}	Cooling Load	T_{max}	T_{med}	Cooling Load	T_{max}	T_{med}	Cooling Load
0 ACH	26,51	25,78	264,4	26,51	25,78	264,4	26,81	26,3	208,3	26,81	26,3	208,3
1 ACH	26,23	25,31	242,4	26,15	25,15	233,7	25,97	25,33	180,2	25,73	25,06	166,2
2 ACH	26	24,91	223,5	25,9	24,72	212,1	25,36	24,63	151,7	25,07	24,3	136
4 ACH	26,53	24,3	191,2	25,51	24,08	179,7	24,56	23,7	111,3	24,22	23,3	90
8 ACH	25,16	23,48	146,2	25,04	23,27	134,1	23,64	22,64	54,1	23,33	22,3	33,8
12 ACH	24,85	22,95	115	24,73	22,75	101,2	23,14	22,06	21,3	22,86	21,74	8,1

DISCUSSION OF RESULTS

Figure 3 shows the amount in reduction of the cooling loads as a percentage relative to the most unfavorable situation (264,4 kWh).

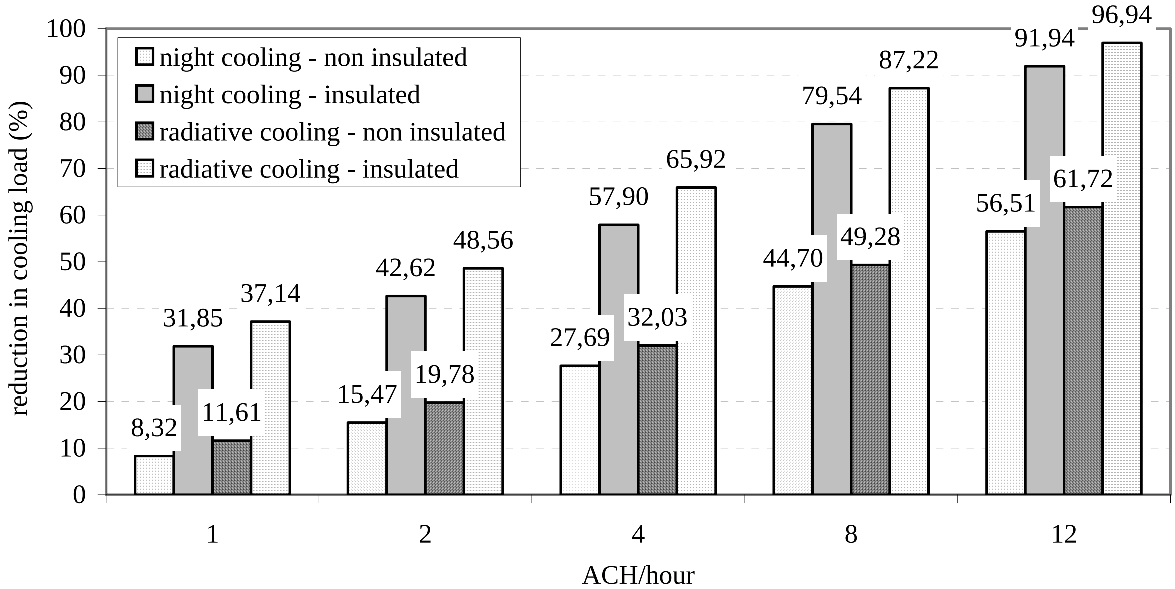

Figure 3: The reduction of cooling load

As seen in Figure 3, ventilation associated with either night cooling or radiative cooling is always benefic, leading to significant reduction of cooling loads, as it was expected. The reduction of the cooling load can be as high as 96% for the insulated building.

However, in order to assess for the contribution of the radiative cooling alone, the “night cooling” results have been compared with “radiative cooling” results. Figure 4 shows the further reduction in cooling load achieved by the radiative cooling system alone as a percentage relative to the reference case of no ventilation.

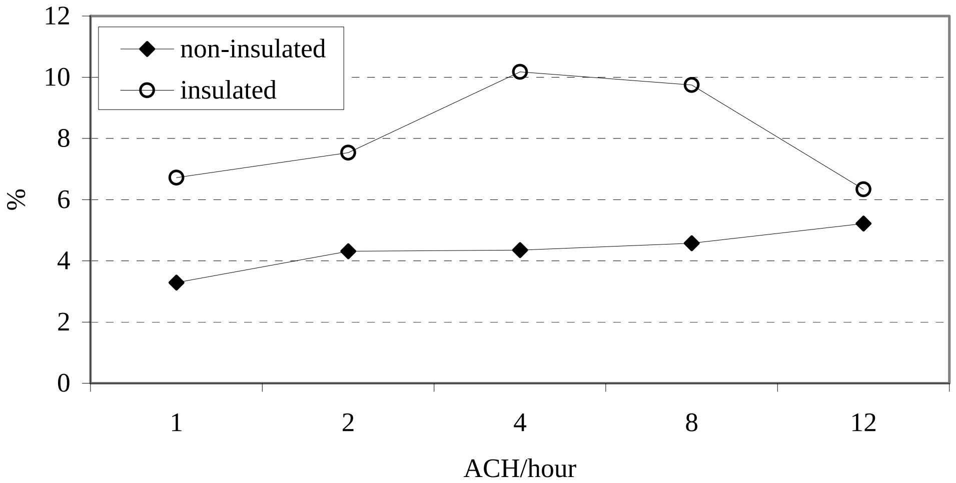

Figure 4: The contribution of the radiative cooling in further reducing the cooling load

As seen in Figure 4, the utilization of radiative cooling can further reduce the cooling load up to approximately 10%. With the increasing of the air changes, however, the potential contribution of the radiative cooling system diminishes. On the other hand, the results show that the maximum reduction of the peak indoor temperature is about 0.34 ºC, the benefits in which regard this aspect being less relevant than those reported for reduction of the cooling loads.

The present investigation reveals once more the limited potential of radiant cooling as a cooling source. When analyzing the results, however, it should be kept in mind the fact that, at its best, the radiative cooling system lowers the temperature of the outdoor air with only 2 ºC. It is believed that the reduction of the wind convective gains, which impede the process of heat extraction from the radiator, might further improve the effectiveness of the radiative system.

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NOMENCLATURE

H	flat plate collector height
L	length of the flat plate collector
T	fluid temperature
T_a	ambient air temperature
T_{in}	inlet fluid temperature
T_{out}	outlet fluid temperature
T_r	radiative plate temperature
u_{in}	inlet fluid velocity
u	velocity component on x-axis
v	velocity component on y-axis
p	pressure
$\dot{m}$	mass flow rate
k_f	thermal conductivity of the fluid
h	convective heat transfer coefficient on the external side of the metal plate