Renewable and Sustainable Energy Reviews 77 (2017) 803–820

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Radiative cooling as low-grade energy source: A literature review

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ARTICLE INFO

Keywords:
Radiative cooling
Renewable cooling
Night sky radiation
Low-grade cooling

ABSTRACT

Radiative cooling is a technology intended to provide cooling using the sky as a heat sink. This technology has been widely studied since 20th century but its research is scattered all over the literature, requiring of a review to gather all information and a state-of-the-art. In the present article, the research has been classified in: (1) radiative cooling background, (2) selective radiative cooling, (3) theoretical approach and numerical simulations, and (4) radiative cooling prototypes. Even though this is a low-grade technology it can dramatically reduce the energy consumption, since it is renewable and requires low energy for its operation. However, new functionalities of the device, apart from radiative cooling, are required for profitable reasons. Some recommendations extracted from the literature to improve the efficiency of radiative cooling are: to use a cover to achieve low temperatures, to use water instead of air as heat-carrier fluid, and to couple the device with heat storage. Finally, further research should be focused in the development of new materials with improved radiative properties, the measurement of incoming infrared atmospheric radiation and/or new technics to predict it, and the evaluation of new device concepts.

1. Introduction

The environmental awareness is growing fast nowadays with special attention to the energy consumption and environment preservation. Regarding to energy consumption, the building sector can contribute in a remarkable way in achieving the transition to a less energy intensive system. There is huge potential in reducing energy consumption with profitable measures that reduce the economic and environmental costs. The energy consumption of buildings represents 40% of total energy consumption in the European Union [1], where space conditioning of buildings represents almost half of the building energy consumption.

For space conditioning, especially in hot climate countries, most of the buildings use reversible heat pumps which consume a large amount of electrical energy. New legislations consider electrically driven heat pumps as a renewable source of energy when they achieve seasonal average efficiencies higher than $SCOP_{NET} \geq 2.5$ [2,3], since they take advantage of the air temperature to reduce electrical consumption. However, there are other renewable sources that further reduce the use of non-renewable energy, since they can achieve the required temperature level with no or very low electrical use. Solar energy is one of the most widely studied sources; however, its use for cooling is limited by the implementation of absorption heat pumps.

Another technology that has been studied in order to provide cooling and displace the use of heat pumps is radiative cooling. This technique is based on emitting long-wave thermal radiation from a terrestrial body toward space through the infrared atmospheric window between 8 and 13 μm wavelengths. The atmosphere infrared window is the dynamic behaviour of earth's atmosphere that allows some infrared radiation pass through the atmosphere without being absorbed and, thus without heating the atmosphere.

It is known that a body emits electromagnetic radiation in a wavelength range depending on its temperature. At ambient temperature most of the radiation is emitted in the infrared spectrum. Radiative cooling technique uses these properties to generate a cooling net balance between the emitted thermal radiation from the terrestrial surface and the received from the atmosphere.

Using this technology for cooling purposes will dramatically reduce the energy consumption; depending on the case, the energy consumption can be zero or just the energy consumed by a small pump running on the operating hours. The performance of the radiative cooling technology is affected by the physical properties of the device and also by the surrounding conditions. Therefore, special attention must be paid to materials and environmental conditions.

From early 20th century, several authors have worked on the field of radiative cooling. However, in the present all the information is scattered in the literature, making it difficult to identify new research opportunities. Although Lu et al. developed a practical review of radiative cooling [4], they focused in passive radiative cooling in buildings, and they did not include detailed information about the phenomenon and the studied materials for radiative cooling as well as the radiative cooling devices and models. Therefore, there is a clear need to compile and structure all this information. For that reason, this

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http://dx.doi.org/10.1016/j.rser.2017.04.010
Received 3 August 2016; Received in revised form 24 January 2017; Accepted 10 April 2017

Nomenclature

Symbol	Description Equation where appears Variable adapted
Δt	maximum day length (h) 24
$\Delta\varepsilon$	correction factor to take into account the day-night and seasonal variation (-) 24
$\Delta\varepsilon_e$	pressure correction factor (-) 19, 20
$\Delta\varepsilon_h$	diurnal correction factor (-) 17, 18, 19 $\Delta\varepsilon$ in [23].
A	factor that takes into account the variation of the emissivity 24
clf	cloud fraction term (-) (see [38]) 41
C_p	specific heat of the fluid ($J \cdot kg^{-1} \cdot K^{-1}$) (see [115]) 52
e_0	partial pressure of water vapour (mbar). 4, 5, 6, 9, 10, 11, 12, 25, 26, 29, 30, 31, 32, 33, 40, 41, 42, 44, 45 e in [5,9–12,29,38,42,43], e_d in [39].
$\bar{\varepsilon}_s^H$, $\bar{\varepsilon}_{s,2}^H$ and η^H	parameters to compare radiative cooling selective materials (see [45]) (-) 49, 50, 51
f	factor that takes into account the delay of the emissivity cycle in relation to the solar cycle (-) 24
$f_{8,i}$	fraction of black body radiation emitted through the infrared window by layer "i" (-) 37
F	collector efficiency factor (-)(see [115]) 52 F' in [115].
H	relative humidity (%), 14
$I_{b,\lambda}$	spectral radiance of a blackbody ($W \cdot m^{-3}$) 49, 50 W in [45].
k	empirical coefficient depending on the cloud type, to be defined in the original paper (-) 34
$K(t)$,$L(t)$	correction factors (see values in [25]) 23 $K(H)$, $L(H)$ in [25].
K_0	daily clearness index (-) (see [37]) 40
$\dot{m}$	mass flow rate ($kg \cdot s^{-1}$) (see [115]) 52
n	number of parallel tubes (-)(see [115]) 52
P_0	atmospheric pressure (mbar) 20 P in [24].
R	effective outgoing infrared radiation from a surface on earth ($W \cdot m^{-2}$) 1, 34 I in [5], R_W in [33].
$R_\uparrow$	infrared radiation emitted by a surface on earth ($W \cdot m^{-2}$) normally calculated using Stefan-Boltzmann law 1 $I_\uparrow$ in [5].
$R_\downarrow$	infrared radiation from atmosphere, absorbed by a surface on earth ($W \cdot m^{-2}$). 1, 35, 37 $\mathrm{R_T}$ in [35], $\mathrm{R_{ldc}}$ in [36], $\mathrm{LW_d}$ in [38], $\mathrm{I_\downarrow}$ in [5].
$R_{\downarrow,0}$	infrared radiation from atmosphere under clear sky conditions ($W \cdot m^{-2}$) 7, 35, 37, 45 $I_{\downarrow,0}$ in [5], E_a in [9,10,33],R in [11,14,15], R_A in [18], $F_\downarrow$ in [29], $F_{LW,clr}^{\downarrow}$ in [27], R_{LD} in [19], F in [31], R_a in [35], R_{ld} in [36], LW_{in} in [39].
R_0	effective outgoing infrared radiation under clear-sky conditions ($W \cdot m^{-2}$) 34, 43 R in [33].
s	ratio between the measured solar irradiance to the clear-sky irradiance (-) 41
S	absorbed solar radiation per unit area ($W \cdot m^{-2}$) (see [115]) 52
$SCOP_{NET}$	estimated average seasonal performance factor of electrically driven heat pumps (-)
t	time of the day (hour) 18
t'	approximate hour of sunrise in solar time (hour) 24
$[t(\lambda)/t_{av}]$ and b	empirical parameters (see [46]) (-) 48
T_a	ambient dry bulb temperature (K). 3, 7, 8, 9, 10, 11, 12, 23, 30, 31, 32, 33, 40, 41, 42, 52 T in [5,11,14,15,31,38,39,43], T_A in [18], T_0 in [19,20,27,29,30].
$T_{a,corrected}$	corrected ambient dry bulb temperature (K) 23
$T_{c,i}$	cloud temperature of layer "i" (K) 37 T_i in [35].
T_{dp}	dew point temperature (ºC) 15, 16, 21, 22, 23, 27, 28 t_d in [25].
T_s	surface temperature (K) 49, 50
T_f	temperature of the fluid at the desired point (normally the outlet fluid temperature) (K) (see [115]) 52
T_{fi}	inlet fluid temperature (K) (see [115]) 52
T_{sky}	effective sky temperature (K) 2, 40, 45 T_s in [37].
u, v	empirical parameters with different values depending on the different cloud types (-) (see [36]) 39
U_L	collector overall heat loss coefficient ($W \cdot m^{-2} \cdot K^{-1}$) (see [115]) 52
w	distance between parallel tubes (m) (see [115]) 52 W in [115].
W	fractional area of sky covered by clouds (-) 34, 35, 36, 38, 39 A/A_i in [34,35], N in [22], n in [24], m_c in [36].
y	tubes length (m) (see [115]) 52
Z	altitude above sea level (km) 14
α, β, γ, a, b	empirical coefficients, to be defined in the original paper (-) 4, 5, 45
γ	parameter to take into account humidity (see [42]) 43, 44
Γ	factor depending on the cloud base temperature (-) (see [24]) 38
ε_{sky}	effective sky emissivity (-) 3, 35, 36, 38, 39, 41, 42, 47, 48 ε in [22,24,38].
$\varepsilon_{sky,0}$	effective sky emissivity under clear sky conditions (-) 4, 5, 6, 7, 8, 9, 12, 14, 15, 16, 17, 19, 21, 22, 25, 26, 27, 28, 29, 30, 31, 32, 33, 35, 36, 38, 39, 48 ε_a in [7,20,29], $\varepsilon_0$in [22,24], ε_{sky} in [8,28], ε in [5,23,25], ε_{a0} in [19], ε_c in [38], e_a in [45],ε_s in [46].
$\varepsilon_{10.5-12.5,0}$ and $\varepsilon_{8-13,0}$	effective sky emissivity for the wavelength rage showed, under clear sky conditions (-) 10, 11 $\varepsilon_{10.5-12.5}$ and $\varepsilon_{8-13,0}$ in [20].
$\varepsilon_{cloud,i}$	emissivity of cloud layer "i" (-) 37 ε_i in [35], ε_c in [24].
$\varepsilon_{cloudy\ sky}$	equivalent sky emissivity with entirely cloudy sky 36 A in [22].
θ	zenith angle (rad) 43, 45, 46, 47, 48 z in [5,42,43].
λ	wavelength (μm) 46, 47, 48
ξ	parameter to take into account humidity and ambient temperature (see [30]) ($g \cdot cm^{-2}$) 31
σ	Stefan-Boltzmann's constant: $5.6704 \cdot 10^{-8}(W \cdot m^{-2} \cdot K^{-4})$ 2, 3, 33, 37, 45
ρ	reflectivity (-) 49, 50 R in [45].
τ	parameter to take into account humidity and ambient temperature (see [31]) 32
τ_8	transmittance of the atmosphere in the infrared window (-) 37

paper reviews all different aspects of radiative cooling, such as the environmental conditions affecting the phenomena, the selection and development of materials, the analytical and numerical methods, and the experimental prototypes.

2. Radiative cooling background

Radiative cooling is the thermal process by which a body loses heat by emitting long-wave radiation to another body at lower temperature. Referred to buildings, radiative cooling is a passive cooling technique which uses thermal radiation properties to cool a body or part of a building facing a colder surface such as the sky. This cooling process occurs when a surface presents a cooling net balance between the emitted and the absorbed radiation, considering also convection and conduction between the surface and the surroundings. With this technique, temperatures below ambient temperature can be achieved. The effective outgoing infrared radiation from a surface on earth (R) is defined as the difference between the infrared radiation emitted by this