15TH IEA HEAT PUMP CONFERENCE
MAY 26–29, 2026 | HOFBURG
VIENNA 2026
DECARBONISATION THROUGH INNOVATION

Development and Application of CO_2 Cascade Air Source Heat Pumps for Space Heating in China

Li Xiaoyu[a,b*], Ma Li[a,c], Li Conghui[a], Xu Wei[a], Yuan Jing[a,d], Shi Lin[b], Wang Tiansheng[a,e], Li Bing[a], Gao Tong[a]

[a]Institute of Building Environment and Energy, China Academy of Building Research, 30# Beisanhuandonglu, Chaoyang District, Beijing 100013, China
[b]Department of Energy and Power Engineering, Tsinghua University, Tsinghua University, Haidian District, Beijing 100084, China
[c]Department of Building Science, School of Architecture, Tsinghua University, Tsinghua University, Haidian District, Beijing 100084, China
[d]College of Engineering, Peking University, No.5 YiHeYuan Road, Haidian District, Beijing 100871, China
[e]College of Civil Engineering and Architecture, Hebei University, No.180 Wusi Dong Road, Lian Chi District, Baoding 071002, China

Abstract

In northern China, space heating consumes 19% of the total energy and emits 22% of the carbon dioxide in the building operation sector. Against the background of China's "carbon peaking and neutrality" goals, improving building electrification rates and renewable energy utilization rates have become critical development pathways. As a state-of-the-art solution for this transition, the CO_2 air source heat pumps (ASHP) are applicable to both retrofitted and newly constructed buildings. Taking distributed heating system projects using CO_2 ASHPs as the research object, this paper illustrates the technology's development status and investigates its operational performance. Analysis of the projects applied in cold and severe cold zones revealed that CO_2 cascade ASHPs achieve favorable efficiency, with a seasonal heating COP ranging from 2.24 to 2.92. Moreover, they can operate stably at ambient temperatures around -22℃ while maintaining indoor temperatures that meet relevant standards. To guide and regulate the further development of such applications, a national standard has been released in response to the growing adoption of CO_2 ASHPs in space heating and other heating systems.

Keywords: CO_2 air source heat pump; distributed central heating system; COP; national standard

1. Introduction

Since China proposed the "dual carbon" goals in 2020 [1], the urban and rural construction sector has remained a key area for their implementation [2]. By 2023, the total heating floor area in northern urban regions of China had reached 17.3 billion square meters. The associated space heating consumed 222 million tons of standard coal and resulted in 500 million tons of CO_2 emissions, accounting for approximately 19% of building operational energy use and 22% of its carbon emissions [3]. To advance the "dual carbon" targets in building heating, the government has issued a series of policy plans [4-7], outlining a transition toward electrification, clean energy, and low-carbon development in this sector. CO_2 air source heat pumps (ASHPs) have emerged as a promising technical pathway, primarily due to their excellent low-temperature adaptability and high heating capacity [8,9] that enable applications in severe cold zones. This promotion in severe cold zones is supported by ASHPs proven contributions to energy savings and emission reductions in cold zones under China's clean heating initiatives in recent years [10-12]. In accordance with China's implementation of the Kigali Amendment, the production of certain heat pump units using refrigerants with a

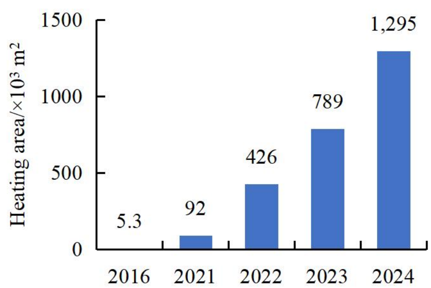
*Corresponding author. Tel.: +89-186181386168
E-mail address: 18618138616@163.com

global warming potential (GWP) greater than 750 will be prohibited starting in January 2029 [13]. This regulation further highlights the advantage of CO_2 ASHPs using natural refrigerants, and China's National Development and Reform Commission has thus emphasized the need to strengthen the research and application of transcritical CO_2 heat pump technology [14].

The application of CO_2 ASHPs in China aligns with the global trend, being predominantly utilized in water heating and vehicle air conditioning systems. Their use in space heating, however, remains in a preliminary stage. Since 2018, following the successful pilot implementation of CO_2 ASHPs in railway heating projects, the scale of their application has been steadily expanding [15]. This paper reviews the current status of CO_2 ASHPs implementation in China, focusing on space heating projects and the associated standards.

2. Application projects status

Owing to the thermodynamic properties of CO_2 [15], the compact structure of single CO_2 ASHP unit provides it with higher heating capacity, making it suitable for distributed central heating systems. In recent years, the application of CO_2 ASHPs in space heating in China has achieved large-scale growth, with the accumulated heating area reaching 1.29 million square meters (see Figure 1). These projects cover buildings of different functions and are applicable to both new constructions and renovation projects, all achieving high efficiency with an average COP of 2.24-2.92 during the heating season (see Table 1). Moreover, even when the outdoor temperature drops to -22.2℃, CO_2 ASHP can still operate stably and efficiently, with an hourly COP of 2.70. These results indicate that CO_2 ASHPs have great application potential for space heating in cold and severe cold zones.



Note: Data is sourced from the National Center of Quality Inspection and Testing for Building Energy Conservation and published journals.

Figure 1. Accumulation heating area of record CO_2 ASHP application in space heating in China.

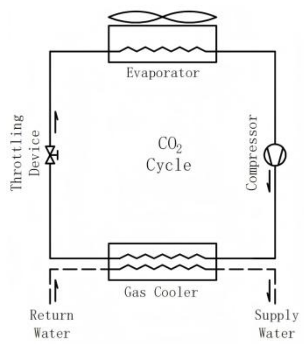


Figure 2. Transcritical cycle [19]

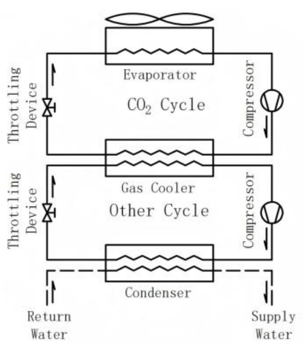


Figure 3. Cascade cycle [22]

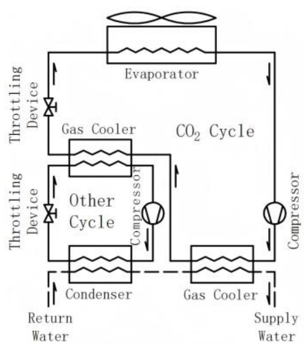


Figure 4. Semi-cascade cycle [18]

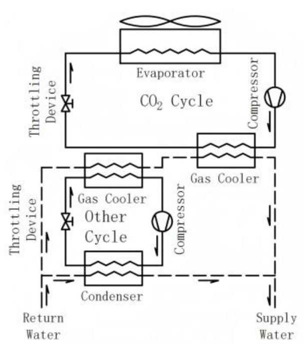


Figure 5. Coupled cycle [17]

The applications of CO_2 ASHPs in recent years present three main development trends. First, the heating capacity of single unit has increased significantly, from 40 kW up to 1992 kW. Second, the heating scale has expanded remarkably as the heating scope has shifted from single low-rise building with a floor area of thousands square meters to multiple building clusters with a total floor area exceeding tens of thousands of square meters. Third, with advancements in CO_2 ASHP technology and control strategies, the average COP during the heating season has been gradually improved.

Among all the applications, the transcritical cycle (see Figure 2) serves as the foundational technology. The large temperature glide of CO_2 in supercritical region in gas-cooler is enable the production of high-temperature water even under low ambient temperatures. However, the relatively high return water temperature for space heating, typically exceeding 40℃ [24], can degrade the heating performance of the transcritical cycle. To address this technical challenge, cascade cycle, semi-cascade cycle and combined cycle have been proposed (see Figures 3-5) to subcooled the gas-cooler outlet temperature.

Table 1. Information of CO_2 ASHP application projects

Year	City	Building Type	FA/m^2	HC of unit/kW	Average COP	COP at lowest AT
2016[16]	Dalian	Office Building	3550	40 (0℃)	2.33 (3.3℃)	1.66 (-10.4℃)[a]
2021[17]	Hohhot	Civil Building	1200	46 (-12℃)	2.58 (/)	1.87 (-21.0℃)[a]
2021[18]	Qinhuangdao	Office Building	30262	375 (-12℃)	2.85 (-4.4℃)[e]	2.82 (-14.8℃)[b,j] 2.94 (-14.8℃)[b,j]
2021[18]	Shijiazhuang	Residential Compounds	55000	685 (-12℃)	2.68 (0.6℃)[g,j] 2.56 (0.6℃)[g,j]	2.47 (-9.2℃)[b,j] 2.33 (-9.2℃)[b,i]
2022[19]	Dalian	Residential Building	3401	100 (15℃)	2.24 (1.9℃)	2.12 (-8.7℃)[a]
2022*[20]	Ulanqab	Railway Station	1292	68 (/)	/	2.75 (-11.0℃)[d,i] 2.25 (-11.0℃)[d,i]
2022[21]	Shijiazhuang	Residential Compounds[l]	55000	685 (-12℃)	2.58 (3.2℃)	2.49 (-6.8℃)[a]
2022[21]	Shijiazhuang	Residential Compounds	130800	1992 (-12℃) 1210 (-12℃)	2.92 (2.6℃)[j] 2.88 (2.6℃)[j]	2.80 (-7.6℃)[a,j] 2.78 (-7.6℃)[a,j]
2022*[20]	Baiyin	Railway Station	1000	115 (/)	/	2.20 (-10.7℃)[d]
2023[22]	Shijiazhuang	Residential Compounds	130000	670.7	2.50 (-1.3℃)[h]	2.60 (-14.1℃)[a,d]
2024	Chengde	Office Building	8788	585 (-12℃)	2.89(-5.2℃)	2.70(-22.2℃)[c]
2024*[23]	Beijing	Office Building[k]	6000	/	2.67(-4.7℃)[d,f,]	2.60 (-13.0℃)[a,d]

Note:
1. All projects comply with national standards for indoor conditions. 2. COP values refer to the heat pump unit only.
3. Project year is assigned based on the test data year or, if unavailable, the year prior to the paper's publication (marked with *).
4.FA: Floor Area; HC: Heating Capacity; AT: Ambient Temperature.
[a] 24-hour average. [b] 2-hour average. [c] 1-hour average. [d] Value read from figure. [e] Test duration: 10 days.
[f] Test duration: 30 days. [g] Test duration: 87 days. [h] Test duration: 88 days.
[i] System tested under two conditions with supply water flow rates of 16.5 m^3 /h and 11 m^3 /h.
[j] COPs correspond to unit #1 and unit #2 in the heating system, respectively.
[k] Direct expansion heat pump system [l] Re-analysis of different operation periods for a previously listed project.

3. Standards status

Based on climatic characteristics, China is classified into five primary building climate zones (see Table 2) [25]. With continuous technological breakthroughs in the low-temperature performance of ASHPs [26], their application in the heating sector has been expanding northward. Reflecting this, national standards have systematically expanded the nominal testing conditions from 7℃ to -35℃, concurrently raising the minimum performance coefficient requirements for these conditions [27-29]. This progression in standards and technology provides a crucial foundation for the long-term stable operation of ASHPs throughout China's varied building climate zones.

Since the low-temperature adaptability of CO_2 ASHPs makes them suitable for space heating in cold and severe cold zones, a dedicated standard system for CO_2 ASHPs has been established under the guidance of China's dual-carbon standard framework [32], and by fully drawing on the domestic and international practices of formulating separate standards for CO_2 heat pumps and conventional refrigerant heat pumps. The first product standard, *Air source heat pump packages with carbon dioxide as refrigerants GB/T 45650—2025,* has been released [29]. This standard extends the testing conditions for ASHPs to -35℃ and classifies units into two types based on their application area, which are low-ambient-temperature and ultra-low-ambient-temperature types. Their testing conditions and corresponding minimum performance requirements are summarized in Table 3. Given the excellent thermal properties of CO_2, the production of MW-class single units is feasible. To address the difficulty of testing large-scale air source units in conventional enthalpy difference laboratories, a field testing method has been proposed. This method accounts for the instability of on-site conditions relative to laboratory conditions, strictly adheres to laboratory testing requirements and instrument accuracy standards, and incorporates a long-term testing scheme to ensure coverage of required testing conditions. To resolve the deviation between on-site measured operating conditions and the testing conditions specified in the standard, thermodynamic perfection has been introduced as a unified criterion for comparing the performance of laboratory-tested units with that of on-site units. Thermodynamic perfection is defined as the ratio of a device's actual efficiency (COP or EER) to the efficiency of the reverse Carnot cycle under the same operating conditions [33]. It exhibits greater stability, comparability, relativity, statistical validity, and rationality than COP alone [34], making it suitable for a horizontal performance comparison of similar or identical products under different operating conditions. This standard is scheduled to be implemented in November 2025.

Table 2. Testing conditions for ASHP in different building climate zones [27-31]

Zones	indicators	Nominal Condition	Low-temperature Condition	Standards
Severe Cold Zone	A≤-10℃； C≥145 d	-25℃/—	-35℃/—	GB/T 45650—2025
Cold Zone	-10℃<A≤0℃；90 d≤B<145 d	-12℃/-13.5℃	-20℃/—	GB/T 25127.1-2020
Hot Summer and Cold Winter Zone	0℃<A≤10℃；0 d≤C<90 d 25℃<B≤30℃；40 d≤D<110 d	-2℃/-3℃	/	GB/T 18430.1—2024
Hot Summer and Warm Winter Zone	10℃<A； 25℃<B≤29℃；100 d≤D<200 d	7℃/6℃	/	GB/T 18430.1—2024
Moderate Climate Zone	0℃<A≤13℃；0 d≤C<90 d 18℃<B≤25℃；	-2℃/-3℃	/	GB/T 18430.1—2024

Note:
1. A: Average temperature of the coldest month. 2. B: Average temperature of the hottest month.
3. C: Number of days with a mean daily temperature ≤5℃. 4. D: Number of days with a mean daily temperature ≥25℃.
5. All test condition temperatures: dry-bulb/wet-bulb temperatures.

Table 3. Test condition and COP limits for CO_2 ASHP [29]

Unit type		Low-ambient-temperature type		Ultra-low-ambient-temperature type	
Application area		Cold zone and south part of severe cold zone		Severe cold zone	
Conditions		Nominal condition	Low-temperature condition	Nominal condition	Low-temperature condition
Outdoor side parameters	Dry-bulb Temp.	-12℃	-25℃	-25℃	-35℃
	Wet-bulb Temp.	-13.5℃	—	—	—
Use side parameters	Sup. Water Temp.	60℃			
	Ret. Water Temp.	40℃			
COP		2.50	2.20	2.20	1.70

4. Conclusion

With the continuous advancement of technology, the application of CO_2 ASHPs in space heating in China has formed an initial scale. They can operate efficiently throughout the heating season, achieving a COP of 2.24 to 2.92 while ensuring that indoor temperatures meet standards. Also they exhibit good low-temperature adaptability, with a maximum COP of 2.70 recorded at -22.2℃. Thus, CO_2 ASHPs represent a primary technical route for distributed central heating in northern China.

To standardize and guide the development of CO_2 ASHPs, the national standard *Air source heat pump packages with carbon dioxide as refrigerants GB/T 45650—2025* has been released. This standard not only broadens the operating conditions to adapt to severe cold zones but also specifies performance requirements tailored to the characteristics of CO_2 ASHP.

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