PERFORMANCE ANALYSIS OF AN AIR COMPRESSION REFRIGERATION SYSTEM FOR DATA CENTER COOLING

***Weilai RONG*[1], *Guoyuan MA*[1], *Cong HAN*[2], *Shuxue XU*[*1], *Shangyu SUN*[1], *Guoxin YU*[2]**

([1]Department of Refrigeration and Cryogenic Engineering, Beijing University of Technology, Beijing 100124, China)

([2] Haier Smart Home Co.Ltd., Qingdao 266103, China)

* Shuxue XU; E-mail: xsx@bjut.edu.cn

An air compression refrigeration performance calculation model applied to data center cooling was established, which is a reverse Brayton cycle system, the operation performance was studied by numerical simulation and the influence of supply air temperature, ambient temperature, pressure ratio, data center room temperature was analysed. The results showed that when the pressure ratio of the air compressor is 1.3, the system obtains the maximum cooling COP; heat exchanger efficiency have a significant effect on the cooling capacity and cooling COP, the efficiency of the heat exchanger increases from 0.6 to 0.8, and the increase in cooling capacity is 4.84 kJ/kg, cooling COP increased by 23.2%; Compared to conventional vapour compression/loop heat pipe natural cooling systems, in cold regions, the annual energy efficiency of air compression refrigeration can reach to 13.85.

Key words*: air cooling; cooling COP; data center; cooling capacity; reverse Brayton*

1. Introduction

With the development of society, the deepening of the degree of information technology, the number of data center rooms is increasing, and the demand for air conditioning in data center rooms is also increasing [1]. The heat load of the data center room is high, and the heat of a single cabinet is currently 20-30kW. In order to provide a safe and efficient working environment, the air conditioning system must operate in an all-weather wide temperature zone [2]. Conventional cooling methods for data center mainly include air-cooled direct evaporative air-conditioning systems, water-cooled direct evaporative air-conditioning systems, and chilled water-type server room air-conditioning systems, etc. [3]. And the vapour compression refrigeration using Freon as the work material has a high refrigeration efficiency [4], but Freon destroys the atmospheric ozone layer or brings about global warming. With the promulgation of the Montreal Protocol, the use of Freon refrigerants will be completely banned in the future, and countries are actively looking for and researching new environmentally friendly refrigerants to replace Freon.

Air compression reverse Brayton cycle system uses air as refrigerant, air as a natural working medium, does not pollute the environment, easy to obtain and low cost, non-toxic, non-combustible, non-explosive [5]. In recent years, it has developed rapidly in the fields of aircraft air conditioning, food refrigeration, rail transportation, petrochemical industry, low temperature superconductivity and so on. Air refrigeration systems use air as the compressed mass and the cycle is in the form of an inverse Brayton cycle, which has excellent performance over a wide range of operating conditions [6]. Numerous scholars have studied the application of air cooling system, Lin et al. introduced the air cooling system applied in aircraft air conditioning, and pointed out the development trend of air cooling [7]. Zhang et al. conducted research on air cooling for train air conditioning, the results showed that there is an optimal pressure ratio in the system, which is about 1.5 under the design condition of train air conditioning, and the performance coefficient COP is at its maximum [8].

Wang et al. studied the open inverse pressurization cycle system, and built a full fresh air household air cooling system experimental bench, to obtain the cooling capacity and air supply parameters, that air cooling can give the room a direct air supply and supply air temperature adjustable [9]. Liu et al. conducted a study on two-stage compression of air refrigeration, and the results showed that the two-stage compression COP was 10.2 higher than the single-stage when the pressure ratio was 1.8, and the difference increased with the increase of the pressure ratio [10]. Li et al. analyzed the performance of positive and reverse pressurization systems, and the results show that there is an advantage of adopting positive pressurization system at small pressure ratio and reverse pressurization system at large pressure ratio [11]. Hou et al. proposed an open inverse Brayton cycle using wet air regeneration. The air compression alone has less sensible heat and fully utilizes the latent heat of water vapour, which gives a higher performance than the conventional air cycle [12]. Ren et al. applied a two-stage compressed air reverse Brayton cycle system in train air conditioning to cool down the temperature, the results showed that the increase of the regenerator in the system effectively improved the performance of the system, and it could reduce the compression ratio and the expansion ratio [13]. A. M. Foster et al. introduced a compression expansion refrigeration machine using air as the working fluid. When the isentropic efficiency of the main compressor is between 0.77 and 0.78, and the isentropic efficiency of the turbine is between 0.7 and 0.77, a temperature of -140℃can be achieved [14]. Sui et al. simulated and calculated the law of influence of different pressure ratios and indoor and outdoor parameters on the performance of air compression systems applied in data centers by establishing a thermodynamic model [15].

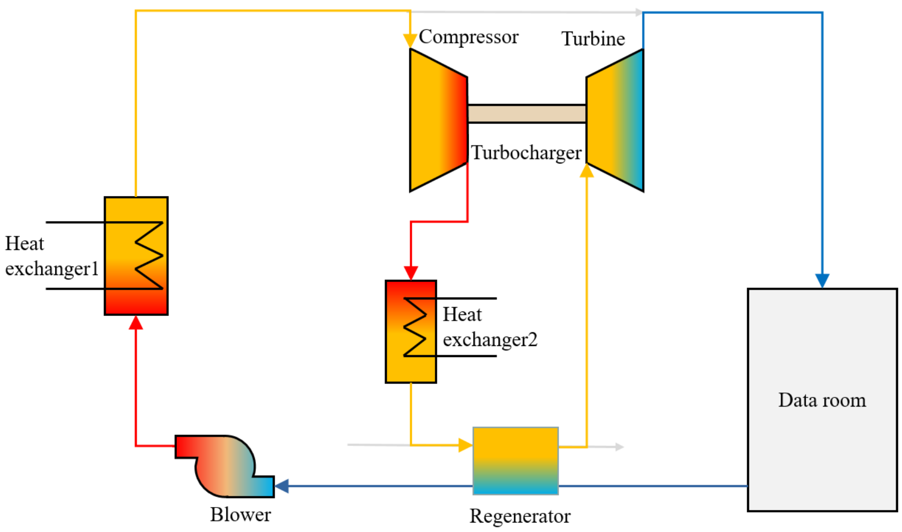
Zhang et al. established a calculation model for an air refrigeration system, the effect of environmental temperature, pressure and other parameters on system performance and optimal pressure ratio were analyzed. The results showed that as the ambient temperature increased, the system COP decreased [16]. Yang Han et al. analyzed the air reverse Brayton cycle system, including the thermal processes of secondary compression, intermediate cooling, and regenerator. Results showed that the electric booster module, secondary heat exchanger, and air circulation machine are key components of the system [17]. José Ramon Serrano et al. used thermal and fluid dynamics models to determine the key components that affect COP, and the results showed that the turbine had the most critical impact [18]. Li Wang et al. proposed a centrifugal reverse Brayton cycle system, and utilizes the conversion mechanism between equipotential energy and pressure energy to improve system performance. The research results indicate that the COP of the system is roughly inversely proportional to the density of the working fluid. When the isentropic efficiency exceeds 95%, cooling COP is from 5.31 to 5.7[19]. Data center server room heat dissipation is large, with over 90% being sensible heat and an average heat dissipation of around 175W per square meter; the moisture dissipation is small, with an average of 8-16g per square meter. The relative humidity range in the computer room is between 40-55%, the cooling system requires large air volume and small enthalpy difference, large air volume can be discharged in a timely manner from the large amount of heat generated by the equipment, small enthalpy difference in air supply can prevent equipment condensation.

This paper proposes an air inverse Brayton cycle refrigeration system applied to data center cooling, which can satisfy the characteristics of large air volume and small enthalpy difference of supply air, and the system is simple, reliable and low cost. The system process is optimized to improve the year-round energy efficiency level by incorporating natural cooling when the outdoor temperature is low. The air cooling cycle performance is simulated to study the influence of key parameters on the overall performance of the system, and representative cities in five climate zones are selected to calculate the annual energy efficiency when applied to data centers in the region, and to compare the performance with that of the traditional vapour compression refrigeration/loop heat pipe natural cooling integrated machine room air conditioning [20], to provide a theoretical basis for application.

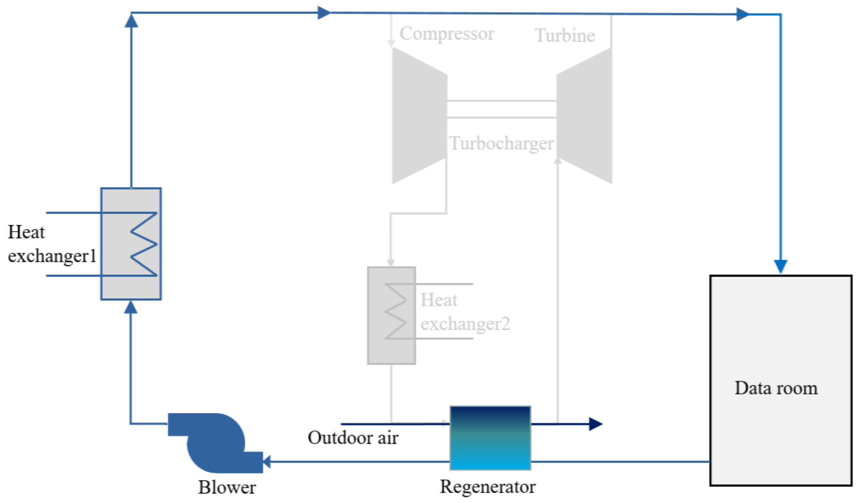
2. System principle

Figure.1 is schematic diagram of air compression cooling for data center cooling. The system consists of a blower, turbocharger, heat exchanger, regenerator and so on. In the air compression refrigeration mode, the blower is the first stage of compression, the turbocharger is used as the second stage of compression, and the air in expansion end of the turbocharger expands and expansion work is transmitted to the compression end through the shaft. The blower provides power for the system, inhales the air from the heat exchanger in the server room after the regenerator, and the discharged high temperature and high pressure air is sent to the heat exchanger 1, and the heat exchanged air is warmed up and pressurized at the compression end of the turbocharger, and then sent to the heat exchanger 2 for cooling, and then it is sent to the regenerator, where it is heat exchanged with the air discharged from the server room of the data center and is sent to the expansion end of the turbocharger to expand and cool down, and finally sent to the data center room. The regenerator can recover the cooling capacity of the exhaust air in the data center room, reduces the temperature entering the expander, which can improve system energy efficiency.

When the ambient temperature is low, the natural cooling mode is turned on, turbocharger and other components are turned off. The low-temperature outdoor air passes through the regenerator before being discharged to the outdoors, and the hot air in the data center room is cooled down by the regenerator and then enters into the blower, which sends the cooled down air into the data room. At this point, the blower operates at a low frequency and only provides power for air circulation.



（a）**Air Compression Cooling Mode**



（b）**Natural cooling mode**

Fig.1 Schematic diagram of air compression cooling for data center cooling system

To analyze the impact of parameters, the assumptions used in the model development are presented below [21].

1) Neglect the heat loss of pipelines;
2) Neglect the pressure loss of each pipe and heat exchanger;
3) The air is an ideal gas;
4) The efficiency of the regenerator is 60%.

The outlet temperature and power of the blower are obtained from Equation 1 and 2:

$$T_{G,out} = T_{G,in} + \left(\left(T_{G,in} \right) \pi_G^{\frac{k-1}{k}} - T_{G,in} \right) / \eta_G \tag{1}$$

$$W_G = c_P q_m \left(T_{G,out} - T_{G,in} \right) \tag{2}$$

Where, $T_{G,out}$ is the exit temperature of the blower (℃); $T_{G,in}$ is the inlet temperature of the blower (℃); η_G is the blower efficiency; W_G is blower power (kW); c_p is the specific heat capacity of air (J kg^{-1} ℃$^{-1}$); k is the adiabatic index of the air ,1.4; π_G is the blower pressure ratio; q_m is the air flow rate (kg/s).

The outlet temperature and power of the turbocharger compressor are obtained from Equation 3 and 4:

$$T_{c,out} = T_{c,in} + \left(\left(T_{c,in} \right) \pi_c^{\frac{k-1}{k}} - T_{c,in} \right) / \eta_c \tag{3}$$

$$W_c = c_p q_m \left(T_{c,out} - T_{c,in} \right) \tag{4}$$

Where, $T_{c,out}$ is the exit temperature of the compressor (℃); $T_{c,in}$ is the compressor inlet temperature (℃); η_c is the compressor efficiency; W_c is compressor power (kW); π_c is the compressor pressure ratio.

The outlet temperature of the heat exchanger is obtained from Equation 5:

$$T_{h,out} = T_{h,in} - \left(T_{h,in} - T_{cold,in} \right) \eta_{ex} \tag{5}$$

Where, $T_{h,out}$ is the exit temperature of the heat exchanger (℃); $T_{h,in}$ is the inlet temperature of the heat exchanger (℃); $T_{cold,in}$ is the inlet temperature of the cold side heat exchanger (℃); η_{ex} is the heat exchanger efficiency..

The outlet temperature and power of the turbocharger expander are obtained from Equation 6 and 7:

$$T_{e,out} = T_{e,in} - \left(T_{e,in} - \left(T_{e,in} \right) / \pi_e^{\frac{k-1}{k}} \right) \eta_e \tag{6}$$

$$W_e = c_p q_m \left(T_{e,in} - T_{e,out} \right) \tag{7}$$

Where, $T_{e,out}$ is the exit temperature of the expander (℃); $T_{e,in}$ is the inlet temperature of the expander (℃);η_e is the expander efficiency; W_e is expander power (kW); π_e is the expander pressure ratio.

The total power W is obtained from Equation 8:

$$W = W_G + W_c - W \tag{8}$$

The system cooling capacity Q is obtained from Equation 9:

$$Q = c_p q_m (T_0 - T_s) \tag{9}$$

Where, T_0 is the temperature of the data center room (℃); T_s is the temperature of the supply air temperature (℃).

The cooling COP is obtained from Equation 10:

$$COP = \frac{Q}{W} \tag{10}$$

The calculation flow chart of the air compression cooling for data center cooling is shown in Fig 2.

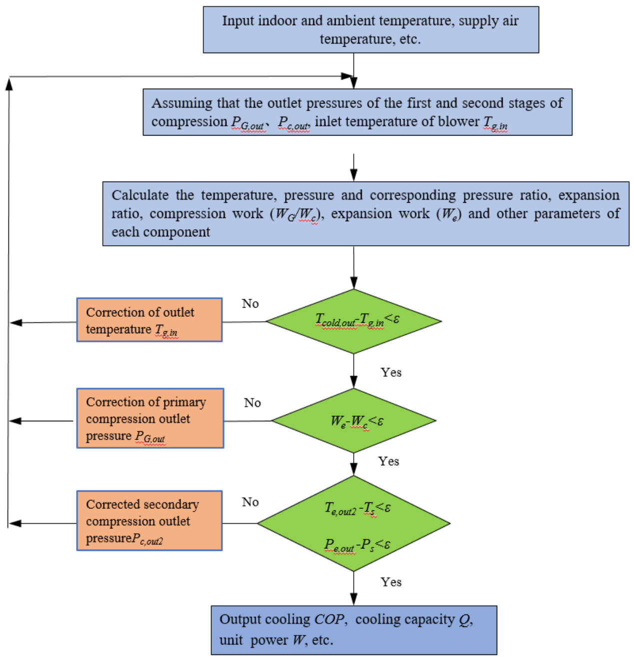


Fig.2 Calculation flow chart

Table 1 shows the simulated working conditions of the air cooling cycle, including supply air temperature, ambient temperature, pressure ratio and temperature range of the date room. Table 2 shows the performance parameters of the main components of the system.

Table. 1 Simulated working conditions.

Cooling capacity/kW	Supply air temperature/°C	ambient temperature/°C	Pressure ratio	Data center room temperature/°C	dimensions of the data center room/m
1.5	12~17	15~35	1.2~2.0	18~28	3.5*2.5*2.5

Table. 2 Main component parameters.

Main components	Parameter
Blower	π_G =1.1～2，η_G =0.8，
Turbocharger compression end	π_c =1.1～1.3，η_c =0.76
Turbocharger expansion end	π_e =1.1～2，η_e =0.76
Heat exchanger	Air-to-air heat exchanger，η_{ex} =0.6

3. Model validation

Reference [15] studied the effect of pressure ratio and efficiency of rotating components on the performance of an air compression refrigeration system. To verify the accuracy of the model, the performance parameters of the air refrigeration cycle system were simulated and calculated under the same operating conditions data points in reference [15]. When the efficiency is 0.8, the difference between the simulated value and the reference value is less than 7.2%, when the efficiency is 1, the difference between the simulated value and the reference value is less than 5.4%, which indicates that the model can accurately reflect the change of the operating performance of the system.

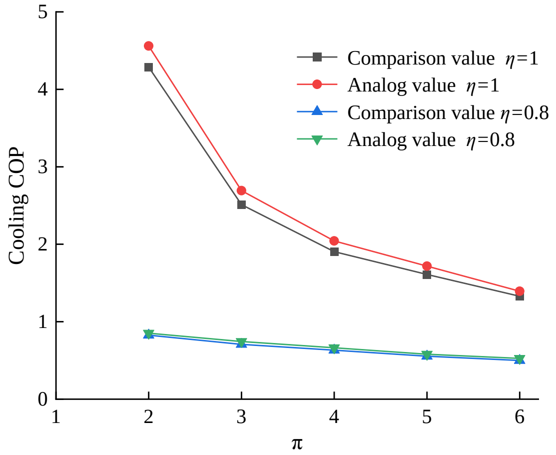


Figure. 3 Comparison results of model validation.

4. Results and analysis

4.1 Effect of pressure ratio

Figure. 4 shows the variation of cooling capacity and cooling *COP* with the pressure ratio. Under the conditions of T_k=35℃, T_0=24℃, data center room pressure P=101.3kPa, As the pressure ratio increases, the expansion ratio increases, the outlet temperature of the expander decreases, and the unit cooling capacity q increases. Cooling *COP* increases and then decreases with the increase of pressure ratio, and the system has the highest cooling *COP* when the pressure ratio is 1.3. When the pressure ratio is greater than 1.3, although the unit cooling capacity increases as the pressure ratio increases, but the compression power consumption also increases, and the final cooling *COP* decreases as the pressure ratio increases. In actual operation to meet the requirements of the data center room cooling capacity, the pressure ratio should be controlled at 1.3.

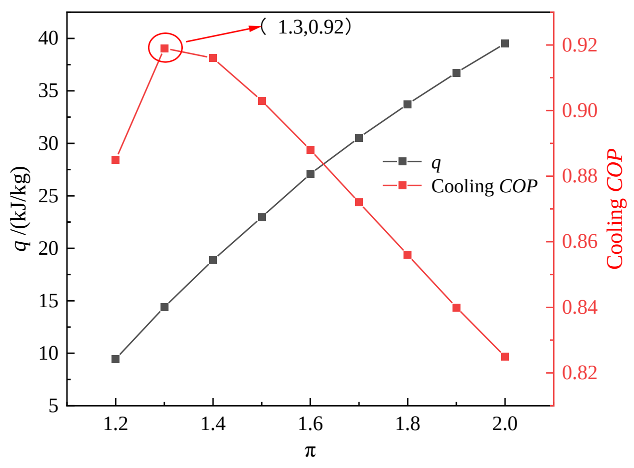
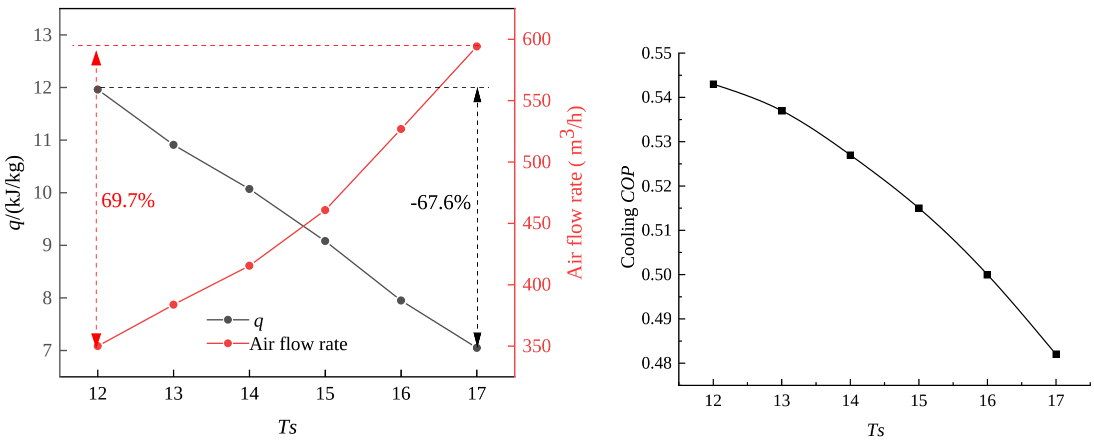


Figure. 4 Variation of cycle performance parameters with pressure ratio

4.2 Effect of supply air temperature

Figure.5 shows the changes of system performance parameters with supply air temperature T_s. It can be seen that as the supply air temperature T_s increases, the temperature of the data room remains constant, the system unit cooling capacity q gradually decreases, and the air flow rate gradually increases. The supply air temperature increases from 12°C to 17°C, the unit cooling capacity decreases from 11.9kJ/kg to 7.1kJ/kg, decreased by 67.6%, and the air flow rate increases from 350.1m^3/h to 594.1m^3/h, decreased by 69.7%. The higher the supply air temperature, the higher the rate of increase of the air flow rate. From Fig.5 (b), it can be seen that as the supply air temperature T_s increases, the system cooling *COP* gradually decreases, and the higher the supply air temperature, the faster the cooling *COP* decreases. Although the increase in supply air temperature reduces the unit compression power consumption, the increase in air flow rate has a greater impact on system performance, resulting in a decrease in system *COP*. In actual operation, it is necessary to adjust the supply air temperature reasonably. It is not allowed to cause the supply air temperature to be too high, resulting in a lower COP of the system, or to cause the supply air temperature to be too low, resulting in a decrease in air flow rate and not meeting the requirements of the data room.

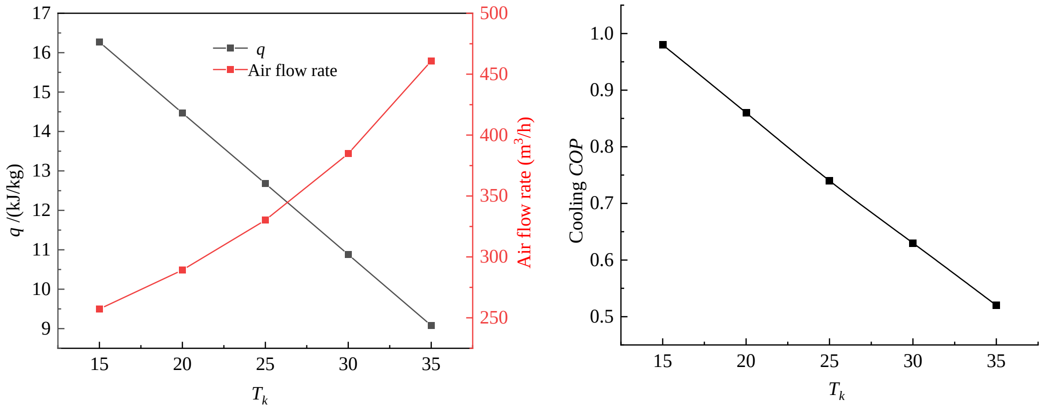


(a) *q* and air flow rate **(b) Cooling COP**

Figure. 5 Variation of system performance parameters with supply air temperature

4.3 Effect of ambient temperature

Under the conditions of T_0=24°C, pressure ratio of 1.3, and data center room pressure P=101.3kPa, the changes of performance parameters corresponding to T_k=15°C, 20°C, 25°C, 30°C, and 35°C，the effect of ambient temperature are calculated, and the results are shown in Figure 6. From Fig.6(a), with the increase of ambient temperature T_k, the unit cooling capacity q gradually decreases, the system air flow rate increases, due to the increase of ambient temperature T_k leads to the condenser side outlet temperature increases, the expander inlet temperature increases, which makes the expander outlet temperature increases, the unit cooling capacity q gradually decreases, when the ambient temperature increases from 15°C to 35°C, the cooling capacity from 16.3 kJ/kg decreases to 9.1 kJ/kg. On the contrary, the air flow rate increases with the increase of ambient temperature. From Fig.6(b), with the increase of ambient temperature T_k, the cooling COP decreases gradually, when the ambient temperature is higher, to improve the system performance, the pressure ratio can be appropriately increased to reduce the air flow rate.

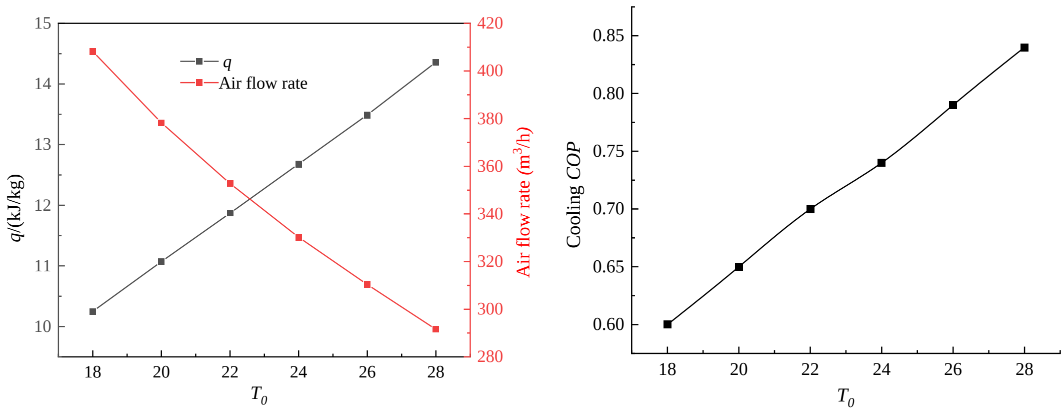


(a) *q* and air flow rate **(b) Cooling COP**

Figure. 6 Variation of system performance parameters with ambient temperature

4.4 Effect of data center room temperature

Under the conditions of ambient temperature T_k=25°C, pressure ratio of 1.3, and data center room cooling load of 1.5kW, the impact of temperature changes in the room on the performance of the system is shown in Figure 7. From Fig. 7(a), as the temperature of the data center room T_0 gradually increases, the system unit cooling capacity q gradually increases, and the air flow rate gradually decreases, when the refrigeration capacity is maintained 1.5kW, the date center room temperature is 22°C and 28°C, the system air flow rate is 352.7m^3/h and 291.5 m^3/h, respectively, the air flow rate reduced by 21%. Fig.7 (b) can be obtained, with the temperature of the date center room T_0 gradually increased, the cooling COP of the system gradually increased. When the temperature required by the data center server room increases, in order to ensure the stability of the temperature in the data room, the supply air temperature also increases, the system's power consumption decreases, the cooling COP increases.



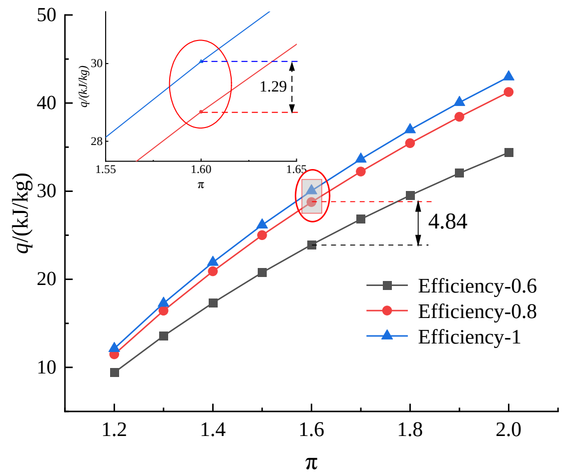
(a) *q* and air flow rate **(b) Cooling COP**

Figure. 7 Variation of system performance parameters with data center room temperature

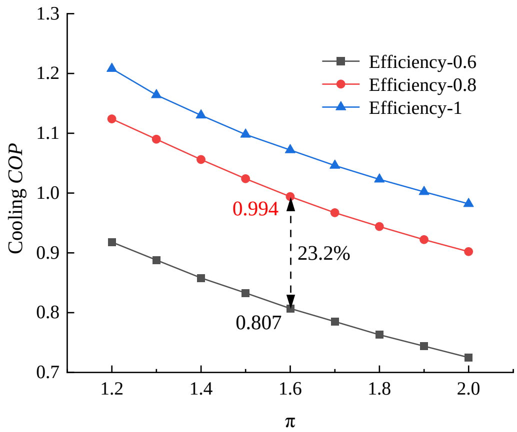
4.5 Effect of heat exchanger efficiency

With data center room pressure P=101.3kPa, T_k=25°C, and T_0=24°C, the effect of different heat exchanger efficiencies on the system performance was analyzed, and the results are shown in Fig. 8. It can be seen from Fig. 8 (a) that unit cooling capacity q of the system gradually increases with the increase of pressure ratio. And the higher the efficiency of heat exchanger is, the higher the unit cooling capacity q is. When the pressure ratio is 1.6, the efficiency of the heat exchanger increases from 0.8 to 1, and the increase in cooling capacity is 1.29kJ/kg, the efficiency of the heat exchanger increases from 0.6 to 0.8, and the increase in cooling capacity is 4.84 kJ/kg. The process of increasing the efficiency of the heat exchanger from 0.6 to 0.8 has a more significant impact on system performance.

From Fig. 8(b), the system cooling *COP* decreases with the increase of pressure ratio. The higher the efficiency of the heat exchanger is, the higher the COP of the system is. The efficiency of the heat exchanger has a significant effect on the COP of the system. At a pressure ratio of 1.6, when the efficiency of the heat exchanger is 0.8, the COP is 0.994, when the efficiency of the heat exchanger is 0.6, the COP is 0.807.



(a) q



(b) Cooling COP

Figure. 8 Variation of circulation performance parameters with pressure ratio at different heat exchanger efficiencies

4.6 Performance comparison

The annual energy efficiency of the air compression refrigeration system applied in the data center was calculated. According to GB50174-2017 "Data Center Design Code", five ambient temperature calculation conditions was selected, respectively, A condition: ambient temperature 35°C; B condition: ambient temperature 25°C; C condition: ambient temperature 15°C; D condition: ambient temperature 5°C; E condition: ambient temperature -5°C, the indoor temperature remains unchanged at 24°C. When the ambient temperature is greater than 15°C use air compression refrigeration mode, open the blower and turbocharger, the expander outlet of the low-temperature air into the data center room cooling, refrigeration COP for the unit refrigeration capacity and the blower unit cycle of the work of the ratio. When the ambient temperature is lower than 15°C the system switches to natural cooling mode, at this time the system refrigeration COP is the ratio of the unit refrigeration capacity and the blower unit cycle work. The system's annual energy efficiency AEER is obtained from Equation 11:

$$AEER = EER_A \cdot \lambda_A + EER_B \cdot \lambda_B + EER_C \cdot \lambda_C + EER_D \cdot \lambda_D + EER_E \cdot \lambda_E \quad (11)$$

Where, λ_A~ λ_E is the ratio of the corresponding test conditions A~E to the annual operation; EER_A~ EER_E is the efficiency of cooling under the corresponding test conditions.

According to the Thermal Design Code for Civil Buildings, China's building climate zones can be categorized into five climate zones: severe cold region, cold region, hot summer and cold winter region, hot summer and warm winter region, and mild region. The representative cities of the five climate zones are selected, namely Harbin, Beijing, Shanghai, Guangzhou and Kunming, and the annual energy efficiency values of the system operating in typical regions are calculated respectively. Table 3 shows the annual energy efficiency values of the air compression refrigeration system operating in typical regions of China.

Table. 3 Annual energy efficiency values for air compression refrigeration operating

Working condition	EER	City				
		Harbin	Beijing	Shanghai	Guangzhou	Kunming
A：T=35℃	0.77	0.8%	4.2%	3.5%	10%	0.1%
B：T=25℃	0.92	17.5%	28.5%	38.8%	55.7%	22.8%
C：T=15℃	7.11	24.7%	25.8%	29.8%	31.2%	57.0%
D：T=5℃	15.22	16.9%	23.5%	26.3%	3.1%	19.8%
E：T= -5℃	23.34	40.1%	18.0%	1.6%	0	0.3%
AEER	-	13.85	9.91	6.88	3.28	7.35

Table 3 lists the annual proportion and cooling EER of each calculation working condition of the five representative cities of the five climate zones, calculated its annual performance AEER. The calculation results were compared with the reference [20], which analyzed the annual energy efficiency of the air conditioner in the integrated room with vapour compression/loop heat pipe natural cooling, and the comparison results were shown in Table 4.

Table. 4 Comparison of year-round performance of air compression refrigeration system and vapour compression/loop heat pipe natural cooling system

Region	Severe cold	Cold	Mild	Hot summer and cold winter	Hot summer and warm winter
Air compression refrigeration system	13.85	9.91	7.35	6.88	3.28

Vapour compression/loop heat pipe natural cooling [20]	13.0	9.0～13.0	7.0～8.0	6.0～10.0	4.0

The results show that the energy efficiency of air compression refrigeration system is higher than that of vapor compression/loop heat pipe natural cooling system in severe cold regions. The annual energy efficiency of air compression refrigeration system in cold region, mild region, hot summer and cold winter region is 9.91, 7.35 and 6.88, respectively. The energy efficiency range of vapor compression/loop heat pipe natural cooling system is 9.0～13.0, 7.0～8.0 and 6.0～10.0, respectively, and the annual energy efficiency of air compression refrigeration system is within its range. In hot summer and warm winter region, the annual energy efficiency value of the air compression refrigeration system is 3.28, which is lower than the annual energy efficiency value of the vapor compression/loop heat pipe natural cooling system is 4.0. Air compression refrigeration systems have excellent performance in severe cold regions, cold regions and mild regions, and have broader application prospects.

5. Conclusions

An air compression refrigeration performance calculation model applied to data center cooling was established, and its operation performance was studied by numerical simulation method. The influence laws of air supply temperature, ambient temperature, pressure ratio, room temperature, heat exchanger efficiency on system refrigeration performance were analyzed. Compared with conventional vapour compression refrigeration, and the most important conclusions of this study are as follows:

1. With the increase of the pressure ratio, the unit cooling capacity increases and the cooling COP first increases and then decreases, and the cooling COP is the highest when the pressure ratio is 1.3.

2. As the temperature of the data center room rises, the unit cooling capacity and the cooling COP gradually increase, while the system air flow rate gradually decreases. With the increase of the supply air temperature, the unit cooling capacity gradually decreases and the cooling COP decreases with the constant temperature of the data center room. With the increase of ambient temperature, the unit cooling capacity and the cooling COP decrease. When the ambient temperature is high, the pressure ratio can be appropriately increased to improve the system performance.

3. Under different heat exchanger efficiency, the unit cooling capacity of the system gradually increases with the increase of pressure ratio. The process of increasing the heat exchanger efficiency from 0.6 to 0.8 has a more significant impact on the system performance than that of increasing the efficiency from 0.8 to 1.

4. In severe cold regions, the annual energy efficiency of air compression refrigeration systems can reach to 13.85, it is higher than that of vapour compression/loop heat pipe natural

cooling systems. Air compression refrigeration systems have excellent performance in severe cold regions, cold regions and mild regions, and have broader application prospects.

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Nomenclature

COP	coefficient of performance	$T_{cold,in}$	inlet temperature of the cold side heat exchanger, °C
c_p	specific heat capacity, kJ kg^{-1} K^{-1}	$T_{e,out}$	exit temperature of the expander, °C
EER	energy efficiency refrigeration	$T_{e,in}$	inlet temperature of the expander ,°C
k	air adiabatic index,1.4	W_G	blower power, kW
P	pressure, kPa	W_c	compressor power, kW
Q	cooling capacity, kW	W_e	expander power, kW
T	temperature, °C	π_G	blower pressure ratio
$T_{G,out}$	exit temperature of the blower, °C	π_c	compressor pressure ratio
$T_{G,in}$	blower inlet temperature, °C	π_e	expander pressure ratio
$T_{c,out}$	exit temperature of the compressor, °C	η_G	blower efficiency
$T_{c,in}$	compressor inlet temperature,°C	η_c	compressor efficiency
$T_{h,out}$	exit temperature of the heat exchanger, °C	η_{ex}	heat exchanger efficiency
$T_{h,in}$	inlet temperature of the heat exchanger ,°C	η_e	expander efficiency
T_k	ambient temperature ,°C	λ	annual operating proportion
T_o	data center room temperature ,°C		

References

[1] Ma G Y., *et al.*, Application study of a pump-driven circit heat pipe heat exchan ger unit for heat dissipation in a small data center, *Journal of Beijing University of T echnology.41*(2015),03, pp.439-445. [in Chinese]
doi.org/10.11936/bjutxb2014070028.

[2] Wang F., *et al.*, Program analysis of natural cooling technology applied to data centers, *Refrigeration and Air Conditioning*, *20*(2020),02, pp.25-30. [in Chinese]
doi.org/10.3969/j.issn.1009-8402.2020.02.005.

[3] Xu M M., *et al.*, Research progress of data center cooling technology, *Building Science*, *34*(2018),08, pp.124-132. [in Chinese]
doi.org/10.13614/j.cnki.11-1962/tu.2018.08.20.

[4] He S., *et al.*, Design and testing of air circulation chiller test bench, *Cryogenics and Superconductivity*, *46*(2018),08, pp.54-57+81. [in Chinese]
doi.org/10.16711/j.1001-7100.2018.08.011.
[5] Wang P., *et al.*, Thermal analysis of a new air cooling cycle with a dew point evaporator, *Journal of Refrigeration*, *42*(2021),02, pp.77-82. [in Chinese]
doi.org/10.3969/j.issn.0253-4339.2021.02.077.
[6] Zhao X X., *et al.*, Numerical study of dynamic cooling characteristics of an inverse Brayton air cooler, *Cryogenic Engineering*, (2013),02, pp.46-51. [in Chinese]
doi.org/10.3969/j.issn.1000-6516.2013.02.009.
[7] Lin S N., *et al.*, The application of air cooler in aircraft air conditioning system, *Fluid Mechanics*, *32*(2004),10, pp.46-49. [in Chinese]
doi.org/10.3969/j.issn.1005-0329.2004.10.012.
[8] Zhang Z Y., *et al.*, Analysis of the application of air coolers in train air conditioning, *Cryogenics and Superconductivity*, *37*(2009),05, pp.57-60+65. [in Chinese]
doi.org/10.3969/j.issn.1001-7100.2009.05.011.
[9] Wang Z F., *et al.*, Performance testing of all-fresh air domestic air cooling systems, *Journal of Refrigeration*, *42*(2021),06, pp.15-20. [in Chinese]
doi.org/10.3969/j.issn.0253-4339.2021.06.015.
[10] Liu Y X., *et al.*, Scheme design of air cooling system for train air conditioning, *Fluid Mechanics*, *31*(2003),06, pp.48-51. [in Chinese]
doi.org/10.3969/j.issn.1005-0329.2003.06.016.
[11] Li J B., *et al.*, Analysis of the factors affecting the performance of domestic air conditioners using air cooling technology, *Refrigeration and Air Conditioning (Sichuan)*, *36*(2022),03, pp.508-512. [in Chinese]
doi.org/10.3969/j.issn.1671-6612.2022.03.027.
[12] Hou S., *et al.*, An open Reversed Brayton cylce with Regeneration Using Moist Air for Air Conditioning Cooled by Circulating Water, *Procedia Environmental Sciences*, *11*(2011), pp.733-740.
doi.org/10.1016/j.proenv.2011.12.114.
[13] Ren J L., Air Cooler, *Refrigeration and Air Conditioning*, *8*(2008),06, pp.15-21. [in Chinese]
doi.org/10.3969/j.issn.1009-8402.2008.06.003.
[14] Foster A M., *et al.*, Air cycle combined heating and cooling for the food industry, *International Journal of Refrigeration*, *34*(2011),05, pp.1296-1304.
doi.org/10.1016/j.ijrefrig.2011.03.016.
[15] Sui Q Y., *et al.*, Performance analysis of an air cooling cycle system applied to data center cooling, *Journal of Refrigeration*, *43*(2022),05, pp.16-23. [in Chinese]
doi.org/10.3969/j.issn.0253-4339.2022.05.016.
[16] Zhang C H., *et al.*, Analysis of the Influence of Environmental Parameters on COP and Energy Efficiency of Regenerated Air Refrigeration Systems with Optimal Compression Ratio, *Heating Ventilating and Air Conditioning*, *53*(2023), 09, pp.141-145+140.
doi.org/10.19991/j.hvac1971.2023.09.21.

[17] Han Yang., *et al*., Optimization of a Reverse-Brayton cycle with inter-cooling and regeneration, *Case Studies in Thermal Engineering*, *53*(2024),103865.
doi.org/10.1016/J.CSITE.2023.103865.
[18] José Ramón Serrano., *et al*., Advanced exergy analysis of a reverse Brayton cycle using air as working fluid for cryogenic purposes, *International Journal of Refrigeration,*2023.
doi.org/10.1016/j.ijrefrig.2023.12.002.
[19] Li Wang., *et al*., Thermodynamic investigation of a centrifugal reverse Brayton c ycle for refrigeration in air conditioning filed, *International Journal of Refrigeration,15 2*(2023)176-191.
doi.org/10.1016/j.ijrefrig.2023.04.022.
[20] Si C Q., *et al*., Analysis of annual energy efficiency ratio of loop heat pipe natural cooling/vapor compression refrigeration integrated machine room air conditioner, *Refrigeration and Air Conditioning*, *19*(2019),06, pp.87-91. [in Chinese]
doi.org/10.3969/j.issn.1009-8402.2019.06.021.
[21] Li S S., et al., Using an air cycle heat pump system with a turbocharger to supply heating for full electric vehicles, *International Journal of Refrigeration,77*(2017), pp. 11-19.
doi.org/10.1016/j.ijrefrig.2017.03.004.

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