IEA EBC - ANNEX 85

Energy in Building and
Communities Programme

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DEW POINT INDIRECT EVAPORATIVE COOLER: KPI, SEER AND HYBRID SYSTEM



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I. Intro IEC air cooler

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Evaporative Cooling systems

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  - Cooling towers
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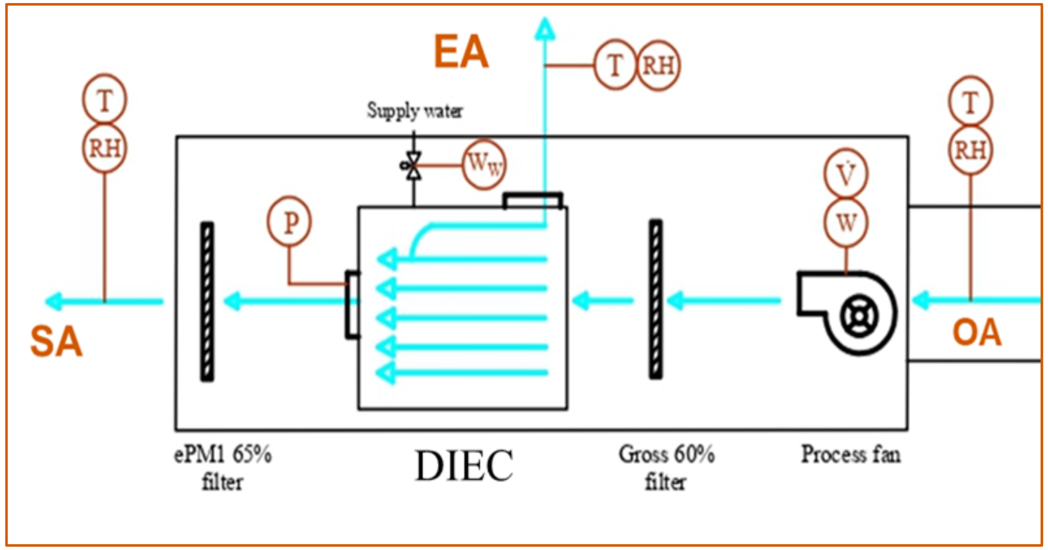
- Air cooler
  - Direct, DEC
  - **Indirect, IEC**
    - Traditional, IEC
    - Maisotsenko cycle, MIEC
    - **Dew-point, DIEC**

IEC air cooler studied by the University of Cordoba, UCO, team.



I. Intro IEC air cooler

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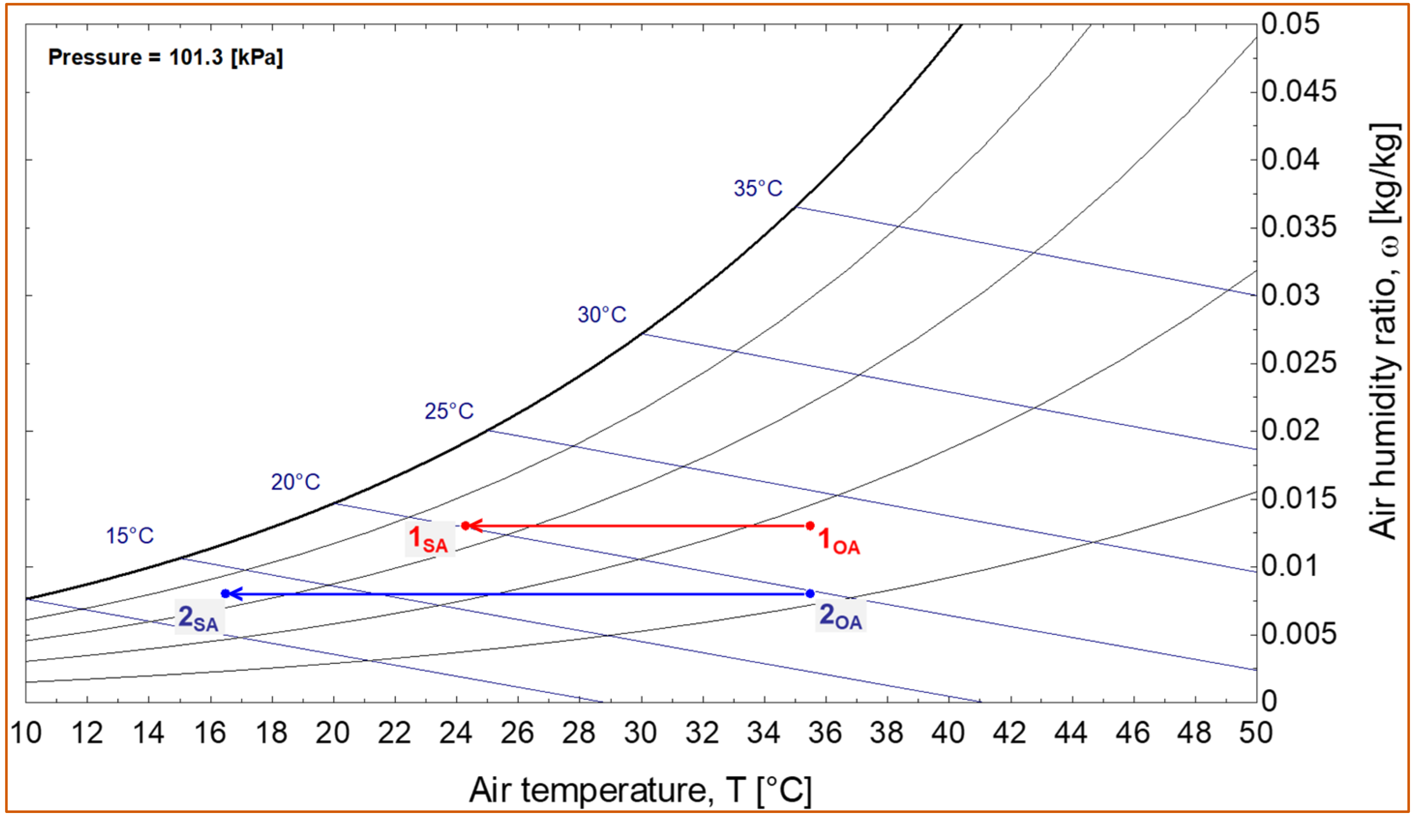
- DIEC was able to significantly reduce the temperature of the inlet airflow, T_{OA}, to the DIEC. The DIEC outlet airflow temperature, T_{SA}, was lower than the DIEC inlet airflow temperature. Also, in this air-cooling process, no moisture is added to the supply airflow.

- An example of process chart of this DIEC system, through experimental results, is shown. It can be observed the high influence of the outdoor air humidity ratio, ω_{OA}, on the T_{SA} value.

- **Process chart:**

Test	T_{OA}	ω_{OA}	T_{SA}	ω_{SA}	$\dot{V}_{SA}$
	°C	g/kg	°C	g/kg	m³/h
1	35.5	13.0	24.3	13.0	2880*
2	35.5	8.0	16.5	8.0	2880*

*Nominal value for our DIEC



I. Intro IEC air cooler

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- Several experimental tests were based on the statistical technique of design of experiments, DOE, specifically the Box-Behnken design. This design consisted of 27 experimental tests with 3 specific points as central points.

- The input parameters of the experimental tests were outdoor air temperature, T_{OA}, outdoor air humidity ratio, ω_{OA}, outdoor volumetric air flow, $\dot{V}_{OA}$, and exhaust air rate, R_{exh}. The R_{exh} value was defined as the ratio between the exhaust airflow, EA, and the outdoor airflow, OA.

- The ranges of the **DIEC input parameters** values were:

Input variable	Low value - High value	Unit
T_{OA}	26.0 - 43.0	°C
ω_{OA}	8.0 - 13.0	$g\ kg^{-1}$
$\dot{V}_{OA}$	3000 - 4500	$m^3\ h^{-1}$
R_{exh}	0.3 - 0.7	-

- The **DIEC output parameters** were:
  - Cooling capacity [kW]

$$\dot{Q}_{cooling} = \rho_{air} \cdot \dot{V}_{SA} \cdot (h_{OA} - h_{SA})$$

  - Power consumption [kW]

$$\dot{W} = \dot{W}_f + \dot{W}_p$$

f = fan ; p = pump

  - Energy efficiency ratio [-]

$$EER = \frac{\dot{Q}_{cooling}}{\dot{W}}$$

I. Intro IEC air cooler

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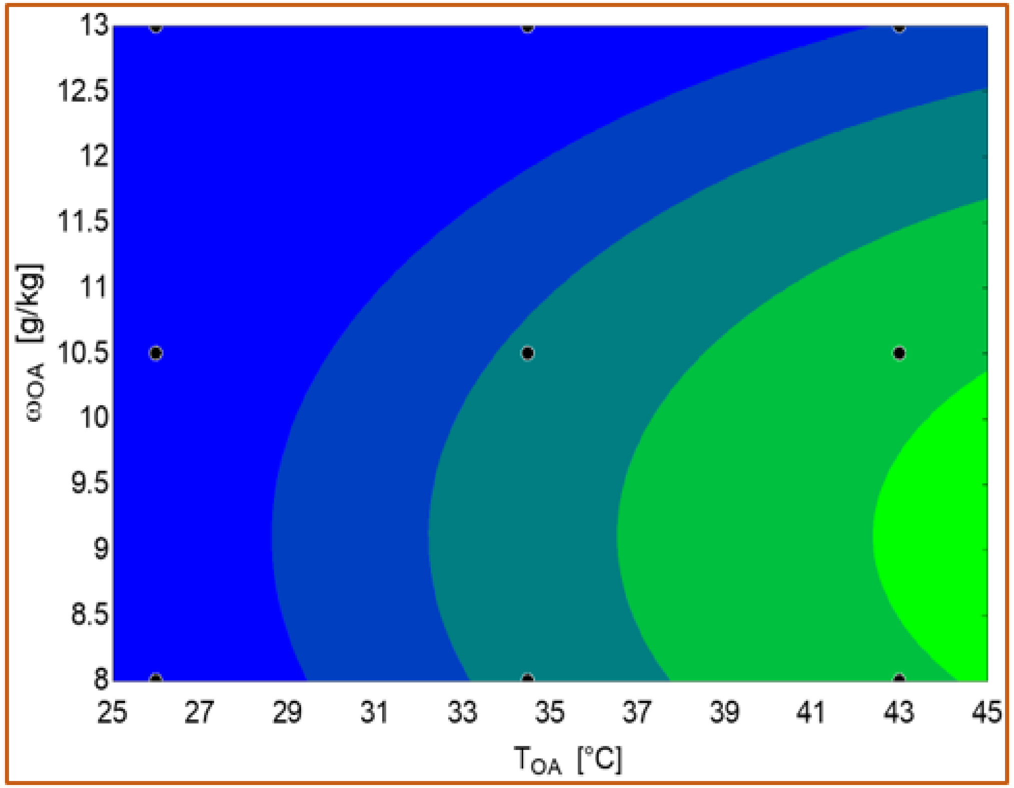
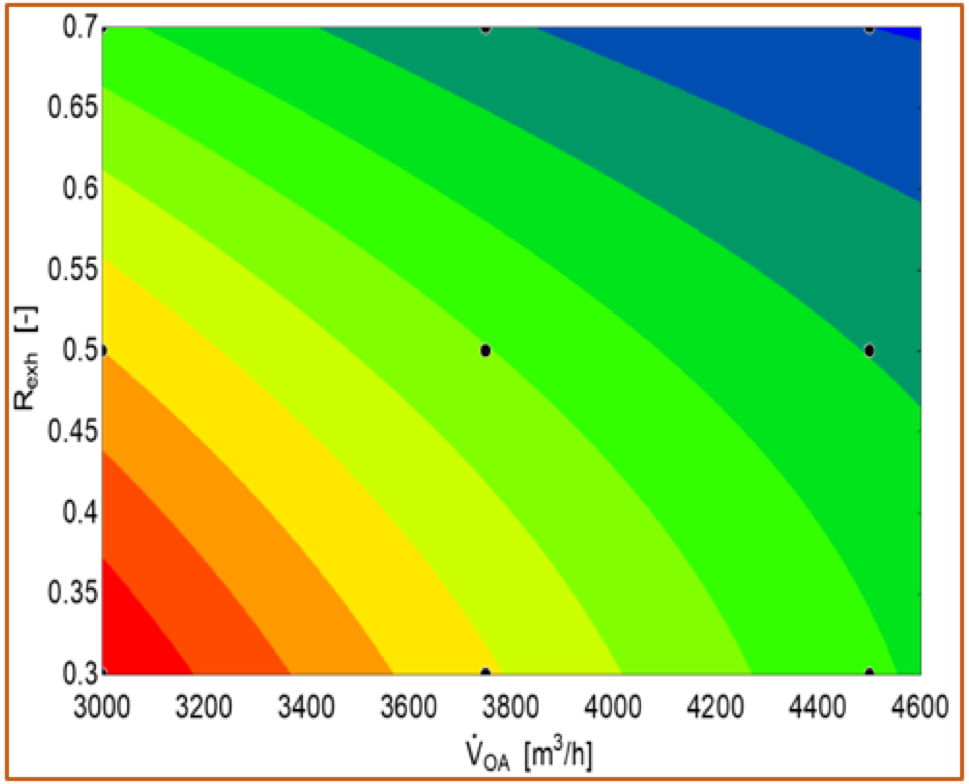
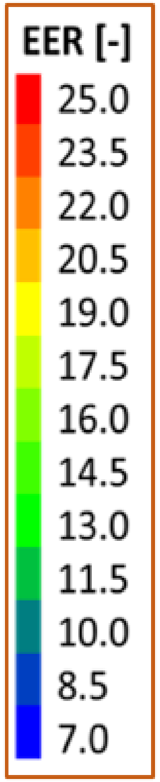
- The coefficients of determination, R^2, of the $\dot{Q}_{cooling}$, $\dot{W}$ and EER empirical models of the DIEC system were 0.9991, 0.9997 and 0.9973, respectively.



The $\dot{V}_{OA}$ and R_{exh} values were set to the nominal values, 5236 m^3 h^{-1} and 0.45, respectively, for this *EER* trend.





The T_{OA} and ω_{OA} values were set to the mean values of their ranges, 34.5 °C and 10.5 g kg^{-1}, respectively, for this *EER* trend.

II. Key Performance Indicators, KPI

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- The main performance indicators recommended by the "IEA EBC - Annex 85 - Indirect Evaporative Cooling" group were:
  - Outlet air temperature, T_{SA}
  - Wet bulb efficiency, ε_{wb}
  - Dew point efficiency, ε_{dp}
  - Supplied cooling power, $\dot{Q}_{supply}$
  - Coefficient of performance/Energy efficiency ratio, **COP/EER**
  - Cooling capacity per unit of water consumed, KPI_{CW}
  - Number Transfer Unit, **NTU***
- The UCO team determined the values of each of these indicators as indicated:

$$\varepsilon_{wb} = \frac{T_{OA} - T_{SA}}{T_{OA} - T_{SA,wb}}$$

$$\dot{Q}_{supply} = \rho_{air} \cdot cp_{air} \cdot \dot{V}_{SA} \cdot (T_{OA} - T_{SA})$$

$$\varepsilon_{dp} = \frac{T_{OA} - T_{SA}}{T_{OA} - T_{SA,dp}}$$

$$EER = \frac{\dot{Q}_{supply}}{\dot{W}_{electricity}}$$

$$KPI_{CW} = \frac{\dot{Q}_{supply}}{\dot{V}_{water}}$$

Indirect evaporative cooler

$C_c^* = m$

$C_h^* = M^*$, where $M^* = MC_p/a$

$C_{min} = \min(C_c^*, C_h^*)$

$C_{max} = \max(C_c^*, C_h^*)$

$C_r = C_{min}/C_{max}$

$NTU^* = U^*A/C_{min}$

where $U^* = \dfrac{1}{a\left(\frac{1}{\alpha_d} + \frac{\delta}{k}\right) + \frac{1}{\beta}}$

$\varepsilon^* = f(NTU^*, C_r)$

$q_{max} = C_{min}(h_s(T_i) - h_i)$

$\varepsilon^* = \dfrac{q}{q_{max}}$

$q = \varepsilon^* C_{min}(h_s(T_i) - h_i)$

$\varepsilon^* = \dfrac{C_h^*(h_s(T_i) - h_s(T_o))}{C_{min}(h_s(T_i) - h_i)}$

or $\varepsilon^* = \dfrac{C_c^*(h_o - h_i)}{C_{min}(h_s(T_i) - h_i)}$

Ala Hasan (2012)
doi:10.1016/j.apenergy.2011.07.005

II.A KPI for $\dot{V}_{SA}$ 1200 m^3 h^{-1}

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Test point	T_{OA}	ω_{OA} (=ω_{SA})	HR_{OA}	T_{SA}	ε_{wb}	ε_{dp}	$\dot{Q}_{supply}$	EER	KPI_{CW}
	[°C]	[g/kg]	[%]	[°C]	[%]	[%]	[kW]	[-]	[Wh/l]
N1	35	7.0	20	22.9	0.75	0.46	5.0	32.7	213.3
N2	35	10.5	30	21.9	0.97	0.65	5.3	29.5	213.0
N3	35	14.1	40	30.4	0.42	0.30	1.9	18.7	34.1
N4 [a]	35	21.4	60	-	-	-	-	-	-
N5 [a]	35	28.9	80	-	-	-	-	-	-
N6	30	5.3	20	26.1	0.27	0.15	1.6	25.2	299.2
N7	30	7.9	30	21.3	0.73	0.45	3.6	26.3	139.4
N8	30	10.6	40	21.6	0.85	0.56	3.4	23.1	134.0
N9 [a]	30	16.4	60	-	-	-	-	-	-
N10 [a]	30	21.5	80	-	-	-	-	-	-
N11 [a]	25	3.9	20	-	-	-	-	-	-
N12	25	5.9	30	24.5	0.43	0.24	0.2	19.1	397.2
N13	25	7.9	40	21.3	0.42	0.25	1.5	19.6	20.4
N14	25	11.9	60	23.6	0.25	0.17	0.6	13.3	5.2
N15 [a]	25	15.9	80	-	-	-	-	-	-

[a] The humidity ratio values established for tests N4, N5, N9, N10, N11 and N15 are not within the range for which the DOE of our **DIEC** was performed. Therefore, invalid values are obtained for indicators.

- The Number Transfer Unit, NTU, value for our DIEC under $\dot{V}_{SA}$ value equal to 1200 m^3 h^{-1} and T_{OA} range 25-35 °C was:

NTU* = 5.8 [-]

II.B KPI for $\dot{V}_{SA}$ 2880 $m^3\ h^{-1}$

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Test point	T_{OA}	ω_{OA} ($=\omega_{SA}$)	HR_{OA}	T_{SA}	ε_{wb}	ε_{dp}	$\dot{Q}_{supply}$	EER	KPI_{CW}
	[°C]	[g/kg]	[%]	[°C]	[%]	[%]	[kW]	[-]	[Wh/l]
N1	35	7.0	20	18.8	0.99	0.62	15.9	8.2	839.4
N2	35	10.5	30	21.4	1.00	0.67	13.3	8.9	453.4
N3	35	14.1	40	33.4	0.14	0.10	1.6	2.0	107.6
N4 [a]	35	21.4	60	-	-	-	-	-	-
N5 [a]	35	28.9	80	-	-	-	-	-	-
N6	30	5.3	20	20.4	0.67	0.38	9.4	3.2	889.9
N7	30	7.9	30	18.1	0.98	0.61	11.6	7.2	591.7
N8	30	10.6	40	21.0	0.89	0.59	8.7	6.9	329.3
N9 [a]	30	16.4	60	-	-	-	-	-	-
N10 [a]	30	21.5	80	-	-	-	-	-	-
N11 [a]	25	3.9	20	-	-	-	-	-	-
N12	25	5.9	30	19.4	0.53	0.30	5.5	2.2	599.5
N13	25	7.9	40	18.2	0.78	0.47	6.7	4.8	423.3
N14	25	11.9	60	24.4	0.11	0.07	0.6	2.9	79.4
N15 [a]	25	15.9	80	-	-	-	-	-	-

[a] The humidity ratio values established for tests N4, N5, N9, N10, N11 and N15 are not within the range for which the DOE of our **DIEC** was performed. Therefore, invalid values are obtained for indicators.

II.C Analysis of KPI

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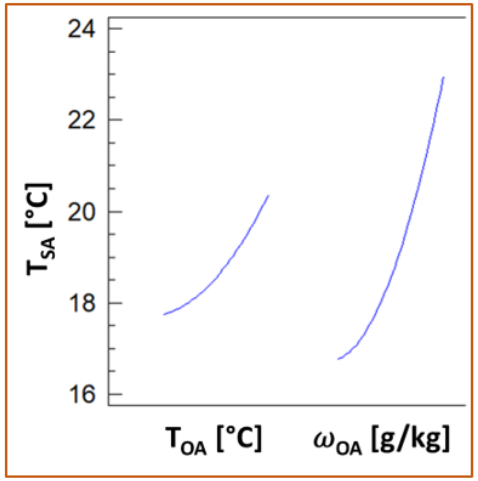
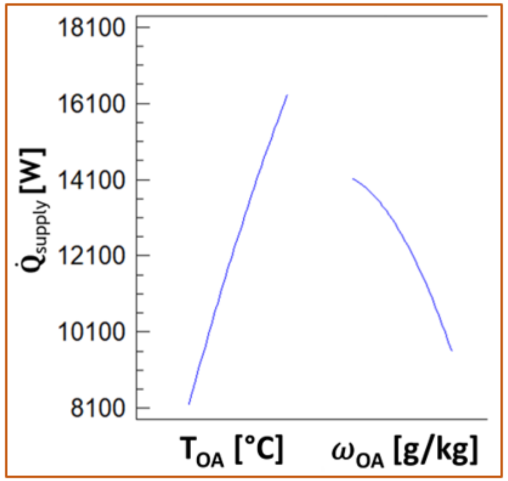
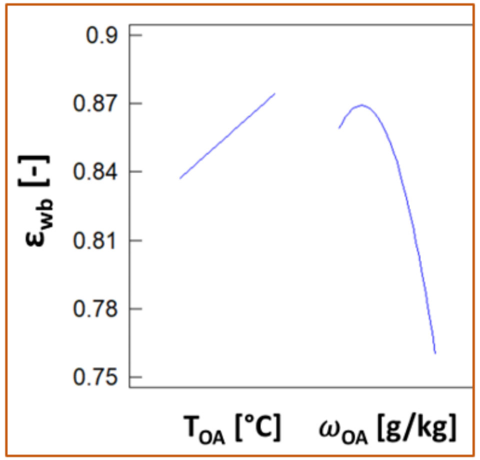
- The influence of the outdoor conditions, T_{OA} and ω_{OA}, on the output parameters was the same for both situations. The main effects plots are shown:



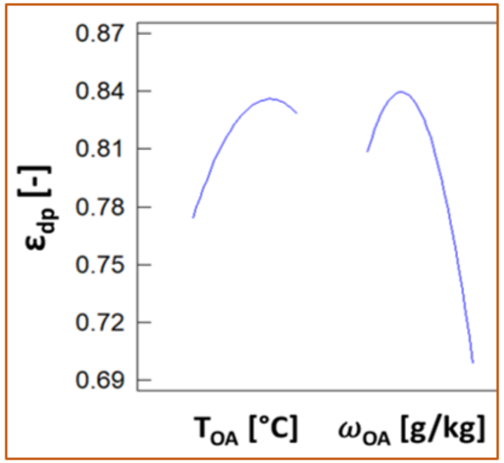
(a) Supply air temperature



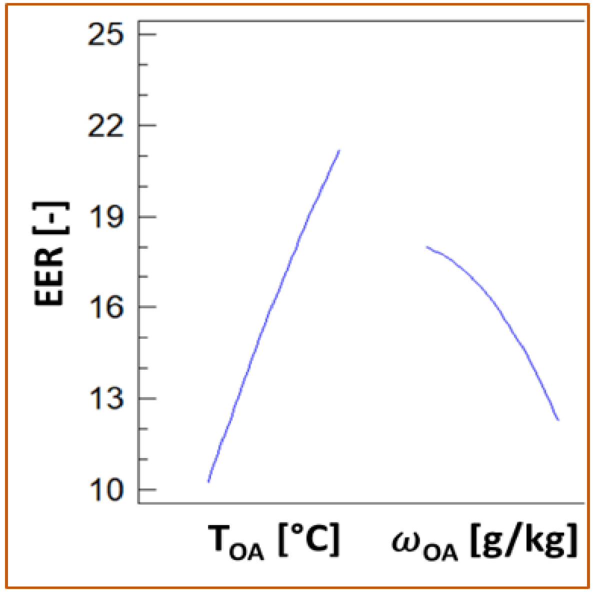
(b) Cooling capacity



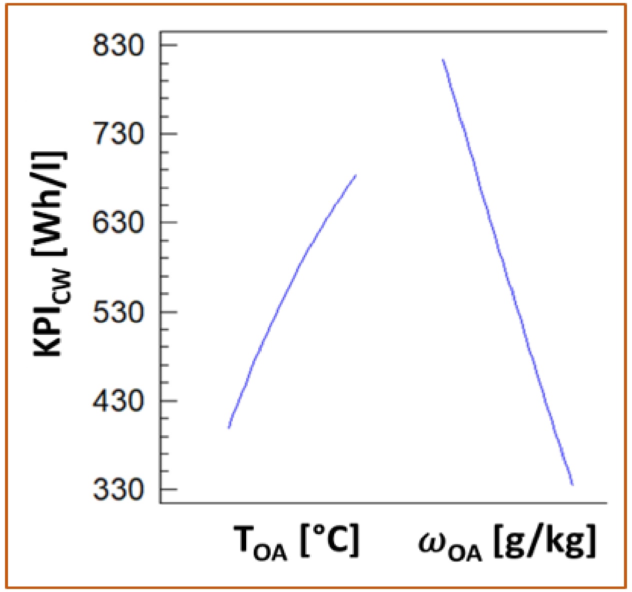
(c) Wet bulb efficiency



(d) Dew point efficiency



(e) Energy efficiency ratio



(f) Cooling capacity per water consumption

III. Seasonal Energy Efficiency Ratio, SEER

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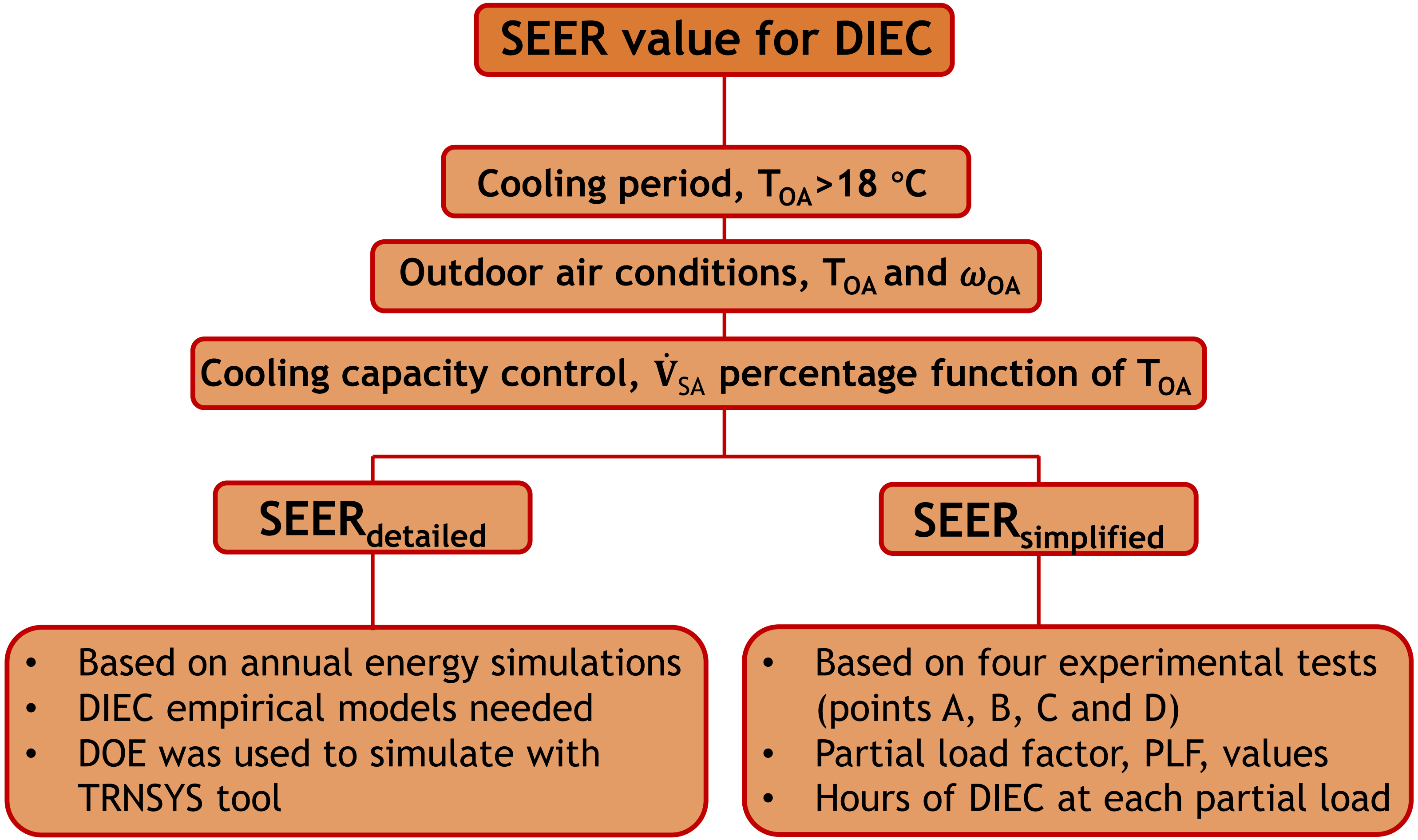
- The Seasonal Energy Efficiency Ratio, **SEER**, value for DIEC depended on the following parameters:



III. Seasonal Energy Efficiency Ratio, SEER

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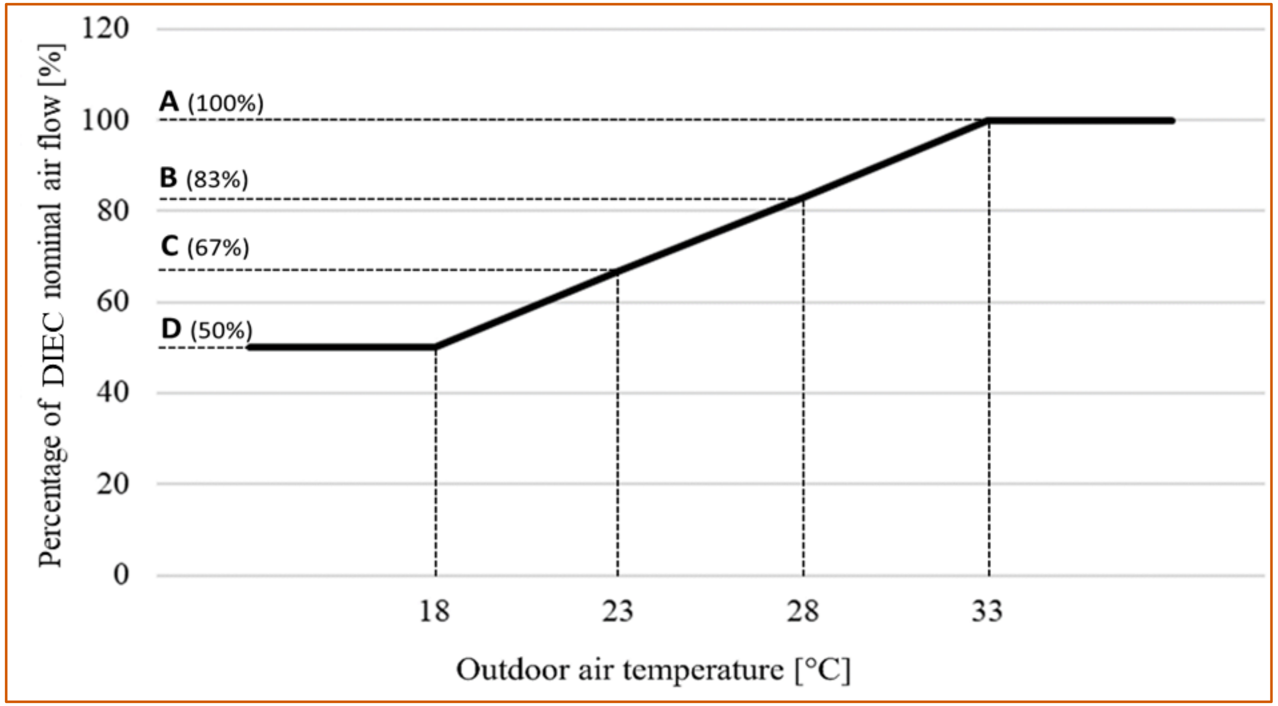
- The Seasonal Energy Efficiency Ratio, **SEER**, value for DIEC was calculated according to the established cooling capacity control:



  - This control strategy was based on the European Standard EN 14825:2018 for the calculation of SEER in air conditioners, chillers and heat pumps.
  - Five different climate zones from Mediterranean area (Cairo, Madrid, Pescara, Napoli and Murcia) were selected to calculate the DIEC SEER value.

III. Seasonal Energy Efficiency Ratio, SEER

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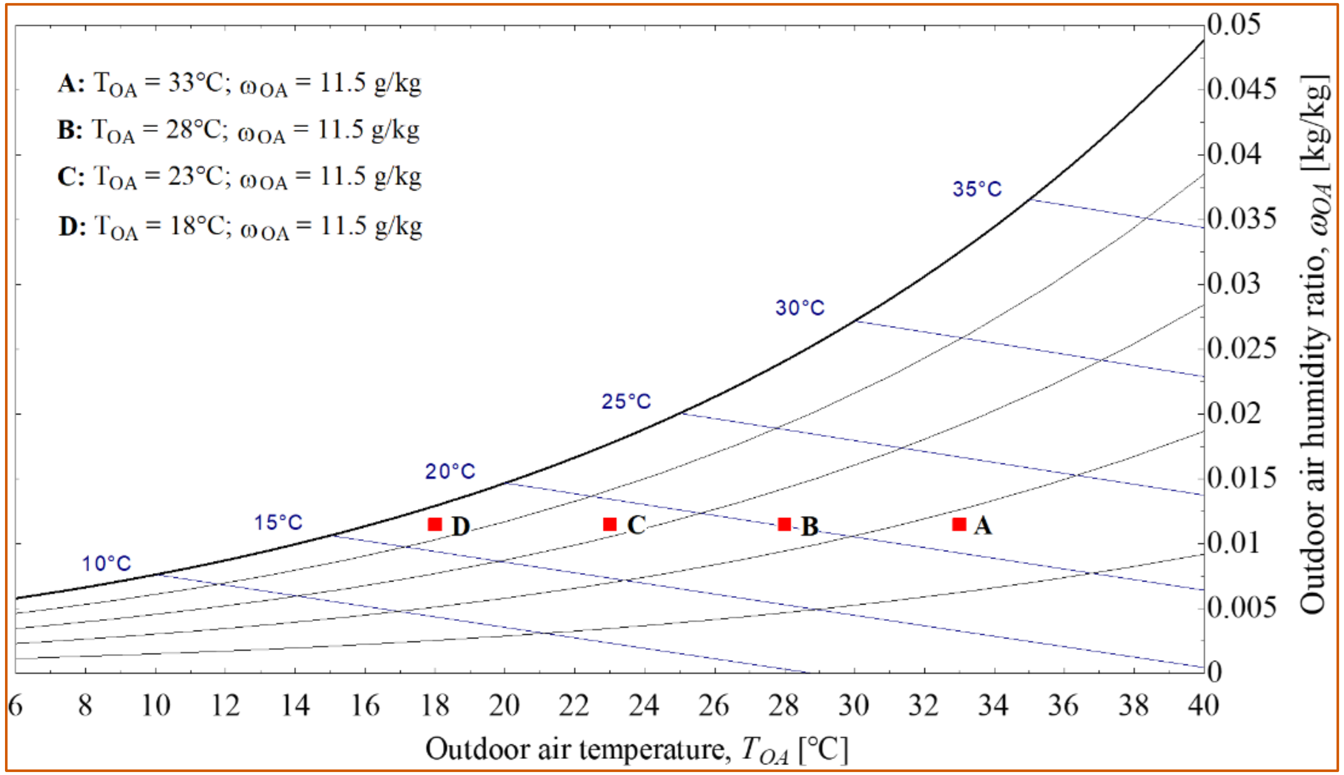

- A **simplified method of testing and calculating SEER for the DIEC system was proposed.** It consisted of carrying out four experimental tests (A, B, C and D) under specific conditions of outdoor air, following a similar approach to that described in the European Standard EN 14825:2018 for other HVAC systems.
- The ω_{OA} value was constant for the four experimental tests, 11.5 g kg^{-1}. This humidity value was the average value calculated for the five climate zones selected.

III. Seasonal Energy Efficiency Ratio, SEER

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- The SEER value was calculated using the innovative simplified method and using the traditional detailed method.

  - Simplified SEER calculation method → based on four experimental tests (A, B, C and D).

$$SEER_{simplified} = \frac{\dot{Q}_{coolingA} \cdot PLF_A \cdot H_A + \dot{Q}_{coolingB} \cdot PLF_B \cdot H_B + \dot{Q}_{coolingC} \cdot PLF_C \cdot H_C + \dot{Q}_{coolingD} \cdot PLF_D \cdot H_D}{\dot{W}_A \cdot PLF_A \cdot H_A + \dot{W}_B \cdot PLF_B \cdot H_B + \dot{W}_C \cdot PLF_C \cdot H_C + \dot{W}_D \cdot PLF_D \cdot H_D}$$

The **partial load factor** considered were 1.00, 0.83, 0.67 and 0.50 for partial load A, B, C and D, respectively.
These values represented the work of the DPIEC at each partial load and were significant in the simplified SEER calculation.
H_A, H_B, H_C and H_D were the number of hours in range T_{OA}>33 °C, 33-28 °C, 28-23 °C and 23-18 °C, respectively.

  - Detailed SEER calculation method → based on annual energy simulations (DOE was used to simulate with TRNSYS tool).

$$SEER_{detailed} = \frac{\sum \dot{Q}_{cooling}}{\sum \dot{W}} = \frac{Q_{cooling}}{W}$$

*** Reminder:**
Coefficients of determination, R^2, of DIEC empirical models

R^2= 0.9991 (Cooling capacity, $\dot{Q}_{cooling}$)
R^2= 0.9997 (Power consumption, $\dot{W}$)

III. Seasonal Energy Efficiency Ratio, SEER

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- The SEER values for the innovative simplified method were compared with the SEER values for the traditional detailed method.

Climate zone	$SEER_{simplified}$	$SEER_{detailed}$	Relative error
	[-]	[-]	[%]
Cairo	4.1	4.0	**2.4**
Madrid	4.1	4.3	**4.9**
Pescara	4.0	3.9	**2.5**
Napoli	4.0	4.1	**2.5**
Murcia	3.9	4.3	**9.3**

- SEER values for Mediterranean climate area were around 4.0.
- Mean relative error value was 4.3%.

IV. Hybrid air-cooling system (RACU = DIEC + DW)

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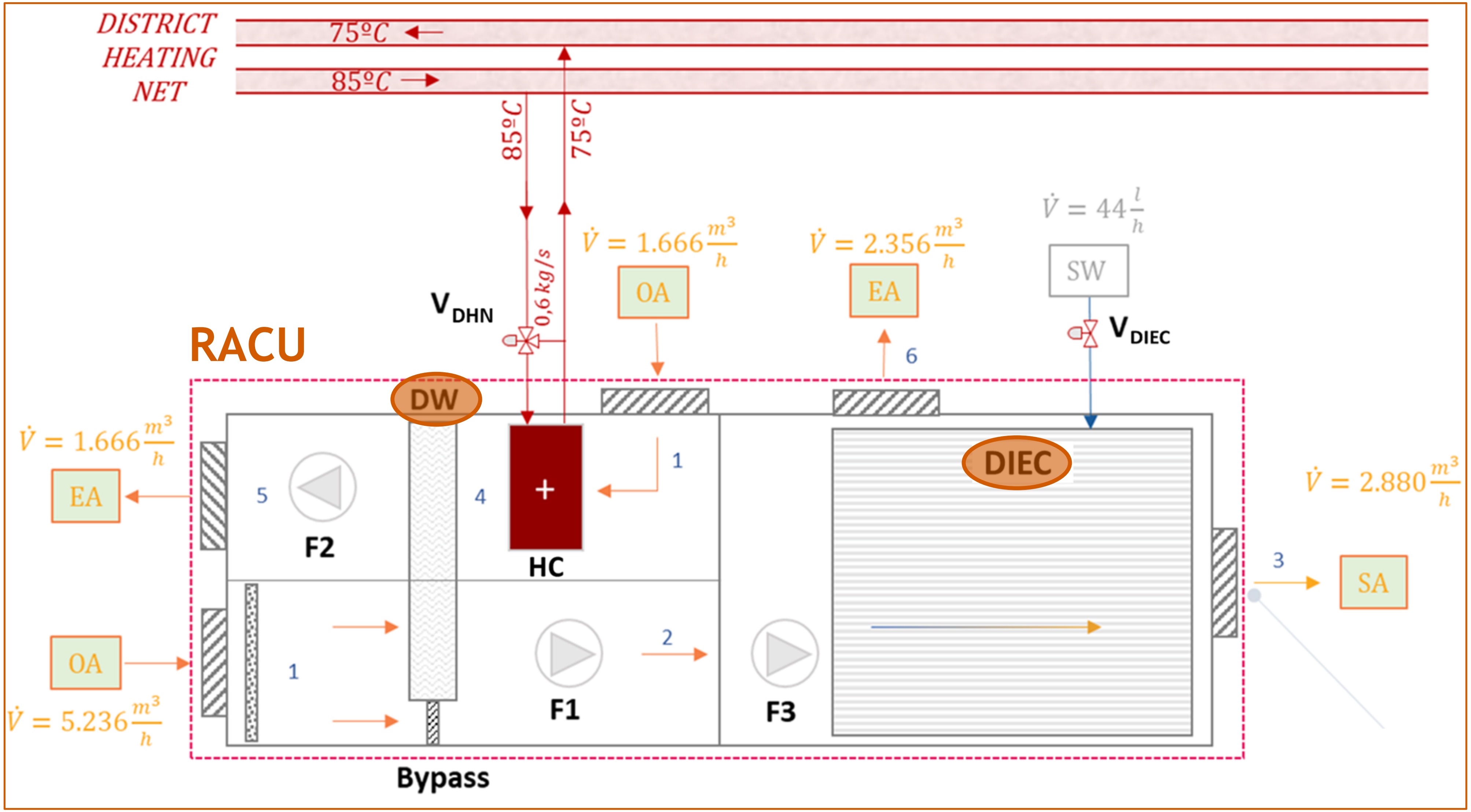

Nomenclature

EA: Exhaust air
OA: Outdoor air
SA: Supply air

DIEC: Dew point indirect evaporative cooler
DW: Desiccant wheel
RACU: Renewable air cooling unit (DIEC+DW)

F1: Process fan
F2: Regeneration fan
F3: DIEC fan
HC: Heating coil

DHN: District heating net
SW: Supply water
V: Valve
$\dot{V}$: Volumetric air flow rate (nominal values [m³/h])

IV. Hybrid air-cooling system (RACU = DIEC + DW)

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- An extensive number of experimental tests, 64, were performed to obtain several empirical models of the RACU hybrid air-cooling system.

- The input variables considered for this experimental study were:

Input variable	Low value	High value	Unit
Process inlet air temperature, T_{pOA}	24	40	ºC
Process inlet air humidity ratio, ω_{pOA}	8	14	g kg^{-1}
Process inlet volumetric air flow, $\dot{V}_{pOA}$	3000	4500	m^3 h^{-1}
Regeneration inlet air temperature, T_{rOA}	24	40	ºC
Regeneration inlet air humidity ratio, ω_{rOA}	8	14	g kg^{-1}
Regeneration inlet volumetric air flow, $\dot{V}_{rOA}$	1000	2000	m^3 h^{-1}
Exhaust air ratio, R_{pEA}	0.3	0.7	-

$$\dot{Q}_{supply} = \rho_{air} \cdot \dot{V}_{SA} \cdot (h_{pOA} - h_{SA})$$

→

$$EER = \frac{\dot{Q}_{supply}}{\dot{W}_{electricity}}$$

IV. Hybrid air-cooling system (RACU = DIEC + DW)

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Test point	T_{OA}	ω_{OA}	HR_{OA}	$T_{SA,DIEC}$	$T_{SA,RACU}$	$\omega_{SA,DIEC}$	$\omega_{SA,RACU}$	EER_{DIEC}	EER_{RACU}
	[°C]	[g/kg]	[%]	[°C]	[°C]	[g/kg]	[g/kg]	[-]	[-]
N1	35	7.0	20	18.8	15.2	7.0	5.2	8.2	6.4
N2	35	10.5	30	21.4	20.1	10.5	8.5	8.9	4.6
N3	35	14.1	40	33.4	23.0	14.1	11.9	2.0	4.8
N4 [a]	35	<u>21.4</u>	60	-	-	<u>21.4</u>	-	-	-
N5 [a]	35	<u>28.9</u>	80	-	-	<u>28.9</u>	-	-	-
N6	30	5.3	20	20.4	13.6	5.3	3.9	3.2	6.6
N7	30	7.9	30	18.1	17.1	7.9	6.2	7.2	4.7
N8	30	10.6	40	21.0	19.4	10.6	8.5	6.9	3.8
N9 [a]	30	<u>16.4</u>	60	-	-	<u>16.4</u>	-	-	-
N10 [a]	30	<u>21.5</u>	80	-	-	<u>21.5</u>	-	-	-
N11 [a]	25	<u>3.9</u>	20	-	-	<u>3.9</u>	-	-	-
N12	25	5.9	30	19.4	16.4	5.9	4.8	2.2	4.5
N13	25	7.9	40	18.2	18.0	7.9	6.3	4.8	3.4
N14	25	11.9	60	24.4	19.5	11.9	9.3	2.9	3.1
N15 [a]	25	<u>15.9</u>	80	-	-	<u>15.9</u>	-	-	-

[a] The humidity ratio values established for tests N4, N5, N9, N10, N11 and N15 are not within the range for which the DOE of our <u>DIEC</u> and our <u>RACU</u> were performed. Therefore, invalid values are obtained for indicators.

- **Coefficients of determination, R^2, for the RACU empirical models:**

$T_{SA,RACU}$ → 0.9356

$\omega_{SA,RACU}$ → 0.9430

EER_{RACU} → 0.9707

- These results were obtained for R_{pEA} and $\dot{V}_{pOA}$ values set to nominal values, 0.45 and 5236 $m^3 h^{-1}$, respectively.

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THANKS FOR YOUR ATTENTION!



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