Cooling Efficiency And Operational Stability Of Indirect-Direct Evaporative Cooling Under Diurnal Hot-Humid Conditions

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Abstract

Cooling equipment for humid buildings should be evaluated using both cooling magnitude and outlet-condition stability. This study compares the diurnal performance of DEC and IDEC using a 16-hour hot-humid operating record. DEC gave a mean cooled-air temperature of 24.75 °C, a range of 10.62 °C and a standard deviation of 4.40 °C. IDEC gave a mean cooled-air temperature of 19.23 °C, a range of only 0.17 °C and a standard deviation of 0.06 °C. The mean efficiency also increased from 64.05% for DEC to 91.30% for IDEC. The stability metrics show that IDEC is not only colder on average; it also delivers a nearly constant supply condition over the evaluated operating sequence.

Keywords: cooling efficiency; operational stability; standard deviation; indirect-direct evaporative cooling; humid climate

1. Introduction

Evaporative cooling performance changes with dry-bulb temperature, wet-bulb temperature and relative humidity [1]. A single design-hour calculation can therefore hide periods of weak operation [2]. Indirect-direct evaporative cooling can improve the daily profile because the indirect stage reduces the load carried by the wetted pad [3]. Experimental and modelling studies have shown that heat-exchanger arrangement, pad condition, water flow and air velocity strongly affect system performance [4], [5], [6].

For humid Nigerian buildings, stability is a design issue rather than a statistical luxury. A system that gives low outlet temperature early in the morning but rises above comfort-relevant values later in the day would be difficult to control [7]. Standard deviation and range are simple metrics for this problem because they describe how much the supply condition moves across the operating sequence [8]. Water consumption, fouling and air-side resistance still need field verification, but the stability indicators give a useful first ranking [9].

For evaporative coolers, range, standard deviation and coefficient of variation are useful because they describe different aspects of operating reliability. The range shows the maximum swing that the downstream space or air-distribution system must absorb. The standard deviation describes the typical departure from the mean outlet condition. The coefficient of variation allows the spread to be judged relative to the mean temperature, which is helpful when two systems have different average outlet temperatures.

2. Data and analytical method

2.1 Research process flowchart

Figure 1 presents a standard research process flowchart for the cooling-efficiency and operational-stability assessment. The flowchart is placed first in the method section so that the reader can see how the dataset is organised, how the hourly variables are calculated and how the stability statistics are obtained.

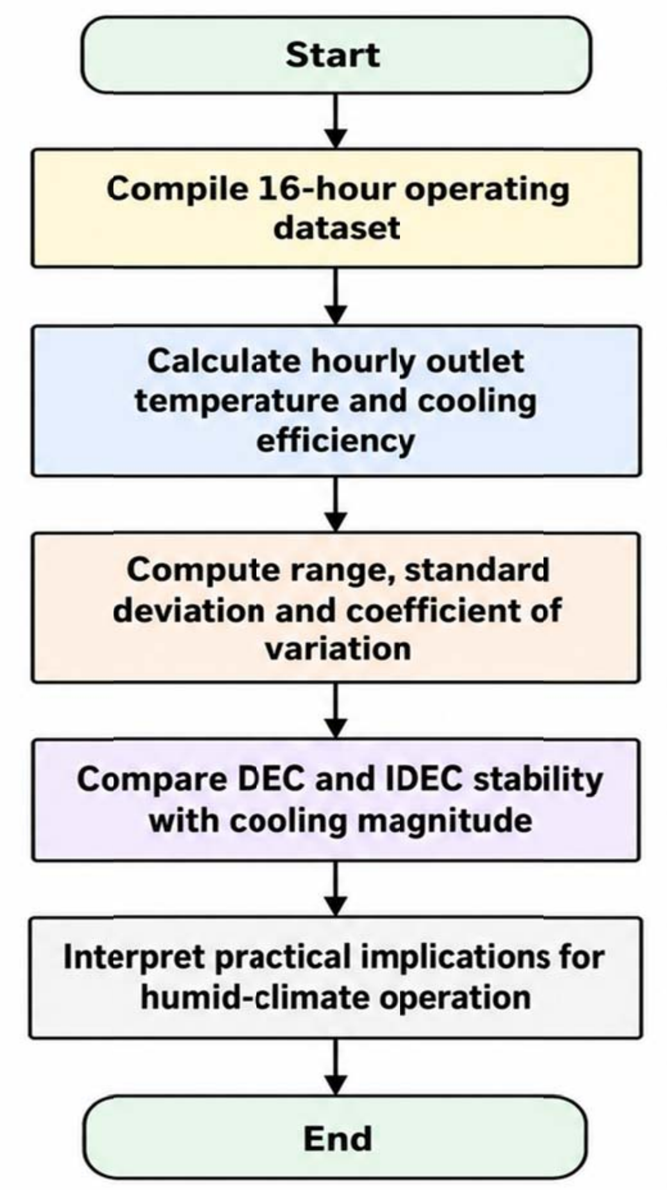

Figure 1. Standard research process flowchart for the cooling-efficiency and operational-stability assessment.

The flowchart uses a stepped layout to emphasise the progressive nature of the analysis. The 16-hour record is compiled first, the hourly outlet temperature and cooling efficiency are then calculated, and the stability statistics are obtained before the DEC and IDEC responses are compared. The final step interprets what the statistical differences mean for humid-climate operation and prototype selection.

Three stability statistics were calculated from the hourly outlet temperatures. The range represents the largest supply-temperature swing; the standard deviation measures dispersion around the mean; and the coefficient of variation normalises that dispersion by the mean value. Together, these indicators distinguish a system that cools strongly for a short period from one that supplies steady air throughout the day.

The dataset contains 16 hourly records from 07:00 to 22:00. For each hour, ambient dry-bulb temperature, relative humidity, DEC outlet temperature, DEC efficiency, IDEC outlet temperature and IDEC efficiency were evaluated. The sequence is used as a diurnal screening record; it represents a controlled comparison between system configurations under identical boundary conditions.

Table 1. Sixteen-hour performance data used for stability analysis.

Hour	Ambient DB (°C)	RH (%)	DEC outlet (°C)	DEC eff. (%)	IDEC outlet (°C)	IDEC eff. (%)
07:00	23.65	68.49	19.73	68.1	19.15	87.5
08:00	26.3	68.58	22.79	65.6	19.21	91.0
09:00	26.05	68.57	22.09	68.2	19.21	90.7
10:00	25.8	68.56	21.39	70.5	19.2	90.5
11:00	25.6	68.56	20.68	73.3	19.19	90.4
12:00	25.4	68.55	19.98	74.7	19.19	90.1
13:00	25.2	68.54	20.58	71.6	19.19	89.8
14:00	25.6	68.56	22.39	63.5	19.19	90.4
15:00	26.35	68.58	24.25	53.1	19.21	91.1
16:00	26.6	68.59	25.37	58.5	19.22	91.3
17:00	27.65	68.62	27.15	55.5	19.24	92.1
18:00	29.3	68.67	29.01	58.0	19.28	92.9
19:00	30.3	68.71	30.21	50.0	19.31	93.3
20:00	30.7	68.72	30.35	68.6	19.32	93.4
21:00	30.8	68.72	30.25	57.8	19.32	93.4
22:00	30.75	68.72	29.8	67.8	19.32	93.4

Temperature range, standard deviation and coefficient of variation were used to compare stability:

$$R_T = T_{out,max} - T_{out,min} \quad (1)$$

$$s_T = \sqrt{\frac{\sum_{i=1}^{n}(T_i - \bar{T})^2}{n-1}} \quad (2)$$

$$CV_T = \frac{s_T}{\bar{T}} \times 100\% \quad (3)$$

Three stability indicators were therefore calculated: temperature range, sample standard deviation and coefficient of variation. The range gives the largest swing the building ventilation system must absorb. The standard deviation measures the spread of the outlet temperatures around the mean. The coefficient of variation normalises that spread by the mean outlet value, allowing the stability of two configurations with different mean temperatures to be compared on a common basis.

The 16-hour record was analysed as a continuous operating sequence rather than as isolated hourly points. This choice matters because evaporative-cooling usefulness depends on whether the outlet condition remains acceptable as outdoor temperature changes. A single peak cooling value can be misleading if it occurs only during a cool morning period.

3. Results

Table 2. Descriptive stability statistics for DEC and IDEC.

Stability indicator	DEC	IDEC
Mean outlet temperature	24.75 °C	19.23 °C
Minimum outlet temperature	19.73 °C	19.15 °C
Maximum outlet temperature	30.35 °C	19.32 °C

Stability indicator	DEC	IDEC
Temperature range	10.62 °C	0.17 °C
Standard deviation	4.09 °C	0.06 °C
Mean efficiency	64.05%	91.30%

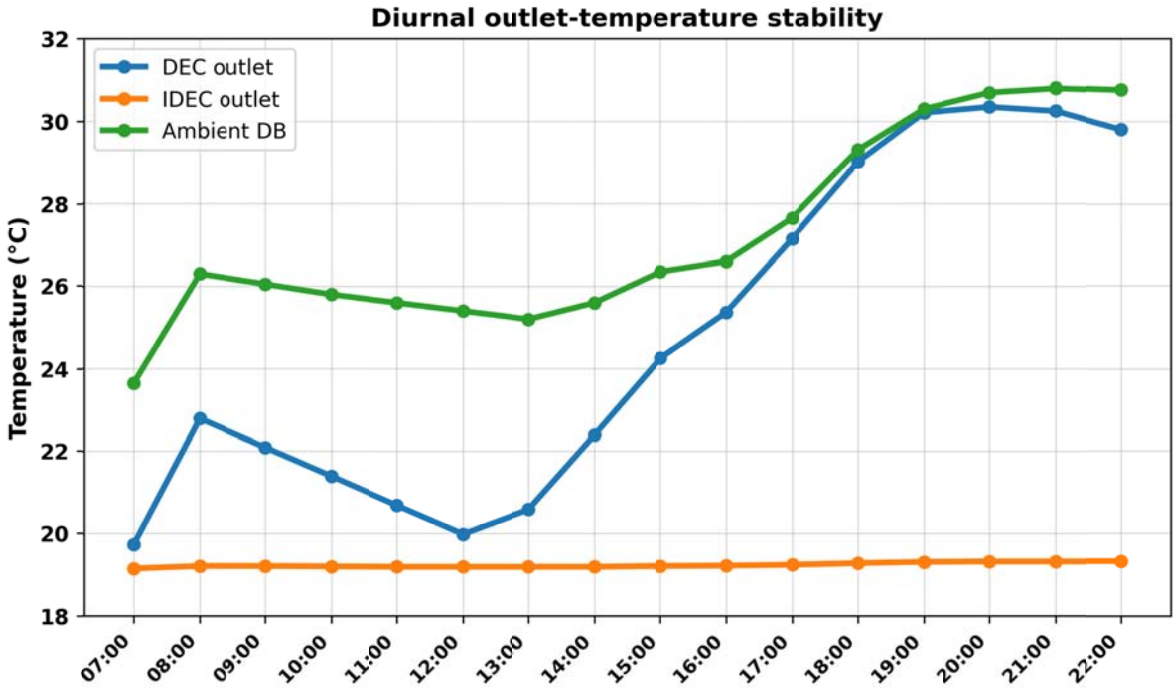

Figure 2. Hourly cooled-air temperature of DEC and IDEC compared with ambient dry-bulb temperature.

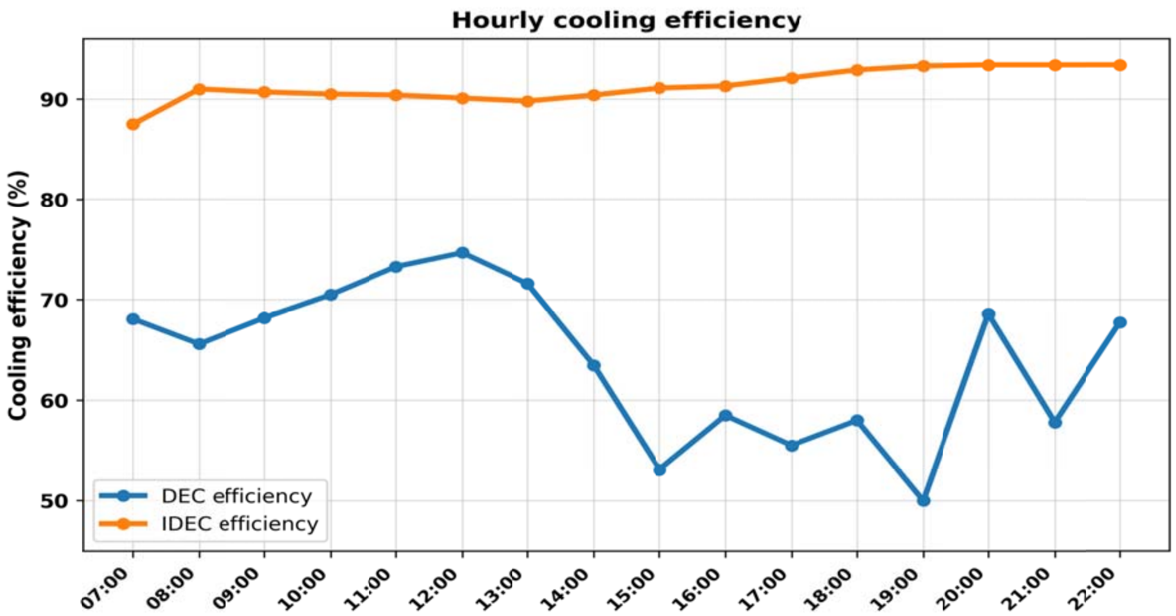

Figure 3. Hourly cooling efficiency of DEC and IDEC.

DEC followed the ambient trend and weakened during the warmer hours. Its outlet temperature rose above 29 °C after 18:00 and reached 30.35 °C at 20:00. The system still produced some cooling relative to the ambient condition, but the cooled stream was not steady enough for dependable supply-air service without supplementary measures.

IDEC showed a different operating character. Its outlet temperature remained almost flat, moving only from 19.15 to 19.32 °C. The efficiency record was also steadier: the lowest IDEC efficiency was 87.5%, while DEC dropped to

50.0%. The difference between the two standard deviations, 4.09 °C for DEC and 0.06 °C for IDEC, gives a clear numerical measure of the stability advantage.

4. Discussion

The stability result has a practical control implication. A supply stream that moves by more than 10 °C would require frequent control correction or backup cooling, whereas a supply stream that changes by less than 0.2 °C can be handled with simpler airflow and water-management control. The numerical contrast therefore has design significance beyond the mean temperature difference.

The hourly data indicate why peak cooling alone can mislead design decisions. DEC achieved low outlet temperatures at the start of the day but could not sustain them. IDEC avoided that swing by using the indirect stage to moderate the pad inlet condition. In practical terms, the system with the lower mean outlet temperature also had the smaller control burden because the supply condition hardly moved.

For locally fabricable buildings, stable output can reduce the need for complex control. A nearly constant supply temperature allows the designer to focus on air distribution, humidity management and water hygiene rather than chasing a moving outlet set point. The stability result identifies IDEC as the stronger candidate for prototype testing, but it indicates which configuration should be tested first.

5. Conclusion

IDEC outperformed DEC in both efficiency and operational stability. Outlet-temperature range fell from 10.62 °C to 0.17 °C, standard deviation fell from 4.09 °C to 0.06 °C, and mean efficiency increased from 64.05% to 91.30%. The stable IDEC response makes it the stronger candidate for hot-humid supply-air cooling applications that cannot tolerate large diurnal outlet-temperature swings.

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