Experimental assessment of a resilient air-cooling system under extreme heat events in southern European climate conditions

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ABSTRACT

The global rise in average outdoor air temperatures has led to a significant increase in the demand for cooling energy in recent years. The development of resilient air-cooling systems capable of handling extreme heat events is essential to achieve the aim of Nearly Zero Energy Buildings. Ventilative cooling technologies based on indirect evaporative cooling systems are considered a sustainable solution in terms of indoor air quality and energy performance.

In this study, the daily energy performance of a renewable air-cooling unit (RACU) based on a dew-point indirect evaporative cooler (DIEC) and a desiccant wheel (DW) was experimentally evaluated under the real extreme heat events in southern Europe. The RACU prototype has been developed to be integrated into renewable District Heating and Cooling Networks. This air-cooling system allows controlling air humidity through the DW and air temperature and carbon dioxide emissions through the DIEC. The RACU system works with two inlet air streams: outdoor air (OA) and outdoor air for regeneration (ROA) to thermally activate DW. For the purposes of this work, both inlet air streams were 100% outdoor air. The RACU prototype does not use refrigerants.

The daily energy performance of the RACU was obtained in terms of Daily Energy Efficiency Ratio (DEER). The RACU system operated during four different days under the severe heat weather conditions in Cordoba, Spain, during office hours. Therefore, four different case studies were established to analyse the supply air conditions, sensible and latent capacities and DEER values for the RACU in this work.

Results indicated high DEER values for the RACU, ranged between 7.0 and 14.8. High values of daily sensible cooling energy, up to 177.0 MJ/day, and daily total latent capacity, up to 38.6 MJ/day, were also evident for the RACU. These results suggest that the use of resilient air-cooling systems as the RACU could be interesting under southern European climatic conditions of extreme heat, demonstrating high daily energy efficiency performance.

KEYWORDS

Experimental results, evaporative cooling technology, Daily Energy Efficiency Ratio, severe weather conditions.

1 INTRODUCTION

Heating and cooling of buildings constitute 50% of the overall energy consumption in the European Union. Currently, 70% of this energy is generated from fossil fuels (Eurostat, 2023). In addition, one of the primary effects of climate change is the rise in outdoor temperatures worldwide, which directly increases the demand for cooling energy (IEA, 2023). Thus, designing and optimizing resilient air-cooling systems for extreme heat event scenarios is crucial to achieving the Nearly Zero Energy Buildings (NZEB) goal. Air-cooling systems based on the indirect evaporative cooling technology could be a potential solution in terms of thermal comfort, indoor air quality, reduction of carbon dioxide (CO_2) emissions and higher energy efficiency (Romero-Lara, Comino, and Ruiz de Adana, 2021).

Thus, the main objective of the present work was to experimentally evaluate the daily energy performance of a renewable air-cooling unit (RACU) based on a dew-point indirect evaporative cooler (DIEC) and a desiccant wheel (DW), under real conditions of extreme heat in southern Europe. In this research work, the outdoor air conditions and supply air conditions for the RACU during four different days were also analysed to demonstrate the advantages of this prototype over traditional air-cooling systems, in terms of thermal comfort and energy savings.

2 MATERIAL AND METHODS

2.1 Description of the renewable air-cooling unit

The RACU prototype has been developed to be integrated into Renewable District Heating and Cooling Networks (RDHCN). This air-cooling system is mainly composed of a desiccant wheel (DW) for air humidity control and a dew-point indirect evaporative cooler (DIEC) for air temperature and indoor CO_2 level control. The RACU works with two inlet air streams: outdoor air (OA) for the process side and outdoor air for regeneration (ROA), the latter being used to thermally activate the DW. The process side air is divided into supply air (SA), which supplies cool air to a building, and exhaust air (EA), which expels moist air after the indirect evaporative cooling process, as illustrated in Figure 1.

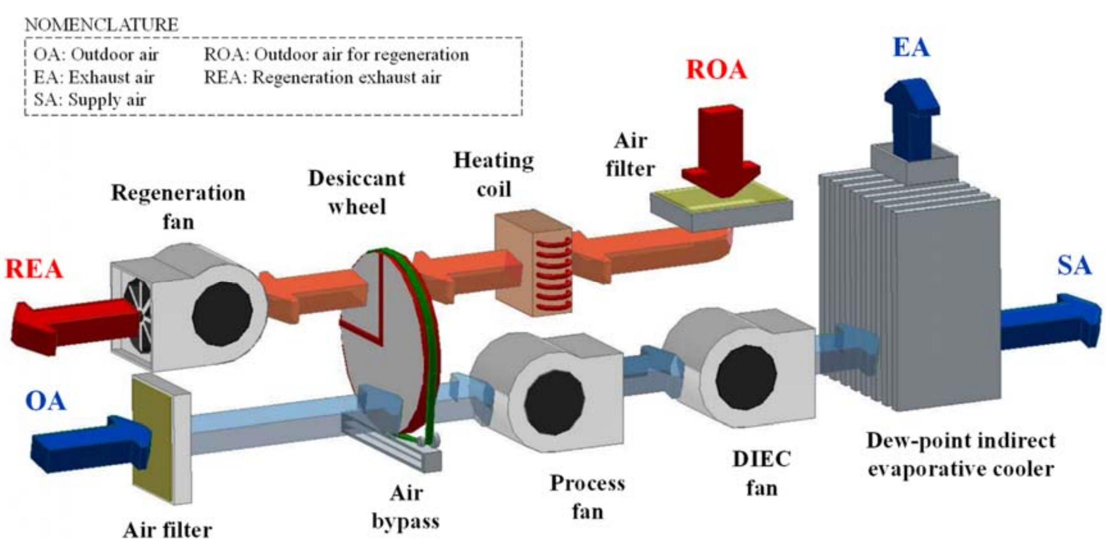

Figure 1: Main components of the renewable air-cooling unit (RACU).

The RACU operates without refrigerant gases and uses several elements to handle 100% outdoor air. The main technical characteristics of these components are described in a recent published work by the authors (Romero-Lara, Comino, and Ruiz de Adana, 2024). However, the main thermal characteristics of the RACU prototype are shown in Table 1.

Table 1: Thermal characteristics of the RACU.

Parameter	Value	Unit
Nominal process air flow rate	5236	m^3/h
Nominal regeneration air flow rate	1745	m^3/h
Nominal supply air flow rate	2880	m^3/h
Nominal dehumidification capacity	16	kg/h

Nominal cooling capacity	18	kW
Process fan nominal power	2.65	kW
Regeneration fan nominal power	1.00	kW
DIEC fan nominal power	1.50	kW
Hydraulic pump nominal power	0.60	kW

2.2 Control system and operation modes

The RACU has been designed to independently control the indoor air temperature, indoor air humidity, and indoor air CO_2 concentration in a building. In this work, an occupied room was not included since the main objective was to study the energy performance of the RACU. As can be observed from section 2.1.2 of the authors recent work (Romero-Lara, Comino, and Ruiz de Adana, 2024), three independent control loops were included to the RACU control system: temperature control (T), humidity control (H) and ventilation control (V). Seven different operation modes were established for the RACU according to these control loops. For this work, to analyse the energy performance of the RACU prototype under real severe outdoor air conditions in Cordoba, variable air flow rates were used, as illustrated in Figure 2.

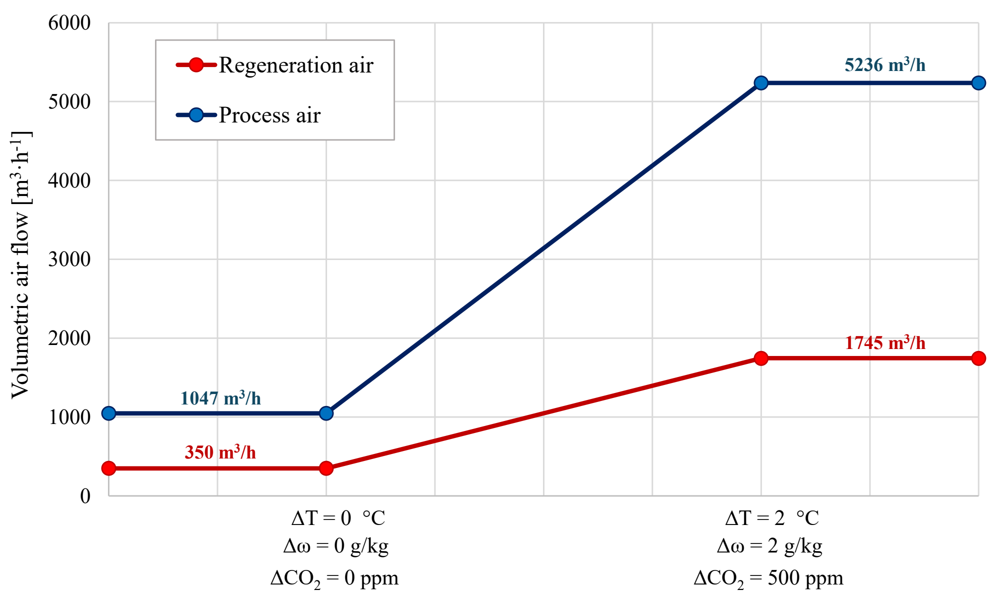

Figure 2: Variable volumetric air flow rates control for the RACU.

The process and regeneration volumetric air flows were adjusted from 20% to 100% of the respective nominal values, as shown in Figure 2. RACU worked at 100% of its nominal air flow rate when the increases of temperature (ΔT), humidity ratio (Δω) and carbon dioxide (ΔCO_2) were equal to 2 °C, 2 g/kg and 500 ppm, respectively. When the set point (SP) conditions of temperature, humidity and CO_2 were achieved, the percentage of these volumetric air flows was maintained at 20% to provide a minimum ventilation air flow rate, as observed in Figure 2.

2.3 Case studies under Cordoba weather conditions

For this work, the RACU operated under the severe summer weather conditions in Cordoba, Spain. According to the climate classification of the Basic Document HE Energy Savings – CTE (Ministerio de Fomento España, 2019), Cordoba has a "B4" classification, where "4" is the highest value of climate severity in summer, see Figure 3.

The RACU operated in four different days during office hours, that is, from 9:30 a.m. to 4:30 p.m. Therefore, four different case studies were generated for evaluating the SA conditions and the energy performance values for the RACU. Average value of OA temperature ($T_{OA,avg}$) for study cases 1 and 2 was 25 °C. However, $T_{OA,avg}$ value for study cases 3 and 4 was 33 °C. Average value of OA humidity ratio ($\omega_{OA,avg}$) for study cases 1 and 3 was approximately 8 g/kg. However, $\omega_{OA,avg}$ value for study cases 2 and 4 was approximately 9 g/kg. In addition, different values of set-point for temperature (16 or 18 °C) and humidity ratio (6 or 8 g/kg) were established to research the energy behaviour of the RACU under different working conditions.

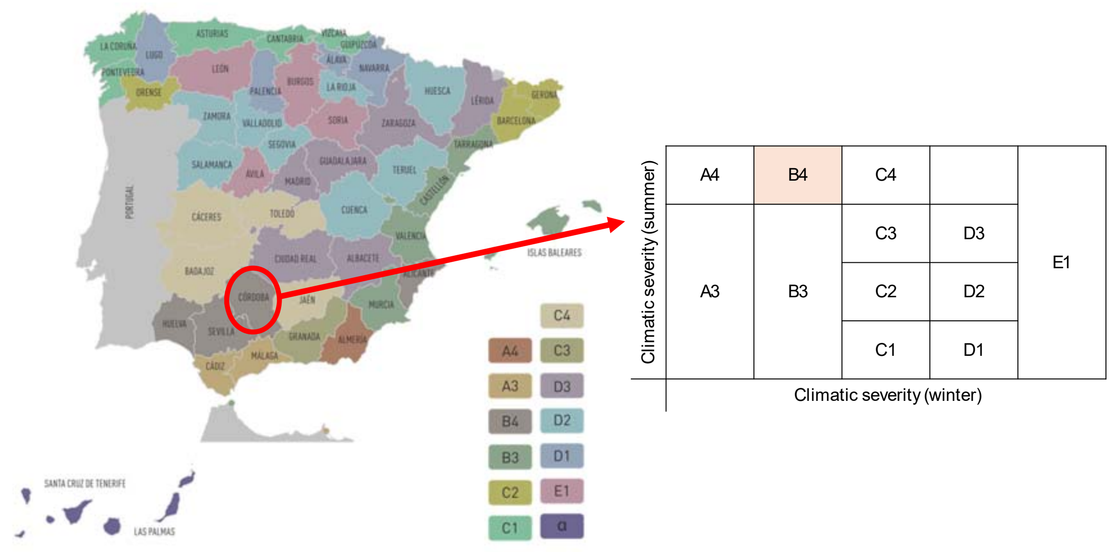

Figure 3: Climate classification for Cordoba, Spain.

2.4 Energy performance evaluation

In this work, the energy performance of the RACU was evaluated in terms of supply air conditions and Daily Energy Efficiency Ratio (DEER) for the four experimental cases studies. Sensible cooling capacity ($\dot{Q}_S$), latent capacity ($\dot{Q}_L$), and electrical power consumption ($\dot{W}_{el}$) were calculated for the RACU according to Eq. 1, Eq. 2 and Eq.3, respectively.

$$\dot{Q}_S = \rho_{SA} \cdot \dot{V}_{SA} \cdot (h_{aux} - h_{SA}) \quad (1)$$

$$\dot{Q}_L = \rho_{SA} \cdot \dot{V}_{SA} \cdot (h_{OA} - h_{aux}) \quad (2)$$

$$\dot{W}_{el} = \dot{W}_{Process\ fan} + \dot{W}_{Regeneration\ fan} + \dot{W}_{DIEC\ fan} + \dot{W}_{motor,DW} + \dot{W}_{Hydraulic\ pump} \quad (3)$$

Where ρ_{SA} was the supply air density [kg/m^3], $\dot{V}_{SA}$ was the supply air volumetric air flow [m^3/s] and h was the air specific enthalpy [kJ/kg]. An auxiliary air state (aux) was defined as the combination of outdoor air temperature (T_{OA}) and supply air humidity ratio (ω_{SA}). This auxiliary point was necessary to independently obtain the sensible capacity and latent capacity of the RACU. The $\dot{W}_{elect}$ value for the RACU was obtained as the sum of the electrical power consumed by the three fans (process, regeneration and DIEC), the DW drive motor and the internal hydraulic pump in the DIEC, as shown in Eq. 3.

The $\dot{Q}_S$, $\dot{Q}_L$ and $\dot{W}_{el}$ values for the RACU were obtained for each time interval (dt) of 30 seconds for each case study. Daily sensible cooling energy (Q_S), daily latent capacity energy (Q_L) and daily electrical energy consumption (W_{el}) were calculated for the RACU as the sum of sensible, latent and electrical energy shown for the RACU for one day operation (from 9:30 a.m. to 4:30 p.m). DEER values for the RACU were calculated as the ratio of daily sensible and latent energy to daily electrical consumption, as shown in Eq. 4.

$$\mathrm{DEER} = \frac{Q_S + Q_L}{W_{el}} = \frac{\int (\dot{Q}_S + \dot{Q}_L)\cdot dt}{\int \dot{W}_{el}\cdot dt} \tag{4}$$

3 RESULTS AND ANALYSIS

Experimental results of four case studies are presented in this section. The values of supply air conditions of the RACU were analysed under real outdoor air conditions in Cordoba, Spain. The energy performance of the RACU in terms of daily sensible cooling capacity, daily latent capacity and DEER was also shown as main results of this work.

3.1 Daily air conditions for Case study 1

Case study 1 consisted of the operation of the RACU during May 10, 2023, in Cordoba, Spain. The daily variation of T_{OA} and ω_{OA} from 9:30 a.m. to 4:30 p.m. for this day can be observed in Figure 4. T_{OA} values were between 17.2 °C and 29.8 °C and ω_{OA} values were between 7.4 g/kg and 9.3 g/kg for this case study 1. According to these OA conditions values, the RACU came into operation 28.9% of period between 9:30 a.m. and 4:30 p.m. of that day. Since the values of T_{SP} and ΔT were 18 °C and 2 °C, respectively, the DIEC of the RACU came into operation when T_{SA} value was higher than 20 °C and operated at the minimum air flow rate (20%) when T_{SA} of 18 °C was achieved, see Figure 4. According to the control system design for the RACU, the DW of the RACU came into operation if the DIEC was activated. A value of ω_{SP} of 8 g/kg and a value of $\Delta\omega$ of 1 g/kg were established for this case study 1. Thus, the DW worked when the DIEC was activated and ω_{SA} value was higher than 9 g/kg, until ω_{SP} of 8 g/kg was reached, see Figure 4. For this case study 1, the DIEC operated 85.6% of the RACU's daily operating time. However, the DW only operated 22.2% of that period due to the low outdoor air humidity values, as shown in Figure 4.

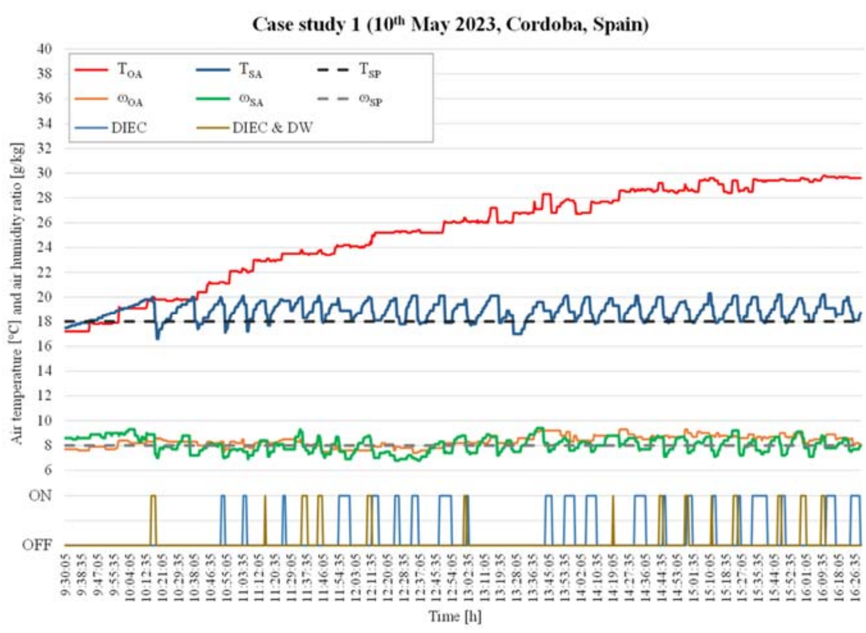

Figure 4: Air temperature and humidity values for Case study 1.

3.2 Daily air conditions for Case study 2

Case study 2 consisted of the operation of the RACU during October 4, 2023, in Cordoba, Spain. The daily variation of T_{OA} and ω_{OA} from 9:30 a.m. to 4:30 p.m. for this day can be observed in Figure 5. T_{OA} values were between 17.7 °C and 29.9 °C and ω_{OA} values were between 7.3 g/kg and 10.4 g/kg for this case study 2. According to these OA conditions values, the RACU came into operation 24.8% of period between 9:30 a.m. and 4:30 p.m of that day. Since the values of T_{SP} and ΔT were 16 °C and 3 °C, respectively, the DIEC of the RACU came into operation when T_{SA} value was higher than 19 °C and operated at the minimum air flow rate (20%) when T_{SA} of 16 °C was achieved, see Figure 5. A value of ω_{SP} of 6 g/kg and a value of $\Delta\omega$ of 2 g/kg were established for this case study 2. Thus, the DW worked when the DIEC was activated and ω_{SA} value was higher than 8 g/kg, until ω_{SP} of 6 g/kg was reached, see Figure 5. For this case study 2, both the DIEC and the DW operated 98.1% of the RACU's daily operating time due to the higher outdoor air humidity values, as observed in Figure 5.

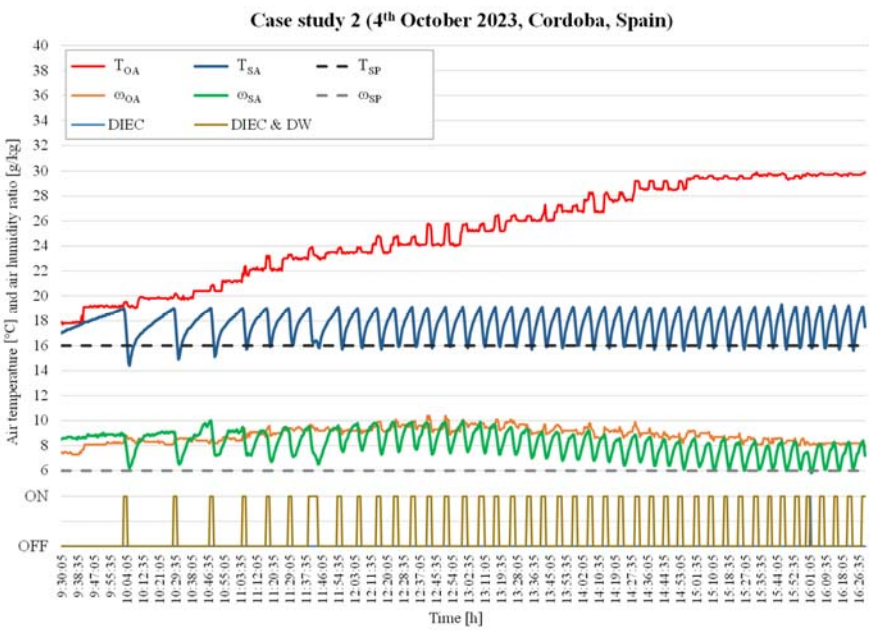

Figure 5: Air temperature and humidity values for Case study 2.

3.3 Daily air conditions for Case study 3

Case study 3 consisted of the operation of the RACU during June 14, 2023, in Cordoba, Spain. The daily variation of T_{OA} and ω_{OA} from 9:30 a.m. to 4:30 p.m. for this day can be observed in Figure 6. T_{OA} values were between 25.2 °C and 38.4 °C and ω_{OA} values were between 7.3 g/kg and 9.8 g/kg for this case study 3. According to these OA conditions values, RACU came into operation 52.0% of period between 9:30 a.m. and 4:30 p.m of that day. Since the values of T_{SP} and ΔT were 18 °C and 3 °C, respectively, the DIEC of the RACU came into operation when T_{SA} value was higher than 21 °C and operated at the minimum air flow rate (20%) when T_{SA} of 18 °C was achieved, see Figure 6. A value of ω_{SP} of 8 g/kg and a value of $\Delta\omega$ of 1 g/kg were established for this case study 3. Thus, the DW worked when the DIEC was activated and ω_{SA} value was higher than 9 g/kg, until ω_{SP} of 8 g/kg was reached, see Figure 6. For this case study 3, the DIEC operated 97.04% of the RACU's daily operating time due to the high outdoor air temperature values. However, the DW only operated 3.2% of that period due to the low outdoor air humidity values, see Figure 6.

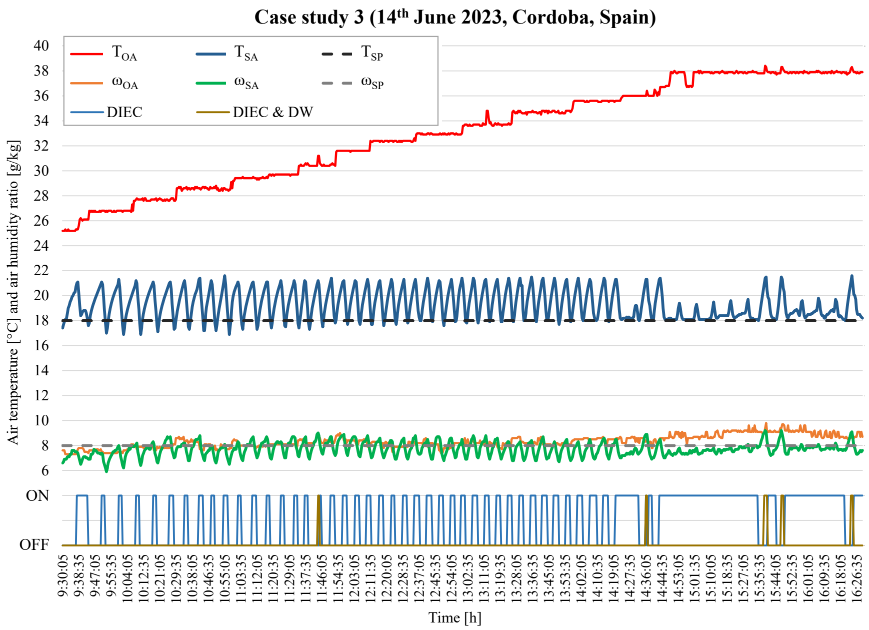

Figure 6: Air temperature and humidity values for Case study 3.

3.4 Daily air conditions for Case study 4

Case study 4 consisted of the operation of the RACU during July 27, 2023, in Cordoba, Spain. The daily variation of T_{OA} and ω_{OA} from 9:30 a.m. to 4:30 p.m. for this day can be observed in Figure 7. T_{OA} values were between 26.0 °C and 38.3 °C and ω_{OA} values were between 7.0 g/kg and 10.8 g/kg for this case study 4. According to these OA conditions values, RACU came into operation 70.7% of period between 9:30 a.m. and 4:30 p.m of that day. Since the values of T_{SP} and ΔT were 16 °C and 3 °C, respectively, the DIEC of the RACU came into operation when T_{SA} value was higher than 19 °C and operated at the minimum air flow rate (20%) when T_{SA} of 16 °C was achieved, as shown in Figure 7. A value of ω_{SP} of 6 g/kg and a value of $\Delta\omega$ of 2 g/kg were established for this case study 4. Thus, the DW worked when the DIEC was activated and ω_{SA} value was higher than 8 g/kg until ω_{SP} of 6 g/kg was reached, as illustrated in Figure 7. For this case study 4, both the DIEC and the DW operated 96.8% of the RACU's daily operating time due to the high outdoor air temperature and humidity values, as observed in Figure 7.

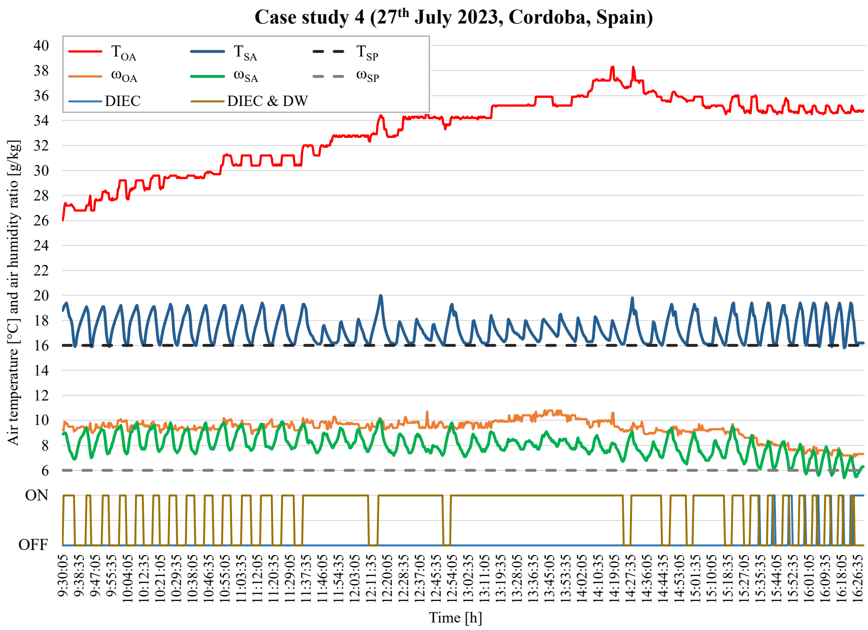

Figure 7: Air temperature and humidity values for Case study 4.

3.5 Comparative analysis of the RACU energy performance

Experimental results of the energy performance of the RACU are shown and analysed for the four case studies, as observed in Figure 8. The daily sensible cooling capacity, daily latent capacity, daily electrical-energy consumption and DEER values for RACU were calculated according to Eq. 1, Eq. 2, Eq. 3 and Eq. 4, respectively.

Q_S values were between 28.1 MJ/day and 177.0 MJ/day for the RACU, as shown in Figure 8. Higher Q_S values were achieved for case study 3 (107.8 MJ/day) and case study 4 (177.0 MJ/day), the two days with the highest average T_{OA} values, around 33 °C. Regarding Q_L values, the RACU showed a lower range of values, between 4.6 MJ/day and 38.6 MJ/day, see Figure 8. The highest Q_L value was also achieved for case study 4 (38.6 MJ/day) due to the highest average ω_{OA} value, around 9.3 g/kg. Therefore, the RACU achieved higher values of the total cooling capacity under more severe outdoor air conditions, that is, higher T_{OA} and ω_{OA} values.

W_{el} values for the RACU were between 2.7 MJ/day and 20.9 MJ/day, see Figure 8. The lowest W_{el} value (2.7 MJ/day) was shown for case study 1, for which T_{SP} and ω_{SP} values were 18°C and 8 g/kg, respectively. In addition, low average T_{OA} and ω_{OA} values were shown, 25 °C and 8 g/kg, respectively, for case study 1. However, the highest W_{el} value (20.9 MJ/day) was shown for case study 4, for which T_{SP} and ω_{SP} values were 16°C and 6 g/kg, respectively. In addition, high average T_{OA} and ω_{OA} values were shown, 33 °C and 9.3 g/kg, for case study 4, as illustrated in Figure 8. Therefore, higher W_{el} values were shown for higher OA conditions and lower SP conditions, due to the need for higher volumetric working airflow in RACU.

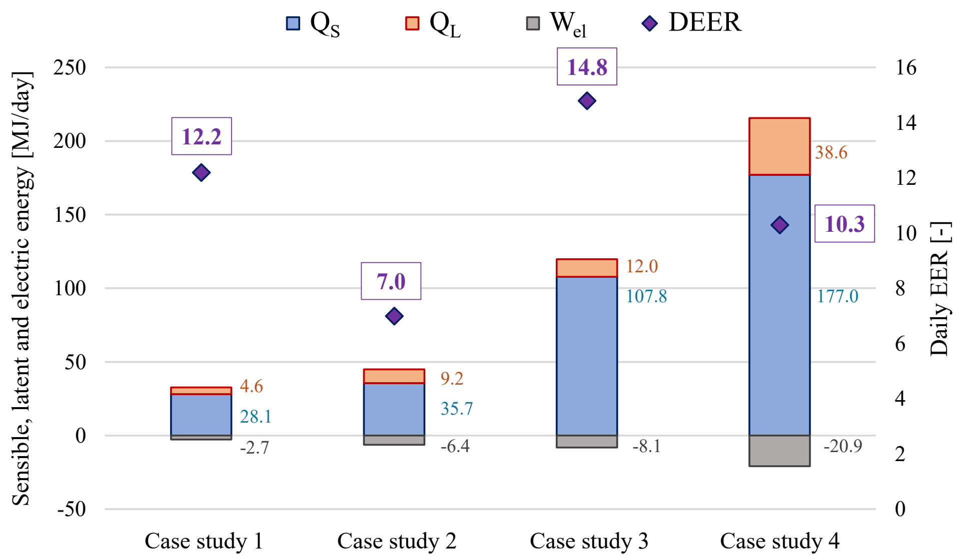

Figure 8: Energy performance values for the four case studies.

High DEER values were shown for the RACU in this work, between 7.0 and 14.8, see Figure 8. The lowest DEER value (7.0) was shown for case study 2, due to the low T_{OA} values range, as observed in Figure 5. Since the high ω_{OA} values during that day, high operating percentage (98.1%) of the DW was shown, so, high value of working air flow in the RACU. However, the highest DEER value (14.8) was shown for case study 3, due to the high T_{OA} values range, see Figure 6. In addition, low ω_{OA} values were shown for that day and, so, a low percentage of DW operation (3.2%). Therefore, higher DEER values were achieved for the RACU under lower values of outdoor air relative humidity and higher set-point conditions, due its higher Q_L and Q_S values and lower W_{el} values.

4 CONCLUSIONS

The worldwide increase in average outdoor air temperatures has resulted in a higher demand for cooling energy in recent years. Developing resilient air-cooling systems for extreme heat event scenarios is essential to achieve high energy efficiency while improving thermal comfort and indoor air quality. In this work, the supply air conditions, and daily energy performance of a renewable air-cooling unit (RACU) are analysed for four different days under the severe heat weather conditions in Cordoba, Spain. The main findings obtained from this experimental evaluation were:

- Low supply air temperature values were reached, between 16°C and 18°C, despite high outdoor air temperatures, up to approximately 40°C. Supply air humidity was also reduced, showing values between 6 g/kg and 8 g/kg.
- High values of daily sensible cooling energy, up to 177.0 MJ/day, were achieved for the RACU, due to the high difference between outdoor air temperature and supply air temperature. High values of daily latent energy, up to 38.6 MJ/day, were also achieved for the RACU due to the DW operation. However, low consumed electrical energy values were shown for the RACU during the four different days, between 2.7 MJ/day and 20.9 MJ/day.
- The RACU achieved high values of daily energy efficiency ratio (DEER), between 7.0 and 14.8, despite using 100% outdoor air under severe heat weather conditions.

These results show that the use of resilient air-cooling systems as RACU could be a potential solution under southern European climatic conditions of extreme heat showing high daily energy efficiency performance.

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6 REFERENCES

Energy, Climate change, Environment. Heat pumps. Official website of the European Union. (2023). Available: https://energy.ec.europa.eu/topics/energy-efficiency/heat-pumps_en.

IEA - International Energy Agency's. (2023). Keeping cool in a hotter world is using more energy, making efficiency more important than ever. Available: https://www.iea.org/commentaries/keeping-cool-in-a-hotter-world-is-using-more-energy-making-efficiency-more-important-than-ever.

Ministerio de Fomento, España. (2019). Documento Básico HE Ahorro de Energía 2019. *Código Técnico de La Edificacion* 1–129.

Romero-Lara, M.J.; Comino, F.; Ruiz de Adana, M. (2021). Seasonal analysis comparison of three air-cooling systems in terms of thermal comfort, air quality and energy consumption for school buildings in Mediterranean climates. *Energies* 14(4436).

Romero-Lara, M.J., Comino F., Ruiz de Adana, M. (2024). Experimental assessment of the energy performance of a renewable air-cooling unit based on a dew-point indirect evaporative cooler and a desiccant wheel. *Energy Conversion and Management* 310(January):118486.