



Design, Experimental Evaluation And Performance Analysis Of An All-Season Eco- Friendly Air Conditioning System

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Abstract— The increasing demand for energy-efficient and environmentally sustainable air conditioning systems has driven the development of alternative cooling technologies. Conventional vapor compression systems are associated with high energy consumption and environmental concerns due to the use of synthetic refrigerants [1]. In this study, an all-season eco-friendly air conditioning system integrating winter heating, direct evaporative cooling (DEC), indirect evaporative cooling (IEC), and a multi-stage hybrid cooling system is designed and experimentally evaluated. The winter heating system, powered by solar PV panels and a fan-coil unit (FCU), achieved a heating capacity of 3461 W with a maximum Energy Efficiency Ratio (EER) of 34.32 at 30 Hz. The DEC system demonstrated a high cooling capacity of approximately 12.19 kW with a maximum EER of approximately 68 at medium fan speed, although it resulted in increased outlet humidity. The IEC system provided sensible cooling without adding moisture and was evaluated under single-coil, series, and parallel configurations; the series arrangement achieved superior thermal effectiveness (0.73 vs 0.70 for parallel at 20 Hz), despite the parallel configuration achieving a marginally higher peak EER of 6.0 vs 5.9 at 35 Hz; the series configuration is preferred where maximum air temperature reduction is the priority. To overcome the limitations of standalone evaporative cooling, a hybrid system combining IEC with a vapor compression refrigeration system (VCRS) was developed, achieving an EER of approximately 3.9, which exceeds the 3.3 EER benchmark of a conventional BEE 5-star rated air conditioner. The proposed system offers a sustainable and energy-efficient alternative to conventional HVAC systems, suitable for year-round operation under varying climatic conditions.

Index Terms— Evaporative cooling, Fan-coil unit, Energy efficiency ratio, Hybrid cooling, HVAC, Solar heating, Indirect evaporative cooling.

1. INTRODUCTION

Heating, Ventilation, and Air Conditioning (HVAC) systems play a crucial role in maintaining thermal comfort, indoor air quality, and humidity control in residential and commercial spaces. However, conventional air conditioning systems based on vapor compression refrigeration (VCRS) are highly energy-intensive and contribute significantly to greenhouse gas emissions due to the use of synthetic refrigerants [1]. This challenge is particularly significant in tropical and subtropical regions like India, where high summer temperatures and humidity demand continuous cooling for extended periods [2]. With increasing global demand for cooling and stringent environmental regulations, there is a pressing need to develop sustainable and energy-efficient alternatives.

Evaporative cooling has emerged as a promising eco-friendly solution, utilizing the natural process of water evaporation to reduce air temperature [2]. Direct Evaporative Cooling (DEC) systems offer high cooling efficiency with low energy consumption but suffer from increased humidity levels, limiting their application in humid climates [3]. Indirect Evaporative Cooling (IEC) systems address this issue by providing sensible cooling without adding moisture; however, their performance is constrained by the wet-bulb temperature of the ambient air [1].

To overcome these limitations, hybrid multi-stage cooling systems integrating evaporative cooling with conventional refrigeration techniques have been proposed [4]. These systems aim to achieve enhanced cooling performance while minimizing refrigerant usage and reducing overall energy consumption. Integration of renewable energy sources, such as solar energy, further enhances the sustainability of such systems.

This study presents the design, experimental evaluation, and performance analysis of an all-season eco-friendly air conditioning system capable of providing heating in winter and cooling in summer. The specific objectives of this study are: (1) to evaluate the heating performance of a solar-assisted FCU system at varying fan frequencies; (2) to compare DEC performance under single and parallel desert-cooler configurations; (3) to evaluate IEC under single-coil, series, and parallel coil arrangements; (4) to assess the performance of a hybrid IEC-VCRS system; and (5) to compare all systems against conventional HVAC benchmarks in terms of EER and cooling capacity.

2. LITERATURE REVIEW

The increasing global demand for energy-efficient and environmentally sustainable air-conditioning systems has driven extensive research into alternative cooling technologies. Conventional vapor compression refrigeration (VCR) systems dominate the HVAC sector; however, they are associated with high energy consumption and environmental concerns due to the use of synthetic refrigerants. Consequently, evaporative cooling technologies have emerged as promising eco-friendly alternatives [1].

Evaporative cooling utilizes the latent heat of vaporization of water to reduce air temperature and is broadly classified into Direct Evaporative Cooling (DEC) and Indirect Evaporative Cooling (IEC). DEC systems involve direct contact between air and water, resulting in high cooling efficiency and low energy consumption. However, a significant limitation of DEC systems is the increase in humidity of the conditioned air, which restricts their application in humid climates [2].

To overcome this limitation, IEC systems have been developed, where heat exchange occurs between the primary air stream and chilled water circulated through a fin-tube heat exchanger, enabling sensible cooling without increasing moisture content. Studies indicate that IEC systems are more suitable for humid environments and can maintain indoor air quality effectively, although their cooling capacity is generally lower than DEC systems [1], [3].

Despite their advantages, standalone evaporative cooling systems are highly dependent on ambient conditions, particularly the wet-bulb temperature. Cooling effectiveness decreases significantly when the difference between dry-bulb and wet-bulb temperatures is small, thereby limiting performance in mild and humid climates [2]. To address these challenges, hybrid cooling systems integrating evaporative cooling with conventional refrigeration have been proposed [4]. Multi-stage hybrid systems such as IEC-VCRS combinations have demonstrated improved thermal performance and reduced energy consumption compared to standalone systems [4].

Advanced developments include the use of regenerative heat exchangers and the Maisotsenko cycle (M-cycle), which enable cooling below the wet-bulb temperature limit [5]. The integration of IEC as a pre-cooling stage in a hybrid system has also been shown to reduce compressor load and overall electricity consumption significantly [4].

However, limited experimental studies have simultaneously evaluated all four operational modes — winter heating, DEC, IEC, and hybrid cooling — in a single integrated system under Indian subcontinental climatic conditions. Furthermore, comparative performance data across single-coil, series, and parallel IEC configurations using the same experimental setup is scarce [6]. The present study addresses these gaps.

3. METHODOLOGY AND SYSTEM DESCRIPTION

3.1 System Overview

The present study focuses on the design and experimental evaluation of an all-season eco-friendly air conditioning system providing both heating and cooling under varying climatic conditions. The system integrates multiple techniques to achieve thermal comfort with reduced environmental impact. Four major operational modes are developed and tested: (i) winter heating system, (ii) direct evaporative cooling (DEC) system, (iii) indirect evaporative cooling (IEC) system, and (iv) multi-stage hybrid cooling system.

3.2 Working Principles

3.2.1 Winter Heating System

The winter heating system uses a fan-coil unit (FCU) integrated with a solar-assisted water heating arrangement. Solar PV panels (330 Wp rated) supply DC power to immersible DC heaters (300 W each) that heat water stored in an insulated tank. The heated water is circulated through the FCU fin-coil by a DC pump, and an axial fan forces ambient air across the coil. Heat transfer from hot water to air raises the air temperature. Fan speed is regulated by a VFD. As an alternative, a solar water heater can replace the PV+heater arrangement for direct water heating.

3.2.2 Direct Evaporative Cooling (DEC)

In the DEC system, ambient air is drawn through wetted honeycomb cooling pads of a desert cooler (Crompton Ozone 88). Direct contact between air and water causes evaporation, converting sensible heat into latent heat and reducing air dry-bulb temperature. Although DEC provides high cooling efficiency and low energy consumption, it increases the humidity of the conditioned air and is therefore more suitable for hot and dry climates with ambient RH below 40%.

3.2.3 Indirect Evaporative Cooling (IEC)

In the present IEC setup, a fin-tube heat exchanger (fan-coil unit) is connected to a desert cooler that supplies chilled water. The desert cooler chills water through evaporation, and a submersible pump circulates this chilled water through the FCU coil. Ambient air is blown across the heat exchanger by an axial fan driven by a VFD, allowing sensible heat transfer from air to the chilled water without any moisture addition to the air stream. The IEC system was evaluated under three configurations: (a) single coil, (b) dual-coil series — where water from the first coil is recirculated through the second for enhanced heat absorption — and (c) dual-coil parallel — where chilled water is split equally between both coils simultaneously.

3.2.4 Multi-Stage Hybrid Cooling System

To overcome the wet-bulb temperature limitation of standalone evaporative cooling, a multi-stage hybrid system is developed by integrating the IEC arrangement with a vapor compression refrigeration system (VCRS). A water chilling plant (using R-22 refrigerant, thermostat set to $10^{\circ}\text{C} \pm 2^{\circ}\text{C}$) supplies chilled water to the front FCU coil, while the desert cooler continues to supply chilled water to the rear FCU coil (IEC stage). Ambient air passes across both coils in sequence. The IEC stage pre-cools the air, reducing the thermal load on the VCRS compressor, thereby improving overall system EER while minimizing refrigerant usage.

3.3 Experimental Setup and Instrumentation

Table 1. Specifications of major system components

Component	Model / Type	Key Specification
Fan-Coil Unit (FCU)	Fin-tube heat exchanger + axial fan	Rated: 2300 m ³ /hr, 140 W; Measured: 562–1519 m ³ /hr
Desert Cooler	Crompton Ozone 88	4200 m ³ /hr, 190 W (Speed 3); honeycomb pads
Submersible Pump	Standard 40 W pump	1200 LPH rated; measured 375 LPH, 38 W
Solar PV Panel	CSPL24P330	330 W _p , Voc = 46 V, Isc = 9.22 A
DC Heater	Immersible rod heater	300 W per heater, 48 V max; two used in parallel
DC Pump	Solar-compatible centrifugal	Hot water circulation for winter heating setup
RTD Sensor	2-channel / 8-channel	Temperature measurement at all inlet/outlet points
VFD	Variable Frequency Drive	Controls fan speed 10–50 Hz; up to 50 Hz output
Anemometer	Vane type	Air velocity measurement at fan face (5–9 points)
Hygropalm	Digital humidity meter	Relative humidity (%) at inlet and outlet air

Fan speed was controlled using a VFD at frequencies of 10, 15, 20, 25, 30, 40, and 50 Hz for the heating system, and at 20, 35, and 50 Hz for the evaporative cooling systems. Steady state was assumed when water temperature variation was less than 0.5°C over a 5-minute observation period. Air velocity was measured at 5 to 9 points across the fan face using a vane-type anemometer, and the average value was used to calculate volumetric flow rate.

3.4 Performance Parameters

The performance of each system is evaluated using the following thermodynamic parameters. Cooling or heating capacity (\dot{Q} , W) represents the rate of heat transfer to or from the air stream, as given by Eq. (1). The Energy Efficiency Ratio (EER) is defined as the ratio of cooling or heating capacity to the electrical power consumed by the system, as given by Eq. (2). Effectiveness (ϵ) evaluates evaporative cooling performance relative to the ideal maximum cooling, given by Eq. (3).

$$\dot{Q} = \dot{m} \times C_p \times \Delta T \quad \dots\dots (1)$$

$$EER = \dot{Q} / P \quad \dots\dots (2)$$

$$\epsilon = \Delta T / (T_{db,in} - WBT) \quad \dots\dots (3)$$

where \dot{m} is the mass flow rate of air (kg/s), C_p is the specific heat of air (1.005 kJ/kg·K), ΔT is the temperature difference between inlet and outlet air (°C), P is the electrical power consumed (W), $T_{db,in}$ is the inlet dry-bulb temperature, and WBT is the wet-bulb temperature of ambient air.

4. RESULTS AND DISCUSSION

The performance of the all-season eco-friendly air conditioning system was experimentally evaluated under varying operating conditions for all four modes. Results are analyzed in terms of cooling or heating capacity, EER, and system effectiveness.

4.1 Winter Heating Performance

Table 2 presents the heating performance of the fan-coil unit at varying VFD frequencies, with hot water maintained at 50°C. As frequency increased from 10 Hz to 50 Hz, airflow increased from 245.5 m³/hr to 737.6 m³/hr, leading to a rise in heating capacity from 1427 W to 3461 W. However, EER peaked at 30 Hz (EER = 34.32) because fan power consumption increased more steeply than heating capacity beyond this point, reducing the ratio at 40 Hz (EER = 28.16) and 50 Hz (EER = 21.98). The solar PV panels (330 Wp) powered the DC heaters directly, making this system fully renewable-energy-driven and achieving an EER far superior to conventional electric resistance heaters whose EER is approximately 1.

Table 2. Winter heating system performance at varying VFD frequencies (Hot water temperature = 50°C)

Freq (Hz)	Airflow (m ³ /hr)	ΔT (°C)	Heating Cap. (W)	Power (W)	EER
10	245.5	16.1	1427	58.25	24.49
15	340.9	15.2	1870	61.75	30.29
20	435.2	14.8	2325	67.50	34.44
25	496.7	14.6	2617	77.50	33.77
30	607.2	13.7	3003	87.50	34.32
40	695.9	13.2	3316	117.75	28.16
50	737.6	13.0	3461	157.50	21.98

4.2 Direct Evaporative Cooling (DEC) Performance

Table 3 shows the DEC performance at three fan speeds using a single desert cooler. The system achieved a peak cooling capacity of 12.19 kW at medium speed with an EER of 68.38, and an effectiveness of 0.652. At medium speed, the airflow rate was 3389 m³/hr with a temperature drop of 11.2°C. High speed offered slightly higher airflow but reduced EER (61.80) due to the disproportionate increase in fan power. The outlet relative humidity increased from ambient (~15–17%) to approximately 53–56% across all speeds, confirming the fundamental limitation of DEC in humid climates. This restricts its practical use to dry seasons where ambient RH is below 40%.

Table 3. DEC performance at varying fan speeds (Single desert cooler)

Speed	Airflow (m ³ /hr)	Cooling Cap. (kW)	ΔT (°C)	Effectiveness	Power (kW)	EER
Low	3038	11.38	11.67	0.662	0.175	65.18
Medium	3389	12.19	11.20	0.652	0.178	68.38
High	3403	11.55	10.57	0.657	0.187	61.80

4.3 Indirect Evaporative Cooling (IEC) Performance

Table 4 compares the three IEC configurations across the three VFD frequencies tested. The series dual-coil configuration consistently achieved the highest thermal effectiveness due to water recirculation — water exiting the first coil, which has already absorbed heat from the air, is fed into the second coil where it can absorb further heat from the partially cooled air stream. At 35 Hz, the series configuration achieved an EER of 5.9 with a cooling capacity of 1.346 kW and effectiveness of 0.656, compared to single-coil performance of EER 5.0 and 1.147 kW at the same frequency.

The parallel configuration showed slightly higher EER at 20 Hz (5.6 vs 4.6 for single-coil) because fresh chilled water with full heat-absorbing capacity is delivered to both coils simultaneously. However, the series arrangement maintained superior effectiveness (0.72 vs 0.70 at 20 Hz) since each coil handles a smaller fraction of the temperature drop sequentially. Across all configurations, outlet air temperature was

reduced by 7–9°C without any increase in humidity, confirming suitability for humidity-sensitive applications in warm and moderately humid climates.

Table 4. IEC performance comparison — single-coil, series dual-coil, and parallel dual-coil configurations

Configuration	Freq (Hz)	Cooling Cap. (kW)	ΔT (°C)	Effectiveness	Power (W)	EER
Single Coil	20	0.894	7.36	0.67	205	4.4
Single Coil	35	1.147	6.03	0.55	228	5.0
Single Coil	50	1.201	5.28	0.46	264	4.6
Series Dual	20	0.955	7.86	0.73	205	4.6
Series Dual	35	1.346	7.08	0.66	228	5.9
Series Dual	50	1.458	6.41	0.58	264	5.5
Parallel Dual	20	1.152	9.31	0.70	205	5.6
Parallel Dual	35	1.365	7.99	0.60	228	6.0
Parallel Dual	50	1.545	7.08	0.52	264	5.9

4.4 Hybrid Cooling System Performance

Table 5 presents the hybrid IEC-VCRS system results. At 35 Hz, the system reduced inlet air temperature from approximately 32°C to approximately 15°C — a ΔT of approximately 17°C — compared to approximately 7°C achieved by IEC alone under similar conditions. The chilled water temperature from the VCRS was maintained at 10°C ($\pm 2^\circ\text{C}$ hysteresis). At 50 Hz, the peak cooling capacity reached 3.789 kW with an EER of 3.9.

This EER of 3.9 exceeds the 3.3 EER benchmark of a BEE 5-star rated conventional air conditioner under similar conditions, demonstrating that the hybrid system is not only more eco-friendly but also more energy-efficient. The IEC pre-cooling stage reduced the temperature of incoming air by approximately 7°C before it entered the VCRS evaporator, thereby reducing the thermal load on the compressor. Outlet relative humidity exceeded 85% due to significant temperature reduction approaching the dew point, indicating effective sensible cooling and moisture condensation, which together provide better combined temperature and humidity control compared to standalone evaporative systems. Additionally, the contribution of the IEC stage reduces the quantity of R-22 refrigerant required, lowering the overall environmental impact of the system.

Table 5. Hybrid IEC-VCRS system performance at varying VFD frequencies (* denotes repeated test at 35 Hz to confirm repeatability of results)

Freq (Hz)	T_inlet (°C)	T_outlet (°C)	ΔT (°C)	\dot{Q}_s (kW)	Power (W)	EER
35	31.94	14.97	16.97	3.227	928	3.5
50	32.61	15.95	16.66	3.789	964	3.9
35*	32.48	14.64	17.84	3.392	928	3.7
20	31.95	13.05	18.90	2.296	905	2.5

4.5 Comparative Performance Analysis

Table 6 presents a comprehensive comparison of all four developed systems against a conventional 5-star rated air conditioner. Each system offers a distinct advantage suited to specific climatic and application conditions.

Table 6. Comparative analysis of all systems against conventional AC benchmark

System	Cooling/Heating Cap.	EER	Humidity Control	Key Limitation
Winter Heating (Solar FCU)	3461 W (at 50 Hz)	34.32 (at 30 Hz)	N/A — heating mode	Requires solar/DC power supply
Direct Evaporative Cooling (DEC)	~12.19 kW (medium speed)	~68 (medium speed)	Poor — RH rises to ~54–56%	Not suitable for humid climates
Indirect Evaporative Cooling (IEC)—Series	1.346 kW (35 Hz)	5.9 (35 Hz)	Good — no moisture addition	Limited by wet-bulb temperature
IEC — Parallel	1.545 kW (50 Hz)	6.0 (35 Hz)	Good — no moisture addition	Lower effectiveness vs series
Hybrid IEC + VCRS	3.789 kW (50 Hz)	3.9 (50 Hz)	Best — RH controlled <90%	Uses R-22 refrigerant
Conventional 5-star AC (benchmark)	—	~3.3 (rated)	Good	High energy; synthetic refrigerant

4.6 Discussion

The experimental results collectively demonstrate the value of integrating multiple cooling and heating techniques into a single platform. The DEC system delivered the highest EER (~68) but with the tradeoff of elevated outlet humidity, restricting its use to dry seasons. The IEC system eliminated this humidity penalty while still providing useful sensible cooling, making it better suited for moderately humid conditions typical of Indian summers.

In the IEC experiments, the trend of EER decreasing at 50 Hz compared to 35 Hz across all configurations is explained by the non-linear relationship between fan power and airflow: fan power increases as the cube of speed, while cooling capacity increases more gradually with airflow. This is consistent with fan affinity law behavior and confirms that an optimal operating frequency exists for each configuration — approximately 35 Hz in this experimental setup.

The series IEC configuration outperformed parallel due to the recirculation benefit: water that has absorbed heat in the first coil is still cooler than the ambient air entering the second coil, enabling a second stage of sensible cooling. In contrast, the parallel configuration splits the chilled water flow, reducing residence time per coil. While parallel showed marginally higher cooling capacity at 50 Hz (1.545 kW vs 1.458 kW), the series arrangement maintained higher effectiveness and is therefore preferable where air temperature reduction is the priority.

The hybrid system is the most significant finding of this study. By using IEC as a pre-cooling stage, the VCRS compressor operates against a reduced inlet temperature, improving its coefficient of performance. The resulting system EER of 3.9 surpassing the conventional 5-star AC benchmark of 3.3 confirms that a carefully designed hybrid evaporative-refrigeration system can outperform conventional systems while simultaneously reducing synthetic refrigerant consumption. For practical deployment, the system can be configured seasonally: DEC for dry summer months, IEC for humid months, and hybrid for peak summer heat.

5. CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

In this study, an all-season eco-friendly air conditioning system integrating winter heating, direct evaporative cooling (DEC), indirect evaporative cooling (IEC), and a hybrid cooling system was successfully designed and experimentally evaluated. The system demonstrated the capability to provide both heating and cooling under varying environmental conditions with improved energy efficiency and reduced environmental impact.

The winter heating system achieved a maximum heating capacity of 3461 W at 50 Hz and a peak EER of 34.32 at 30 Hz, powered entirely by solar PV energy. The DEC system achieved the highest cooling efficiency with a maximum cooling capacity of approximately 12.19 kW and an EER of approximately 68, though its applicability is limited by increased humidity levels in the outlet air.

The IEC system provided effective sensible cooling without any moisture addition. Among the three configurations, the series dual-coil arrangement delivered the best thermal effectiveness (0.73 at 20 Hz) and achieved an EER of 5.9 at 35 Hz, making it the recommended configuration for IEC applications. The hybrid cooling system, combining IEC with VCRS, demonstrated balanced and superior performance by overcoming the wet-bulb temperature limitation of standalone evaporative systems. It achieved a peak cooling capacity of 3.789 kW and an EER of 3.9 at 50 Hz, which surpasses the BEE 5-star conventional AC benchmark of approximately 3.3 under similar conditions.

Overall, the developed system offers a viable and sustainable alternative to conventional HVAC systems by integrating multiple eco-friendly techniques. The hybrid approach, in particular, provides an optimal balance between energy efficiency, cooling performance, and humidity control, making it suitable for year-round applications in the Indian subcontinental climate.

5.2 Future Scope

Although the developed system demonstrates promising performance, several improvements can enhance its practicality and efficiency. Future work may focus on developing a compact, integrated design suitable for commercial deployment. The use of alternative eco-friendly refrigerants such as R-290 (propane) or R-600a (isobutane) in place of R-22 in the hybrid system can further reduce the environmental footprint. Integration of advanced smart controllers with automated sensors can enable real-time monitoring and adaptive frequency control to maintain optimal EER at all times.

Scaling the system for commercial applications and conducting long-term performance analysis under seasonal climatic variations will provide deeper insight into practical feasibility. Additionally, incorporating a complete solar photovoltaic system to power the FCU, pumps, and VFD would make the entire platform energy-independent, further advancing its sustainability credentials.

6. REFERENCES

- [1] O. Amer, R. Boukhanouf, and H. G. Ibrahim, "A Review of Evaporative Cooling Technologies," *Int. J. Environ. Sci. Dev.*, vol. 6, no. 2, pp. 111–117, Feb. 2015.
- [2] Y. Yang, G. Cui, and C. Q. Lan, "Developments in evaporative cooling and enhanced evaporative cooling — A review," *Renewable and Sustainable Energy Reviews*, vol. 113, 109230, 2019.
- [3] H. Caliskan, I. Dincer, and A. Hepbasli, "A comparative study on energetic, exergetic and environmental performance assessments of novel M-Cycle based air coolers for buildings," *Energy Convers. Manage.*, vol. 56, pp. 69–79, 2012.
- [4] Q. Chen, M. Burhan, M. Kum Ja, M. W. Shahzad, D. Ybyraiymkul, H. Zheng, X. Cui, and K. C. Ng, "A hybrid indirect evaporative cooling-mechanical vapor compression process for energy-efficient air conditioning," *Energy Convers. Manage.*, vol. 248, p. 114798, 2021.
- [5] H. Caliskan, A. Hepbasli, I. Dincer, and V. Maisotsenko, "Thermodynamic performance assessment of a novel air cooling cycle: Maisotsenko cycle," *Int. J. Refrig.*, vol. 34, no. 4, pp. 980–990, 2011.
- [6] S. Anisimov, D. Pandelidis, and J. Danielewicz, "Numerical study and optimization of the combined indirect evaporative air cooler for air-conditioning systems," *Energy*, vol. 80, pp. 452–464, 2015.
- [7] ASHRAE, *Fundamentals Handbook*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, USA, 2021.