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Modelling and experimental analysis of three radioconvective panels for night cooling

J.A. Ferrer Tevar[a,*], S. Castaño[a], A. Garrido Marijuán[a], M.R. Heras[a], J. Pistono[b]

[a] Department of Energy, Energy Efficiency in Buildings R&D Unit, CIEMAT, 28040 Madrid, Spain
[b] Department of Energy, University of Oviedo, Oviedo, Spain

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ABSTRACT

The use of heat dissipation on buildings by means of night radiative and convective processes is an effective technical approach to meet user comfort requirements while reducing the conventional energy consumption employed in refrigeration processes. The paper describes the design and development of three different night cooling systems being installed in the Solar Platform of Almeria for experimental purpose. The three systems used low cost, easy to install panels resulting in significant reduction of the cooling load. A model of the radioconvective systems was developed taking into account the main physical and mechanical phenomena occurring in the process. The model allowed evaluating the performance of the system, and it was further compared with the experimental test results to analyze its validity.

1. Introduction

In warm climate countries, as those on southern Europe, refrigeration demand is experiencing an important growth during last years, contributing to a large extent to the increase of peaks of electricity demand in urban areas during summer. The importance of these units lies in the fact that they are generally all operating at the same time [1,2]. Efficient cooling is one of the major issues regarding Net Zero Energy District, and it is fundamental to innovate with bioclimatic building initiatives to face this situation, combining active and passive techniques that reduce cooling load.

According to Dimoudi et al. [18], Farahania et al. [3] and Parker et al. [4], night radiative cooling of buildings has been extensively studied because of its potential as heat dissipation systems with low energy consumption. These systems are based on radiative heat loss by long-wave radiation emission towards the night sky plus convective heat losses. Thus, we are able to lower the thermal load of the buildings in superheating periods and delay the use of AC active systems, displacing the building's demand profile towards the peak sun hours, powering the use of solar cooling systems [19].

As it is pointed out by Eicker and Dalibard [5], night radiative cooling is still not applied widely in today's buildings, as there are no commercially available components. However, it has been considerably studied, e.g. the Harold Hay "skytherm" (1978), the "roof pond" extensively described by Givoni [6] or the studies carried out by Santamouris and Asimakopoulos [13].

More recent developments of Bagiorgas et al. [17], include a radiative cooling system based on air circulation through aluminum tubes at night time. In this experiment, the outlet temperature of the system was calculated using stagnation temperature models. Results from a 5-day of August test show that a nocturnal radiator of 0.93 emittance for space cooling is able to reduce the temperature 2.5–4 °C during summer nights. Moreover, simulation studies of Sima et al. [7], showed significant improvement of internal thermal comfort by using the night sky cooling in the testing office building.

Few studies have provided experimental data from operational night cooling systems. It is important to remark the need of a robust model validated with experimental data. Without a good model capable of predicting the amount of heat dissipated by the radioconvective system, an important term would be missing on the calculation of the energy balance of the system and the equilibrium conditions wouldn't be properly calculated.

In the present work, three system prototypes for night radiative cooling of buildings were designed, theoretical evaluated and experimental analyzed in the Laboratory of Energy Test Building Components (LECE) located in the Solar Platform of Almeria (PSA) in southern Spain. At the core of this technology were three different prototypes of radioconvective panels with high, medium and low emittance each one. As the heat carrier (water) flows through the panels, heat loss due to radiation and convection cools down the system.

* Corresponding author. Tel.: +34 914962500.
E-mail address: ja.ferrer@ciemat.es (J.A.F. Tevar).

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Nomenclature

A_i	area of surface i (m^2)
b	width of the bond (m)
γ	thickness of the bond (m)
C_b	thermal resistance of the bond ($W\,m^{-2}\,K^{-1}$)
C_{cover}	index for cloudy-sky
C_{pf}	specific heat capacity of the flow ($W\,m^{-2}\,K^{-1}\,kg^{-1}$)
C_{SI}	index for clear-sky of Marty and Philipona
D	outside diameter of the pipe (m)
D_i	inside diameter of the pipe (m)
σ	Stefan–Boltzmann's constant ($5.67 \times 10^{-8}\,W\,m^{-2}\,K^{-4}$)
e	thickness (m)
ε_{cloud}	cloudy-sky emittance
ε_{cs}	clear-sky emittance
ε_i	emittance of surface i
ε_p	emittance of panel
ε_{sky}	sky emittance
F'	efficiency factor of the panel
F_{ij}	efficiency factor between the surfaces "i" and "j"
f_{cloud}	sky clearness index of Berdhal and Martin
G	global solar radiation ($W\,m^{-2}$)
G_{0h}	hourly extraterrestrial solar radiation ($W\,m^{-2}$)
G_{ch}	hourly global solar radiation with clear sky at the earth's surface ($W\,m^{-2}$)
G_d	diffuse solar radiation ($W\,m^{-2}$)
G_h	hourly global solar radiation with clear sky at the earth's surface ($W\,m^{-2}$)
G_R	Grashof number
H	height of clouds (m)
h_c	convective heat transfer coefficient
h_{cinf}	convective heat transfer coefficient, lower side of the panel
h_{csup}	convective heat transfer coefficient, upper side of the panel
h_f	heat transfer coefficient for free convection
h_{rinf}	radiative heat transfer coefficient, lower side of the panel
h_{rsup}	radiative heat transfer coefficient, upper side of the panel
h_w	heat transfer coefficient for forced convection
k_{air}	thermal conductivity of air ($W\,m^{-2}\,K^{-1}$)
k_b	thermal conductivity of the bond ($W\,m^{-2}\,K^{-1}$)
k_c	coefficient of atmospheric clarity
k_f	thermal conductivity of the flow ($W\,m^{-2}\,K^{-1}$)
k_p	thermal conductivity of the panel ($W\,m^{-2}\,K^{-1}$)
k_{pipe}	thermal conductivity of the pipe ($W\,m^{-2}\,K^{-1}$)
L_c	characteristic length of the panel (m)
L_{Wd}	incoming long-wave radiation ($W\,m^{-2}$)
L_{Wnet}	net long-wave radiation ($W\,m^{-2}$)
L_{Wu}	outgoing long-wave radiation ($W\,m^{-2}$)
$\dot{m}$	mass flow rate ($kg\,h^{-1}$)
N	index for cloudy-sky
n_P	number of pipes
Nt	index for cloudy-sky, Heliosat-2 model
Nu	Nusselt number
np	number of pipes
Pr	Prandtl number

Nomenclature

Q_b	heat transfer through the bond ($W\,m^{-2}$)
Q_{conv}	convective heat transfer to the surroundings ($W\,m^{-2}$)
Q_{panel}	heat transfer through the panel ($W\,m^{-2}$)
Q_{pconvb}	convective heat transfer from the atmosphere to the lower side of the panel ($W\,m^{-2}$)
$Q_{pconvup}$	convective heat transfer from the atmosphere to the upper side of the panel ($W\,m^{-2}$)
Q_{pradb}	radiation heat transfer from the ground to the panel ($W\,m^{-2}$)
Q_{pradup}	radiation heat transfer from the panel to the atmosphere ($W\,m^{-2}$)
Q_{rad}	radiation heat transfer ($W\,m^{-2}$)
Q_t	heat transfer through the circular pipe ($W\,m^{-2}$)
Q_{tconvb}	convective heat transfer from the atmosphere to the pipes ($W\,m^{-2}$)
Q_{tradb}	net radiative heat transfer from the upper part of the pipes ($W\,m^{-2}$)
Q_u	useful energy ($W\,m^{-2}$)
Re	Reynolds number
RH	relative humidity
Ri	Richardson number
r_i	internal radius of the pipe (m)
r_o	external radius of the pipe (m)
S	ingoing long-wave length radiation on the radiator ($W\,m^{-2}$)
T_{amb}	dry bulb temperature (K)
T_b	bond temperature (K)
T_{dp}	dew point temperature (K)
T_f	flow temperature (K)
T_{fin}	inlet flow temperature (K)
T_{fout}	outlet flow temperature (K)
T_i	temperature of surface i (K)
T_{grnd}	ground temperature (K)
T_{med}	average temperature between the panel surface temperature and sky temperature (K)
T_{rad}	temperature of the upper side of the panel (K)
T_{radinf}	temperature of the lower side of the panel (K)
T_{sky}	sky temperature (K)
T_{tint}	temperature of the inner pipe (K)
T_{tsup}	temperature of the outer pipe (K)
U_b	coefficient of back losses ($W\,m^{-2}\,K^{-1}$)
U_f	coefficient of front losses ($W\,m^{-2}\,K^{-1}$)
U_L	overall heat loss coefficient ($W\,m^{-2}\,K^{-1}$)
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
W	distance between the pipe axis (m)
Y	length of the plate (m)

2. System description

Fig. 1 shows a general sight of the test layout located in the Laboratory of Energy Test Building Components (LECE) within the Solar Platform of Almeria (PSA). This layout consisted of the three radioconvective panels, thermal energy storage, auxiliary energy system and pump.

Since the panels' properties are critically dependent on the material, different materials were used for each panel to study the influence of this parameter by analytical comparison. Specifically, the first system was an uncovered panel from organic material, consisting of a series of joint pipes unattached to any plate with emittance 0.9; the second panel employed a conventional selective absorbent plate normally used on solar collectors, but no glass covering was used resulting in a low emittance ($\varepsilon = 0.02$); while the third of them is a white painted metallic panel of medium emittance ($\varepsilon = 0.5$) (Figs. 2–4).