COMBINING RADIATIVE COLLECTOR AND EMITTER WITH COMPRESSION HEAT PUMP: NUMERICAL ANALYSIS

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Summary

A Radiative Collector and Emitter (RCE) is a technology which combines solar collection and radiative cooling to provide both heat and cold from renewable sources. Solar collection uses radiation coming from the Sun to heat up a fluid, while radiative cooling takes advantage of the atmospheric window to emit thermal radiation to the sky with no interference with the atmosphere to cool down a fluid. However, temperatures achieved by radiative cooling are not always suitable for cooling applications. Combining the RCE with a compression heat pump (HP) can improve the coefficient of performance (COP) of the heat pump by using a colder heat sink for the condenser, the cold produced by the RCE. A numerical analysis using TRNSYS is done to determine the improvements in the COP of the HP when combined with an RCE. Results show an increase of the COP of both the heat pump and the whole system when combined with the RCE. The COP of the heat pump is the one with a higher increase, from 2.5-3.5 to 3.5-5.

Keywords: radiative cooling, heat pump, coefficient of performance, numerical simulation

1. Introduction

In the last decades, climate change and global warming have become a major concern for society. The energetic model, based on fossil fuels, is one of the main contributors to these problems. In order to address them, governments have promoted energy savings policies (Directive 2010/31/EU) as well as renewable energy implementation (Directive 2009/28/EC). One of the main consumers of energy is the building sector, which consumes around one-third of the global worldwide energy consumption (https://www.iea.org/topics/buildings). Moreover, in terms of pollution in Europe, the commercial, institutional and households sector is the largest contributor to Benzo[a]pyrene (BaP), primary particulate matter (PM), Carbon monoxide (CO) and Black carbon (BC), and it also contributes to Non-methane volatile organic compound (NMVOC), Cadmium (Cd), Sulphur oxides (SO_X), Nickel (Ni), and Nitrogen oxides (NO_X) emissions (European Environment Agency).

Renewable energies are becoming more important every day. While technologies such solar thermal collection are mature technologies able to produce hot water and are already introduced in the market, there is no renewable technology with such development in terms of cooling potential. Radiative cooling is a technology with the potential of producing cold water from a renewable source by emitting thermal energy to the sky (Vall and Castell, 2017) through the infrared atmospheric window. Although this technology has been previously studied, the main focus has been placed in analysing the infrared atmospheric window and the atmospheric infrared radiation (Bell et al., 1960). However, its development has not reached the market yet.

The combination of radiative cooling with other renewable technologies could foster its development and implementation in the market. A Radiative Collector and Emitter (RCE) is a technology which combines solar collection and radiative cooling to provide both heat and cold from renewable sources. While solar collection uses radiation coming from the Sun to heat up a fluid, radiative cooling takes advantage of the atmospheric window transparency in the 7-14 µm range to emit thermal radiation to the sky with no interference with the atmosphere to cool down a fluid.

This concept was first proposed by Vall et al. (Vall et al., 2018), determining its potential in terms of energy production and demand coverage of different buildings under different weather conditions, and demonstrating its suitability for certain building typologies and climates. However, temperature levels and integration with the building system were not studied. The concept was based on an adaptive cover, which could adapt its optical properties to perform both functionalities: solar collection and radiative cooling. This adaptive cover was a sliding cover composed of two materials, one for each functionality (glass for solar collection and polyethylene for radiative cooling).

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Compression heat pumps (HP) are widely used for heat and cold production in buildings, being the main cooling system worldwide. Although heat pumps are considered as a renewable energy source depending on their seasonal performance (Directive 2009/28/EC), the efficiency of HP depends dramatically on the temperature level of the heat sink, which usually is the ambient air. The fact that HP usually operate under hot weather conditions, and during the hottest hours of the day, raises the temperature level of the heat sink, thus reducing its coefficient of performance (COP). The combination of HP with RCE could improve the COP of the system by using the cold produced by the RCE at nighttime as a heat sink for the HP operating at daytime.

This study presents a numerical analysis of the combination of HP with RCE in order to determine the potential improvements in the COP of the system.

2. Methodology

A numerical model of the RCE is published in the literature (Vall et al., 2020). This model, developed as TRNSYS type, simulates the behavior of an RCE device, and was validated with experimental results.

The model is based on the energy balance between the RCE and the ambient air and the sky, in order to determine the net heat flux entering or leaving the RCE (Fig. 1). The RCE is discretized in different nodes based on an electric analogy in a one-dimension approach (1D) in order to reduce the computation time. However, some 2D effects are introduced into the model based on detailed simulations performed on Comsol Multiphysics (Vall et al., 2020).

The equivalent resistance network of the model is shown in Fig. 2. There is one temperature node for the screen (c), the RCE surface (1), the pipe (2) and its internal (outlet) fluid (w2), and the back insulation (3). The fluid enters the pipe at temperature T_{w1}.

The relations between the nodes are based on basic heat transfer equations. Each node has a thermal capacity and each relation between nodes is represented by a thermal resistance. The thermal resistance between the fluid at the outlet of the pipe (node w2) and a fictitious node (w1) which represents the fluid at the inlet of the pipe is used to introduce a second dimension required in the model to determine the heat flux between the inlet and the outlet of the pipe. Thus, this node has no capacitance, and can be considered as an input to the model.

The radiation balance is done for 4 different wavelength ranges (0-4 µm, 4-7 µm, 7-14 µm and >14 µm). The model also allows using 2 different cover materials. These two functionalities allow the RCE model to distinguish between radiation for different wavelength, with special interest in the atmospheric window (7-14 µm) to simulate the double functionality solar collector – radiative cooler.

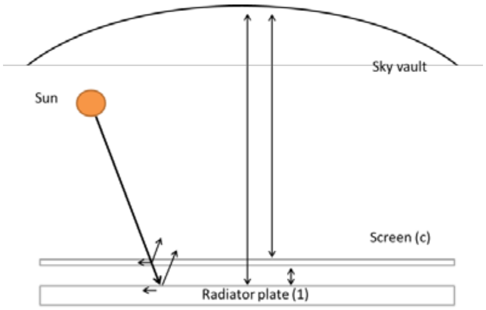

Fig. 1 Global energy balance scheme (Vall et al., 2020).

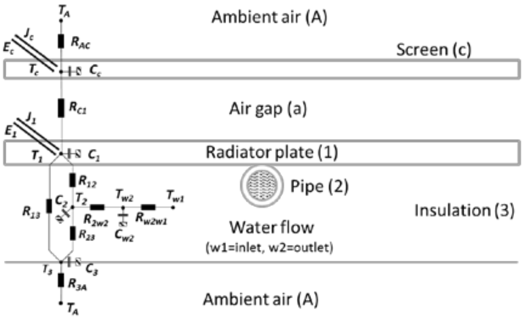

Fig. 2. Scheme of the 1D resistance-capacitance model (Vall et al., 2020).

This model has been used in this study, combined with a heat pump (Type 927 from TRNSYS TESS library, which simulates a water-water heat pump of 2 kW of power with variable COP).

The RCE field (10 RCE devices of 2 m^2 connected in parallel) produces heat during the day, which is stored in a hot water tank (1 m^3, using Type 156 which simulates a water tank with an internal coil heat exchanger) for later use as domestic hot water (DHW). Similarly, it produces cold during the night, which is stored in a cold water tank (0.15 m^3, using Type 158 which simulates a water tank with no internal heat exchanger), which will be used as a heat sink for the condenser of the HP during the day. The HP absorbs heat from the cooling tank (0.25 m^3 using Type 158, where heat from the building is rejected by the cooling distribution system) and releases it to the cold water tank. An air-water heat exchanger (Type 5c from TRNSYS) is coupled to the cold water tank from the RCE field. The HP is releasing the heat absorbed from the cooling demand at this tank, thus increasing its temperature. The heat exchanger dissipates this heat to the ambient air during daytime to avoid overheating. A conceptual scheme of the installation is presented in Fig. 3.

A thermostat (Type 2b) is used to set the outlet temperature of the HP to keep the cooling tank at a temperature below 10 ºC. The flow rate passing through the RCE field is simulated using Type 110, a variable flow pump. Based on previous experience, for solar collection mode the flow rate is set to 170 kg/h, while for radiative cooling mode the flow rate is set to 72 kg/h.

To control the operation mode, which determines the flow rate and the position of the adaptive cover, a new type was developed. The RCE field operates under solar collection mode during daytime if solar radiation is higher than 100 W/m^2, and at night operates under radiative cooling mode if the net radiation balance in the radiator is higher than 25 W/m^2. Otherwise, the RCE field is stopped. To determine daytime and nighttime hours, the average sunrise and sunset time for each month is used.

The demand of hot and cold water is simulated using Type 14b (Replacement water) and Type 14e (Mains temperature). For cold water, the demand simulates that of an office during summer months. Thus, 100 kg/h of cooling water are used during the hottest hours of the day (from 13:00 to 17:00). This water returns to the cooling tank at a temperature of 20 ºC. For hot water, the demand is not focused on any specific application, but on consuming the energy stored and discharging the tank. Thus, a flow rate of 100 kg/h is used during the night (from 21:00 to 7:00) to cool down the tank. The water returns to the tank at a temperature of 20 ºC.

The COP of such system is compared to that of a heat pump alone covering the same cooling demand (Fig. 3).

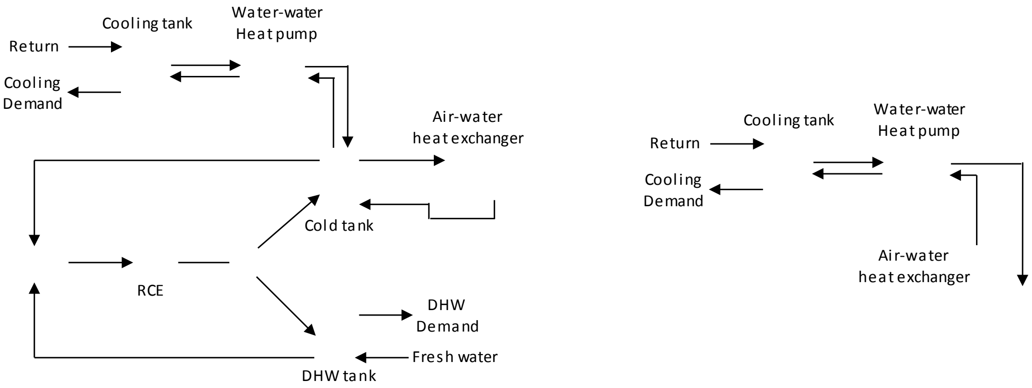

Fig. 3. Conceptual scheme of the RCE combined with a HP (left), and the HP alone (right).

Simulations have been performed for the hottest months of the year, when both DHW and cooling are required. Thus, the months considered are June, July, August, and September. The weather data is extracted from the EnergyPlus weather file for Lleida (Catalonia, Spain), using Type 15-3 of TRNSYS. An additional processing of the data is required to determine the horizontal infrared radiation, which is not provided by the weather file. For such calculations the methodology proposed by EnergyPlus has been used (Eq. 1 and Eq. 2), using the ambient temperature (T_{ambient}), the dew point temperature (T_{dp}), and the opaque sky cover (N) taken from the EnergyPlus weather data file for Lleida.

$$IR_{radiation} = sky_{emissivity} \cdot \sigma \cdot T_{ambient}^{4} \qquad \text{Eq. 1}$$

$$sky_{emissivity} = \left(0.787 + 0.764 \cdot ln\left(\frac{T_{dp}}{273}\right)\right) \cdot (1 + 0.0224N - 0.0035N^{2} + 0.00028N^{3}) \qquad \text{Eq. 2}$$

Where:

$sky_{emissivity}: Sky\ emissivity\ [-]$

$T_{dp}: Dew\ point\ temperature\ [K]$

$N: Opaque\ sky\ cover\ [-]$

$IR_{radiation}: Horizontal\ Infrared\ Radiation\ \left[\frac{W}{m^{2}}\right]$

$\sigma: Stefan - Boltzmann\ constant \left[5.6704 \cdot 10^{-8}\ \frac{W}{m^{2} \cdot K^{4}}\right]$

$T_{ambient}$: $Ambient\ temperature\ [K]$

Simulations were performed using a time step of 5 minutes. The main parameters analyzed are the power generated by the RCE ($\dot{Q}_{RCE}$, Eq. 3), and the coefficient of performance of the heat pump (COP_{BC}, Eq. 4) and the whole system (COP_{syst}, Eq. 5).

The thermal power generated by the RCE is determined as:

$$\dot{Q}_{RCE} = \dot{m} \cdot Cp \cdot (T_{in} - T_{out}) \qquad \text{Eq. 3}$$

Where:

$\dot{Q}_{RCE}$: power generated by the RCE field [W]

$\dot{m}$: mass flow rate circulating through the RCE field [kg/s]

Cp : specific heat of the fluid circulating through the RCE field [J/kg·K]

T_{in} : inlet temperature of the fluid at the RCE field [K]

T_{out} : outlet temperature of the fluid at the RCE field [K]

The COP of the heat pump is determined as:

$$COP_{BC} = \frac{\dot{Q}_{BC}}{\dot{W}_{e,BC}} \qquad \text{Eq. 4}$$

Where:

COP_{BC} is the COP of the heat pump [-]

$\dot{Q}_{BC}$ is the power generated by the heat pump [W]

$\dot{W}_{e,BC}$ is the electric consumption of the heat pump [W]

The COP of the whole system is determined as:

$$COP_{sist} = \frac{\dot{Q}_{BC}}{\dot{W}_{e,sist}} \qquad \text{Eq. 5}$$

Where:

COP_{syst} is the COP of the whole system [-]

$\dot{Q}_{BC}$ is the power generated by the heat pump [W]

$\dot{W}_{e,sist}$ is the electric consumption of the whole system [W]

3. Results and discussion

Fig. 4 shows the daily average power per surface unit of RCE for both solar collection and radiative cooling modes for the RCE+HP circuit. Results show that the cooling power of the RCE is one order of magnitude lower than the heating power, following the proportion of available solar radiation to available radiative cooling potential.

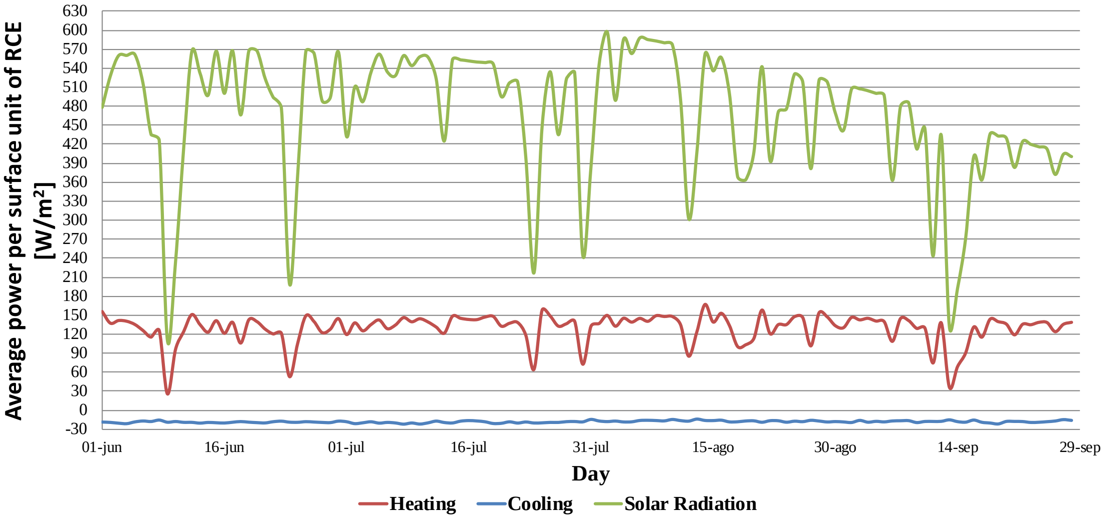

Fig. 4. Daily average power per surface unit of RCE in the RCE+HP circuit.

Fig. 5 shows the average temperature difference between the outlet RCE water temperature and the ambient temperature for the RCE+HP circuit for the month of July. During solar collection mode, temperature differences up to 45ºC are achieved, while during radiative cooling mode, up to 5ºC sub-ambient temperatures are achieved.

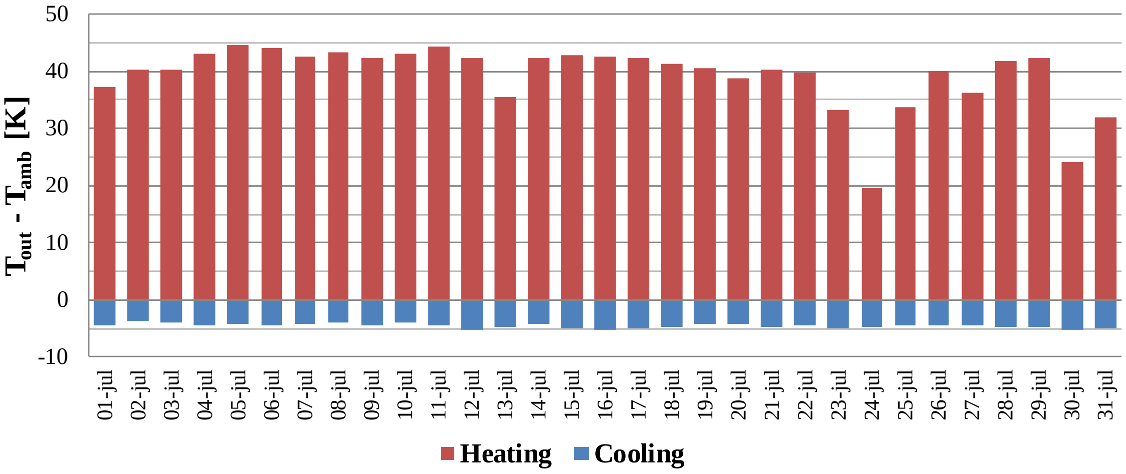

Fig. 5. Average temperature difference between the outlet RCE water temperature and the ambient temperature for the RCE+HP circuit for the month of July.

A comparison of the COP of the heat pump for both cases is presented in Fig. 6 for the month of July. Results show that the COP of the heat pump is significantly improved by its combination with the RCE. While the COP of the heat pump when operating alone ranges from 2.5 to 3.5 depending on the day, the COP of the heat pump when operating in combination with the RCE ranges from 3.5 to 5.

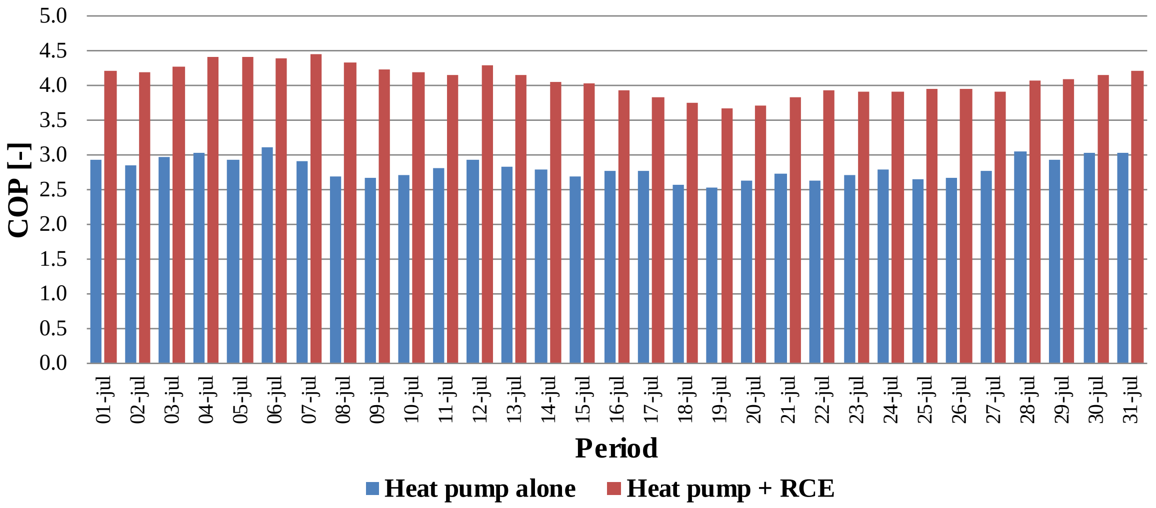

Fig. 6. Comparison of the COP of the heat pump when operating the heat pump alone and the heat pump in combination with the RCE for the month of July.

On the other hand, when the COP of the whole system is considered (taking into account all the energy consumptions needed for the pumps and heat exchanger), the improvements are significantly reduced. While the COP of the system with the heat pump operating alone ranges from 2 to 3, the one for the system with the heat pump operating in combination with the RCE ranges from 2.5 to 3. A comparison of the COP of the system for both cases is presented in Fig. 7 for the month of July.

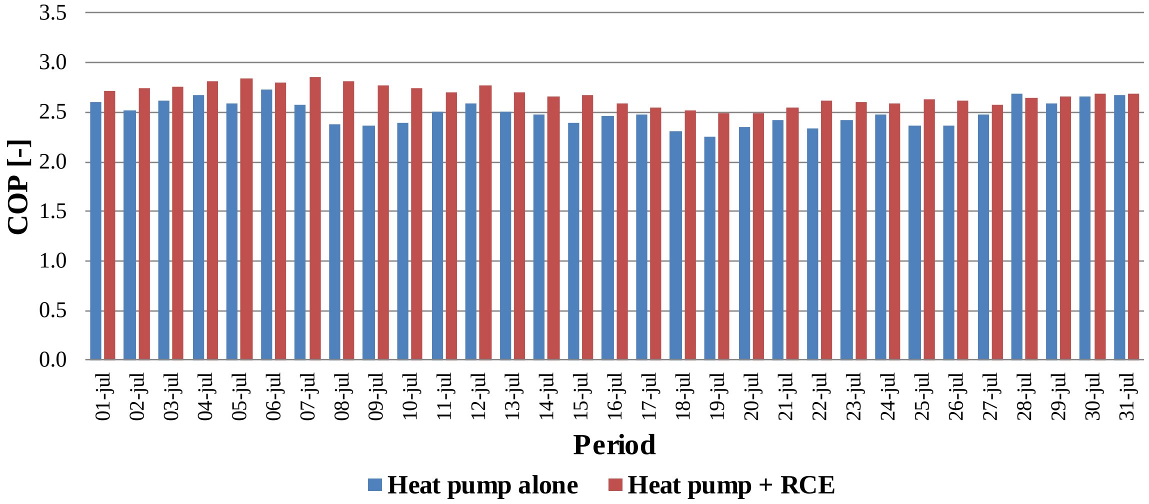

Fig. 7. Comparison of the COP of the whole system when operating the heat pump alone and the heat pump in combination with the RCE for the month of July.

4. Conclusions

By means of numerical simulation it has been demonstrated that the use of an RCE device can achieve both hot water production during daytime and sub-ambient temperatures during nighttime for the hottest months of the year. However, the average power is one order of magnitude higher for hot water generation than for cold water generation, following the proportion of available solar radiation to available radiative cooling potential.

The increase of the coefficient of performance of the heat pump and the whole system when combined with the RCE has been analyzed numerically. The results show that the combination of the HP with the RCE increases the COP for both the heat pump and the whole system. This increase is more significant when considering the heat pump (from 2.5-3.5 to 3.5-5), and it is reduced when considering the whole system (from 2-3 to 2.5-3) due to the energy use for auxiliary equipment. Thus, the use of pumps and the heat exchanger must be optimized in order to maximize the increase of the COP of the system.

5. Acknowledgements

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