Radiative Collector and Emitter: Experimental Results

Sergi Vall, Albert Castell, Cristian Solé and Marc Medrano

Department of Computer Science and Industrial Engineering, University of Lleida, Edifici CREA, Pere de Cabrera s/n, 25001 Lleida, Spain

Abstract

In order to increase the use of renewable energy in buildings, solar collection and radiative cooling can be combined in a single device (Radiative Collector and Emitter (RCE)) to produce both hot and cold water. In this paper, the potential of such a device to produce hot and cold water is evaluated experimentally, determining the capacity of such system to produce hot water during day and cool down water below ambient temperature during night. Experimental results demonstrate the capability of the RCE to produce heat during the day as well as to cool down water during night.

Keywords: Radiative cooling, Solar collection, Renewable energy production.

1. Introduction

In the roadmap to a new renewable energy model, the building sector is identified as a crucial user of non-renewable energy. It accounts for 40% of total energy consumption in the European Union (European Parliament), representing space conditioning (space heating and cooling) 65% of the building energy budget and 13.8% for domestic hot water (DHW) (ODYSSEE-MURE project). In order to improve this situation, passive strategies are fostered to reduce energy demands. However, energy consumption is not reduced to zero if thermal comfort conditions are to be preserved (Yang et al., 2014). Therefore, renewable energy sources are required to cover these energy needs.

Domestic Hot Water (DHW) can be achieved by solar thermal collectors. However, for cooling there is still no simple renewable alternative with such potential and development. Two possibilities for cooling are compression heat pumps and absorption heat pumps. However, they are either non-renewable or too complex. Compression heat pumps are the most common cooling devices. Although compression heat pumps are considered as a renewable source under certain circumstances (European Commission, 2013/114/EU; European Parliament. Directive 2009/28/EC), they consume high amounts of electricity. On the other hand, although absorption heat pumps may use solar energy as driving heat (Yin et al., 2000), they present some important disadvantages, such as being not available for residential applications, having low overall efficiencies, requiring high operation temperatures, and needing large cooling towers (Hassan and Mohamad, 2012).

On the other hand, radiative cooling uses the sky as a heat sink taking advantage of its effective temperature lower than ambient. Energy is dissipated to the sky taking advantage of the infrared atmospheric window (7-14μm) that allows some infrared radiation pass directly to space without intermediate absorption and re-emission (Bell et al., 1960; Berdahl and Fromberg, 1982). A comprehensive review of radiative cooling is presented in (Vall and Castell, 2017).

Research evaluating experimentally this technology is scarce. First attempts used unglazed solar collectors to behave as radiative collectors (Erell and Etzion, 2000; Hosseinzadeh and Taherian, 2012). The capability of such modified solar collectors to produce cold was demonstrated, although the efficiency and power were low. Other authors focused on the development and evaluation of more sophisticated materials (Raman et al., 2014; Chen et al., 2016), allowing lower temperatures by providing radiative cooling even under sunlight conditions. On the other hand, some research has been conducted in the development of numerical models (Ferrer Tevar et al., 2015). However, none of such systems has reached the market due to its low available cooling rates (between 20-80 W/m^2 (Cavelius et al., 2005), with peak values of 120 W/m^2 (Eicker and Dalibard, 2011)).

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Therefore, significant improvements in the materials or the concept need to be developed for radiative cooling to become feasible.

The combination of solar collection and radiative cooling into a single device could result in a significant improvement of the feasibility of the device. The new device would be capable to produce both heat and cold, thus covering, partially or totally, the Domestic Hot Water and the cooling demands. However, these two technologies are not generally prepared to work together when they are designed to work autonomously (Hu et al., 2015); therefore some adjustments have to be done for this purpose.

Radiative cooling and solar thermal collection use different radiation wavelength (longwave radiation for radiative cooling and shortwave radiation for solar thermal collection), and solar thermal collection takes place during sunlight hours while radiative cooling mainly when there is no sunlight. However, it is possible to couple them as they are not used at the same time, so there is no interference between them.

Moreover, the combination of radiative cooling and solar collection in a single device would be a qualitative leap forward to renewable suitability for meeting different energy demands. The use of both technologies may substantially reduce the non-renewable primary energy consumption for space conditioning and domestic hot water. This new concept that combines solar thermal collection and radiative cooling in a single device is based on radiation heat transfer, since it collects radiation (solar) from the Sun as a heat source, and emits radiation (thermal) to the sky to provide cooling. Therefore, this concept will be mentioned from here on as Radiative Collector and Emitter (RCE). In this paper, first experimental results of an RCE system are presented.

To combine both functionalities, a device with architecture similar to a flat plate solar thermal collector could be used (an absorber/emitter surface and a cover on top of it). To modes of operation would be possible: solar collection mode and radiative cooling mode. The use of a movable cover would allow the RCE system to change functionality. This cover would be composed of two different sections (one for each operation mode) made of different materials. The section of the cover used for the solar collection mode would let solar radiation pass through and block mid and far infrared radiation (glass will be used in this paper). On the contrary, the section used for radiative cooling would let thermal radiation pass through (polyethylene will be used in this paper). A sliding cover system would allow the two different sections to be exchanged to perform each function (solar collection during the day and radiative cooling during the night). This concept has been theoretically presented in (Vall et al., 2018).

The present paper explains the first experimental results of the concept of Radiative Collector and Emitter (RCE), combining both solar collection and radiative cooling production.

2. Experimental set-up

The experimental setup consisted of a solar collector, a radiative cooler, 2 water tanks, a pump, 6 temperature sensors, 2 flow meters, a pyrgeometer and the control and data acquisition systems. The solar collector used is model FUJI-P. It is a 2m x 1m x 80mm aluminum frame collector, with transparent 3mm glass and 30mm glass-wool back insulation. The collector has 8 cooper pipes of 8mm diameter and 0.6mm thick. On the other hand, the radiative cooler is the same solar collector (FUJI-P) but replacing the glass screen by a 0.6mm thick Polyethylene (PE) film and painting the surface of the radiator with black paint in order to adapt it to the required characteristics of radiative cooling mode (Fig. 1).

Fig. 1: Solar collector (left), and modified solar collector used as radiative cooling device (right).

For the sake of simplification, two separate devices were used instead of a single RCE device. This was sufficient to provide accurate data for model and concept validation, which was the main objective of this research. Four temperature sensors (Pt-100, with an accuracy of 0.1ºC) were used to monitor the inlet and outlet water temperature of the solar collector and the radiative cooling device. Water flow rates were monitored using a flowmeter for the operation under solar collection mode (Badger Meter – Primo Advanced, 0.25% accuracy), and a flowmeter for the radiative cooling mode (Schmidt Mess – SDNC 503 GA-20, 4% accuracy). Weather data was extracted from a nearby weather station. However, incoming infrared radiation was measured using a pyrgeometer on-site (LP PIRG 01 – DeltaOhm, 5% accuracy).

Water was circulated through the solar collector during daylight hours in order to determine the solar collection power. Water was stored in a 150L tank were average water temperature was monitored. On the other hand, during night, water was circulated through the radiative cooler to determine the energy dissipation and RCE cooling performance. For this operation mode, water was stored in a 50L water tank, were average water temperature was monitored. Experiments were performed for short periods of time (3-4 days) combining solar collection mode (8-20h) and radiative cooling mode (20-8h). In each mode, only one of the collectors and one of the water tanks were used. The experiments were performed during summer period in Lleida (Dry Mediterranean Continental climate), since in this period both domestic hot water and cooling are required.

To evaluate the performance of the device, production rates were calculated for both solar collection and radiative cooling modes (Eq. 1). In order to obtain accurate results, the transition period from one operation mode to the other one was not considered in the evaluation (7-9h and 19-21h).

$$\dot{q} = \upsilon \cdot \rho \cdot Cp \cdot \Delta T \qquad \text{(Eq. 1)}$$

Where:

$\dot{q}$ is the power of the device in [W].

υ is de volumetric flow rate in [m^3/s].

ρ is the density of the fluid [kg/m^3].

Cp is the heat capacity of the fluid [J/kg·K].

ΔT is the temperature difference between inlet flow and outlet flow in [K].

3. Results and discussion

Experiments presented in this paper represent two typical weather scenarios: clear day (from July 26th-28th 2017) and cloudy day (from July 31st – August 4th 2017). During both periods, nights had clear skies. For the clear day experiments, the meteorology was stable with all day clear and sunshine, the outdoor temperature oscillated form 19 to 40°C, with Global Horizontal Irradiance (GHI) peak values up to 960 W/m² and Incoming Infrared Radiation average value on 340 W/m². For the cloudy day experiments, the meteorology was stable with cloudy days, the outdoor temperature oscillated from 23 to 42°C, with GHI peak values up to 935 W/m² and Incoming Infrared Radiation average value on 355 W/m².

3.1. *Clear day experiments*

Under clear sky condition the RCE was capable to produce heat, reaching maximum outlet temperature values close to 65ºC (Fig. 2), achieving average heating powers 300-350 W/m^2 (Fig. 3 and Tab. 1), and average temperature differences between the outlet water and the ambient around 17-22ºC (Tab. 1). On the other hand, the RCE also showed the capability to produce cold water, reaching minimum outlet water temperatures close to 16ºC (Fig. 2), with average cooling powers between 12-34 W/m^2 (Fig. 3 and Tab. 1), and average temperature differences between the outlet water and ambient around 2-3 ºC (Tab. 1).

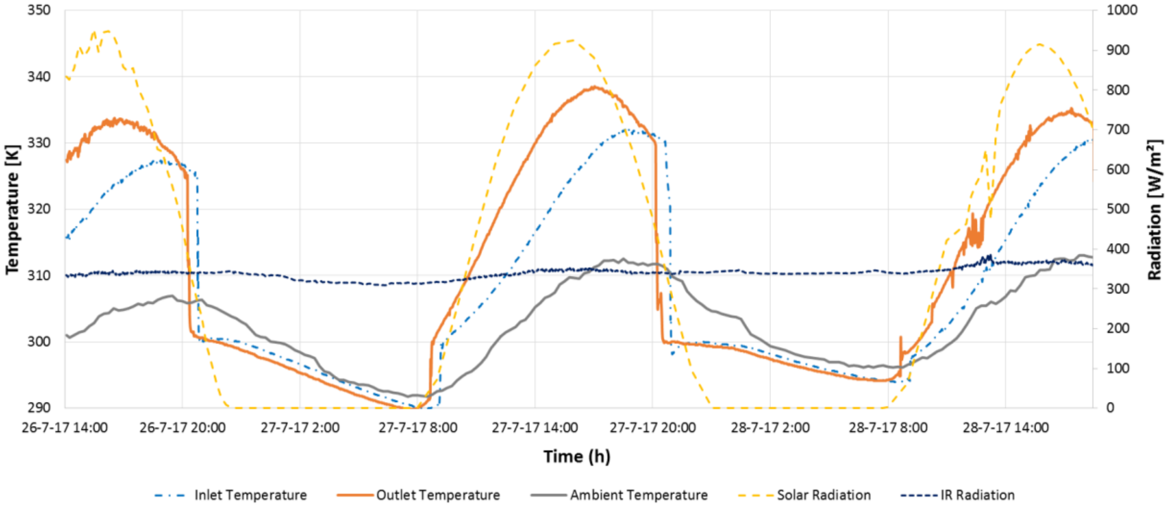

Fig. 2: Experimental results of the RCE concept for clear day experiments.

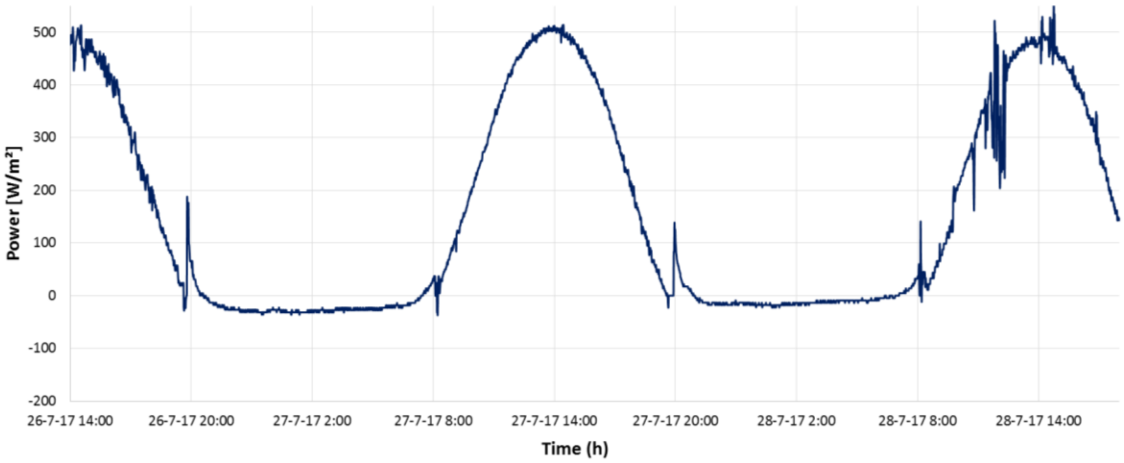

Fig. 3: Available power from the RCE concept for clear day experiments.

3.2. Cloudy day experiments

Under cloudy sky condition the RCE was capable to produce heat, reaching maximum outlet temperature values close to 65ºC (Fig. 4), achieving average heating powers 135-280 W/m^2 (Fig. 5 and Tab. 1), and average temperature differences between the outlet water and the ambient around 8-14ºC (Tab. 1). No cloudy conditions were observed during the night; therefore, no experimental data is available for cloudy conditions under radiative cooling operation.

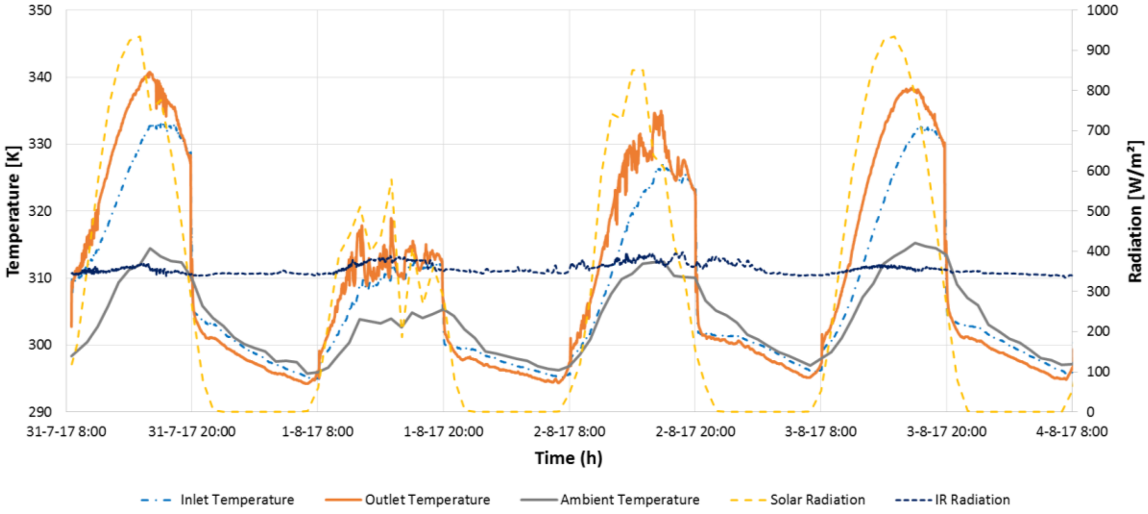

Fig. 4: Experimental results of the RCE concept for cloudy day experiments.

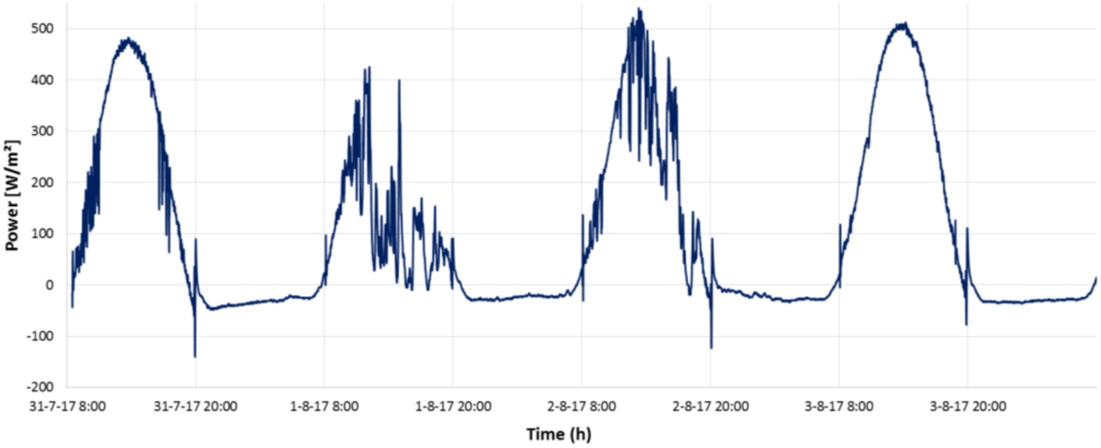

Fig. 5: Available power from the RCE concept for cloudy day experiments.

Tab. 1: Average power produced by the RCE for both heat and cold production.

		Average power (W/m^2)		Average $T_{out} – T_{amb}$ (K)	
		Heating	**Cooling**	**Heating**	**Cooling**
Clear sky	27/07/17 (9:00 – 19:00)	345.36	–	21.31	–
	26/07/17 (21:00) – 27/07/17 (7:00)	–	26.06	–	-2.14
	27/07/17 (21:00) – 28/07/17 (7:00)	–	12.65	–	-2.68
	31/07/17 (21:00) – 01/08/17 (7:00)	–	33.35	–	-2.47
	01/08/17 (21:00) – 02/08/17 (7:00)	–	23.85	–	-2.56
	02/08/17 (21:00) – 03/08/17 (7:00)	–	22.70	–	-2.63
	03/08/17 (21:00) – 04/08/17 (7:00)	–	30.65	–	
Cloudy sky	31/07/17 (9:00 – 19:00)	305.44	–	21.55	–
	01/08/17 (9:00 – 19:00)	136.25	–	8.74	–
	02/08/17 (9:00 – 19:00)	277.95	–	13.83	–
	03/08/17 (9:00 – 19:00)	342.82	–	17.14	–

4. Conclusions

Experimental results demonstrate the potential of the RCE concept to heat up water during daylight hours and to cool down water during night. Although improvements are required in order to maximize the cold production and reach useful temperature levels, the concept is probed to cool down water below ambient temperature by the use of sky night radiation, while heating up water during day.

The cold produced during night can be used either as a cooling source or as a heat sink for other cooling technologies (such as heat pumps) in order to improve its efficiency, thus reducing the use of non-renewable energies. However, further improvements are required to take full advantage of this new concept.

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