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Improving Cooling Production Combining Radiative Cooling and Phase Change Materials

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ABSTRACT

Radiative cooling is a process by which a surface reduces its temperature by emitting thermal radiation towards outer space. Devices using this process to produce cooling are commonly named Radiative Coolers (RC). The energy transmitted to the sky by RC highly depends on the temperature of its surface; the higher the RC surface temperature, the more energy it radiates. In order to increase the potential of cooling production, this paper presents a numerical approach to the use of Phase Change Materials (PCM) as storage system in combination with RC. The use of PCM can result in a higher and more constant RC temperature during the cooling process compared to that when using conventional water tanks. Results show the combination of PCM and RC can improve the cooling production, in both summer and winter periods, compared to the conventional water tank system.

Keywords: radiative cooling, phase change material, renewable energy.

NONMENCLATURE

Abbreviations	
RC	Radiative Cooler
PCM	Phase Change Material
Symbols	
$E_{radiator,net}$	Net cooling energy per surface area produced by the radiative cooler [W·h·m^{-2}]
$P_{radiator,net}$	Net cooling power per surface area produced by the radiative cooler [W·m^{-2}]
$T_{radiator}$	Temperature of the radiator surface [K]
$T_{radiator,PCM}$	Temperature of the radiator surface for the scenario with a PCM tank [K]
$T_{radiator,water}$	Temperature of the radiator surface for the scenario with a water tank [K]
T_{sky}	Temperature of the sky [K]
$\Delta E_{radiator,net}$	Increase of the net cooling energy per surface area produced by the radiative cooler [W·h·m^{-2}]
$\Delta P_{radiator,net}$	Increase of the net cooling power per surface area produced by the radiative cooler [W·m^{-2}]
Δt	Time step [h]
$\varepsilon_{radiator}$	Emissivity of the radiator [-]
ε_{sky}	Emissivity of the sky [-]
σ	Stefan–Boltzmann constant [W·m^{-2}·K^{-4}]

1. INTRODUCTION

The effects of climate change are becoming more dangerous and destructive day after day. The building stock is responsible for 40% of the energy consumption and 36% of all CO_2 emissions in the EU. Spacing cooling represents nearly 20% of the total electricity used in buildings around the world today, which will be more than tripled by 2050 due to the world's economic and demographic growth [1]. Special efforts are being made in renovating the current building stock by energy efficiency means as well as considering the deployment of renewables [2]. The use of renewable energy sources to cover space conditioning and DHW demands seems more likely over the years.

Thus, an alternative solution like radiative cooling can become a renewable and clean technology for this purpose. Radiative cooling is the process by which a surface -named radiative cooler- cools down by emitting thermal radiation towards outer space taking advantage of the infrared atmospheric window transparency in the range of 7-14 µm [3]. This is obtained during night time, when solar radiation is zero, due to a net imbalance between the emitted radiation from the radiative cooler and the radiation coming from the atmosphere. Nowadays it is also possible to obtain radiative cooling during daytime thanks to the development of new materials [4].

However, the potential of RC for cooling is intimately related to the temperature at the surface of the emitter. Thus, the higher the RC temperature, the higher the cooling production. During the cooling process, energy is emitted towards the sky, gradually reducing the temperature of the RC. This reduction results in a decrease of the cooling produced.

Over the last three decades, Phase Change Materials (PCM) have been studied and proved to be a very good alternative to traditional Thermal Energy Storage, as they make use of latent heat, rather than sensible heat; thus, achieving a higher energy storage density at a more constant temperature, the phase change temperature. A lot of research has been done analyzing the possibility to replace water tanks with PCM tanks, or at least to improve those with small PCM containers [5-6].

The combination of a radiative cooling system with PCM storage could result in a more constant RC surface temperature, thus improving the cooling production of the radiative cooling.

Previous research addressing the combination of radiative cooling and PCM focus on the use of passive radiative cooling to reduce cooling loads in buildings [7-10] or to dissipate heat generated in electronic equipment [11]. This paper analyses numerically the combination of PCM with active radiative cooling in order to store cold for later uses in a storage tank.

2. MATERIAL AND METHODS

In order to determine the potential improvements achieved by the combination of the RC with a PCM tank, the cooling power and energy are determined using Eq. 1 and Eq. 2.

$$P_{radiator,net}\left(\frac{W}{m^2}\right) = \varepsilon_{radiator} \cdot \sigma \cdot T_{radiator}^4 - \varepsilon_{sky} \cdot \sigma \cdot T_{sky}^4 \qquad \text{Eq. 1}$$

$$E_{radiator,net}\left(\frac{Wh}{m^2}\right) = P_{radiator,net} \cdot \Delta t \qquad \text{Eq. 2}$$

Two different scenarios are considered: water tank and PCM tank.

1. Water tank (Fig. 1): This scenario simulates the use of a conventional water tank to store the cold produced. Thus, the storage temperature decreases during the cooling process, and so does the water inside the RC and the RC surface. For this scenario, a linear decrease of the RC surface temperature was assumed (Table 1).

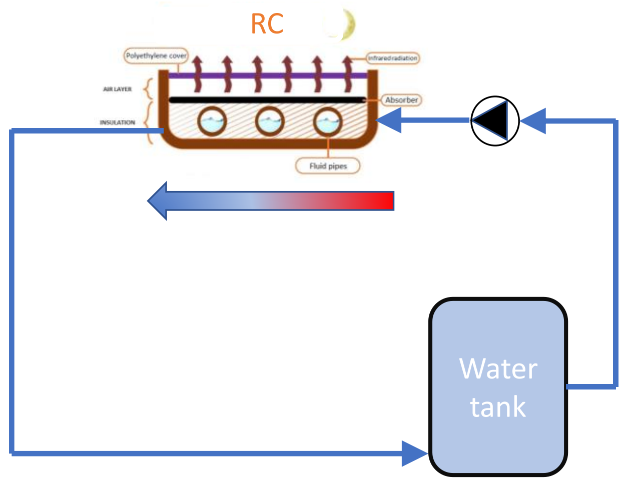

Fig. 1. Scheme of RC with water tank

2. PCM tank (Fig. 2): This scenario simulates the use of a PCM tank to store the cold produced. In this case, during the cooling process, the cold is mainly stored at the phase change temperature, and thus the RC temperature remains constant most of the time (Table 1). For the sake of simplicity, the PCM considered is an ideal PCM with a constant phase change temperature of 22ºC and a phase change enthalpy of 200 kJ/kg. The temperature profile for the PCM tank is determined considering a constant cooling power of 40 W/m^2.

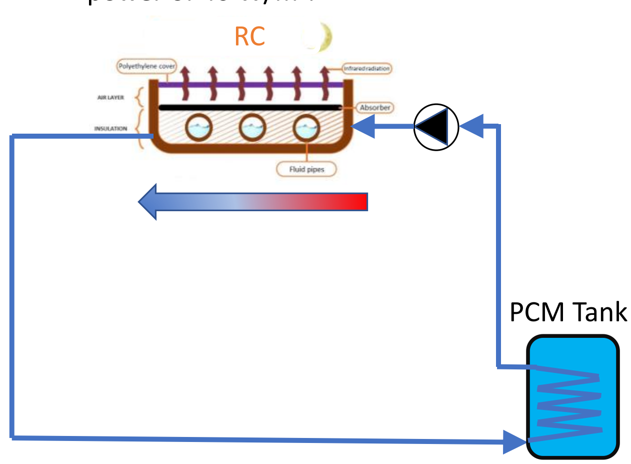

Fig. 2. Scheme of RC with PCM tank

Hour of night/day	Temperature in the radiator circuit [K]			
	Scenario 1: Water tank		Scenario 2: PCM tank	
	Summer	Winter	Summer	Winter
20:00	-	298.0	-	298.0
21:00	-	297.3	-	295.0
22:00	298.0	296.7	298.0	295.0
23:00	297.3	296.0	295.0	295.0
24:00	296.7	295.3	295.0	295.0
1:00	296.0	294.7	295.0	295.0
2:00	295.3	294.0	295.0	295.0
3:00	294.6	293.3	295.0	295.0
4:00	294.0	292.7	295.0	295.0
5:00	293.3	292.0	295.0	295.0
6:00	292.6	291.3	295.0	295.0
7:00	292.0	290.7	295.0	295.0
8:00	-	290.0	-	290.0

Table. 1. Temperatures of the water circuit during night time for summer and winter and for the two scenarios: water tank and PCM tank.

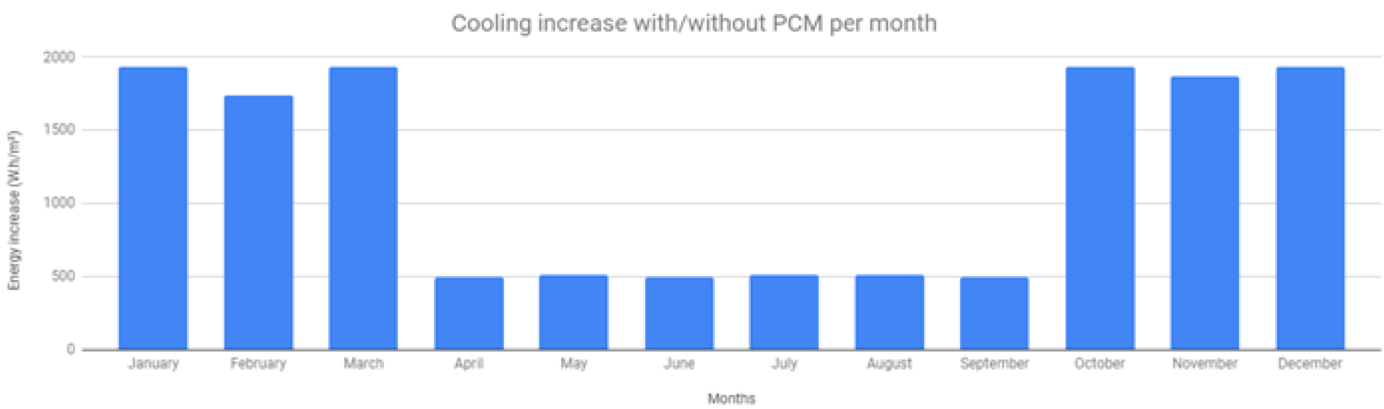

Fig. 3. Increase of the cooling energy production when using a PCM tank instead of a water tank.

The cooling produced is considered to be used to cool down a room with a set-point of 26ºC, which could be a realistic situation for households during summer and for other specific applications (such as commercial buildings or data centers) during both summer and winter. In order to determine the maximum potential of radiative cooling, the emissivity of the radiator ($\varepsilon_{radiator}$) was considered to be 1. The temperature of the water at the beginning of the radiative cooling period is considered to be close to the set-point, and it is stablished at 25ºC. For summer conditions, the cold production period, is considered from 22:00 to 7:00 (when nighttime radiative cooling can be achieved). On the other hand, for winter conditions, the cooling period is considered from 20:00 to 8:00 (Table 1). A time step (Δt) of 1 hour was used for the calculations.

Since the main objective of this research is to determine the potential benefits of combining the use of PCM with RC, the difference in the cooling power and cooling energy for both scenarios is to be compared. Considering that the atmospheric IR radiation (represented by the term $\varepsilon_{sky} \cdot \sigma \cdot T_{sky}^4$ in Eq. 1) will be the same for the different scenarios, based on Eq. 1 and Eq. 2, the differences in the cooling power and energy are determined by Eq. 4 and Eq. 5.

$$\Delta P_{radiator,net}\left(\frac{W}{m^2}\right) = \varepsilon_{radiator} \cdot \sigma \cdot \left(T_{radiator,PCM}^4 - T_{radiator,water}^4\right) \quad \text{Eq. 4}$$

$$\Delta E_{radiator,net}\left(\frac{Wh}{m^2}\right) = \Delta P_{radiator,net} \cdot \Delta t \quad \text{Eq. 5}$$

From Eq. 4 and Eq. 5 it can be deduced that, in absolute values, the improvements achieved by the combined use of PCM and RC does not depend on the location and the weather conditions, but on the RC temperature only. Thus, the results presented can be generalized (in absolute values) to any location.

3. RESULTS AND DISCUSSION

Fig. 3 presents the monthly increase in the cooling energy per unit of surface when implementing the use of a PCM tank instead of a water tank. Results demonstrate the capacity of the use of a PCM tank instead of a water tank to increase the cold production. Since the improvement (in absolute values) does not depend on the weather conditions, and the RC temperature profile is considered the same throughout the year for each scenario, the differences in the improvements are due to the hours of RC production, being longer during winter period than during summer period. The maximum increase in the monthly energy production during the winter period is 1930.96 Wh/m^2, while it is reduced to 516.19 Wh/m^2 for the summer period.

4. CONCLUSIONS

By means of the natural process of radiative cooling, a surface can be cooled down to temperatures below ambient. However, this cooling power not only depends on the design features of the Radiative Cooler; the water temperature in the radiator also plays a key role. This article presented a way to improve the cooling performance of a RC, through the use of phase change materials as storage system instead of water.

Based on a constant radiative cooling power of 40 W/m^2, results from the numerical simulations demonstrated the potential of using PCM in combination with RC to increase the cooling production. During summer period a maximum increase of 516.19 Wh/(m^2·month) was observed, while the maximum increase during winter period was of 1930.96 Wh/(m^2·month). These values are independent of the weather conditions, but restricted to the assumption of a constant radiative cooling power of 40 W/m^2. Therefore, in order to determine the exact improvement that can be achieved and its significance referred to the energy production without the use of PCM for a specific location, detailed simulations must be done.

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6. ACKNOWLEDGEMENTS

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