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Operational Performance of a Water-Source Variable Refrigerant Flow System Coupled with a Dual-Season Cooling Tower in Actual Operation

Huiying Ma[1*], Hang Li[1], Yong Wang[1], Saleh Al-Saadi[2], Lin Gao[3]

[1] Chongqing University, Chongqing, China
[2] Sultan Qaboos University, Muscat, Oman
[3] PowerChina Hubei Engineering Co., Ltd, Wuhan, China

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ABSTRACT

To investigate the suitability and operational characteristics of a water-source variable refrigerant flow (WSVRF) system coupled with a dual-season cooling tower in regions with hot summers and cold winters, a small-scale test platform was established in an office building in Chongqing, China. Field experiments were conducted under representative summer cooling and winter heating conditions. On the basis of field-measured data, this study analysed the changing rules of circulating water temperature, WSVRF operational performance, and overall system coefficient of performance (COP) with variable outdoor meteorological parameters and operating loads. Seasonal differences in system behaviour were also evaluated. Results showed that, under summer wet-bulb temperatures (Twb) of 25.0–28.8 °C, the cooling tower effectively satisfied the system's heat rejection requirement and maintained stable circulating water temperatures. The system COP ranged from 3.46 to 4.29. Under winter Twb of 11.9–13.6 °C, COP ranged from 2.90 to 4.09, while the cooling tower operated stably with water as the circulating medium and exhibited good performance under partial-load conditions. When the outdoor Twb fell below 8.65 °C, the cooling capacity of the cooling tower declined markedly. The circulating water temperature approached the lower operational limit of 5 °C for the WSVRF system, resulting in unstable operation and failure to sustain normal performance. This threshold therefore marked the minimum operating limit for reliable winter performance with the given configuration. The results presented herein enable quantification of the operating range for WSVRF systems integrated with dual-season cooling towers, and offer a benchmark to assess the feasibility of deploying such systems in regions featuring hot summers and cold winters.

KEYWORDS Water-source variable refrigerant flow system, Dual-season cooling tower, Field experiment, Coefficient of performance

1. Introduction

Buildings account for approximately 30–40% of global final energy consumption (Cuce and Cuce 2026), with heating, ventilation, and air-conditioning (HVAC) systems constituting the largest share of building energy use (Anarene 2024). In response to global decarbonization goals, improving HVAC energy efficiency and increasing the utilization of renewable and low-grade energy sources have become key priorities in the building sector. Compared with conventional air-source systems, water-source heat pump (WSHP) systems utilize water as both the heat transfer medium and energy source (Jung *et al.* 2022; Wang *et al.* 2025; Du *et al.* 2024; Sezer *et al.* 2024). Benefiting from higher heat transfer efficiency, more stable operation, and superior annual energy performance, WSHP systems have been widely adopted in public buildings (Mo *et al.* 2025; Shin *et al.* 2025). By combining WSHP and

* Corresponding author. Email address: mhylzly@163.com (Huiying Ma)

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variable refrigerant flow (VRF) technologies, the water-source variable refrigerant flow (WSVRF) system integrates the efficient heat transfer characteristics of water-based systems with the operational flexibility of VRF systems (Tang *et al.* 2023). It enables independent control of indoor terminals and simultaneous cooling and heating in different zones (Hu *et al.* 2024), thereby offering considerable potential for building energy conservation. Furthermore, unlike conventional water-loop heat pump systems, in which each outdoor unit serves a single indoor terminal, a WSVRF system allows a single outdoor unit to connect up to 64 indoor terminals via refrigerant piping (Kamal and Khan 2021). This configuration substantially enhances the flexibility and adjustability of the system.

In practical applications, WSVRF systems are commonly coupled with a cooling tower–boiler configuration to meet year-round cooling and heating demands (Sa 2022). In this arrangement, the cooling tower functions as the heat rejection device during summer, while the boiler provides the heating source during winter. Although this configuration ensures reliable winter heating performance, it increases system complexity, energy consumption, and carbon emissions. To overcome these limitations, energy tower heat pump technology has attracted increasing attention. By incorporating antifreeze into the circulating fluid, the cooling tower can operate safely under low-temperature winter conditions (Li *et al.* 2024; Xiao *et al.* 2021; Wang *et al.* 2021; Huang *et al.* 2021). At the same time, low-grade ambient thermal energy can be utilized as a heat source, eliminating the need for conventional auxiliary heating equipment. Consequently, this technology offers considerable energy-saving potential and broad environmental adaptability, particularly in regions characterized by hot summers and cold winters (Xie *et al.* 2021). Previous studies have also investigated the application of energy tower technology coupled with WSVRF systems (Zhou 2021). However, the use of antifreeze introduces several challenges, including increased initial system cost, equipment corrosion, complicated concentration management, and concerns over long-term operational reliability (Yao *et al.* 2024).

To avoid the limitations associated with antifreeze-based energy tower systems, the direct utilization of conventional cooling towers as dual-season devices has been proposed for regions with relatively mild winter climates. In regions characterized by hot summers and cold winters, where winter climatic conditions are relatively mild, conventional cooling towers can be directly employed as heat absorption devices during the heating season (Tan and Deng 2002). This approach enables year-round operation of dual-season cooling towers, providing heat rejection in summer and heat absorption in winter for heat pump systems. By eliminating the need for antifreeze and reducing reliance on auxiliary heating, it offers the potential to further simplify system configuration and reduce operational complexity. For WSVRF systems, this configuration provides a potential alternative to both conventional cooling tower–boiler systems and antifreeze-based energy tower systems. However, studies on WSVRF systems coupled with dual-season cooling towers remain limited. Existing investigations have mainly focused on theoretical analyses, numerical simulations, or performance predictions, whereas experimental validation under realistic building operating conditions remains insufficient. Therefore, the relationships among outdoor climatic conditions, circulating water temperature, heat pump performance, and dynamic building loads, as well as the winter operating boundaries of water-only circulation systems, have not been fully established through field measurements. These knowledge gaps hinder the transition of dual-season cooling tower concepts from theoretical feasibility assessment to reliable engineering applications and restrict the development of practical design and operation control strategies.

Chongqing, China, is a representative hot-summer and cold-winter region with substantial year-round cooling and heating demands. These climatic characteristics provide favourable conditions for the application of WSVRF systems coupled with dual-season cooling towers. To investigate the operational performance of this system under actual operating conditions, a field-scale experimental platform was established in an office building in Chongqing. Field measurements were conducted during typical summer cooling and winter heating periods. The variations in circulating water

temperature and overall system energy performance were evaluated under different outdoor environmental conditions and building load levels. In addition, the operational characteristics of the system in cooling and heating modes were compared, and the environmental applicability limits for stable winter operation without antifreeze were identified. The findings provide insights into the design, operation, and engineering application of WSVRF systems coupled with dual-season cooling towers in hot-summer and cold-winter regions.

2. System description and experimental methods

2.1. Project overview

To evaluate the applicability and operational characteristics of a WSVRF system coupled with a dual-season cooling tower in a hot-summer and cold-winter region, a full-scale engineering system was implemented in an office building in Chongqing, China. Field measurements were conducted under both summer cooling and winter heating conditions. The system schematic was shown in Figure 1. During the experiments, the system operated in accordance with the actual cooling and heating demands of the building, thereby reflecting its performance under real operational conditions.

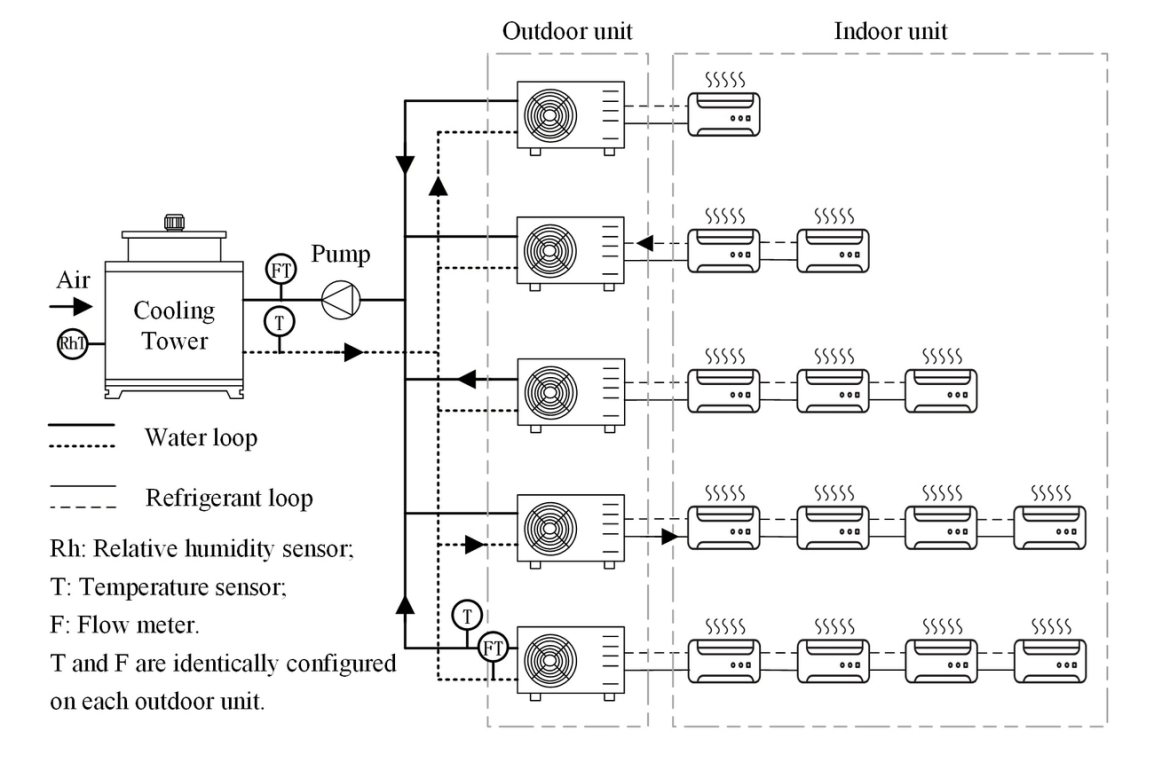

Figure 1. Schematic diagram of the experimental platform.

The experimental platform consisted of an open cross-flow cooling tower, multiple WSVRF configurations (including one outdoor unit connected to one indoor unit, one outdoor unit connected to two indoor units, one outdoor unit connected to three indoor units, and two outdoor units each connected to four indoor units), a circulating water pump, and the associated piping and valve network. The field layout of the equipment was shown in Figure 2. The experimental platform was designed to evaluate the operational performance of cooling towers with different configurations and capacities and to assess the energy performance of WSVRF systems under both winter and summer conditions.

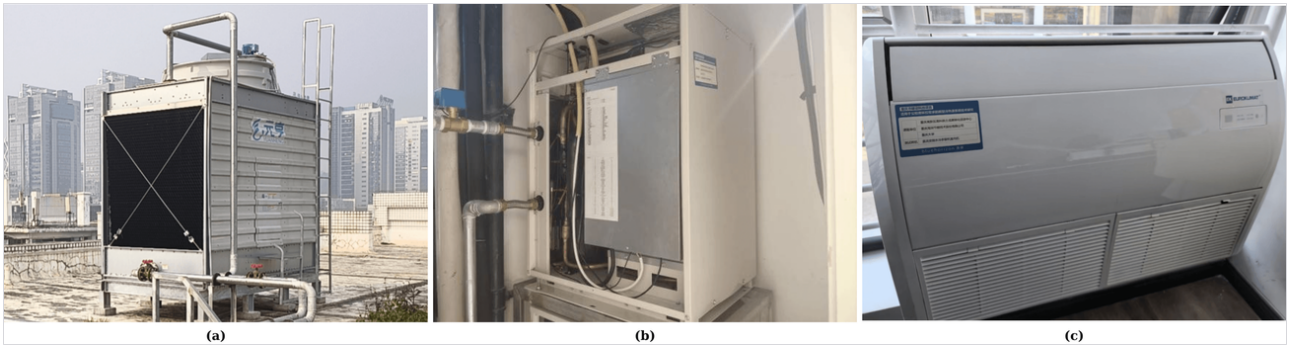

Figure 2. Photographs of the key components of the experimental platform: (a) open cross-flow cooling tower; (b) 1-to-4 outdoor unit; (c) 1-to-4 indoor unit.

The technical parameters of the YHKR-120 open cross-flow cooling tower were summarized in Table 1, while the key specifications of the WSVRF system were provided in Table 2.

Table 1. Technical specifications of the YHKR-120.

Water flow rate (m^3/h)	Tower length (m)	Tower width (m)	Tower height (m)	Fan diameter (m)	Fan power (kW)	Packing volume (m^3)	Airflow rate (m^3/h)
57	1.75	2.18	3.4	1.5	1.1	6.3	42480

Table 2. Materials of the main components of the WSVRF system.

No.	System configuration	DC inverter outdoor unit		Floor-standing indoor unit	
		Model / Specifications	Quantity	Model / Specifications	Quantity
System 1	One-to-one	MDS-W010CR5 Nominal cooling capacity: 2.5 kW; Nominal heating capacity: 2.8 kW; Cooling input power: 0.5 kW; Heating input power: 0.5 kW; Refrigerant: R410A	1	MCM025SP Nominal cooling capacity: 2.5 kW; Nominal heating capacity: 2.8 kW; Input power: 50 W	1
System 2	One-to-two	MDS-W040CR5 Nominal cooling capacity: 11.2 kW; Nominal heating capacity: 12.5 kW; Cooling input power: 2.1 kW; Heating input power: 1.9 kW; Refrigerant: R410A	1	MCM050SP Nominal cooling capacity: 5.0 kW; Nominal heating capacity: 5.6 kW; Input power: 100 W	2
System 3	One-to-three	MDS-W060CR5 Nominal cooling capacity: 16.0 kW; Nominal heating capacity: 18.0 kW; Cooling input power: 3.35 kW; Heating input power: 2.95 kW; Refrigerant: R410A	1	MCM050SP Nominal cooling capacity: 5.0 kW; Nominal heating capacity: 5.6 kW; Input power: 100 W	3

Table 2. (continued)

No.	System configuration	DC inverter outdoor unit		Floor-standing indoor unit	
		Model / Specifications	Quantity	Model / Specifications	Quantity
System 4	One-to-four	MDS-W060CR5 Nominal cooling capacity: 16.0 kW; Nominal heating capacity: 18.0 kW; Cooling input power: 3.35 kW; Heating input power: 2.95 kW; Refrigerant: R410A	1	MCM025SP Nominal cooling capacity: 2.5 kW; Nominal heating capacity: 3.0 kW; Input power: 50 W	2
				MCM050SP Nominal cooling capacity: 5.0 kW; Nominal heating capacity: 5.6 kW; Input power: 100 W	2
System 5	One-to-four	MDS-W080CR5 Nominal cooling capacity: 25.2 kW; Nominal heating capacity: 28.0 kW; Cooling input power: 3.85 kW; Heating input power: 4.02 kW; Refrigerant: R410A	1	MCM050SP Nominal cooling capacity: 5.0 kW; Nominal heating capacity: 5.6 kW; Input power: 100 W	4
Total cooling capacity / kW		70.9		62.5	

2.2. Experimental design and measurement methods

To accurately characterize the operational performance of the WSVRF system coupled with a dual-season cooling tower, measurement points were arranged at key locations of the system, as shown in Figure 2. These points were used to monitor environmental conditions, circulating water parameters, and system operating variables. The measured parameters include outdoor air dry-bulb temperature and relative humidity, inlet and outlet water temperatures and flow rate of the cooling tower, inlet and outlet water temperatures and flow rate of the WSVRF units, cooling tower fan power consumption, circulating water pump power consumption, and electrical power consumption of the WSVRF outdoor units. The detailed specifications of the measurement instruments were presented in Table 3.

Table 3. Experimental instruments and corresponding measured parameters.

Instrument	Model	Measurement range	Accuracy
Ultrasonic heat meter		Temperature: 4–95 °C; Flow rate: 1.6–80 m^3/h	Accuracy class: Class 2
Temperature and humidity data logger	TH41G4-EX	Temperature: −40–85 °C; Relative humidity: 0–100%	Temperature: ±0.2 °C; Relative humidity: ±2%

During the experiments, the outdoor units of the WSVRF system operated under the designed flow conditions. Data acquisition was initiated only after the system reached a steady-state condition for more than 30 min. The summer tests were conducted from June to August 2025, with the indoor terminal setpoint maintained at 26 °C. The winter tests were carried out from January to March 2025 and January 2026, with the indoor setpoint maintained at 22 °C.

2.3. Performance evaluation indicators

To evaluate system performance, the overall energy efficiency was selected as the primary performance indicator.

The heat transfer rate of circulating water on the outdoor side of the WSVRF system was calculated using Equation (1):

$$Q = \frac{c\rho L\Delta t}{3.6\times10^{6}} \tag{1}$$

Where:

- Q = heat transfer rate of circulating water on the outdoor side (kW)
- c = specific heat capacity of water (J/(kg·°C)); 4200 J/(kg·°C) for water
- ρ = density of water (kg/m³); 1000 kg/m³ for water
- L = volumetric flow rate (m³/h)
- Δt = temperature difference between supply and return water (°C)

The cooling and heating capacities of the WSVRF system was calculated using Equation (2):

$$Q_{load} = Q \pm W_{WSVRF} \tag{2}$$

Where:

- Q_{load} = cooling and heating load of the system (kW)
- W_{WSVRF} = power consumption of the WSVRF unit (kW)
- "–" = cooling conditions
- "+" = heating conditions

The overall system coefficient of performance (COP) was defined as the ratio of the system cooling and heating load to the total electrical power consumption of all system components, as expressed in Equation (3):

$$COP = \frac{Q_{load}}{\sum W_{WSVRF} + \sum W_{WP} + \sum W_{F}} \tag{3}$$

Where:

- W_{WP} = power consumption of the circulating water pump (kW)
- W_{F} = power consumption of the cooling tower fan (kW)

2.4. Uncertainty and error analysis

To evaluate the uncertainty of the experimental measurements, an uncertainty analysis was conducted for the main measured parameters. According to relevant measurement standards (State Administration for Market Regulation of China 2024), the maximum permissible relative error of the Class 2 heat meter was calculated using Equation (4):

$$E = \pm\left(3 + 4\frac{\Delta T_{\min}}{\Delta T} + 0.02\frac{q_p}{q}\right)\% \tag{4}$$

Where:

- E = maximum permissible relative error of the heat meter
- $\Delta T_{\min}$ = minimum temperature difference specified for the heat meter (°C)
- ΔT = measured temperature difference (°C)
- q_p = nominal flow rate of the heat meter (m^3/h)
- q = actual flow rate (m^3/h)

For air-side measurement parameters, the uncertainty was evaluated using the maximum relative error method, as expressed in Equation (5):

$$\delta = \frac{\varphi_x M_i}{x_i} \times 100\% \tag{5}$$

Where:

- δ = maximum relative error
- φ_x = accuracy class of the instrument
- M_i = full-scale range of the instrument
- x_i = measured value under test conditions

Based on the measurement ranges and technical specifications of the instruments, the maximum permissible relative error of the heat meter was 8.57%, while the relative errors for dry-bulb temperature and relative humidity were 1.48% and 3.60%, respectively. These uncertainty levels were within the typical ranges for HVAC experimental measurements, which ensured the reliability of the measured data for system performance evaluation and subsequent analysis.

3. Results and discussion

3.1. Summer operation performance

The circulating water temperature is a key operating parameter linking the dual-season cooling tower and the WSVRF system. Variations in circulating water temperature directly affect the operational performance of the WSVRF system and COP. Figure 3 showed the variation in cooling tower outlet water temperature (Tout) under different outdoor wet-bulb temperatures (Twb) during summer operation. During the test period, the outdoor dry-bulb temperature ranged from 32.9 to 38.6 °C, while Twb varied between 25.0 and 28.8 °C. As the outdoor Twb increased, the cooling tower Tout exhibited a corresponding increase. This trend was attributed to the reduced heat and mass transfer driving potential between circulating water and ambient air at higher Twb. Consequently, the heat rejection capacity of the cooling tower decreased, leading to an elevated Tout. Nevertheless, during the entire test period, the circulating water temperature remained within the allowable operating range for stable cooling operation of the WSVRF system.

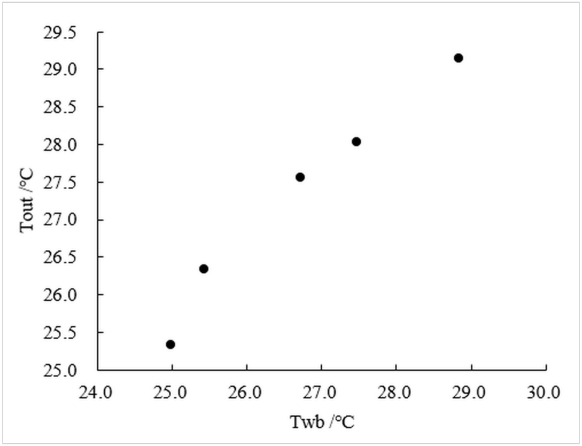

Figure 3. Variation in cooling tower Tout under summer operation.

Figure 4 illustrated the variation in COP under different test conditions. Because the system served an actual office building, the cooling load varied dynamically during the measurements. COP was therefore affected by both building load and outdoor conditions. However, no clear monotonic relationship between part-load level and COP was observed in the available measurements; thus, the present analysis focuses on the influence of outdoor Twb. COP ranged from 3.46 to 4.29 over the test period. As the cooling tower Tout increased, the condensing temperature of the WSVRF system also increased, leading to higher compressor power consumption and reduced unit efficiency. Consequently, COP declined. This physical relationship is consistent with the established operating characteristics of water-source heat pump systems, for which a lower heat-rejection temperature generally improves refrigeration-cycle efficiency.

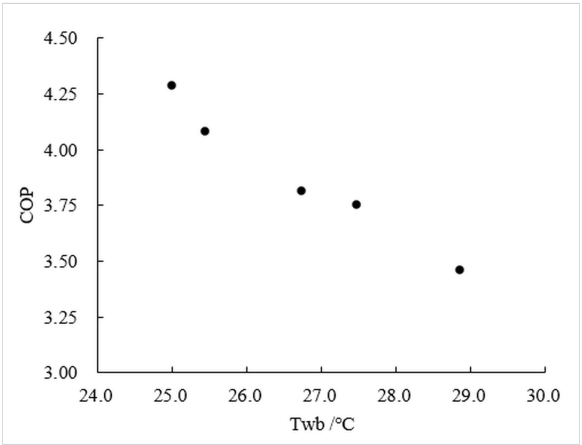

Figure 4. Variation in COP under summer operation.

Figures 3 and 4 showed that the outdoor Twb had a significant influence on system performance during summer operation. As Twb increased, both the cooling tower Tout and COP varied accordingly. Nevertheless, throughout the entire tested operating range, the WSVRF system maintained stable operation and exhibited satisfactory energy performance. The measured COP values were comparable to those reported in previous studies under similar temperature and humidity conditions (Lee *et al.* 2018a), while the present study further provides field evidence for a dual-season cooling tower serving as the heat-rejection device in summer and the heat-source device in winter.

3.2. Winter operation performance

During winter operation, the cooling tower switched from a heat rejection mode to a heat absorption mode. The circulating water absorbed sensible and latent heat from the ambient air and supplied the recovered low-grade heat to the WSVRF system. Operation without antifreeze introduced additional challenges to system stability. Figure 5 showed the variation in cooling tower Tout under different outdoor Twb conditions. At an outdoor Twb of 13.6 °C, the cooling tower exhibited enhanced heat absorption capacity, and the circulating water temperature remained at a relatively high level. As the outdoor Twb decreased, the available heat-source potential of the ambient air decreased, resulting in reduced heat absorption and a corresponding decrease in circulating water temperature.

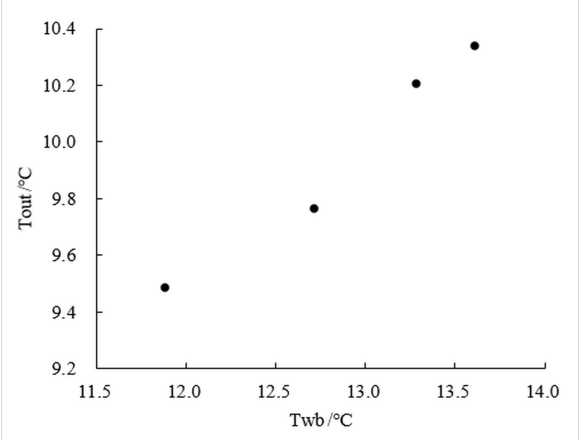

Figure 5. Variation in cooling tower Tout under winter operation.

Figure 6 presented the variation in COP across different winter operating conditions. During the test period, the outdoor Twb ranged from 11.9 to 13.6 °C, while indoor spaces were under normal occupancy, resulting in fluctuating building loads. In this context, COP ranged from 2.90 to 4.09. As in summer operation, COP was affected by both outdoor conditions and dynamic building load. However, no clear monotonic relationship between part-load level and COP was observed; therefore, the following analysis focuses on the influence of outdoor Twb on COP. Overall, COP decreased with decreasing outdoor Twb and circulating water temperature, while remaining at a relatively high level. The lower water temperature increased the heat-pump temperature lift and consequently increased compressor power consumption, contributing to the reduction in COP. Compared with conventional air-source multi-split systems (Lee *et al.* 2018b; Zhang *et al.* 2018), the system exhibited approximately 40% higher winter energy efficiency. This difference can be attributed primarily to the relatively stable heat-source temperature provided by the water loop, which buffers the direct influence of outdoor air conditions on the heat-pump evaporator under the tested winter conditions. Accordingly, the WSVRF system demonstrated considerable potential for improving winter energy efficiency compared with conventional air-source multi-split systems.

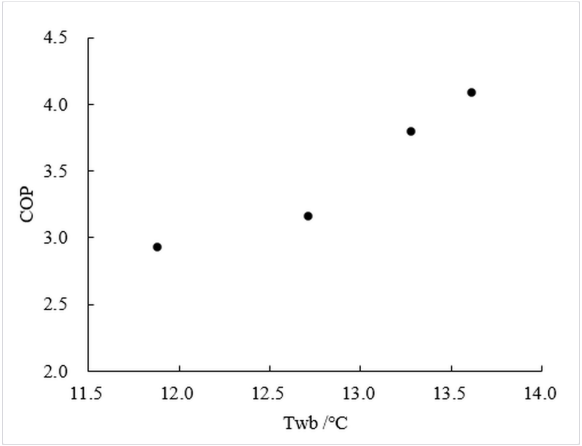

Figure 6. Variation in COP under winter operation.

The combined results from Figures 5 and 6 indicated that the dual-season cooling tower could meet the heating demand of the WSVRF system under typical winter test conditions. Unlike conventional WSVRF systems that rely on dedicated heating sources to provide the required winter heat, the present system indirectly extracts low-grade thermal energy from the outdoor air through the cooling tower and transfers it to the WSVRF unit via the circulating water. This suggested its feasibility for winter operation in hot-summer and cold-winter regions.

3.3. Applicability of winter operation

Figure 5 indicated that the circulating water temperature decreased continuously as the outdoor Twb decreased. When the outdoor Twb was above approximately 11.9 °C, the circulating water temperature remained within the normal operating range of the WSVRF system, thereby maintaining stable heat supply. As the outdoor Twb further decreased, the availability of low-grade heat sources gradually decreased, while the building heating demand increased, resulting in a reduced operational margin of the system.

According to relevant specifications (National Technical Committee on Refrigeration and Air-Conditioning Equipment Standardization 2013), antifreeze protection measures were required for WSHP systems, and the supply water temperature should not be lower than 5 °C. Experimental results showed that when the outdoor Twb approached 8.65 °C, the cooling tower outlet water temperature decreased to 5.75 °C, triggering partial unit shutdown protection and indicating that the system entered a low-temperature constrained operating state. In this condition, the heat transfer capacity of the evaporative heat exchanger side was significantly reduced, affecting unit operational stability. As the outdoor Twb further decreased, the circulating water temperature could no longer satisfy normal operation and antifreeze protection requirements, resulting in a reduction in system heating capacity.

Based on the overall operational characteristics, two boundary states were identified under winter operation. At an outdoor Twb of approximately 11.9 °C, the system began to transition from stable operation to a performance degradation regime. When the outdoor Twb decreased to approximately 8.65 °C, the system entered a restricted operating state, accompanied by unit shutdown protection events. Therefore, under the engineering conditions of this study, 11.9 °C was considered the lower limit for stable heating operation, while 8.65 °C was identified as the critical Twb for the onset of restricted operation. Within this range, the system remained operational, but with gradually reduced efficiency and stability. Below 8.65 °C, auxiliary heat sources would be required in practical applications to ensure safe and reliable system operation.

These experimentally identified operating boundaries provide practical criteria for determining when a dual-season cooling tower can serve as the sole heat source and when auxiliary heating

should be introduced. Although the specific threshold values depend on equipment characteristics and system configuration, the observed relationship between outdoor Twb, circulating water temperature, and unit operating stability provides a useful basis for the design and control of similar water-source systems.

To evaluate the climatic applicability of this threshold, hourly outdoor Twb data from a standard meteorological year in Chongqing were analysed, and the annual distribution was shown in Figure 7. The results indicated that, when 8.65 °C was used as the critical criterion, the cumulative duration below this threshold reached 1578 h, representing a considerable fraction of the annual heating period. Most of these hours occurred during nighttime, while the system remained applicable to daytime-operating public buildings such as offices and schools. With the equipment used in this study, stable operation could be maintained at an outlet water temperature as low as 2 °C under appropriate conditions (Tibet Autonomous Region Administration for Market Regulation 2025). In addition, by adopting a large-flow and small-temperature-difference strategy and appropriately increasing cooling tower capacity, the duration of restricted operation could be reduced to 64 h. This result indicates that the identified climatic threshold is an operating boundary of the investigated system rather than an absolute limitation of the system concept, and can be extended through improved equipment performance, increased cooling tower capacity, and appropriate control strategies. Although the threshold values are specific to the investigated equipment and operating conditions, the boundary-identification approach can be applied to similar systems under different climates. Accordingly, system design and operation should consider equipment performance, load profiles, and building types when evaluating the demand for auxiliary heat source operation under water-only operation conditions.

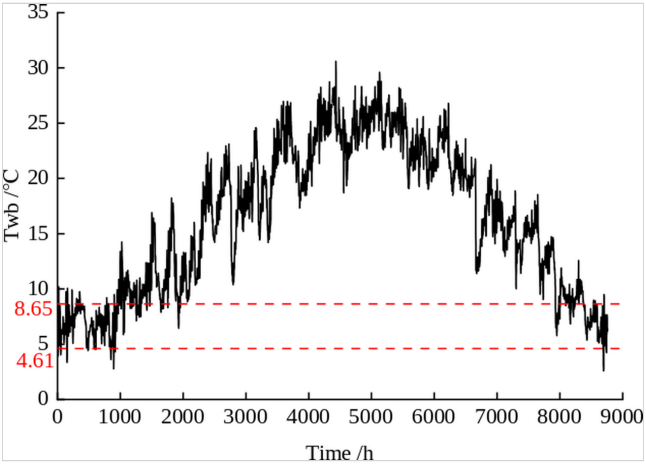

Figure 7. Hourly variation of outdoor Twb in Chongqing.

Beyond demonstrating the feasibility of the investigated system, the present study provides a practical basis for evaluating the winter applicability of dual-season cooling towers in WSVRF systems. The results establish a relationship among outdoor Twb, circulating water temperature, and the operating state of the WSVRF unit, from which stable and constrained operating boundaries can be identified. By combining these experimentally derived boundaries with hourly climatic data, the study extends the analysis beyond a single building case to a climate-based assessment of system applicability.

4. Conclusion

Based on an office building in Chongqing, China, a small-scale demonstration system without antifreeze was constructed. The system was coupled with dual-season cooling towers and WSVRF units, enabling year-round operation under both cooling and heating conditions. Experimental tests under typical operating conditions were carried out to analyse the year-round operating

characteristics of the system and its applicability under winter conditions. The main conclusions are as follows:

(1) Under summer test conditions, the outdoor Twb ranged from 25.0 to 28.8 °C. The dual-season cooling tower adequately satisfied the heat rejection demand of the system. Stable operation was maintained throughout the test period, with COP values ranging from 3.46 to 4.29.

(2) Under winter test conditions, the outdoor Twb varied from 11.9 to 13.6 °C. The dual-season cooling tower was able to utilize low-grade ambient thermal energy as a stable heat source for the WSVRF system. Stable heating operation was achieved under a water circulation mode without antifreeze, with COP values ranging from 2.90 to 4.09. These results demonstrate the feasibility of coupling WSVRF units with dual-season cooling towers under winter conditions.

(3) Based on the engineering conditions of this study, the environmental applicability limits of winter operation were further evaluated, with 5 °C adopted here as the conventional protection criterion. An outdoor Twb of approximately 11.9 °C marked the transition from stable operation to a performance degradation regime, while 8.65 °C defined the critical limit for constrained operation. These thresholds characterize the operating boundaries of the investigated system and provide engineering reference values for the selection of auxiliary heating and control strategies.

(4) For the engineering application of a system integrating dual-season cooling towers and WSVRF units, key parameters, including the inlet and outlet water temperature limits of equipment, applicable building types, load characteristics, and the capacity of auxiliary heat sources, should be comprehensively considered to ensure rational system design and optimize operational control strategies. The main contribution of this study is the field-based identification of the physical operating characteristics and winter climatic boundaries of a dual-season cooling tower coupled with a WSVRF system under actual building conditions, providing field evidence and a practical basis for extending water-source operation beyond conventional single-season applications.

Declarations

Author contributions. Huiying Ma: Methodology, Investigation, Formal analysis, Data curation, Writing (original draft), Visualization, Validation. Hang Li: Methodology, Investigation, Formal analysis, Data curation, Writing (original draft), Visualization, Validation. Yong Wang: Conceptualization, Methodology, Writing (review and editing), Supervision, Project administration, Resources, Funding acquisition. Saleh Al-Saadi: Conceptualization, Methodology, Writing (review and editing), Supervision. Lin Gao: Formal analysis, Visualization.

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Conflicts of interest. The authors declare no competing interests.

Data availability. All data generated or analysed during this study are included in this paper.

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