# Experimental assessment of thermal effectiveness of a regenerative indirect evaporative cooler

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**Abstract.** Heating, ventilation and air-conditioning, HVAC, systems represent a significant energy use in Europe, around 50% of total energy use in buildings. Conventional HVAC systems are mainly based on direct expansion units, whose use of 100% outdoor air leads to high energy use. Then, different innovative and efficient air-cooling systems could be an interesting alternative to approach Nearly Zero Energy Buildings, nZEB. One of these efficient solutions is the technology of indirect evaporative cooling. This work was based on the experimental evaluation of a regenerative indirect evaporative cooler, RIEC. Several empirical tests were carried out under different inlet conditions: inlet air temperature values between 29 °C and 43 °C, $T_{OA}$, and inlet air humidity ratio values between 9 g/kg and 13 g/kg, $\omega_{OA}$, were considered. A constant inlet air stream, $\dot{V}_{0A}$, and a constant supply air stream, $\dot{V}_{SA}$, were adjusted during these tests for a steady-state period of thirty minutes each. The response variables which evaluated the thermal behaviour of this RIEC system were: (i) dew point effectiveness, $\varepsilon_{dp}$; (ii) wet bulb effectiveness, $\varepsilon_{wb}$. High values of $\varepsilon_{dp}$ and $\varepsilon_{wb}$ were reached when the inlet air humidity ratio was 9 g/kg, around 0.87 and 0.92, respectively. However, low values of dew point effectiveness, 0.71, and wet bulb effectiveness, 0.78, were showed when the inlet air temperature was 29 °C and the inlet air humidity ratio was 13 g/kg. According to the results that this study showed, the RIEC system could be an interesting alternative in spaces where improved indoor air quality is required by using 100% outdoor air. This type of systems could achieve high values of thermal performance, specially under hot-dry climatic conditions.

**Keywords.** Regenerative indirect evaporative cooling, effectiveness, air-cooling system.
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## 1. Introduction

Heating, ventilation and air-conditioning, HVAC, systems account for 50% of the total final energy use in buildings [1]. Nowadays, conventional air-cooling systems based on direct expansion units dominate the air-conditioning market, whose the highest values of coefficient of performance, COP, are 4 [2].

However, Directive 2010/31/EU established "to promote an improvement in the energy performance of buildings" as the main objective of the Energy Performance of Buildings Directive (EPBD) [3]. According to the target of the energy use reduction, different solutions such as the modification of the building's thermal envelope, the use of efficient air-cooling systems and the use of renewable energies are proposed. In this way, the achievement of nearly Zero Energy Buildings, nZEB, mainly in the climatic zones of Southern Europe, will be closer.

Efficient evaporative cooling systems can contribute to achieve nZEB. There are two main categories for evaporative cooling systems: direct and indirect. In the first case, the water is evaporated by direct contact with the air stream. Therefore, the dry bulb air temperature is lowered, and the air humidity is increased. In the second case, the heat from the primary air stream is removed by a secondary air stream. It takes place through a heat exchanger. The main components in direct evaporative coolers are water pump, fan motor and a cooling pad which can be made of different materials.

Previous research works on evaporative coolers have been developed by several authors. Most of them were focused on the study of energy performance of different efficient air-cooling systems [4]. An experimental investigation of a direct evaporative cooler, DEC, and an indirect evaporative cooler, IEC, was carried out for buildings under different climatic conditions [5]. Different outdoor conditions and different types of pad material were considered. The results showed that the performance of the DEC system was between 85% and 93%. The IEC-DEC combination presented a higher efficiency value, in the range of 95-110%. Comparative works carried out experimental investigations related to novel organic materials in DEC [6,7]. Eucalyptus fibres and ceramic pipes showed maximum effectiveness values of 72% and 68%, respectively [6]. Other material with high level of porosity was studied with the goal of solving the water stagnation. In this study, the cooling pad and the pump were replaced by the vermicompost material. An energy saving of 21.7% was showed compared to a conventional air-cooling system [7].

There are several works in the literature that studied the thermal behaviour of different types of IEC [8–10]. A study done with the original ε-NTU model compared a traditional heat recovery exchanger with an IEC. The main finding was the counter-flow indirect evaporative cooler was suitable for temperate climates [8]. In addition, in contrast to conventional heat recovery units, this type of IEC allowed to increase the temperature difference during the process of the heat recovery. Regression and numerical models were developed to predict the outlet temperature of a dew point evaporative cooling system. There was a variation between 4% and 10% between these values and the experimental results [9]. In other research work, a novel dew point cooler was investigated as part of a building energy model. The most favourable values of coefficient of performance, COP, were recorded between the months of June and September. The peak of this index, 51.1, was reached in July in the climate of Riyadh, Saudi Arabia [10].

Several hybrid systems composed of IEC and other technology were also analysed in literature [11,12]. A comparative analysis between three different air-cooling systems were carried out in terms of thermal comfort, air quality and energy use in different climates of Mediterranean area [11]. One of these systems was a desiccant regenerative indirect evaporative cooler, DRIEC, composed by an IEC and a desiccant wheel, DW. Results of this study shows that high values of thermal comfort were reached by DRIEC significantly reducing the energy use, four times lower than a direct expansion unit system, DX. The energy use of a hybrid system composed by an IEC and an air handling unit, AHU, was evaluated in other work [12]. In this way, the outdoor air was pre-cooled and pre-dehumidified before supplying it to the room. The reached value of COP in this research study was 14.2.

Regarding the IEC technology, different methods have been used to develop mathematical models of them. Neural network (NN), multiple polynomial regression (MPR) and design of experiments (DOE) are the most used mathematical methods. A prediction of hourly COP and the energy use saving of a dew point cooler, DPC, were studied by the NN method [13,14]. The most important conclusions were that the hourly COP prediction of the optimized IEC was better than the design one [13] and the annual energy use is reduced by up to 49.4% [14]. Other studies developed statistical models of a DPC with the aim of getting different performance indices [15,16]. The regression models developed in these works provided a well solution of forecasting the energy performance of DPCs. In addition, a simplified model of an IEC was developed by the DOE method and a detailed model of this air-cooling system was based on heat and mass transfer equations [16]. The low value of the wet bulb effectiveness deviation in each case, 3.4% and 2.1% respectively, showed they could an interesting tool in simulation works.

The main objective of this study was to evaluate experimentally the dew point effectiveness, $\varepsilon_{dp}$, and wet bulb effectiveness, $\varepsilon_{wb}$, of a regenerative indirect evaporative cooler, RIEC, under different inlet air conditions. This system worked with a single inlet air stream, 100% outdoor air, which was divided into two air streams, exhaust air and supply air.

## 2. Research Methods

### *2.1 Description of the RIEC system*

An innovative air-cooling system based on a regenerative indirect evaporative cooler, RIEC, was studied in this research work. The modelled efficient equipment was composed by the following elements, see Fig. 1:

- A process fan, where a constant inlet air stream of 3700 $m^3/h$ entered.
- A gross 60% filter placed before the heat exchanger.
- The regenerative indirect evaporative cooler based on a counter flow heat exchanger core.
- An ePM1 65% filter, or fine filter, after the RIEC system to improve the supply air quality.
- Several sensors located in the experimental setup:
    - Three air temperature sensors for the outside air stream, OA, the supply air stream, SA, and the exhaust air stream, EA.
    - Three air relative humidity sensors for the three different air streams above.
    - A pressure sensor in the supply air flow damper.
    - A volumetric water flow rate sensor to control the supplied water to the RIEC.
    - An energy consumption sensor in the process fan of this air-cooling system.

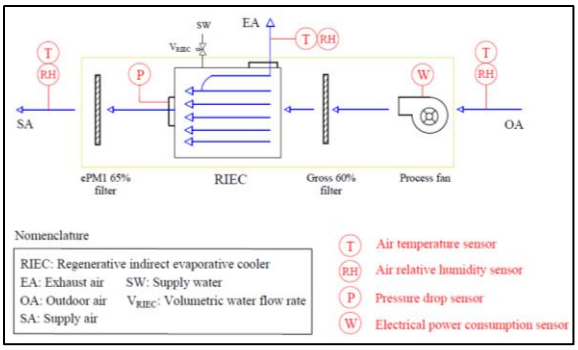


**Fig. 1** – Experimental setup of the RIEC system.

In this research study, the RIEC unit consisted of alternative wet and dry channels separated by thin plates. The supplied air and the outdoor air were the main air streams, primary and secondary, respectively. The last one was cooled by water evaporation in the wet channels, and it was exhausted as humid air. The first one was supplied after being cooled, without moisture added. The main characteristics of this RIEC system are shown in Tab. 1.

**Tab. 1** – Main characteristics of the RIEC system.

| Parameter | Value | Unit |
|---|---|---|
| Nominal cooling capacity | 18 | kW |
| Nominal supply air flow rate | 2880 | $m^3/h$ |
| Inlet air flow rate in tests | 3700 | $m^3/h$ |
| Supply air flow rate in tests | 1850 | $m^3/h$ |
| Maximum water consumption | 44 | l/h |

### *2.2 Experimental tests*

An experimental test rig was built to study the dew point effectiveness and the wet bulb effectiveness of a RIEC under different working conditions. Inlet air temperature and inlet air humidity ratio were considered as input variables. Inlet air temperature values were varied between 29 °C and 43 °C during the experimental tests. Inlet air humidity ratio was set between 9 g/kg and 13 g/kg in these. A constant inlet air stream of 3700 $m^3/h$ was considered for this experimental study. The supply air stream of 1850 $m^3/h$ was also constant during all tests by maintaining a constant pressure of 120 Pa at the supply air flow damper.

The output variables analysed to evaluate the thermal behaviour of this RIEC system were: (i) dew point effectiveness, $\varepsilon_{dp}$; (ii) wet bulb effectiveness, $\varepsilon_{wb}$. Temperature, relative humidity and pressure sensors were used to control the experimental conditions. The type of each sensor and the accuracy of them are shown in Tab. 2.

**Tab. 2** – Accuracy of the input variables sensors

| Input variable | Sensor | Accuracy |
|---|---|---|
| Temperature (T) | PT100 | ±0.2 °C |
| Relative humidity (RH) | Capacitive | ±3 % |
| Pressure drop (P) | Piezo-resistive | ±0.05 hPa |
| Electrical power consumption (W) | 3-phase | ±1% measurement (kW) |

A pressure drop sensor was located in the supply gate of RIEC to adjust the constant supply air volumetric flow rate to 1850 $m^3/h$. The measurement frequency of the different variables was 30 seconds. Data measurements, in steady state conditions, were recorded in a data cloud monitoring system for each tested condition. The design of experiments technique, DOE, was used to develop the RIEC system study. This work was based on the Box-Behnken design. It showed the results of the most representative five experimental tests. They consisted in tests under different working conditions of the single inlet air stream temperature and humidity ratio, see Tab. 3. The values of the inlet air temperature, $T_{OA}$, were between 29 °C and 43 °C. The inlet air humidity ratio values, $\omega_{OA}$, were between 9 g/kg and 13 g/kg. The combination of tests was developed to study the thermal effectiveness of the RIEC system. In this way, performance indexes could be studied under conditions of the same temperature and different humidity ratio, and vice versa. A total of four experimental tests were performed.

**Tab. 3** – Experimental tests conditions for studying the RIEC system.

| Test | $T_{OA}$ [°C] | $\omega_{OA}$ [g/kg] | $\dot{V}_{OA}$ [$m^3/h$] | $\dot{V}_{SA}$ [$m^3/h$] |
|---|---|---|---|---|
| 1 | 29 | 13 | 3700 | 1850 |
| 2 | 43 | 13 | 3700 | 1850 |
| 3 | 43 | 9 | 3700 | 1850 |
| 4 | 29 | 9 | 3700 | 1850 |

The thermal assessment of this regenerative indirect evaporative cooler was carried out by the analysis of the output parameters. The outlet air temperature value, $T_{SA}$, the outlet humidity ratio value, $\omega_{SA}$, and the energy use value in RIEC in each case were the variables which were collected.

Polynomial equations of second order to study the relationship between output and input parameters were obtained with this DOE methodology. These initial tests conditions are represented in the following Fig. 2.

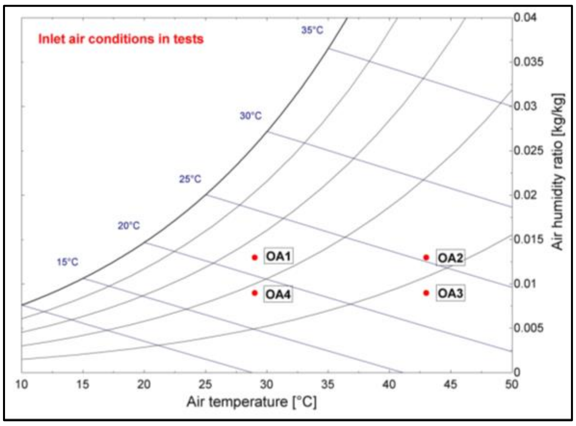


**Fig. 2** – Psychrometric chart with the inlet air conditions of experimental tests in RIEC.

### *2.3 RIEC system evaluation indexes*

This innovative and efficient RIEC system was evaluated in terms of dew point effectiveness, $\varepsilon_{dp}$, and wet bulb effectiveness, $\varepsilon_{wb}$. The values of the response variables described above, $T_{SA}$ and $\omega_{SA}$, were treated to develop the study of these indexes.

Dew point effectiveness and wet bulb effectiveness were calculated according to the equations (1) and (2), respectively.

$$\varepsilon_{dp} = \frac{T_{OA} - T_{SA}}{T_{OA} - T_{SA,dp}} \qquad (1)$$

$$\varepsilon_{wb} = \frac{T_{OA} - T_{SA}}{T_{OA} - T_{SA,wb}} \qquad (2)$$

Where $T_{SA,dp}$ is the outlet dew point temperature and $T_{SA,wb}$ is the outlet wet bulb temperature in each experimental test. The outlet air temperature and outlet air humidity ratio values were necessary to calculate these. The energy use in each test was also saved in this research work.

## 3. Results and Discussion

A summary of the values of outlet air temperature, outlet air humidity ratio, dew point temperature and wet bulb temperature in each experimental test is shown in Tab. 4. It should be noted that the results of the energy use in RIEC did not change, since the inlet air flow and supply air flow were constant during all experimental tests. The experimental analysis was divided into two parts: first, the influence of the inlet air temperature on the dew point effectiveness and the wet bulb effectiveness was analysed; and then, the influence of the inlet humidity ratio on both efficiencies was studied.

**Tab. 4** – Dew point and wet bulb temperatures in each outlet air condition in RIEC testing.

| Test | $T_{SA}$ [°C] | $\omega_{SA}$ [g/kg] | $T_{SA,dp}$ [C] | $T_{SA,wb}$ [C] |
|---|---|---|---|---|
| 1 | 21.3 | 13 | 18.1 | 19.1 |
| 2 | 23.4 | 13 | 18.1 | 19.8 |
| 3 | 16.6 | 9 | 12.5 | 14.1 |
| 4 | 14.6 | 9 | 12.5 | 13.3 |

The tests 1-4 and 2-3 showed the influence of the inlet air humidity ratio on the supply air temperature while the inlet air temperature was constant, 29°C and 43°C, respectively. Test 3 and test 4 showed the influence of the inlet temperature on the supply air temperature while the inlet humidity was constant, 9 g/kg. Test 1 and test 2 showed the influence of the inlet temperature on the supply air temperature while the inlet humidity was constant, 13 g/kg.

### *3.1 Effect of inlet air humidity ratio on supply air temperature*

The experimental tests 1 and 4 were used to study the variation of the supply or outlet air temperature regarding the inlet air humidity ratio level. This research was developed when the inlet air temperature was constant in 29 °C, see Fig. 3.

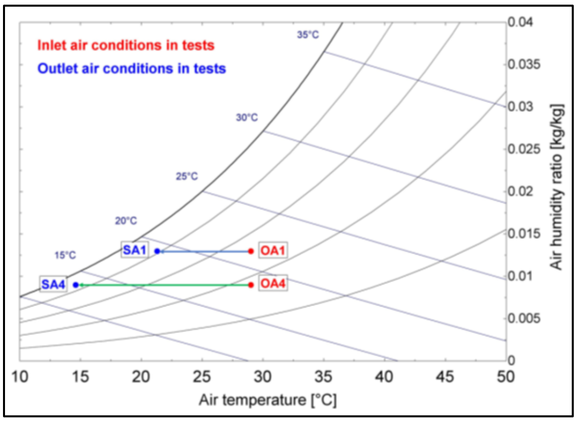


**Fig. 3** – Inlet and outlet air conditions in tests 1 and 4.

The experimental tests 2 and 3 were compared to analyse the influence of the inlet air humidity ratio value on the outlet air temperature. In this case, the inlet air humidity ratio difference between tests also was 4 g/kg. However, the inlet air temperature was maintained constant at 43 °C, see Fig. 4.

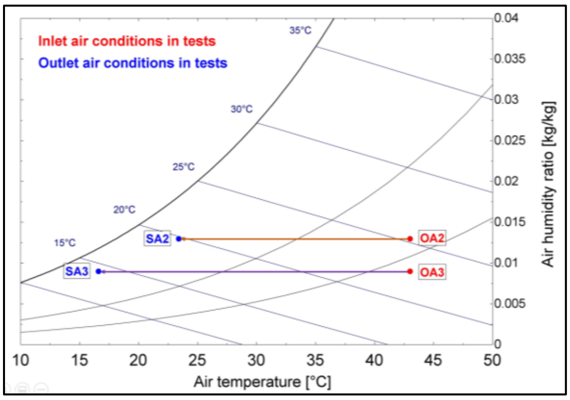


**Fig. 4** – Inlet and outlet air conditions in tests 2 and 3.

It can be observed that the impact of inlet air humidity ratio on outlet air temperature was significant. An increase of 4 g/kg in $\omega_{OA}$ represented an increase in the outlet air temperature of 6.8 °C. This trend was obtained both in the tests 1-4, with a constant $T_{OA}$ of 29 °C (points OA1 and OA4 in Fig. 3), and in the tests 2-3, with a constant $T_{OA}$ of 43 °C (points OA2 and OA3 in Fig. 4).

### 3.2 Effect of inlet air temperature on supply air temperature

The experimental tests 3 and 4 were used to analyse the influence of the inlet air temperature on the supply air temperature when the inlet air humidity ratio was constant in 9 g/kg, see Fig. 5. Tests 1 and 2, described in Tab. 3, were also used to analyse the variation on the supply air temperature when the inlet air humidity ratio was 13 g/kg in both tests, see Fig. 6. For this case study, the inlet air temperature variation was 14 °C in the tests 3-4 and 1-2.

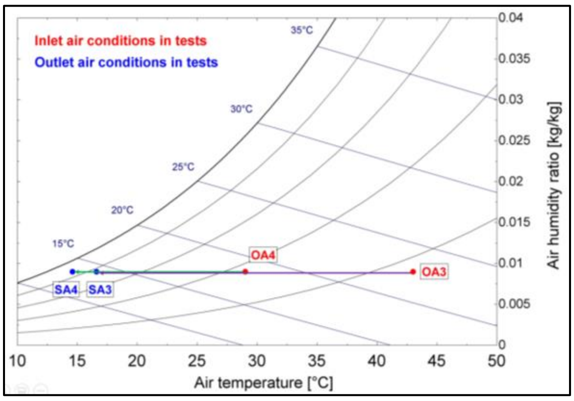


**Fig. 5** – Inlet and outlet air conditions in tests 3 and 4.

Regarding tests 3 and 4, an increase in the outdoor air temperature of 14 °C led to an increase in the supply air temperature of 2.0 °C. The inlet air conditions in tests 1 and 2 showed the same variation in terms of temperature. The humidity ratio value of the inlet air in these cases was 13 g/kg. A increase in supply air temperature of 2.1 °C could be observed in this pair of tests. Therefore, it should be noted the similar trend in both case studies, see Tab. 4.

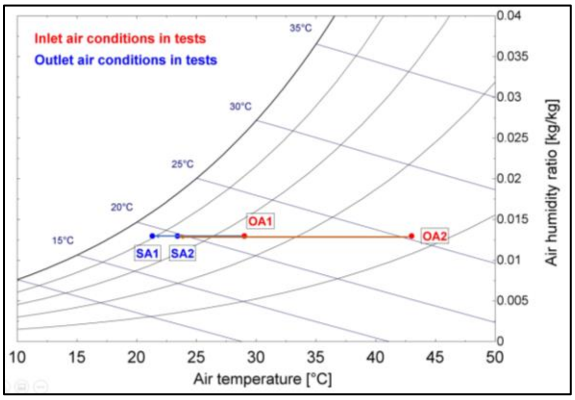


**Fig. 6** – Inlet and outlet air conditions in tests 1 and 2.

This last response variable, $T_{SA}$, increased by a maximum of 2.1 °C when $T_{OA}$ increased 14 °C, in contrast to the previous increase of 6.8 °C, when the difference in $\omega_{OA}$ was 4 g/kg (section 3.1).

Fig. 7 show a gradient plot which summarize the influence of the inlet air temperature, $T_{OA}$, and the inlet air humidity ratio, $\omega_{OA}$, on the outlet air temperature, $T_{SA}$. These results were obtained for constant values of inlet air flow rate and supply air flow rate. It should be noted that the highest values of $T_{SA}$ were shown when $\omega_{OA}$ increased to 13 g/kg. On the contrary, low $T_{SA}$ values could be seen, between 14.6 °C and 17 °C, when the inlet air humidity ratio was 9 g/kg.

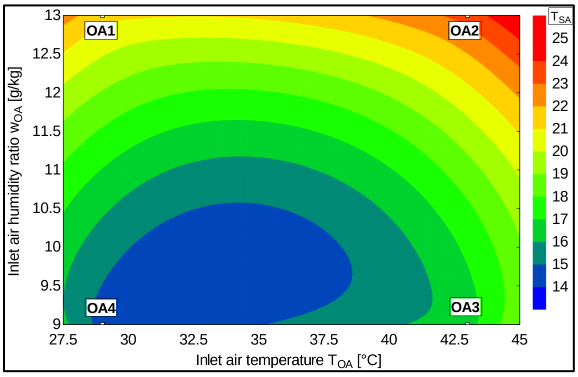


**Fig. 7** – Gradient plot of inlet air temperature and inlet air humidity ratio influence on outlet air temperature.

The $T_{SA}$ value varied between 14 °C and 22 °C when $T_{OA}$ was 29 °C and $\omega_{OA}$ varied between 9 g/kg and 13 g/kg. $T_{SA}$ ranged between 16 °C and 24 °C when $T_{OA}$ was 43 °C and $\omega_{OA}$ was between 9 and 13 g/kg. That is, an increase of 1 g/kg in inlet air humidity resulted in an increase of 2 °C in $T_{SA}$. However, to decrease the supply air temperature by 2 °C, keeping the humidity constant, a reduction of 14 °C in the inlet air temperature was necessary.

### 3.3 Analysis of dew point and wet bulb effectiveness

The influences between the input variables, $T_{OA}$ and

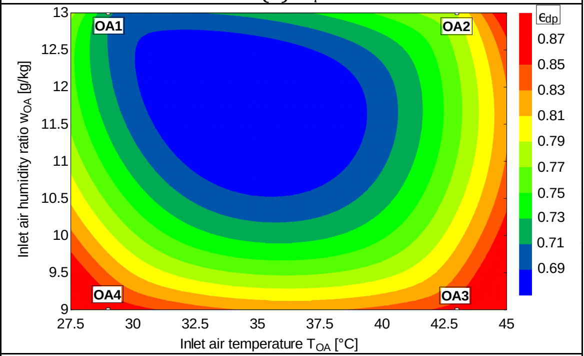
$\omega_{OA}$, and the $T_{SA}$ output variable were reflected in the results of $\varepsilon_{dp}$ and $\varepsilon_{wb}$. According to equations (1) and (2), dew point effectiveness and wet bulb effectiveness were determined for each experimental test. The results of these response variables are shown in Tab. 5.

**Tab. 5** – Evaluation indexes values of the studied RIEC.

| Test | $T_{OA}$ [°C] | $\omega_{OA}$ [g/kg] | $\varepsilon_{dp}$ [-] | $\varepsilon_{wb}$ [-] |
|---|---|---|---|---|
| 1 | 29 | 13 | 0.71 | 0.78 |
| 2 | 43 | 13 | 0.79 | 0.85 |
| 3 | 43 | 9 | 0.86 | 0.91 |
| 4 | 29 | 9 | 0.87 | 0.92 |

High dew point and wet bulb efficiency values, $\varepsilon_{dp}$ and $\varepsilon_{wb}$, were reached when the inlet air humidity ratio was reduced by around 9 g/kg, as shown in Tab. 5. According to the values shown, it should be noted that the greatest difference in the dew point effectiveness was found in tests 1 and 4. $\varepsilon_{dp}$ increased by 16.5% when the inlet temperature was constant at 29 °C and the inlet humidity was reduced by 4 g/kg. However, the pair of tests 3-4 showed similar values of dew point effectiveness with the same inlet air humidity, 9 g/kg, and 14 °C difference in inlet air temperature. The influence of the inlet air conditions, $T_{OA}$ and $\omega_{OA}$, on the dew point effectiveness and the wet bulb effectiveness are shown in Fig. 8a and Fig. 8b, respectively.

(a) $\varepsilon_{dp}$



(b) $\varepsilon_{wb}$

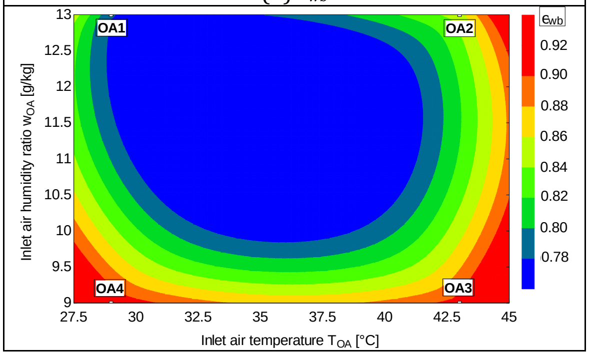


**Fig. 8** – Gradient plot of inlet air temperature and inlet air humidity ratio influence on: (a) dew point effectiveness and (b) wet bulb effectiveness.

$\varepsilon_{dp}$ increased 0.6% when the inlet air humidity ratio was kept at 9 g/kg and the inlet air temperature was reduced by 14 °C. In the tests 2-3 and 1-2, the difference in this dew point effectiveness was very similar, around 8% between the corresponding points. It can be observed that $\varepsilon_{wb}$ showed a similar trend to $\varepsilon_{dp}$, The maximum $\varepsilon_{wb}$ values were obtained for the tests 3 and 4, 0.91 and 0.92, respectively, when the inlet air humidity ratio was 9 g/kg and the inlet air temperature was 43 °C and 29 °C, respectively. The maximum values of $\varepsilon_{dp}$ were shown in these same tests, 0.86 and 0.87, respectively.

## 4. Conclusions

An experimental analysis of a regenerative indirect evaporative cooling system, RIEC, was carried out in this work. This efficient air-cooling system was tested under different working conditions, regarding the inlet air temperature and the inlet air humidity ratio. The DOE methodology was used to determine the influence of the inlet air conditions on the thermal effectiveness. Dew point and wet bulb effectiveness were analysed for these different experimental tests.

Based on the results, the RIEC system showed high values of the dew point effectiveness and the wet bulb effectiveness, up to 0.87 and 0.92, respectively, when the inlet air temperature and the inlet air humidity ratio were 29 °C and 9 g/kg, respectively. However, at this same inlet temperature and an inlet humidity of 13 g/kg, the effectiveness of the dew point was reduced to 0.71 and the wet bulb effectiveness was also reduced to 0.78. Then, a increase in the inlet air humidity ratio of 4 g/kg led to a reduction in the dew point effectiveness of 16.5%. The same trend was obtained in the wet bulb effectiveness index, but the variation in this case was 13.8%. The lowest values of dew point effectiveness and wet bulb effectiveness were obtained with an inlet air temperature of 43 °C and an inlet air humidity ratio of 13 g/kg, below 0.79 and 0.85, respectively. Therefore, the RIEC system could be an interesting alternative to conventional HVAC systems. RIEC system allows achieving a good thermal performance, specially under hot-dry climatic conditions, by using 100% outdoor air.

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### *Data Statement*

The datasets generated during and analysed during the current study are available in the ZENODO repository, doi.org/10.5281/zenodo.6327341.

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