Yue J, Zeng C, Wang Z, et al. Performance evaluation of an energy-efficient oscillating air-conditioning dehumidification system through experimental testing and numerical modelling. Building Services Engineering Research & Technology. DOI: 10.1177/01436244251333135.

Performance Evaluation of an Energy-Efficient Oscillating Air-Conditioning Dehumidification System through Experimental Testing and Numerical Modelling

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Abstract

This study examines the performance of a new oscillating air-conditioning dehumidification system, designed to overcome the limitations of traditional methods, such as energy-intensive defrost cycles and inconsistent dehumidification in high-humidity conditions. Experimental tests demonstrate that the system achieves a dew point as low as -9.38 °C with specific humidity reaching to 1.67 g/kg and coefficient of performance (COP) ranging from 3.3 to 4.7. Apart from testing, numerical modelling of the system has been built in TRNSYS and validated using experimental data. A validated TRNSYS model was used to extend the analysis across various climate zones, revealing that the system performs optimally in high-humidity regions like Hong Kong and Chongqing, with an annual average COP of 3.89 in Hong Kong. In contrast, colder and drier regions like Urumqi maintained lower but stable energy efficiency, with an annual average COP of 2.30. These findings suggest that the oscillating air-conditioning dehumidification system offers versatile, climate-adaptable operation with potential applications in diverse building types.

Practical Application

This study's findings offer built environment professionals an air-conditioning dehumidification solution suited to diverse climate conditions. The oscillating air-conditioning system, with its continuous dehumidification capability and optimised energy efficiency with COP of 3.89 in high-humidity regions, provides an approach for deep dehumidification in demanding environments. By reducing reliance on energy-intensive defrost cycles, this system is ideal for applications in commercial and industrial settings, such as healthcare facilities and battery manufacturing centres, where precise humidity control is critical.

Keywords: Oscillating air-conditioning, Deep dehumidification, Experimental test, Simulation

Nomenclature

COP	Coefficient of Performance
Q_r	Refrigerant side heat transfer (kJ)
m_r	Mass flow rate of refrigerant (kg/s)
c_r	Average specific heat of refrigerant (kJ/kg·K)
h_{r1}	Enthalpy at the inlet of refrigerant (kJ/kg)
h_{r2}	Enthalpy at the outlet of refrigerant (kJ/kg)
t_1	Fluid inlet temperature (°C)
t_2	Fluid outlet temperature (°C)
Q_{air}	Air side heat transfer (kJ)
m_{air}	Mass flow rate of air (kg/s)
h_{air1}	Enthalpy of air at the inlet (kJ/kg)
h_{air2}	Enthalpy of air at the outlet (kJ/kg)
ε	moisture extraction coefficient
C_p	Specific heat capacity of air (kJ/kg·K)
r	Heat loss coefficient
p_1	Pressure at the inlet of the micro-element (Pa)
p_2	Pressure at the outlet of the micro-element (Pa)
G_r	Mass flow rate of refrigerant (kg/s)
f	Friction factor
ρ	Density of the liquid phase (kg/m^3)
L	Length of the micro-element (m)
K	Overall heat transfer coefficient (W/m^2·K)
A	Heat transfer area (m^2)
Δt_m	Mean effective temperature difference (°C)
t_k	Condensing temperature (°C)
Q_w	Cooling water heat transfer amount (kJ)
m_w	Mass flow rate of cooling water (kg/s)
c_w	Specific heat capacity of cooling water (kJ/kg·K)
h_{w1}	Enthalpy at the inlet of cooling water (kJ/kg)
h_{w2}	Enthalpy at the outlet of cooling water (kJ/kg)
C_v	Flow coefficient
A_v	Flow area of the throttle valve (m^2)
P_1	Refrigerant pressure at the inlet (Pa)
P_2	Refrigerant pressure at the outlet (Pa)
h_{in}	Enthalpy of the refrigerant at the inlet of the throttling valve (kJ/kg)
h_{out}	Enthalpy of the refrigerant at the outlet of the throttling valve (kJ/kg)

1. Introduction

1.1 Overview of air-conditioning dehumidification methods

The global energy crisis has intensified in recent years, with the building sector emerging as one of the primary contributors to energy consumption worldwide. Approximately 40% of total global energy demand is attributed to buildings. Among the systems that contribute to this high energy demand, Heating, Ventilation, and Air Conditioning (HVAC) systems play a pivotal role, often accounting for more than half of the energy consumed within buildings.[1] Within HVAC operations, air-conditioning dehumidification stands out as a critical but energy-intensive process, especially in regions with high humidity.[2] Enhancing the efficiency of dehumidification will, therefore, provide substantial energy savings, making the development of improved dehumidification methods a priority to reduce building-related energy demand.

The core mechanism of air-conditioning dehumidification technologies relies on the molecular driving force of vapour pressure difference to facilitate moisture removal. Dehumidification technology, classified in Figure 1, has evolved to meet the growing demand for efficient moisture control in diverse environments. Conventional methods, including cooling dehumidification, liquid absorption, and solid adsorption, have long served as industry standards but exhibit notable limitations.

[insert Figure 1.]

Figure 1 Dehumidification methods

In cooling dehumidification, humid air is directed across a cooled surface, where water vapor condenses due to a vapour pressure differential between the air and the cold surface. While effective, this method suffers from frost formation at lower temperatures and requires frequent defrosting, reducing its energy efficiency and limiting its capacity for deep dehumidification.[3] Liquid dehumidification employs hygroscopic solutions to absorb moisture through a similar vapour pressure gradient. Although this process is stable, it demands energy-intensive regeneration of the absorbent, restricting its scalability.[4] Solid adsorption systems, such as desiccant wheels, attract moisture through physical or chemical bonding, leveraging the vapour pressure difference between the desiccant and the air. However, they face issues of high energy use for regeneration and airflow resistance, making them costly for continuous operation.[5]

Recent innovative dehumidification technologies have sought to address these limitations. Membrane-based dehumidification, for example, selectively filters water vapour from air through a membrane. However, the membrane performance can degrade over time, limiting long-term effectiveness.[6] Thermoelectric condensation utilises the thermoelectric effect to create a temperature gradient, condensing water vapour on a cold surface without conventional refrigerants.[7] Although compact, this method has a relatively low Coefficient of Performance (COP), making it less suitable for large-scale applications.[8] Electrochemical dehumidification is an emerging approach that uses an electric current to remove water vapour at the molecular level.[9] This technique avoids cooling altogether but is more suitable for small-scale control environments.[10]

1.2 Air-conditioning for deep dehumidification and research gap

While various air-conditioning dehumidification methods provide moisture control for domestic and non-domestic environments, achieving deep dehumidification levels for specialised applications presents challenges. For buildings, the ASHRAE Standard 55–2017 recommends a humidity ratio in the comfort zone not exceeding 12.0 g/kg. The widely used vapour compression dehumidification, with a typical chilled water at 7.0 °C, could achieve a humidity threshold of 6.2 g/kg.[11] However, a humidity level below 6.0 g/kg is required in a series of specific environments, such as pharmaceutical manufacturing and storage, lithium-ion battery production, and air compression.[12]

Achieving deep dehumidification below 6.0 g/kg with conventional and advanced air conditioning remains challenging. The existing cooling units struggle to maintain a low dew point without excessive energy use, as deeper dehumidification requires substantial temperature reductions, often leading to frost formation and requiring frequent defrost cycles.[13] This frost reduces cooling efficiency, interrupting the dehumidification process and adding on energy consumption for defrost. To address these limitations, advanced cooling methods have been studied in the academic community, such as multi-stage cooling systems and hybrid configurations with liquid desiccants, as summarised in Table 1. Studies have shown that multi-stage dehumidification systems, such as those incorporating calcium chloride and lithium bromide solutions, can reduce humidity to below 6.0 g/kg. However, they are complex in system design and face operational interruptions due to the need for periodic heat-induced desiccant regeneration. These challenges create significant barriers to achieving continuous, efficient deep dehumidification in high-demand applications. Current methods struggle to maintain sustained performance without interruptions for defrosting or regeneration.

Table 1 Summary of recent studies in deep dehumidification

Dehumidification system descriptions	**Dehumidification achieved**	**Energy performance or Coefficient of Performance (COP)**	**Challenges**	**Year of Publication**	**Study types**
Solar PV/T + condensing cooling + liquid desiccant	From 19/kg to 6 g/kg	n/a	• Complex system integration	2018	Numerical study [14]
Condensing cooling + liquid desiccant	From 20 g/kg to 3.6 g/kg	System COP 2.4 to 3.3	• Desiccant regeneration intermittent dehumidification • Complex maintenance requirements	2019, 2020	Experimental testing, numerical study [15, 16]
Condensing cooling + liquid desiccant	From 12/kg to 5 g/kg	System COP 0.5 to 1.1	• Complex integration of chiller and desiccant systems	2019	Numerical study [17]
Condensing cooling + liquid desiccant	From 10/kg to 5 g/kg	System COP 1.9	• Requiring optimisation of desiccant flows and chilled water allocation	2022	Experimental testing, numerical study [12]
Liquid desiccant reactor	From 6 g/kg to 1.1 g/kg	n/a	• Requires advanced desiccant materials	2023	Experimental testing [18]
Solid desiccant fin-pipe heat exchanger	From 6 g/kg to 0.4 g/kg	System COP < 1	• Desiccant regeneration intermittent dehumidification	2024	Experimental testing [19]

1.3 Innovations of oscillating air-conditioning dehumidification system

Within this context, the authors developed a novel oscillating air-conditioning dehumidification system. The system introduces a solution for achieving deep dehumidification air-conditioning of humidity ratio below 6.0 g/kg, by employing an alternating dual-evaporator design that cycles between dehumidification and passive defrost modes. This configuration overcomes limitations in existing methods, such as energy-intensive desiccant regeneration in hybrid systems and frost accumulation in cooling-based methods, which typically interrupt dehumidification processes. Preliminary feasibility studies have confirmed its potential, leading to an approved patent (CN 116906995 A). However, further in-depth analysis is needed to fully understand its performance under varied environmental conditions and assess its energy efficiency, which this paper addresses through experimental and numerical evaluations.

2. System descriptions

The oscillating air-conditioning dehumidification system operates by alternating between refrigeration cycles for dehumidification and defrost to achieve continuous moisture removal at low humidity levels. As shown in Figure 2, the system utilises two evaporators: one actively engaged in dehumidifying the air, while the other undergoes a defrosting process. When frost accumulates on the primary evaporator, the system redirects airflow to the secondary evaporator, allowing the primary one to defrost naturally through residual heat dissipation. This system configuration enables two setup: (1) single-stage oscillating dehumidification and (2) two-stage oscillating dehumidification. The single-stage oscillating dehumidification involves a single evaporator unit alternately switching between dehumidification and defrost modes. When frost begins to form, airflow is redirected to another coil, allowing passive defrosting of the frosted unit. On the other hand, the two-stage oscillating dehumidification enhances this process by using two evaporators in sequence, providing an additional dehumidification stage. In this setup, both evaporators switch synchronously between dehumidification and defrost cycles, allowing deeper moisture removal. The two-stage design is ideal for achieving low humidity levels in high-demand settings, as it combines staged cooling with oscillating airflow. This oscillating mechanism maintains uninterrupted dehumidification and enhances energy efficiency by eliminating the need for active defrosting, which is a common limitation in conventional cooling systems.

[insert Figure 2.]

Figure 2 Oscillating air-conditioning dehumidification system illustration

The pressure-enthalpy diagrams and the corresponding system schematic for single-stage and two-stage oscillating dehumidification are shown in Figure 3. The single-stage cycle begins with the refrigerant undergoing compression (1-2), followed by a slight pressure and temperature drop due to discharge losses (2-2'). In the condenser (2-3), the refrigerant cools and condenses to a high-pressure liquid. It then passes through the expansion valve (3-4). Next, in the evaporator (4-5), the refrigerant absorbs heat and evaporates. Afterward, it enters a subcooler (5-6), gaining slight temperature before superheating in the suction line (6-6') and returning to the starting point (6'-1). The two-stage cycle begins with 1-3, which similar to the single-stage cycle, representing compression and condensation of the refrigerant. Process 3-4 involves throttling, followed by Process 4-5, where the refrigerant subcools and defrosts. Another throttling occurs in Process 5-5', with heat absorption in Process 5'-6. Finally, the refrigerant superheats (6-6') and completes the cycle at 6'-1.

[insert Figure 3.]

Figure 3 Single-stage and two-stage oscillating dehumidification pressure-enthalpy diagram and system schematics

3. Experimental testing setup and results

Experimental testing for the oscillating air-conditioning dehumidification system have been conducted in June 2024 at Chongqing University to assess its performance under controlled environmental conditions. Figure 4 shows the experimental testing setup. The test chamber is equipped with adjustable parameters for temperature and humidity, creating an environment of air temperature 25 °C and humidity ratio 13 g/kg to benchmark testing environment. Temperature and humidity sensors with accuracies of ±0.8 °C and ±2% were strategically placed at the evaporator inlets and outlets to monitor conditions before and after dehumidification. Pressure transducers with an accuracy of ±2 Pa measured airflow resistance across the evaporators. A variable-speed compressor and expansion valves regulated the refrigerant cycle, adjusting pressures as required to achieve optimal dehumidification levels.

[insert Figure 4.]

Figure 4 Schematic of the experiment testing setup

A series of tests were conducted to evaluate the performance of the air-conditioning dehumidification system under different operational setups. The testing conditions included variations in pre-cooling functionality, oscillation stages, airflow rates set at 800 m^3/h and 1200 ^{3}/h, and oscillation cycles of 10 minutes, with results tabulated in Table 2. For test 2, Figure 5 shows the change of air temperature, humidity and system power consumption when pre-cool enabled with inlet air flow rate of 800 m^3/h. This condition utilises a single-stage oscillating process, engaging only one evaporator for moisture removal. The pre-cooling helps lower the air’s initial temperature, thereby enhancing moisture removal efficiency in the dehumidification stage, which effectively reduced temperature from around 25 °C to -15 °C, while decreasing humidity, from approximately 12.5 g/kg to 2.3 g/kg. Power consumption remained stable, averaging around 3 kW. With the pre-cooling function turned off, the dehumidification system still demonstrated effective moisture control. As presented in Figure 6 (test 4), the system operates in two-stage oscillating dehumidification without pre-cooling with inlet air flow rate of 800 m^3/h, the temperature dropped steadily from about 25 °C to -10 °C, while moisture content decreased from 14.2 g/kg to approximately 1.8 g/kg.

From the experiment testing, the ocsiliation air-conditiong system show a superior energy efficiency performance over the other systems, with COP range from 2.31 to 4.67. Comparing to other air-conditioning dehumidification systems listed in Table 1, such as air conditioning integrated liquid desiccant dehumidifcaiton [15], the ocsiliation system shows an COP improvement of 41%, from COP of 3.3 to 4.67. Also the ocsiliation system can achieve an even lower humidity ratio down to 1.67 g/kg.

[insert Figure 5.]

Figure 5 Single-stage oscillating air-conditioning dehumidification with pre-cooling (test 2)

[insert Figure 6.]

Figure 6 Two-stage oscillating air-conditioning dehumidification without pre-cooling (test 4)

Table 2 Experiment testing results

	Test 1	**Test 2**	**Test 3**	**Test 4**
Preccoling	Yes	Yes	Yes	No
Single / Two stage	Two stage	Single stage	Single stage	Two stage
Air flow rate	800 m^3/h	800 m^3/h	1200 m^3/h	800 m^3/h
Dry-bulb Temperature (°C)	-8.08	-4.21	-2.70	-8.01
Humidity Ratio (g/kg)	1.67	2.31	2.99	1.80
Dew Point Temperature (°C)	-9.38	-5.33	-2.77	-8.06
Cooling Capacity (kW)	19.01	16.54	19.66	18.14
Dehumidification Capacity (g/kg)	12.52	10.21	7.10	11.51
Average Power (kW)	6.35	2.811	2.93	6.09
COP	2.31	4.25	4.67	2.45

4. Numerical modelling and validation

To extend the analysis beyond physical testing constraints, a TRNSYS numerical model was developed to simulate the performance of the oscillating air-conditioning system, with a focus on accurately replicating the dual-evaporator configuration and oscillating airflow mechanism. Customisations were made in TRNSYS using FORTRAN to model key components, including the evaporators, condensers, and expansion valves, allowing for an in-depth analysis of heat and mass transfer dynamics within the system, as shown in Figure 7.

The system is primarily governed by equations for mass and energy conservation and heat transfer, tabulated in Table 3. The list of abbreviation is attached.

Table 3 Critical governing equations for numerical model

Components	Descriptions	Equations
Evaporator / condenser	Heat transfer for the refrigerant	$Q_r = m_r(h_{r1} - h_{r2}) = m_r c_r(t_2 - t_1)$
	Heat transfer for the air	$Q_{air} = m_{air}(h_{air1} - h_{air2}) = \varepsilon m_{air} c_{air}(t_2 - t_1)$
	Air-refrigerant heat transfer	$Q_{air} = rQ_r$
	moisture extraction coefficient	$\varepsilon = \frac{h_{air1} - h_{air2}}{C_{pd}(t_1 - t_2)}$
	Refrigerant pressure drop	$\frac{p_1 - p_2}{L} = \frac{4fG_r^2}{\rho d_i} + \frac{G_r^2}{L}(\frac{1}{p_2} + \frac{1}{p_1})$
	Heat transfer for a heat exchanger	$Q = KA\Delta t_m$
	Mean effective temperature difference	$\Delta t_m = \frac{t_2 - t_1}{\ln(\frac{t_k - t_1}{t_k - t_2})}$
	Heat transfer for cooling water	$Q_w = m_w(h_{w1} - h_{w2}) = m_w c_w(t_2 - t_1)$
Throttle valve	Mass flow rate through the throttle valve	$m_r = C_v A_v \sqrt{2\rho(P_1 - P_2)}$
	Energy equation for the throttling valve	$h_{in} = h_{out}$

[insert Figure 7.]

Figure 7 Oscillating air-conditioning dehumidification TRNSYS model

Model validation was conducted by comparing TRNSYS simulation results with experimental data including temperature, moisture content, and energy consumption under identical operating conditions. As shown in Figure 8, the model demonstrated close alignment with experimental results, particularly in capturing temperature and humidity changes. Error ranges have also been calculated using Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) values. The MAE and RMSE for air temperature are 1.48 °C and 1.74 °C, respectively. For relative humidity, the model yielded an MAE of 6.95% and an RMSE of 0.18%, reflecting a good sensitivity in humidity predictions. Hourly power consumption shows a strong alignment with an MAE of 0.38 kW and an RMSE of 0.60 kW. During the validation process, the model has been refined using the parameters summarised in Table 4.

Minor discrepancies observed in energy usage were attributed to a list of reasons. For instance, the model was compiled with simplified assumptions during the mathematical modelling process, which are necessary to streamline the simulation, may introduce discrepancies. During experiments, uncertainties such as insufficient heat exchange in the heat exchanger and fluctuations in cooling water temperature can affect results. Finally, the TRNSYS simulation focuses on the core components of the dehumidification system rather than connecting sections, such as cooling water pipes and air ducts. These connections can lead to heat losses, which can contribute to additional discrepancies.

[insert Figure 8.]

Figure 8 Model validation by test-simulation comparisons (a) (b) test 2 and (c) (d) test 4

Table 4 Parameter settings in the TRNSYS model

Components	**Module Name**	**Parameter Settings**
Cooling Water Pump 1	Type 114	Flow rate: 1.2 m^3/h, Power: 1.1 kW
Cooling Water Pump 2	Type 114	Flow rate: 1.6 m^3/h, Power: 1.5 kW
Compressor	Type 167	Compressor outlet pressure: 4.88 bar
Fan	Type 662	Flow rate: 800 m^3/h, Power: 0.85 kW
Cooling Coil	Type 52b	Number of rows: 5, number of parallel tubes per row: 30 holes
Cooling Tower	Type 51b	Cooling tower settings: flow 1500 m^3/h, power 0.53 kW

5. Performance analysis of the oscillating air-conditioning dehumidification system in various climatic regions

Using the validated model, this study analyses the performance of the air-conditioning system across different climate regions to assess its adaptability and operational efficiency. With the aim to maximise dehumidification, simulations were conducted under pre-cooling, double-stage oscillation, an airflow rate of 800 m^3/h, and a 10-minute oscillation period (test 1 conditions) to maximise dehumidification and evaluate energy consumption across varying conditions. Selected cities representing different climate zones were analysed, including Urumqi (severe cold region), Beijing (cold region), Hong Kong (hot summer, warm winter), Chongqing (hot summer, cold winter), and Kunming (temperate region) (Figure 9).

[insert Figure 9.]

Figure 9 Climate of the typical regions

Figure 10 presents the achievable moisture content and the dew point temperature of the system under the varying climatic regions. Hong Kong and Chongqing, representing humid subtropical climates, show the highest moisture content, reaching nearly 4.5 g/kg during the peak summer period. This is due to high relative humidity and temperature during these months. Beijing and Kunming experience moderate moisture content levels, peaking around 2.5 g/kg to 3.5 g/kg. These cities have varying seasonal humidity but do not reach the extreme levels seen in Hong Kong and Chongqing. Urumqi, with its dry continental climate, consistently shows the lowest moisture content, remaining below 1.5 g/kg even at its peak in July. This low moisture profile reflects Urumqi's arid conditions. The corresponding dew point temperature also follows a seasonal trend across the regions, rising in the summer and falling in the winter, with significant regional differences. Urumqi has the lowest dew point temperatures with winter dew points dropping to -40 °C. This indicates minimal atmospheric moisture, consistent with its arid climate, requiring less intensive dehumidification. In summary, the data indicate that the oscillating dehumidification system is especially advantageous for high-dew-point regions like Hong Kong and Chongqing. By alternating between dehumidification and passive defrost cycles, the system efficiently handles high humidity loads, maintaining performance even in challenging climates.

[insert Figure 10.]

Figure 10 Output moisture content and dew point temperature of the air-conditioning system

Figure 11 shows the system's performance regarding cooling capacity and dehumidification capacity. Dehumidification capacity refers to the system's ability to remove moisture from the air, being crucial for assessing the effectiveness in managing humidity. With respect to cooling capacity, the annual cooling capacity varies significantly across cities, with higher demands in hot, humid regions. Hong Kong and Chongqing exhibit the highest average annual cooling capacities, peaking around 120 kW. Urumqi, located in a cold climate zone, has the lowest average annual cooling capacity, around 55.16 kW, with limited variation throughout the year. The dehumidification capacity also varies with climate. Hong Kong maintains the highest annual dehumidification capacity, averaging around 11.24 g/kg. Similarly, Chongqing follows closely, averaging 9.29 g/kg. The high dehumidification capacity in these humid regions underscores the system's suitability for environments with persistent moisture. In contrast, Urumqi has the lowest dehumidification demand, averaging only 3.61 g/kg annually, peaking at 6.72 g/kg in July. This lower demand is consistent with Urumqi's dry climate, where deep dehumidification is less critical. The oscillating dehumidification system is especially beneficial for high-humidity regions like Hong Kong and Chongqing, where continuous dehumidification is required.

[insert Figure 11.]

Figure 11 Cooling capacity and dehumidification capacity of the air-conditioning system

Figure 12 shows the corresponding monthly COP (coefficient of performance) value. Hong Kong has the highest and most variable COP, with an annual average of 3.89. The COP peaks at 4.78 in summer (June to August), while dropping to 2.90 in winter. This fluctuation reflects the system's ability to perform efficiently under high humidity, where the oscillating dehumidification mechanism maximises performance during peak demand. Chongqing shows a similar seasonal pattern. Beijing experiences the largest COP fluctuation, with an annual average of 2.72, peaking at 4.16 in summer and dropping to 1.86 in winter. The wide range of 2.3 is due to Beijing's substantial annual humidity variations. Urumqi and Kunming, both in relatively stable climates, have lower but more consistent COP values. Urumqi's annual average COP is 2.30 and Kunming shows slightly better stability, averaging a COP of 2.92. The data indicate that the oscillating dehumidification system performs optimally in hot and humid regions like Hong Kong and Chongqing, where the COP remains high during peak demand periods. However, in climates with lower humidity or more stable temperatures, such as Urumqi and Kunming, the system operates at a lower but steady efficiency.

[insert Figure 12.]

Figure 12 Monthly COP of the air-conditioning dehumidification system

Lastly, for the electricity consumption showing in Figure 13, Hong Kong records the highest annual electricity consumption at 482,526 kWh, driven by its high temperature and humidity throughout the year. Chongqing, another high-temperature, high-humidity region, follows closely with an annual consumption of 441,785 kWh. In Beijing and Urumqi, which experience lower annual humidity, contributing to its reduced energy usage. Kunming demonstrates a more stable consumption pattern, as its moderate climate requires less intensive dehumidification year-round.

[insert Figure 13.]

Figure 13 Monthly electricity consumption

6. Conclusions

This study presents an analysis of new oscillating air-conditioning dehumidification system. By employing an oscillating dual-evaporator design, this system addresses limitations, such as high energy consumption for defrost cycles and the inability to maintain continuous deep dehumidification in high-humidity environments.

Experimental tests conducted in Chongqing's humid climate highlight the system's capability, particularly in the dual-stage configuration, achieving a dew point as low as -9.38 °C, a dehumidification capacity of 12.52 g/kg, and reaching to a specific humidity of 1.67 g/kg. The process is also energy efficient, with COP ranging from 3.3 to 4.7. This is a leap forward on the existing deep dehumidification studies.

The TRNSYS model, validated against experimental data, extends the system's performance assessment across various climatic regions. High-temperature and high-humidity regions like Hong Kong and Chongqing show the best results, with annual average COP values of 3.89 and 3.42, respectively, indicating strong adaptability and effectiveness. In contrast, colder and drier regions like Urumqi exhibit lower demand and a more stable COP of 2.30, confirming the system's flexibility and adaptability in climates with lower dehumidification needs.

For deep dehumidification practitioners, this study provides actionable insights on optimising system parameters to suit specific climates. For example, a 10-minute oscillation cycle demonstrated effective balance in energy efficiency and moisture removal. The system's novel oscillating design, deep dehumidification capability, and adaptable configuration make it a promising solution for indoor climate control, especially in areas with extreme humidity fluctuations.

For future work, the authors recognise limitations in this study, including reliance on simulations and controlled experimental conditions that may not fully capture real-world variability. To address this, further analysis around design conditions, such as the varying indoor environment conditions along with varying climate conditions can be considered in future works. Also, system control strategies, such as dynamic adjustments to oscillation cycles and airflow rates, are needed to enhance the system's adaptability to fluctuating environmental conditions. Additionally, a pilot demonstration shall also be conducted to evaluate the air-conditioning performance under real-life settings.

CRediT Author Statement

The authors' contributions are listed as follows. It is noted that Jianghao Yue and Cheng Zeng contributed equally to this work.

Jianghao Yue: Conceptualisation, Data curation, Formal analysis, Validation, Visualisation, Writing – Original Draft Preparation

Cheng Zeng: Conceptualisation, Methodology, Formal analysis, Validation, Visualisation, Writing – Original Draft Preparation, Writing – Review & Editing

Zhichu Wang: Formal analysis, Visualisation, Writing – Review & Editing

Jun Lu: Conceptualisation, Investigation, Formal analysis, Supervision, Funding acquisition

Jiuyun Qi: Investigation, Data curation

Xiangui Shang: Investigation, Formal Analysis

Liang Liu: Investigation, Formal Analysis

Zhijie Pei: Investigation, Software

Funding statement

The authors from Chongqing University disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the National Natural Science Foundation of China, grant number 51478058.

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