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Environmental and Water-Use Efficiency of Indirect Evaporative Coolers in Southern Europe †

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Abstract: Heating, ventilation, and air-conditioning (HVAC) systems are responsible for about 20% of energy consumption in buildings. In terms of energy saving, evaporative cooling technology presents an interesting solution to conventional vapor compression systems. However, few studies have analyzed water-related indexes in indirect evaporative coolers (IECs). The main objective of this work was to evaluate the environmental impact and water-use efficiency of IECs in Southern Europe. Several models of performance indexes for the evaluated IEC system were developed via experimental tests. Based on energy simulations, the IEC system reached the highest values of annual *SEER* (7.6), $KPI_{C\text{-}W}$ (0.28 kWh/L), and $KPI_{C\text{-}CO2}$ (16.2 kWh/kg CO_2) for Lampedusa weather conditions. These results show that the IEC system for hot climate zones reached the highest environmental and water-use efficiency values.

Keywords: evaporative cooling; experimental tests; air cooling; water-use efficiency; CO_2 emissions

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1. Introduction

According to several studies conducted in the last decade, heating, ventilation, and air-conditioning (HVAC) systems are responsible for about 20% of energy consumption in buildings [1]. Evaporative cooling technology presents an interesting solution to conventional cooling technologies based on vapor compression systems. Most of the experimental studies of indirect evaporative coolers (IECs) focused on the analysis of energy performance. However, few studies have analyzed water-related indexes in this type of air-cooling system. In a previous study, a methodology to determine the water-use efficiency of evaporative coolers was developed [2]. Another work showed high values of water-use efficiency for IEC technology and combined systems with IECs [3].

The main objective of this work was to evaluate the environmental impact and water-use efficiency of indirect evaporative coolers in different countries in Southern Europe.

2. Materials and Methods

2.1. Experimental Setup

An indirect evaporative cooler (IEC) was experimentally studied in the present work. The IEC system was mainly composed of a counterflow heat exchanger, a process fan, a gross 60% filter, and an *e*PM_1 65% filter. The inlet air conditions were adjusted with an AHU, as shown in Figure 1.

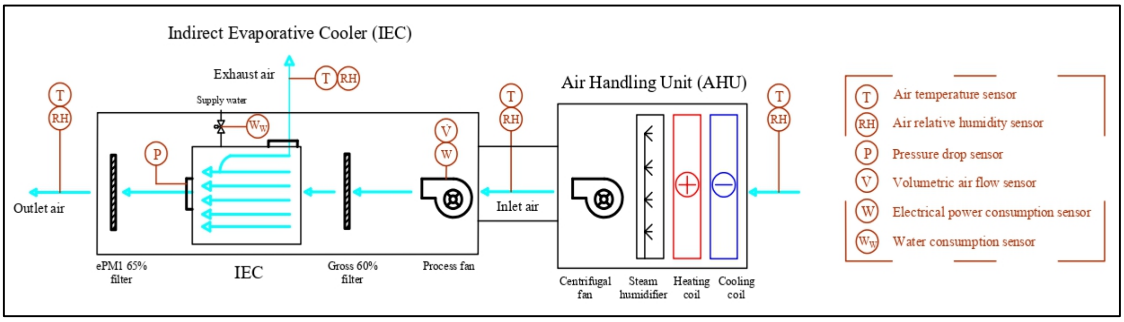


Figure 1. Experimental configuration for the study of IEC.

The evaluated IEC system worked with a single inlet air stream (100% outdoor air), IA, which was divided into two air streams: exhaust air (EA) and outlet air (OA). This air-cooling system consisted of alternative wet and dry channels separated by thin plates. The inlet air flow was cooled without increasing its humidity ratio, and the exhaust air flow was humidified and then exhausted outside. The most important characteristics of this IEC are shown in Table 1.

Table 1. Main characteristics of evaluated IEC system.

Parameter	Value	Unit
Nominal cooling capacity	18	kW
Nominal inlet air flow rate	5000	$m^3\ h^{-1}$
Exhaust air ratio $\left(R_{EX} = \dot{V}_{EA}/\dot{V}_{IA}\right)$	0.45	-
Nominal power consumption	1.5	kW
Maximum water consumption	44	$l\ h^{-1}$

2.2. Description of IEC Evaluation

Each experimental test was carried out under different working conditions during a steady-state period of thirty minutes. The experimental tests were used to obtain the models of the output parameters: cooling capacity ($\dot{Q}_{cooling}$) energy consumption ($\dot{W}_{cons}$), and water consumption ($\dot{V}_W$). Different values of inlet air temperature (T_{IA}), inlet air humidity ratio (ω_{IA}), inlet volumetric air flow ($\dot{V}_{IA}$), and exhaust air ratio (R_{EX}) were considered to develop the mathematical models; see Table 2.

Table 2. Summary of experimental tests in IEC system.

Test	T_{IA} (°C)	ω_{IA} (g/kg)	$\dot{V}_{IA}$ (m^3/h)	R_{EX} (-)	Test	T_{IA} (°C)	ω_{IA} (g/kg)	$\dot{V}_{IA}$ (m^3/h)	R_{EX} (-)
N1	32	11	3000	0.3	N6	40	11	3700	0.7
N2	32	8	3000	0.5	N7	32	11	4500	0.3
N3	32	11	3000	0.7	N8	32	14	4500	0.5
N4	40	11	3700	0.3	N9	32	11	4500	0.7
N5	40	8	3700	0.5					

Second-order polynomial equations were used to obtain the relationship between the input parameters and the output parameters; see Equation (1).

$$\hat{Y} = b_0 + \sum_{i=1}^{k} b_i \cdot X_i + \sum_{i=1}^{k} b_{ii} \cdot X_i^2 + \sum_{i=1}^{k=1} \sum_{i=2;j>i}^{k} b_{ij} \cdot X_i \cdot X_j, \quad (1)$$

where $\hat{Y}$ is the estimated output value; X is the input parameters; b_0 is the average response in each model; and b_i, b_{ii}, and b_{ij} are the estimated parameters of the linear, quadratic, and second-order terms, respectively.

However, energy simulations were carried out to compare the environmental impact of the IEC system under different climate zones in Southern Europe. TRNSYS software was used in the energy simulations. It should be noted that the annual cooling periods and CO_2 emission factors considered, F_{CO2}, for each city were taken from a recently published article [4]. The values of the inlet volumetric air flow rate ($\dot{V}_{IA}$) and R_{EX} were constant for the energy simulations; see Table 1.

2.3. IEC Evaluation Indexes

The IEC system was evaluated in terms of the output parameters of the experimental tests N1–N9 (see Equations (2)–(4)) and environmental impact indexes during annual cooling periods (see Equations (5)–(9)):

$$\text{Cooling capacity}: \ \dot{Q}_{cooling} = \rho_{air} \cdot \dot{V}_{OA} \cdot (h_{IA} - h_{OA}) \ [\text{kW}] \tag{2}$$

$$\text{Energy consumption}: \ \dot{W}_{cons} = \dot{W}_{Process\ fan} + \dot{W}_{Pump} \ [\text{kW}] \tag{3}$$

$$\text{Water consumption}: \ \dot{V}_{W} = \text{Measurement of IEC water consumption} \ [\text{L/h}] \tag{4}$$

$$\text{Annual seasonal energy efficiency ratio}: \ SEER = \frac{\sum \dot{Q}_{cooling}}{\sum \dot{W}_{cons}} \ [-] \tag{5}$$

$$CO_2 \text{ emissions}: \ \dot{E}_{CO2} = F_{CO2} \cdot \sum \dot{W}_{cons} \ [\text{kg } CO_2/\text{year}] \tag{6}$$

$$\text{Cooling capacity per } CO_2 \text{ emission}: \ KPI_{C-CO2} = \frac{\sum \dot{Q}_{cooling}}{\sum \dot{E}CO2} \ [\text{kWh/kg } CO_2] \tag{7}$$

$$\text{Cooling capacity per unit of water consumed}: KPI_{C-W} = \frac{\sum \dot{Q}_{cooling}}{\sum \dot{V}_{W}} \ [\text{kWh/L}] \tag{8}$$

$$\text{Water consumption per } CO_2 \text{ emission}: KPI_{W-CO2} = \frac{\sum \dot{V}_{W}}{\sum \dot{E}CO2} \ [\text{L/kg } CO_2] \tag{9}$$

3. Results and Discussion

3.1. Experimental Results

Cooling capacity, energy consumption, and water consumption were the output parameters evaluated in the IEC system. The results of these performance indexes for each experimental test are shown in Table 3. It can be observed that high values of $\dot{Q}_{cooling}$ were achieved under the working conditions of tests N4 and N7. In both cases, the values of ω_{IA} and R_{EX} were 11 g/kg and 0.3, respectively. However, the value of $\dot{Q}_{cooling,N7}$ was higher than the value of $\dot{Q}_{cooling,N4}$ due to the higher inlet air flow rate and, thus, a higher outlet air flow rate. The lowest values of $\dot{W}_{cons}$ and $\dot{V}_{W}$ were reached when R_{EX} was 0.7.

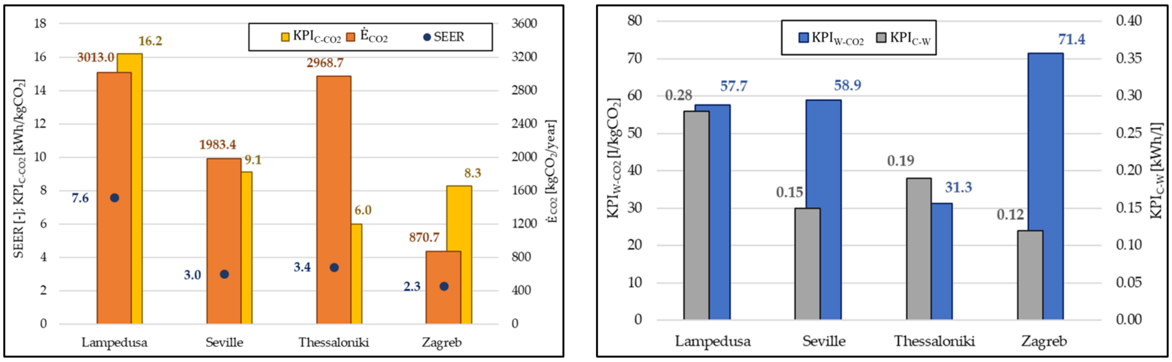
Table 3. Experimental results of the output parameters for the studied IEC.

Test	$\dot{Q}_{cooling}$ (kW)	$\dot{W}_{cons}$ (kW)	$\dot{V}_{W}$ (L/h)	Test	$\dot{Q}_{cooling}$ (kW)	$\dot{W}_{cons}$ (kW)	$\dot{V}_{W}$ (L/h)
N1	17.5	0.377	14.6	N6	22.2	0.669	43.7
N2	16.7	0.399	21.3	N7	33.5	1.130	17.2
N3	13.3	0.376	37.8	N8	26.8	1.126	40.8
N4	30.0	0.692	17.3	N9	24.3	1.079	42.5
N5	28.3	0.703	23.2				

The experimental results allowed for mathematical models of the output parameters to be obtained. The coefficients of determination (R^2) for the $\dot{Q}_{cooling}$ model, the $\dot{W}_{cons}$ model, and the $\dot{V}_W$ model of the evaluated IEC were greater than 0.987 for all output parameters.

3.2. Annual Results of Environmental Impact

The annual values of several indexes related to environmental impact were obtained (see Figure 2) according to Equations (5)–(9). The cooling period considered for each climate zone (Lampedusa, Seville, Thessaloniki, and Zagreb) was defined as the number of hours in which T_{IA} exceeded 18 °C.



(**a**) (**b**)

Figure 2. Results of IEC annual environmental impact: (**a**) $SEER$, $\dot{E}_{CO2}$, $KPI_{C\text{-}CO2}$; (**b**) $KPI_{C\text{-}W}$, $KPI_{W\text{-}CO2}$.

It can be observed that, for all the selected cities, the results of $KPI_{C\text{-}W}$ and $\dot{E}_{CO2}$ increased when the $SEER$ value increased. The IEC system in Lampedusa weather conditions, with the longest cooling period, reached the highest values of $SEER$ (7.6) and $KPI_{C\text{-}W}$ (0.28 kWh/L) but also the highest value of $\dot{E}_{CO2}$ (3013 kg CO_2/year); see Figure 2. According to $KPI_{W\text{-}CO2}$, the results were similar for the Seville and Lampedusa climate zones. The IEC for Zagreb weather conditions showed the highest $KPI_{W\text{-}CO2}$ value (71.4 L/kg CO_2) due to low CO_2 emissions; see Figure 2. The $KPI_{C\text{-}CO2}$ values for Seville, Thessaloniki, and Zagreb were 1.8, 2.7, and 2.0 times lower than the $KPI_{C\text{-}CO2}$ value for the Lampedusa climate zone, respectively; see Figure 2.

4. Conclusions

In the present work, the environmental impact and water-use efficiency of indirect evaporative coolers (IECs) in Southern Europe were analyzed. Mathematical models of several performance indexes for the evaluated IEC system were developed via experimental tests, showing good agreement. Based on the annual results obtained, the IEC for Lampedusa weather conditions reached the highest values of $SEER$ (7.6), $KPI_{C\text{-}W}$ (0.28 kWh/L), and $KPI_{C\text{-}CO2}$ (16.2 kWh/kg CO_2). The IEC system for Zagreb weather conditions showed the highest value of $KPI_{W\text{-}CO2}$ (71.4 L/kg CO_2) due to the lowest value of $\dot{E}_{CO2}$ that IEC also showed (870.7 kg CO_2/year). These results show that the IEC system for hot climate zones reaches the highest environmental and water-use efficiency values.

Author Contributions: M.J.R.-L. carried out the experimental tests and wrote the paper; F.C. discussed the results and revised the paper's writing; M.R.d.A. conceptualized the idea of the paper, discussed the results, and contributed to the paper's development. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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