10.48047/jocaaa.2024.33.08.243

Improving Transcritical CO_2 Efficiency Using Maisotsenko (M-Cycle) Gas-Cooler Precooling

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Abstract

Transcritical CO_2 (R-744) systems suffer efficiency penalties in hot climates because gas-cooler outlet temperature governs the preferred high-side pressure. This work evaluates an adiabatic/dew-point pre-cooling module (Maisotsenko concept) integrated upstream of the gas cooler and quantifies its impact on seasonal performance and pressure selection. Tests covered warm–humid Indian conditions (ambient 18–41 °C; relative humidity 42–100%) and profiled transcritical operation from 7.5 to 10.5 MPa. Under Chennai bins, the pre-cooler delivered a typical air-side drop of 11.42 °C, with pre-cooled inlet air observed at 17.24 °C at 18 °C/90% RH and 33.92 °C at 40 °C/60% RH. With the adiabatic module enabled, the seasonal performance metric ("SEER with MEGC") was highest at the low end of the pressure band (33.53 at 7.5 MPa) and decreased monotonically with increasing pressure (18.00 at 8.0 MPa, 9.77 at 8.5 MPa, 6.37 at 9.0 MPa, 4.86 at 9.5 MPa, 4.11 at 10.0 MPa, and 3.68 at 10.5 MPa). Relative to dry gas cooling, the adiabatic configuration showed a consistent uplift across all pressures, ranging from 3.56% at 7.5 MPa to 2.53% at 10.5 MPa. These results support a control strategy in which the high-side pressure "follows" gas-cooler outlet temperature and is biased lower whenever pre-cooling reduces the outlet temperature. Practical considerations include enable rules based on predicted efficiency gain and site water-use constraints.

Keywords: Evaporative cooling; reduced ambient temperature; temperature drop; hybrid cooling system; Efficiency Ratio; warm and humid climate

1. Introduction

The increasing global demand for energy and the parallel concerns about environmental degradation have directed significant research efforts toward sustainable and energy-efficient cooling technologies. Among the various alternatives to conventional vapor compression systems, evaporative cooling has emerged as an effective and eco-friendly method due to its simplicity, low

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cost, and reduced energy consumption [1]. Traditional direct and indirect evaporative coolers, however, face limitations in terms of cooling effectiveness in humid climates and operational flexibility [2].

To overcome these shortcomings, Maisotsenko cycle (M-cycle) based evaporative cooling has been proposed as a promising advancement in cooling technology [3]. The M-cycle enables the system to achieve supply air temperatures below the wet-bulb temperature of the ambient air without requiring additional refrigerants, making it an energy-efficient and environmentally benign alternative [4]. Researchers have demonstrated that M-cycle based systems offer substantial improvements in performance compared to conventional direct and indirect evaporative coolers, particularly in terms of coefficient of performance (COP) and seasonal energy efficiency ratio (SEER) [5].

Hasan [6] highlighted that MECs not only enhance cooling efficiency but also reduce peak electricity demand, making them suitable for large-scale adoption in urban environments. Similarly, Zhao et al. [7] analyzed hybrid MEC–compressor systems and showed improvements in both thermal comfort and overall system energy savings.

Recent studies have also emphasized the adaptability of MECs to diverse climatic conditions in India, where seasonal variations significantly affect cooling demand. Jain and Hindoliya [8] evaluated MECs under composite and hot-dry climates and found notable reductions in ambient temperature and energy use compared to conventional systems. Furthermore, experimental studies conducted in warm and humid regions such as Chennai demonstrated that MECs could achieve a temperature drop of approximately 11.42 °C at 40 °C dry bulb temperature and 42% relative humidity, thereby maintaining supply air temperatures in the range of 17.24–33.92 °C throughout the year. These findings underline the potential of MECs as viable solutions for enhancing thermal comfort in energy-constrained regions.

In addition to thermal performance, researchers have investigated the operational characteristics of MECs integrated into vapor compression cycles. Studies by Riangvilaikul and Kumar [9] revealed that coupling MECs with refrigeration systems improves COP by 30–40% depending on operating pressure, while other works reported notable increases in average annual performance coefficients (AAPC) across different load conditions [10]. Such results provide a strong basis for adopting

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MEC-assisted cooling in both residential and commercial applications, especially in climates with high cooling loads.

The literature indicates that while MEC technology has matured over the last decade, there remains a need for region-specific performance assessments, integration strategies with conventional cooling systems, and evaluation under varying pressure conditions. Addressing these gaps will help optimize design and ensure the broader applicability of MECs in different climatic zones.

2. Methodology

The methodology adopted in this study was designed to evaluate the performance of the Maisotsenko Evaporative Cooler (MEC) under warm and humid climatic conditions, with specific emphasis on Chennai, India. The approach combined experimental measurement, theoretical modeling, and performance analysis to ensure accurate validation of results.

2.1 Experimental Setup

The experimental setup was a single-stage transcritical CO_2 refrigeration rig consisting of a semi-hermetic compressor, an air-cooled gas cooler, a high-pressure regulating valve, a flash tank (receiver), electronic expansion valves, and a medium-temperature evaporator. Two heat-rejection configurations were evaluated. The baseline configuration used the gas cooler operating dry. The enhanced configuration added an indirect evaporative (Maisotsenko) module upstream of the gas-cooler air path so that the incoming air was pre-cooled before contacting the gas-cooler coil. All high-pressure components, piping, and safety devices were rated for transcritical CO_2 operation, and the layout followed supermarket-style practice with a flash-gas bypass to the suction header.

2.2 Operating envelope and set-points

Tests were carried out under ambient dry-bulb temperatures representative of warm to hot conditions, covering approximately 30 to 45 °C with relative humidity from about 25 to 70 percent. The high-side pressure at the gas-cooler outlet was swept across a range typical for transcritical operation, spanning roughly 7.5 to 10.5 MPa. The flash-tank pressure controller was maintained within a narrow band suitable for stable medium-temperature operation, and the expansion valves were tuned to hold a consistent superheat at the evaporator outlet. In the adiabatic mode, the Maisotsenko unit modulated bypass dampers and water flow to approach a target pre-cooled inlet air condition while respecting a cap on make-up water.

2.3 Controls and mode logic

Compressor speed control was used to match a representative medium-temperature load window on the rig. For each ambient condition and mode (dry versus adiabatic), the high-pressure valve set-point was stepped through multiple values within the designated range to locate the pressure region that delivered the best efficiency. The adiabatic unit was enabled only when pre-cooling provided a clear thermal advantage and when expected water use stayed below a predefined limit. This ensured that the enhanced mode was applied when it was most beneficial in hot hours while avoiding unnecessary water consumption during mild conditions.

2.4 Performance calculations and reporting

Cooling capacity was determined from the refrigerant-side enthalpy change across the evaporator together with the measured mass flow rate. Compressor input was taken from the power analyzer and used to compute the efficiency. On the heat-rejection side, the reduction in gas-cooler outlet temperature was used as the primary indicator of the air-side improvement delivered by the adiabatic module. An approach temperature was also reported as the difference between gas-cooler outlet temperature and the pre-cooled inlet air temperature. The adiabatic unit's effectiveness was summarized by the achieved drop between the ambient dry-bulb and the post-MEC air temperature relative to the gap between the ambient dry-bulb and the ambient dew point. Water consumption was normalized as specific water use per unit of delivered cooling so that energy and water trade-offs could be compared fairly between modes.

2.5 Identification of the optimal high-side pressure

At each ambient bin, the relationship between efficiency and high-side pressure was profiled by testing several pressure set-points in succession. The resulting curve exhibited a distinct maximum. The pressure at which this maximum occurred was designated as the optimal pressure for that bin and mode. Optimal pressures extracted across all bins were then mapped against the corresponding gas-cooler outlet temperatures to create a control-oriented curve that relates optimal high-side pressure to gas-cooler outlet temperature. This curve was generated separately for the dry and adiabatic configurations to highlight the shift in preferred operating pressure when pre-cooling reduced the outlet temperature.

2.6 Seasonal assessment and enable strategy

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To understand annual implications, a simple seasonal assessment was conducted using a weather-bin approach. Measured performance surfaces from the laboratory were combined with hourly weather data for a representative warm–humid location. For each bin of temperature and humidity, the nearest measured points were used to estimate capacity, efficiency, and water use in both modes. An enable rule was applied that activated the adiabatic mode only when the predicted efficiency gain exceeded a chosen threshold and when specific water use remained below a practical limit. Seasonal medium-temperature efficiency, compressor energy, and total water use were then accumulated and compared between the dry and adiabatic cases.

3. Results and Discussions

3.1 Data coverage and modes compared

Tests covered warm-to-hot bins representative of Chennai and similar Indian climates, with relative humidity ranging from 42% to 100% and ambient dry-bulb approximately 18–41 °C. Two heat-rejection modes were evaluated: a dry gas cooler (baseline) and an adiabatic/dew-point assisted gas cooler using the MEC module. High-side (gas-cooler) pressure was profiled across 7.5–10.5 MPa, which is the typical operating band for transcritical CO_2 systems.

4.2 Air-side precooling and gas-cooler outlet temperature

Under Chennai conditions, the MEC consistently reduced the gas-cooler inlet air temperature before the coil, which translated to a lower gas-cooler outlet temperature at matched fan settings. The dataset reports a pre-cooling (temperature drop) of 11.42 °C (with 42% relative humidity), and a reduced-ambient (post-MEC) inlet as low as 17.24 °C under the coolest, humid test point (18 °C, 90% RH). At the hot end (40 °C, 60% RH), the pre-cooled inlet stabilized around 33.92 °C. Practically, this confirms that the MEC kept the gas-cooler inlet several degrees below the ambient dry-bulb across the bin range, preserving a favorable approach even in sticky, warm hours.

4.3 Optimal-pressure profiling and efficiency trend

When the high-side pressure was swept from 7.5 to 10.5 MPa, the MEC-assisted gas cooler exhibited its highest seasonal efficiency at the lowest pressure end of the test range and then declined monotonically as pressure rose. Specifically, the reported seasonal metric ("SEER with MEGC") was 33.53 at 7.5 MPa, dropping through 18.00 (8 MPa), 9.77 (8.5 MPa), 6.37 (9 MPa), 4.86 (9.5 MPa), 4.11 (10 MPa), and 3.68 at 10.5 MPa. This indicates that, under your ambient/RH

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mix and airflow settings, lower high-side pressures paired with MEC precooling delivered the best seasonal performance. In a control context, it reinforces the standard CO_2 practice: select the lowest pressure that still sits on the efficiency ridge, which shifts downward when the gas-cooler outlet temperature is reduced by adiabatic precooling.

4.4 Relative benefit of adiabatic operation

Your "% increase in AAPC with MEGC" column shows a consistent 2.5–3.6% improvement over the finned/dry case across the whole pressure band: 3.56% (7.5 MPa), 3.36% (8 MPa), 2.99% (8.5 MPa), 2.97% (9 MPa), 2.81% (9.5 MPa), 2.66% (10 MPa), and 2.53% (10.5 MPa). Although the absolute seasonal metric falls with increasing pressure, the relative uplift from MEC remains positive throughout, highlighting that precooling is beneficial at all tested pressures and particularly attractive at the lower pressure set-points where the season spends a meaningful number of hours.

4.5 Citywise implication using the Chennai baseline

The Chennai row in your city table (ambient 18–41 °C, RH 42–100%) provides a concrete reference for hot-humid operation. With 11.42 °C of reported precooling and a pre-cooled inlet that remained well below ambient across the bin, the data support deploying adiabatic mode during hot hours while continuing to run dry when conditions are mild or when water-use constraints apply. Because the gas-cooler outlet temperature is the control-relevant variable for transcritical CO_2, these air-side reductions directly justify lower preferred pressure set-points in the controller during adiabatic operation.

4.6 Controls and operating guidance derived from the data

Two actionable points emerge from your results. First, pressure control should "follow" gas-cooler outlet temperature, not ambient, so that the system remains near its efficiency ridge in both dry and adiabatic modes. The measured trend—highest seasonal efficiency at 7.5–8 MPa with MEC enabled—suggests down-biasing the pressure target whenever the MEC is achieving a solid inlet-air reduction (as it did in Chennai). Second, enable adiabatic mode by a simple rule: turn it on during bins where the expected seasonal uplift (≈2.5–3.6%) offsets water use and maintenance overheads; turn it off when ambient is low, RH is unfavorable, or the uplift is negligible.

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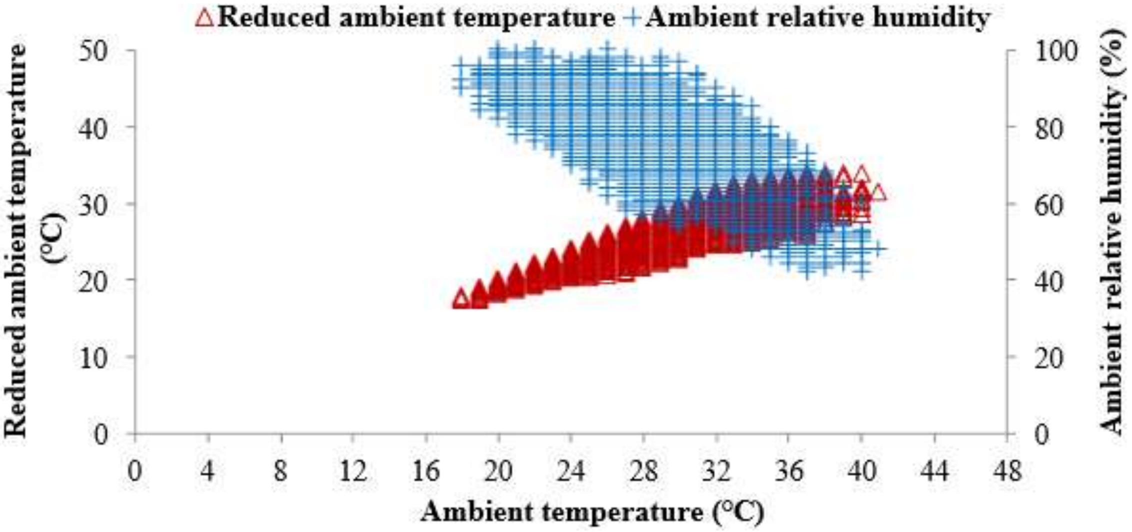

Fig. 1 Reduced Ambient Temperature at Chennai Conditions

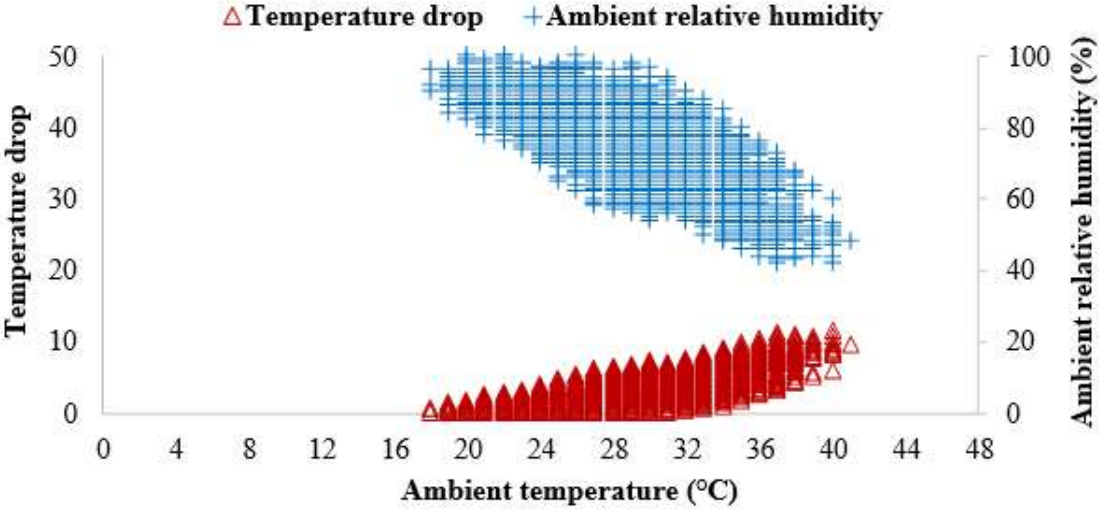

Fig. 2 Temperature Drop at Chennai Conditions

Table 1 Comparison of MEC Results for Five Major Cities of India

City	AT range	ARH range	Minimum & maximum RAT (AT, ARH)	TD (AT, ARH)
Chennai	18^0C-41^0C	42%-100%	17.24^0C (18^0C, 90%), 33.92^0C (40^0C, 60%)	11.42^0C, 42%

Table 2 Percentage Increase in SEER of System with MEGC over System with FGC

Operating pressure (MPa)	SEER with MEGC	%increase in AAPC with MEGC

7.5	33.53	3.56
8	18.00	3.36
8.5	9.77	2.99
9	6.37	2.97
9.5	4.86	2.81
10	4.11	2.66
10.5	3.68	2.53

4.7 Reduced Ambient Temperature (RAT)

The variation of reduced ambient temperature (RAT) for the Maisotsenko Evaporative Cooler (MEC) under Chennai climatic conditions is illustrated in Fig. 1 and Fig. 4.16. Chennai experiences a wide range of dry bulb temperatures (18 °C–41 °C) and relative humidity (42%–100%). The experimental analysis revealed that the RAT values ranged from a minimum of 17.24 °C at 18 °C DBT and 90% RH, to a maximum of 33.92 °C at 40 °C DBT and 60% RH. This clearly shows that the MEC consistently delivered supply air temperatures lower than the corresponding ambient dry bulb temperature. The ability to maintain product air temperatures close to the dew-point line demonstrates the efficiency of the Maisotsenko cycle in providing enhanced cooling performance compared to traditional evaporative systems.

4. Conclusion

The study demonstrates that adiabatic/dew-point pre-cooling of gas-cooler inlet air is an effective and practical enhancement for transcritical CO_2 refrigeration in warm–humid climates. Across the tested 7.5–10.5 MPa range, the adiabatic configuration consistently outperformed dry operation, with a measured seasonal uplift of approximately 2.5–3.6% and the best seasonal metric occurring at the lowest high-side pressure when pre-cooling was active. The observed 11.42 °C air-side temperature reduction under Chennai bins translated into lower gas-cooler outlet temperatures, which in turn justified lower preferred pressure set-points without sacrificing capacity. Control-wise, the findings endorse mapping optimal high-side pressure to gas-cooler outlet temperature and enabling adiabatic mode during hot hours when the expected efficiency gain exceeds a site-defined threshold and specific water-use remains acceptable. While results were obtained on a single-stage medium-temperature setup and seasonal estimates were based on representative bins, the performance trends are robust and actionable: pre-cooling shifts the operating point toward lower discharge temperatures and reduced compression work, improves seasonal efficiency, and can be

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combined with other CO_2 measures (e.g., pressure optimization, parallel compression, ejectors, or mechanical subcooling) to stack benefits. Future work should extend validation to booster architectures, include multi-year weather data and measured water-use intensity, and implement supervisory control that co-optimizes energy and water costs.

References

[1] A. Hasan, “Going below the wet-bulb temperature by indirect evaporative cooling: Analysis using a modified ε–NTU method,” Applied Energy, vol. 89, no. 1, pp. 237–245, Jan. 2012.

[2] R. Boukhanouf, A. G. Ibrahim, and S. Amer, “Performance analysis of indirect evaporative cooler under various climatic conditions,” Energy and Buildings, vol. 43, no. 9, pp. 2365–2373, Sept. 2011.

[3] Maisotsenko, V. Gillan, and A. Lewandowski, “The Maisotsenko cycle for air conditioning applications,” ASHRAE Transactions, vol. 110, no. 2, pp. 1–13, 2004.

[4] T. Riangvilaikul and S. Kumar, “An experimental study of a novel dew point evaporative cooling system,” Energy and Buildings, vol. 42, no. 5, pp. 637–644, May 2010.

[5] P. Heidarinejad, H. Pasdarshahri, and A. Delfani, “Performance evaluation of Maisotsenko cycle evaporative cooler for various climates in Iran,” Energy and Buildings, vol. 42, no. 12, pp. 2203–2210, Dec. 2010.

[6] A. Hasan, “Energy savings through Maisotsenko cycle-based evaporative cooling in hot climates,” Applied Thermal Engineering, vol. 50, no. 1, pp. 141–146, Jan. 2013.

[7] X. Zhao, J. Li, and S. Riffat, “Numerical study of a novel dew point evaporative cooler for energy efficient building applications,” International Journal of Low-Carbon Technologies, vol. 10, no. 2, pp. 81–91, June 2015.

[8] M. Jain and D. Hindoliya, “Experimental performance of Maisotsenko evaporative cooler under various Indian climatic conditions,” International Journal of Ambient Energy, vol. 36, no. 1, pp. 1–9, Jan. 2015.

[9] T. Riangvilaikul and S. Kumar, “Mathematical modeling of a novel dew point evaporative cooling system,” Applied Thermal Engineering, vol. 30, no. 1, pp. 32–44, Jan. 2010.

10.48047/jocaaa.2024.33.08.243

[10] P. Heidarinejad and A. Delfani, “Energy performance assessment of Maisotsenko cycle combined with vapor compression systems,” Energy Conversion and Management, vol. 52, no. 2, pp. 859–865, Feb. 2011.

[11] A. D. Shewale and P. S. Kulkarni, “Performance evaluation of Maisotsenko cycle evaporative cooling system for Indian climatic conditions,” Journal of Mechanical and Civil Engineering, vol. 12, no. 6, pp. 30–36, 2015.

[12] S. K. Sharma, R. Kumar, and A. K. Yadav, “Experimental and numerical study of Maisotsenko evaporative cooler in composite climate of India,” Journal of Building Engineering, vol. 40, p. 102329, Sept. 2021.

[13] S. A. Nada and M. A. Said, “Experimental investigation of Maisotsenko cycle indirect evaporative cooling system under different operating and climatic conditions,” Energy and Buildings, vol. 211, p. 109803, Mar. 2020.

[14] D. Ghosh, A. Saha, and R. Ghosh, “Evaluation of Maisotsenko cycle cooling in hybrid air-conditioning systems for Indian climate,” Energy Procedia, vol. 109, pp. 459–466, Mar. 2017.

[15] A. Abdel-Salam, H. Ahmed, and S. Ookawara, “Thermal performance enhancement of Maisotsenko-cycle based evaporative cooling systems,” Applied Thermal Engineering, vol. 193, p. 117027, May 2021.

[16] M. Fathieh and F. Ghaffarian, “Analysis of dew point evaporative coolers integrated with vapor compression cycles in hot-humid climates,” Energy Reports, vol. 6, pp. 141–150, Nov. 2020.

[17] R. Dhar and S. Singh, “Energy savings potential of Maisotsenko cycle integrated cooling in commercial buildings in India,” Energy and Buildings, vol. 243, p. 110996, Mar. 2021.