

# Experimental Comparison on Performance of a CO<sub>2</sub> Air-conditioning System Using Needle- and Pulse-width-controlled Ejectors<sup>#</sup>

Junan Long<sup>1</sup>, Binbin Yu<sup>2</sup>, Junye Shi<sup>3</sup>, Jiangping Chen<sup>4\*</sup>

1 Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai, China

2 Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai, China

3 Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai, China

4 Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai, China

(Corresponding Author: jpchen\_sjtu@163.com)

## ABSTRACT

In recent years, CO<sub>2</sub> refrigeration systems have attracted significant attention due to their eco-friendly characteristics. However, their substantial throttling losses and significant reduction in cooling efficiency at high ambient temperatures limit their adoption. Although two-phase ejectors have been proven to recover expansion energy and reduce throttling losses, conventional ejectors controlled by needle valves (Needle-EJ) experience a dramatic efficiency decline under low-to-medium load conditions. This phenomenon significantly reduces the energy-saving potential and limits the practical application of ejectors. To address this issue, this research developed a novel pulse width modulation-controlled ejector (PWM-EJ) that integrated a high-speed solenoid valve directly into the motive nozzle. This enabled the effective throat area to be rapidly modulated on and off without altering the downstream geometry. Comparative experiments were conducted under typical air-conditioning conditions (Indoor: 27°C/50% RH; Outdoor: 35 – 42°C) at 2.5 – 5 kW cooling capacity. Results show that both ejector systems achieved a 20% – 28% improvement in coefficient of performance (COP) compared to a baseline expansion valve (EXV) system under maximum load conditions. Furthermore, within the 60% – 80% nozzle opening range, the PWM-EJ exhibited 15% – 18% higher isentropic efficiency and achieved a 3% – 8.5% system COP improvement over the Needle-EJ. These findings validate the PWM regulation as a more practical, robust and efficient ejector flow control technique than needle-valve regulation, representing a critical step towards the real-world deployment of ejector CO<sub>2</sub> refrigeration systems.

**Keywords:** CO<sub>2</sub> refrigeration, transcritical cycle, ejector, work-recovery, pulse-width modulation

## NONMENCLATURE

### Abbreviations

CO <sub>2</sub> , R744	Carbon Dioxide
COP	Coefficient of Performance
EJ	Ejector
EXV	Expansion Valve
GWP	Global Warming Potential
PWM	Pulse-width Modulation
SOV	Solenoid Valve

### Symbols

$h$	Specific enthalpy (kJ/kg)
$\dot{m}$	Mass-flow rate (kg/s)
$p$	Pressure (MPa)
$s$	Specific entropy (kJ/kg·K)
$Q$	Heat-transfer rate (kW)
$W$	Compressor power (kW)
$\omega$	Entrainment ratio
$\eta$	Isentropic efficiency

### Subscripts

evap	Evaporator
gc	Gas cooler
in	Inlet
out	Outlet
sat	Saturated state

## 1. INTRODUCTION

Global cooling demand is rising, contributing significantly to energy use and greenhouse gas emissions. Carbon dioxide, (CO<sub>2</sub>, R744), a natural refrigerant with global warming potential (GWP) of 1, is a promising alternative but suffers from low Coefficient

<sup>#</sup> This is a paper for the 17th International Conference on Applied Energy (ICAE2025), December 8-12, 2025, Bangkok, Thailand.

of Performance (COP) in transcritical cycles at high ambient temperatures [1–4]. Two-phase ejectors have proven effective, with studies reporting COP improvements of 6% – 26% by recovering expansion work [5-10].

A typical two-phase ejector consists of a motive nozzle, a suction chamber, a mixing section and a diffuser. The basic working principle of an ejector is to recover expansion energy released during the throttling process, which would otherwise dissipate to heat in a conventional expansion valve (EXV). The operation of transcritical CO<sub>2</sub> refrigeration systems requires precise control of high pressure to maximize system COP under varying conditions and loads [11]. In conventional systems with expansion valves as throttling devices, high pressure control and flow regulation are typically achieved by modulating the opening of needle valves. In ejector refrigeration, most existing studies follow this approach to control system capacity [9,10,12,13], adjusting the ejector nozzle opening to regulate system flow rate and high pressure. However, needle-valve control only adjusts the nozzle throat, causing geometric mismatch and efficiency drop at part-load [14,15]. Alternative approaches like multi-ejector systems, which feature multiple ejectors installed in parallel, are costly

and impractical for small-capacity applications like automotive AC [16,17].

In addition to the existing technologies for regulating flow, namely the needle valve and parallel ejection, pulse-width modulation (PWM) technology offers an alternative solution, particularly for small-capacity refrigeration systems. Indeed, PWM flow regulation has been applied in expansion valves and capillary tubes [18]. However, studies on the application of PWM flow-regulating technology in ejector systems remain limited.

Therefore, a novel PWM-controlled ejector was developed in this research. The objective of this study is to evaluate the energy-saving performance of ejectors controlled by two different flow-regulating technologies (needle valve and PWM) in a small-capacity CO<sub>2</sub> ejector air-conditioning system through experimentation. Experiments were conducted under typical air-conditioning conditions (indoor: 27°C, 50% RH; outdoor: 35°C – 42°C) with cooling capacities ranging from 2.5 kW to 5 kW. A conventional EXV system served as the baseline. The findings provide valuable insights into the efficacy of PWM flow regulation in ejector systems and offer guidance for optimizing system efficiency under variable operating conditions.

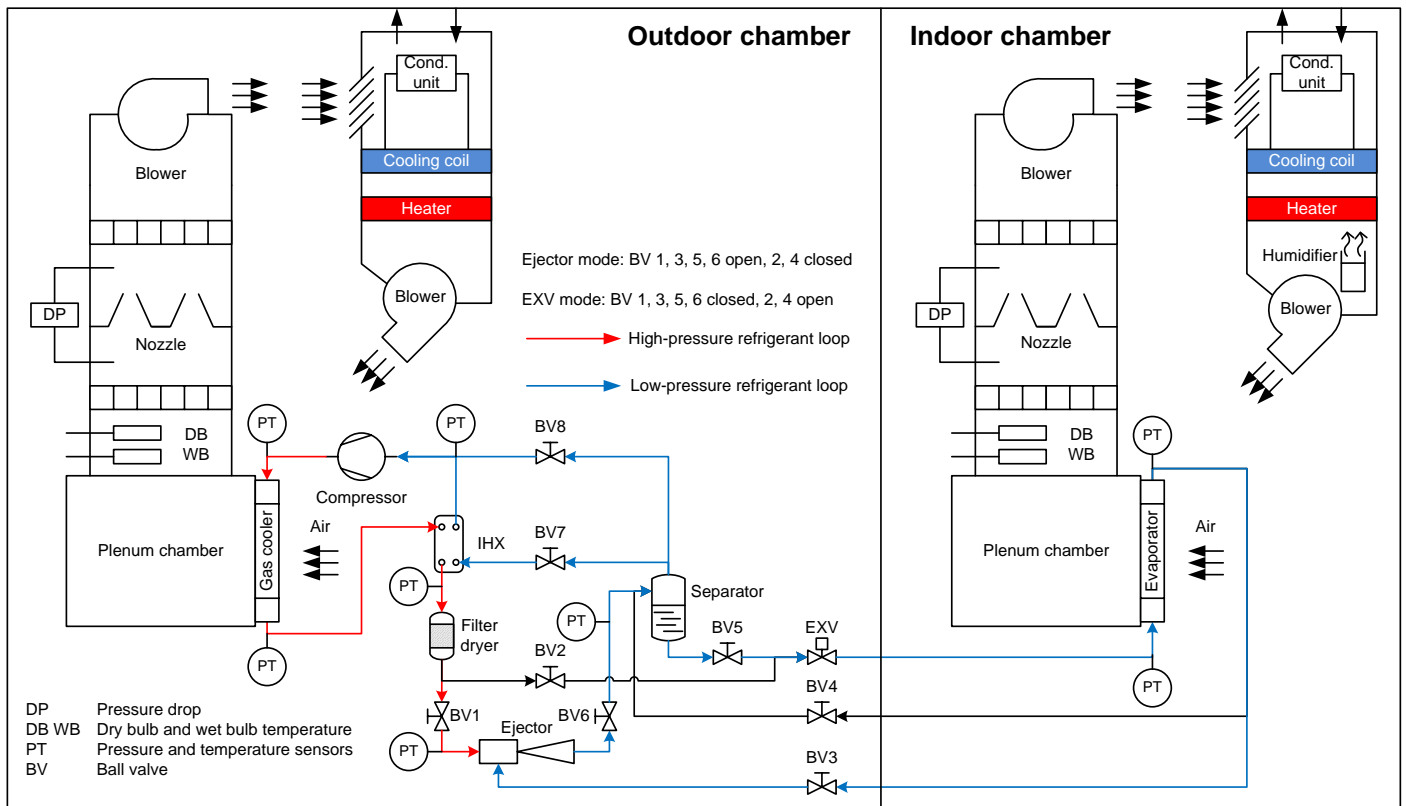


Fig. 1 Schematic diagram of the calorimeter facility for air-conditioning system performance testing

Table 1 Accuracies and calibration range of the measurement equipment

Measured parameter	Instrument	Range	Uncertainty
Air temperature	T-type thermocouples	-50 to 150 °C	±0.1 °C
Relative humidity	Capacitive humidity probe	1 to 100%	±1%
Refrigerant temperature	PT100 RTD	-50 to 150 °C	±0.2 °C
High-side pressure	Pressure transducers	0 to 16 MPa	±0.2% Full scale
Low-side pressure	Pressure transducers	0 to 10 MPa	±0.2% Full scale
Compressor power	Digital power meter	0 to 15 kW	±0.2% Reading

## 2. EXPERIMENTAL FACILITY

### 2.1 Test bench

Tests were performed in an air enthalpy difference calorimeter with independent indoor and outdoor chambers, capable of precise control of air temperature, humidity, and flow rate. Fig. 1 shows the facility used to test the CO<sub>2</sub> air-conditioning system performance.

The CO<sub>2</sub> air-conditioning system used a rotary compressor with a displacement of 8 cm<sup>3</sup>/rev. The compressor speed was controlled by a 15-kW inverter, and its electric power was measured with an additional power meter. The gas cooler and evaporator were parallel microchannel heat exchangers made of aluminium, measuring 655W × 510H × 12D mm and 225W × 250H × 32D mm, respectively. The internal heat exchanger was a stainless-steel plate heat exchanger sized at 155W × 75H × 19D mm. The adjustable CO<sub>2</sub> ejectors used in the experiments were self-developed and are introduced in detail in Section 2.2.

The system could switch between ejector mode and EXV mode by adjusting ball valves, eliminating the need for pipe re-routing. This setup allowed for direct experimental comparison between the two systems using a single test bench. In EXV mode, the EXV regulated the system's mass-flow rate and high pressure. In ejector mode, the system's high pressure was regulated by the adjustable ejector, while the EXV regulated the evaporator mass-flow rate and outlet superheat degree. Measurement instrument accuracies and measurement ranges are provided in Table 1.

### 2.2 Adjustable ejector prototypes

In this study, two types of adjustable ejectors were designed and manufactured for comparative experiments. One was the needle-based adjustable ejector (Needle-EJ), which was a widely used flow-regulating technique in refrigeration. The other was a novel pulse width modulation-based adjustable ejector (PWM-EJ). The PWM-EJ integrated a high-speed solenoid

valve (SOV) into the motive nozzle, modulating the time-averaged mass flow rate by varying the duty cycle. Fig. 2 shows the photos of the two adjustable ejector prototypes. It is worth noting that the two ejectors shared the same geometric design, differing only in their flow-regulating methods. Major geometric parameters of the two ejectors are listed in Table 2.

Table 2 Major geometric parameters of CO<sub>2</sub> ejector

Parameter	Value
Nozzle throat diameter	1.10 mm
Nozzle outlet diameter	1.50 mm
Nozzle divergent angle	2.0 °
Mixing section length	35.00 mm
Mixing section diameter	3.60 mm
Diffuser outlet diameter	10.00 mm
Diffuser divergent angle	3.0 °

## 3. DATA REDUCTION

### 3.1 Performance definition

The performance of the CO<sub>2</sub> air-conditioning system was evaluated by coefficient of performance (COP), which is defined as follows:

$$COP = Q_{\text{evap}}/W \quad (1)$$

The ejector's work recovery performance was evaluated by entrainment ratio and isentropic efficiency, which are determined by the following equations [12]:

$$\omega = \frac{\dot{m}_{\text{evap}}}{\dot{m}_{\text{gc}}} \quad (2)$$

$$\eta_{\text{ej}} = \omega \frac{h(p_{\text{ej out}}, s_{\text{evap out}}) - h_{\text{evap out}}}{h_{\text{ej in}} - h(p_{\text{ej out}}, s_{\text{ej in}})} \quad (3)$$

The mass-flow rates,  $\dot{m}_{\text{evap}}$  and  $\dot{m}_{\text{gc}}$ , were calculated by pressure and temperature sensors connected to the evaporator and gas cooler, respectively:

$$\dot{m}_{\text{evap}} = Q_{\text{evap}}/(h_{\text{satl}}(p_{\text{ej out}}) - h_{\text{evap out}}) \quad (4)$$

$$\dot{m}_{\text{gc}} = Q_{\text{gc}}/(h_{\text{gc in}} - h_{\text{gc out}}) \quad (5)$$

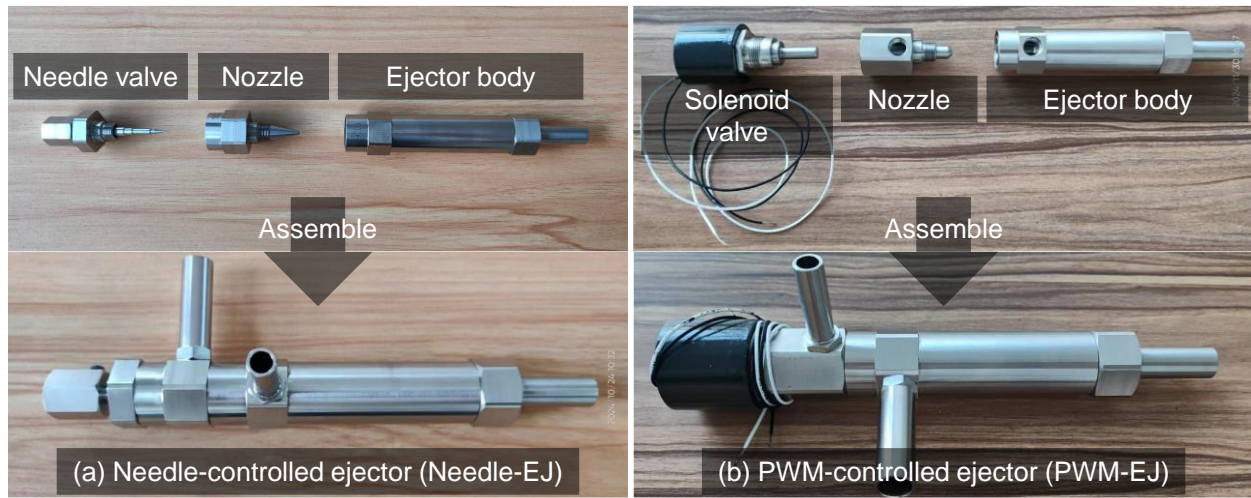


Fig. 2 Adjustable CO<sub>2</sub> ejectors (a) needle-controlled ejector (b) PWM-controlled ejector

### 3.2 Uncertainty analysis

The uncertainties of the directly measured parameters were estimated from the sensor accuracies summarized in Table 1. The overall uncertainties of experimental results were calculated using single-sample analysis method [19]:

$$\delta R(x_1, x_2, \dots, x_N) = \sqrt{\sum_{i=1}^N \left( \frac{\partial R}{\partial x_i} \delta x_i \right)^2} \quad (6)$$

Where the combined uncertainty of quantity  $R$  is a function of quantities  $x_1, x_2, \dots, x_N$ . According to Equation (6), the overall relative uncertainties of cooling capacity, COP and ejector isentropic efficiency were calculated as 4.5%, 4.6% and 7.3%, respectively.

## 4. RESULTS AND DISCUSSIONS

Comparative experiments were conducted on ejector- and EXV-based air-conditioning systems at varying cooling capacity. The dry bulb temperature and wet bulb temperature of the indoor air were controlled at 27 °C and 19.5 °C, respectively. The outdoor air temperature was controlled at 35 °C, 38 °C and 42 °C, respectively, with an outdoor air volume flow rate of 3000 m<sup>3</sup>/h. To adjust the system's cooling capacity, the compressor speed ranged from 2400 r/min to 4800 r/min. Consequently, evaporator's air-side volume flow rate varied between 300 and 500 m<sup>3</sup>/h. The evaporation temperature was maintained at 1±0.3 °C. In the ejector system, the evaporator outlet superheat was controlled within 3 to 5 °C by the EXV. In the EXV system, the evaporator outlet state was not actively controlled. In this case, the separator installed at the evaporator outlet served as a refrigerant charge buffer.

Fig. 3 illustrates the variation in system COP with the gas cooler outlet pressure at different outdoor temperatures. The compressor speed remained constant, while the opening of the ejector nozzle or the EXV was adjusted to modify the system's high pressure. Both ejector types exhibited nearly identical optimal high pressures that maximized COP. However, the optimal high pressure for the ejector system was slightly lower than that of the conventional expansion system, with this reduction becoming more pronounced at higher outdoor temperatures. The optimal high pressure of the ejector system was approximately 0.2 – 0.4 MPa lower than that of the conventional system at 38°C and 42°C, respectively.

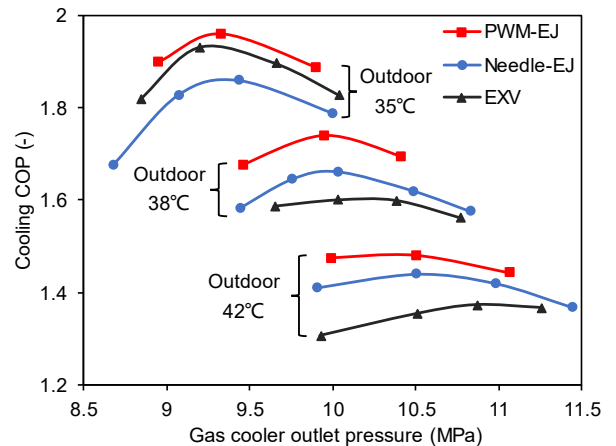


Fig. 3 Variation of system COP with gas cooler outlet pressure at different outdoor temperatures

Fig. 4 shows the COP of ejector and EXV systems at optimal high pressures across cooling capacities and

outdoor temperatures. At 35 °C and 38 °C with the maximum cooling capacity of 4.9 kW, both Needle-EJ and PWM-EJ achieved up to 20% higher COP than EXV. At 42 °C with the maximum cooling capacity of 4.5 kW, ejector systems maintained high COP due to expansion work recovery, outperforming the EXV system by up to 28%. While both ejectors performed similarly at full load, PWM-EJ showed 3% – 8.5% higher COP at part-load (2.5 – 4 kW), peaking at 8.5% (35 °C, 4 kW), indicating better adaptability.

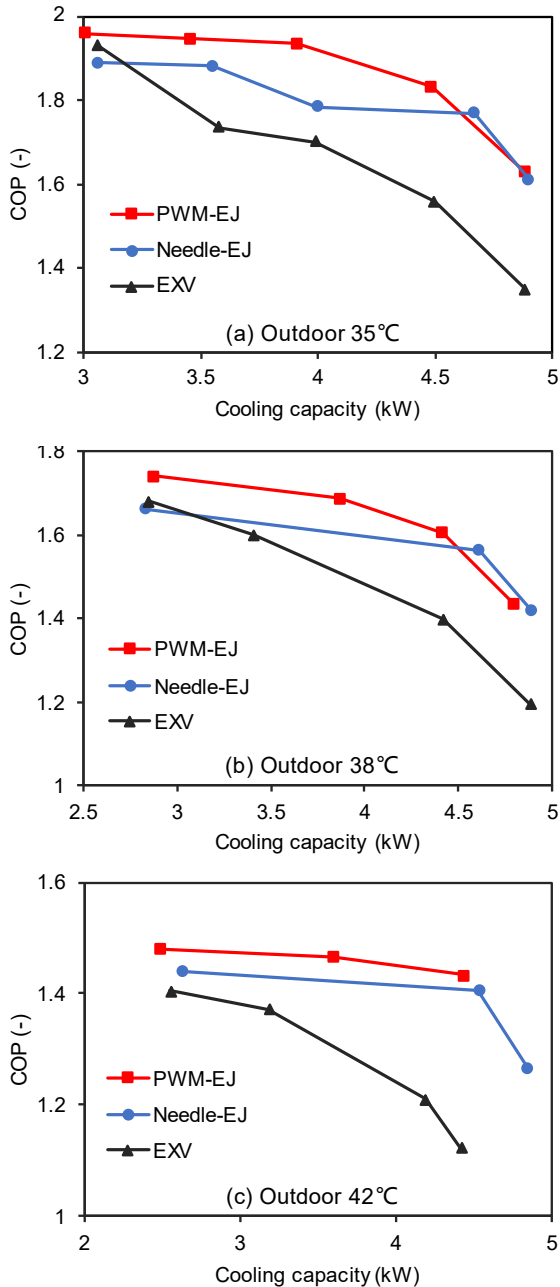


Fig. 4 COP of ejector and EXV systems with varying cooling load at different outdoor temperatures

Fig. 5 compares isentropic efficiency between the two ejectors at varying cooling loads, with an outdoor temperature of 35 °C as an example. As opening decreased from 100% to 60%, Needle-EJ efficiency dropped sharply from 0.384 to 0.187 (–52%), limited by fixed downstream geometry. PWM-EJ declined less (0.401 to 0.220, –45%) and was 15% – 18% more efficient in the 60% – 80% range, explaining the higher COP of the PWM-EJ system at part-load conditions.

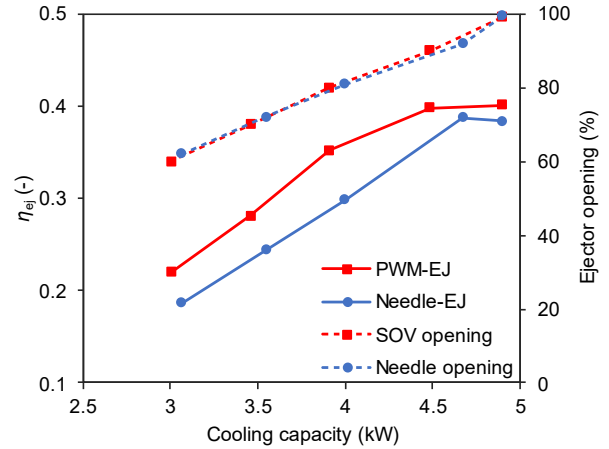


Fig. 5 Ejector efficiency and opening at varying cooling capacity with outdoor temperature of 35°C

## 5. CONCLUSIONS

Ejector technology holds significant potential for reducing energy consumption in transcritical CO<sub>2</sub> air-conditioning systems, particularly under high ambient temperatures. While conventional needle valve-controlled ejectors (Needle-EJ) have been widely studied, their performance deteriorates markedly under part-load conditions, limiting the practical deployment of ejector-based systems. To address this critical issue, this study developed a novel PWM-controlled ejector (PWM-EJ) that integrates a high-speed solenoid valve directly into the motive nozzle, enabling rapid modulation of the effective throat area without altering downstream geometry. The experimental comparison of PWM-EJ, Needle-EJ, and a baseline EXV system yielded three key insights:

- (1) Both ejector systems shared nearly identical optimal high pressures—0.2 – 0.4 MPa lower than that of the EXV system—maximizing COP under the same conditions.
- (2) Ejector-based COP improvement over EXV increased with cooling load, reaching 20% – 28% at full capacity (35 °C – 42 °C), with both ejectors performing similarly.

(3) Crucially, the PWM-EJ outperformed the Needle-EJ at part-load: it maintained 15% – 18% higher ejector efficiency in the 60% – 80% opening range, yielding 3% – 8.5% higher system COP at low-to-medium loads.

This work demonstrates that PWM flow-regulating effectively overcomes the off-design efficiency loss of needle-controlled ejectors, offering a practical, high-performance control strategy for CO<sub>2</sub> ejector systems and advancing their real-world adoption.

Future research should explore the performance of PWM-EJ in subcritical refrigeration and heat pump applications, as well as under smaller opening ranges (e.g., below 50%) and dynamic operating conditions.

#### ACKNOWLEDGEMENT

This work was supported by National Key R&D Program of China (2020YFA0711500), National Natural Science Foundation of China (52376066, 52306104), Shanghai Engineering Research Center of High Efficient Cooling System and Jiangsu Zhongguancun Science and Technology Industrial Park Energy Saving and Environmental Protection Research Co., Ltd.

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