DOI: 10.21134/5y4trp12

CYTEF XII Congreso Ibérico y X Congreso Iberoamericano de Ciencias y Técnicas del Frio
Universidad Miguel Hernández de Elche
26-06 28-06/2024
UNIVERSITAS Miguel Hernández

INNOVATIVE INTEGRATION OF DAILY RADIATIVE COOLING AND SOLAR HEATING: PRESENTING THE AD-RCE FOR COMBINED RENEWABLE HEATING AND COOLING

Roger Vilà[1], Jesús Monterrubio[1], Jonathan Cofré-Toledo[1, 2], Cristian Solé[1], Albert Castell[1], Ingrid Martorell[1], Lídia Rincón[1], Marc Medrano[1*]

1: Sustainable Energy, Machinery and Buildings (SEMB) Research Group, INSPIRES Research Centre, Universitat de Lleida. C/ Pere de Cabrera s/n, 25001, Lleida, Spain
2: Departamento de Ingeniería Mecánica, Facultad de Ingeniería, Universidad de Santiago de Chile, Av. Libertador Bernardo O'Higgins Nº3363, Estación Central, Santiago
*e-mail: marc.medrano@udl.cat

Abstract: *This research introduces the Adaptive Radiative Collector and Emitter (ad-RCE) device, an evolution of the Radiative Collector and Emitter (RCE). The RCE has demonstrated the dual capability of producing hot water using solar collection during the day and cold water below ambient temperature using radiative cooling at night. With the development of new materials, it is now possible to achieve radiative cooling even during daytime. To increase cold production, the ad-RCE integrates daytime radiative cooling (DRC) with nocturnal radiative cooling (NRC) and solar heating (SH) in an active system. The ad-RCE improves the previous RCE as it is designed to dynamically adjust its heat and cold production in response to daily demand. By incorporating a rotating mechanism and novel DRC materials, the ad-RCE allows the transition between radiative cooling and solar heating functions while extending the cooling operation period, representing an innovative approach to harness renewable energy sources for both heating and cooling purposes. This evolution from the RCE to the ad-RCE expands upon the capabilities of the device by increasing the cooling production while reducing the surface requirements of the ad-RCE. This makes the ad-RCE more suitable for energy production in buildings and industrial applications. The paper provides a comprehensive analysis of the ad-RCE, highlighting its benefits and improvements compared to its predecessor, the RCE.*

Keywords: Daytime Radiative Cooling, Solar Energy, Renewable Cooling, Renewable Heating

1. INTRODUCTION

The building sector accounted for 30% of global energy consumption and 26% of CO_2 emissions in 2022 [1]. The demand for energy for cooling has experienced an annual increase of 4% since 2000, being the fastest growing energy use in buildings. Although heat pumps are the main system to cover the cooling demand in buildings, these systems, based on mechanical compression, consume a considerable amount of electricity, and continue to contribute to greenhouse gas emissions. The European Union has committed to becoming an economy based on low energy consumption, stable, secure, competitive, sustainable, and locally produced [2–4].

In this context, radiative cooling technology (RC) emerges as a renewable alternative for cold production in space conditioning. Radiative cooling is a natural phenomenon in which a surface emits infrared radiation towards the outer space, dissipating heat and cooling down in the process [5]. The peaks of radiation emitted fall in the wavelength range of 7 to 14 µm. In this region of the electromagnetic spectrum, called the atmospheric window, the Earth's atmosphere is highly transparent, allowing radiation to escape into outer space and dissipate into the cosmos [6]. The operation of radiative cooling is analogous to solar capture – where a surface heats up by absorbing solar radiation – hence, various authors have proposed the combination of both functions [7–9]. In 2018, we presented the Radiative Collector and Emitter (RCE) [10], a system capable of producing hot water during the day and sub-ambient cold water during the night for applications in buildings and industries (DHW, heating, and cooling). However, the obtained cooling power density was low, ranging from 20-80 W/m^2 on average [11]. This low power density implies that more hours of radiative cooling are needed to produce cold, thus increasing the total energy required to meet demands and compensate for these reduced powers.

The aim of this paper is to present a new concept, the Adaptive Radiative Collector and Emitter (ad-RCE), which represents an evolution of the previous RCE system, capable of harnessing solar energy during the day to produce heat, as well as producing cold both during the day and at night through radiative cooling, thus extending the cooling hours. The design can switch between production modes during the day (between cold and heat), depending on the different requirements and demand profiles of buildings and industries, while cold production continues during the night. The RCE technology has the potential to generate positive long-term changes by decreasing reliance on fossil fuels and reducing greenhouse gas emissions, contributing to climate change mitigation efforts.

2. RADIATIVE COOLING

Radiative cooling occurs when there is a positive difference between the emitted radiation and the absorbed heat, allowing sub-ambient temperatures to be achieved. Initially, radiative cooling was only possible during the night, as the energy balance during the day resulted in gains due to solar radiation. However, with the emergence of new materials, it is now possible to cool a surface during the day. Various studies have proposed different types of materials for daytime radiative cooling (DRC), such as nanoparticles, metamaterials, bioinspired materials, photonic structures, and hierarchically porous polymers [12–17]. However, due to their optical properties, these new materials do not allow for the harnessing of solar energy during the day.

The cooling power of radiative cooling is greater in warm and dry regions, where atmospheric conditions are conducive to a higher net balance of infrared radiation towards outer space. However, this potential decreases with humidity, as the presence of water vapor in the atmosphere increases the atmospheric radiation absorbed by the device, resulting in a lower net energy balance dissipated towards outer space. Recent studies have mapped the maximum radiative cooling power worldwide [18] and for different geographical regions, including areas such as Europe [19,20], China [21], the United States [22], and the countries of the Gulf Cooperation Council [23]. In the specific case of Europe, it has been observed that southern regions, including countries like Turkey and Spain, show particularly high potential for radiative cooling. A relevant finding from these studies is that transitioning from exclusively nocturnal radiative cooling systems (NRC) to daily radiative cooling systems can increase the average annual energy potential by an average of 126.65% in Europe (Figure

1) [19]. This represents a significant increase in refrigeration production per square meter, which can be harnessed by systems such as the ad-RCE.

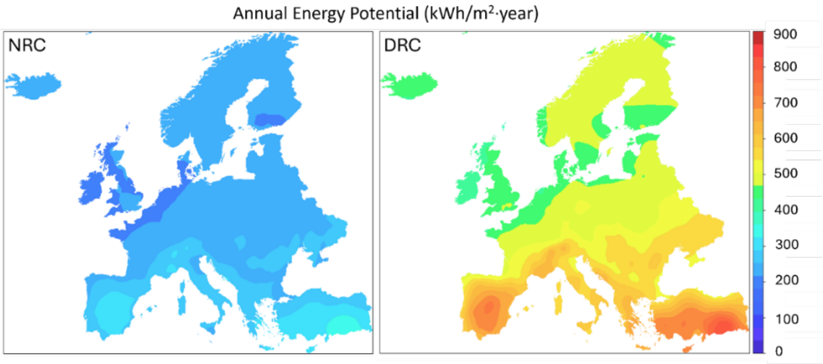

Figure 1. Mapping of the annual energy potential of nocturnal radiative cooling and daily raditive cooling in Europe [19].

3. AD-RCE DESIGN

The dual production of cold and hot water in the ad-RCE is achieved through the combination of three technologies: solar heating, nocturnal radiative cooling, and daytime radiative cooling. Solar heaters and radiative coolers operate at different wavelengths of the electromagnetic spectrum: while radiative coolers emit in the longwave infrared range, daytime solar collectors absorb in the visible range, from 0.2 to 3 µm, and block the infrared radiation necessary for radiative cooling.

The development of the ad-RCE requires two distinct configurations of radiative surfaces. When the ad-RCE operates in solar collection (SC) mode, a typical flat-plate solar collector configuration is used, with a spectrally high absorptivity plate in the range of 0.2 to 3 µm, along with a glass cover with high transmittance in the solar range and very low transmittance in the mid and long-wave infrared band. On the other hand, when the ad-RCE operates in RC mode, a selective surface with high emissivity values in the atmospheric window (7-14 µm) and high reflectivity values in the solar range is required. Additionally, a convective cover transparent in this atmospheric window is used, reducing convection losses, and allowing sub-ambient temperatures to be achieved.

Each functionality of the ad-RCE is integrated into one of the two assembled surfaces, one on top of the other. The switching between functionalities is achieved in a rotating device from its central axis, positioning the active surface horizontally towards the sky and leaving the other surface inactive below. Each surface is in contact to its own piping system through which the heat transfer fluid circulates, ensuring efficient heat transfer from the active surface to the corresponding storage system. Figure 2 shows a schematic representation of this design. Subsequently, the fluid is stored in two separate tanks, one for cold water and the other for hot water, ready for later use in the building.

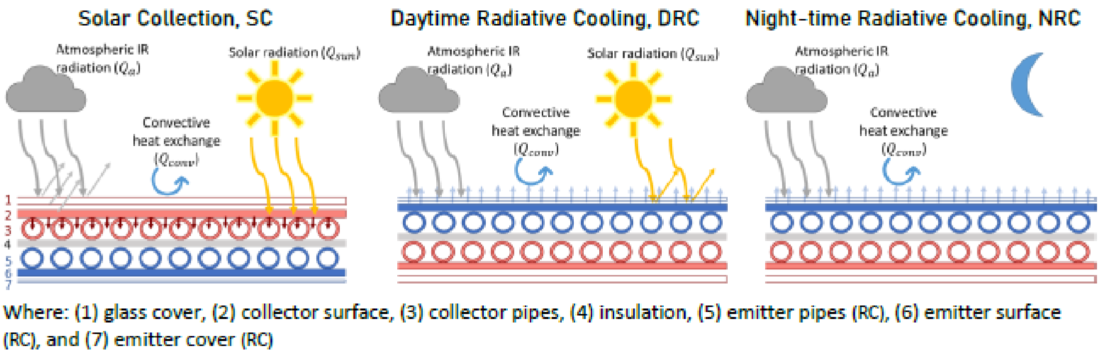

Figure 2. Conceptual design and schematics of the three operations modes of the ad-RCE

4. BENEFITS AND IMPROVEMETNS OF THE AD-RCE

Both the RCE and the ad-RCE present a series of benefits that highlight them as innovative solutions for combined hot and cold water production:

1. **Renewable production and low electricity consumption:** The RCE and the ad-RCE enable the production of both cold and hot water in a renewable manner with almost zero electricity consumption, contributing to the reduction of greenhouse gas emissions associated with conventional heating and cooling.
2. **Continuous 24-hour operation:** Unlike conventional solar collectors or photovoltaic panels, which are limited to daylight hours of solar exposure, the RCE and ad-RCE can operate 24 hours a day, generating two products (cold and hot water) according to demand.

However, the ad-RCE, as an evolution of the RCE system, presents a series of improvements that enhance versatility in combined hot and cold water production. These improvements include:

3. **Space optimization:** The combination of radiative cooling and solar heating functionalities in the RCE is made possible by using an adaptive sliding cover that combines materials with different optical properties for solar collection and radiative cooling. For solar collection, a cover with high radiation transmittance in the wavelength range of 0.2-3 μm (solar radiation) is required, along with low transmittance for other wavelengths, to achieve the greenhouse effect. On the other hand, radiative cooling requires high transmittance in the wavelength range between 7-14 μm (atmospheric window), as it is in these wavelengths that the energy emitted by a body can dissipate into outer space and cool it to temperatures lower than the ambient temperature.

   This cover, which occupies the same surface area as the RCE, slides over it during solar collection mode but needs to move alongside the RCE during radiative cooling mode. This implies that the system occupies twice the surface area of the RCE. However, the ad-RCE resolves this limitation by using a rotating system that allows both functions to be performed in the same space. This optimizes the use of available space, which is especially important in residential buildings where available space is limited.
4. **Greater cold coverage:** Vall et al. demonstrated how the RCE device could be integrated into various types of residential and commercial buildings in different climatic regions worldwide [7]. However, when sizing the installation to meet domestic hot water demands, the cold coverage was modest (less than 25% in 10 out of 15 studied climates). On the other hand, if the installation is sized for cold production, it results in an oversized installation for heat production. Unlike RCE systems, the ad-RCE can produce cold throughout the day, which increases its potential for cold water production. This translates into a 126.65% increase in average annual energy potential in Europe [19]. Thus, the ad-RCE offers a solution that optimizes the available installation surface area on the roof and flexibly adjusts production, avoiding over- or under-sizing for both cold and heat production.

5. CHALLENGES AND FUTURE RESEARCH

Despite the benefits of the ad-RCE, as described in the previous section, there are still technical challenges that require attention and will be addressed in future research. These challenges include:

1. **Development of a durable convective cover:** The convective cover is a necessary element to maximize cooling power. This cover helps reduce parasitic exchanges (convection and conduction), allowing sub-ambient temperatures to be achieved. The cover should have high transmittance in the range of 7-14 μm. To date, polyethylene has been the most widely used material in radiative cooling applications due to its good optical properties. However, polyethylene exhibits mechanical degradation and, to a lesser extent, optical degradation over time [24,25]. Although polyethylene offers excellent optical properties, its mechanical properties do not make it a durable candidate for outdoor applications [26].
2. **Improvement of heat exchange:** The power of radiative cooling, averaging between 20-80 W/m², is an order of magnitude below solar harvesting [26]. It is common in radiative cooling applications to

start with modified flat-plate solar collector designs. However, as noted by Erell and Etzion [27], modifying the radiator design is essential for achieving better cooling performance. To address this challenge, further research is required to improve heat exchange between the heat carrier fluid and the radiative cooling emitter. This involves exploring new radiator geometries that maximize heat transfer.

3. **Material selection for DRC:** At the time of presenting this communication, we are still experimentally evaluating the best daytime radiative cooling material for the device. Ideal materials for DRC should exhibit high reflectance as close to 100% as possible to minimize solar absorption and high emissivity in the infrared range also as close to 100% as possible to facilitate efficient radiative cooling. Additionally, these materials should be cost-effective and environmentally friendly to ensure practicality.

6. CONCLUSIONS

In this article, the ad-RCE system has been presented as a new solution for renewable and low-electricity consumption production of hot and cold water intended for building applications such as domestic hot water, heating, and cooling. This technology represents an evolution of the RCE concept proposed in 2018, which integrated the functionalities of radiative cooling and solar harvesting. Unlike conventional RCE systems, the ad-RCE adjusts its operation between cold and heat during the day, allowing it to adapt to the building's demand. This prevents over-sizing or under-sizing of both functions, optimizes installation space, and increases cold water production. Despite the benefits, the ad-RCE is still in the development phase. There are still technical challenges that need to be addressed, including the development of a durable convective cover, improvement of the heat exchange design between the fluid and the emitter, as well as the selection of the best DRC material.

ACKNOWLEDGEMENTS

This publication is part of the grant PID2021-126643OB-I00, funded by MCIN/ AEI/ 10.13039/ 501100011033 / and by “ERDF A way of making Europe”. This publication is also part of the grant PDC2022-133215-I00, funded by MCIN/AEI/10.13039/501100011033/ and by the “European Union Next Generation EU/PRTR”. The authors would like to thank Generalitat de Catalunya for the project awarded to their research group (2021SGR 01370). Jonathan Cofré-Toledo is grateful to: “Programa de formación académica de la Facultad de Ingeniería de la Universidad de Santiago de Chile”. Jonathan Cofré-Toledo is also grateful to: “Convocatòria 2023 d'Ajuts UdL per la contractació de personal predoctoral en formació. Grant number: 2023 UdL 06”. Jesús Monterrubio would like to thank the grant FPU22/01304 funded by MICIU/AEI /10.13039/501100011033 and by “ESF+”.

REFERENCES

[1] Buildings - Energy System, IEA (n.d.). https://www.iea.org/energy-system/buildings (accessed April 11, 2024).

[2] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, (2009). https://doi.org/10.1007/978-1-137-54507-7_21.

[3] Directive (EU) 2018/ of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, (n.d.) 17.

[4] Council of the European Union. General Secretariat of the Council, Project Europe 2030 : challenges and opportunities : a report to the European Council by the reflection group on the future of the EU 2030, Publications Office, LU, 2010. https://data.europa.eu/doi/10.2860/9573 (accessed April 11, 2024).

[5] S. Vall, A. Castell, Radiative cooling as low-grade energy source: A literature review, Renewable and Sustainable Energy Reviews 77 (2017) 803–820. https://doi.org/10.1016/j.rser.2017.04.010.

[6] M.M. Hossain, M. Gu, Radiative cooling: Principles, progress, and potentials, Advanced Science 3 (2016) 1–10. https://doi.org/10.1002/advs.201500360.

[7] S. Vall, A. Castell, M. Medrano, Energy Savings Potential of a Novel Radiative Cooling and Solar Thermal Collection Concept in Buildings for Various World Climates, Energy Technol. 6 (2018) 2200–

2209. https://doi.org/10.1002/ente.201800164.
[8] M. Matsuta, S. Terada, H. Ito, Solar Heating and radiative cooling using a solar collector-sky radiator with a spectrally selective surface, Solar Energy 39 (1987) 183–186.
[9] M. Hu, G. Pei, Q. Wang, J. Li, Y. Wang, J. Ji, Field test and preliminary analysis of a combined diurnal solar heating and nocturnal radiative cooling system, Applied Energy 179 (2016) 899–908. https://doi.org/10.1016/j.apenergy.2016.07.066.
[10] S. Vall, A. Castell, M. Medrano, Energy Savings Potential of a Novel Radiative Cooling and Solar Thermal Collection Concept in Buildings for Various World Climates, Energy Technol. 6 (2018) 2200–2209. https://doi.org/10.1002/ente.201800164.
[11] R. Vilà, L. Rincón, M. Medrano, A. Castell, Potential Maps for Combined Nocturnal Radiative Cooling and Diurnal Solar Heating Applications. Cases of Spain, Switzerland, Germany and Sweden., in: Proceedings of the 6th International Conference on Polygeneration, International Conference on Poligeneration, Zaragoza (Spain), 2021.
[12] S. Catalanotti, V. Cuomo, G. Piro, D. Ruggi, V. Silvestrini, G. Troise, The radiative cooling of selective surfaces, Solar Energy 17 (1975) 83–89. https://doi.org/10.1016/0038-092X(75)90062-6.
[13] M.A. Kecebas, M.P. Menguc, A. Kosar, K. Sendur, Passive radiative cooling design with broadband optical thin-film filters, Journal of Quantitative Spectroscopy and Radiative Transfer 198 (2017) 179–186. https://doi.org/10.1016/j.jqsrt.2017.03.046.
[14] J. Mandal, Y. Fu, A.C. Overvig, M. Jia, K. Sun, N.N. Shi, H. Zhou, X. Xiao, N. Yu, Y. Yang, Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling, Science 362 (2018) 315–319. https://doi.org/10.1126/science.aat9513.
[15] J.-W. Cho, T.-I. Lee, D.-S. Kim, K.-H. Park, Y.-S. Kim, S.-K. Kim, Visible to near-infrared thermal radiation from nanostructured tungsten anntennas, J. Opt. 20 (2018) 09LT01. https://doi.org/10.1088/2040-8986/aad708.
[16] A.P. Raman, M.A. Anoma, L. Zhu, E. Rephaeli, S. Fan, Passive radiative cooling below ambient air temperature under direct sunlight, Nature 515 (2014) 540–544. https://doi.org/10.1038/nature13883.
[17] B. Ko, D. Lee, T. Badloe, J. Rho, Metamaterial-Based Radiative Cooling: Towards Energy-Free All-Day Cooling, Energies 12 (2018) 89. https://doi.org/10.3390/en12010089.
[18] A. Aili, X. Yin, R. Yang, Global Radiative Sky Cooling Potential Adjusted for Population Density and Cooling Demand, Atmosphere 12 (2021) 1379. https://doi.org/10.3390/atmos12111379.
[19] R. Vilà, M. Medrano, A. Castell, Mapping Nighttime and All-Day Radiative Cooling Potential in Europe and the Influence of Solar Reflectivity, Atmosphere 12 (2021) 1119. https://doi.org/10.3390/atmos12091119.
[20] R. Vilà, M. Medrano, A. Castell, Climate change influences in the determination of the maximum power potential of radiative cooling. Evolution and seasonal study in Europe, Renewable Energy 212 (2023) 500–513. https://doi.org/10.1016/j.renene.2023.05.083.
[21] K. Chang, Q. Zhang, Modeling of downward longwave radiation and radiative cooling potential in China, Journal of Renewable and Sustainable Energy 11 (2019) 066501. https://doi.org/10.1063/1.5117319.
[22] M. Li, H.B. Peterson, C.F.M. Coimbra, Radiative cooling resource maps for the contiguous United States, Journal of Renewable and Sustainable Energy 11 (2019) 036501. https://doi.org/10.1063/1.5094510.
[23] A.S. Farooq, K. Alkaabi, S.B. Hdhaiba, Exploring radiative sky cooling resource map and the impact of meteorological conditions on radiative emitters. A perspective of GCC countries, Energy Reports 10 (2023) 473–483. https://doi.org/10.1016/j.egyr.2023.06.054.
[24] A.H.H. Ali, H. Saito, I.M.S. Taha, K. Kishinami, I.M. Ismail, Effect of aging, thickness and color on both the radiative properties of polyethylene films and performance of the nocturnal cooling unit, Energy Conversion and Management 39 (1998) 87–93. https://doi.org/10.1016/S0196-8904(96)00174-4.
[25] I. Martorell, J. Camarasa, R. Vilà, C. Solé, A. Castell, RCE as a device to produce heating and cooling. Transmittance and aging study for cover materials suitable for radiative cooling, in: Proceedings of the 6th International Conference on Polygeneration, International Conference on Poligeneration, Zaragoza (Spain), 2021.
[26] R. Vilà, I. Martorell, M. Medrano, A. Castell, Adaptive covers for combined radiative cooling and solar heating. A review of existing technology and materials, Solar Energy Materials and Solar Cells 230 (2021) 111275. https://doi.org/10.1016/j.solmat.2021.111275.
[27] E. Erell, Y. Etzion, Radiative cooling of buildings with flat-plate solar collectors, Building and Environment 35 (2000) 297–305. https://doi.org/10.1016/S0360-1323(99)00019-0.