

Performance analysis and application of air compression refrigeration system for air conditioning

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Abstract: Among crude refrigerants, air and water are most friendly to humans and the environment. Calculates its actual performance according to typical air parameters in and out of an air conditioning room when the evaporation temperature changes. Analyses its main performance parameters and compares the values with those of Freon steam compression refrigeration system in the same conditions. According to result of calculation and the performance of concerned equipments, demonstrate its applicable fields and development trend.

Keywords: air compression refrigeration system, damp air, refrigeration coefficient, compression ratio

1. Instruction

Due to the damage of CFC refrigerants to the stratosphere, as for the refrigeration and air-conditioning industry, it is a very important problem to find proper refrigerants as the substitutes.

At present, besides replacing R12 and R11 with man-made refrigerants such as HCFC and HFC, it is an important method to find the natural refrigerants as the substitutes. Compared with man-made refrigerants, the natural refrigerants, such as air, N_2 , CO_2 and hydrocarbon, have affluent sources and are easy to obtain and eliminate the atmosphere pollution.

In air conditioning systems, compared with the style of Freon steam compression, the style of air compression has the following advantages (3):

- 1) The refrigerant is air and easy to get and does not pollute the environment.
- 2) The capacity is convenient to be modulated.
- 3) Because air is not only the refrigerant, but also cooling media, velocity of temperature dropping and the rate of energy utilization are both high.
- 4) The system is convenient to run and manage.
- 5) The performance is reliable in that only cooling turbine needs maintenance.

So, the air compression refrigeration system is used in not only big and middle refrigerators with compressed-air source, but also specific air conditioning fields such as aviation and watercrafts. But as common ground air conditioning system, it does not prevail.

The article calculates the actual performance of air

compression system used for air-conditioning rooms and compares its main performance parameter with those of R22 steam compression system in the same conditions. And extend the comparison to other air conditioning and refrigeration systems that need different refrigeration temperatures.

2. The thermodynamic process of air compression refrigeration system

The ideal thermodynamic process of air compression refrigeration system is composed of four processes (as shown in Fig. 1): The air enters the compressor, and is compressed adiabatically to increase its pressure and temperature (1~2), and enters the air cooler to be cooled (2~3) and enters the turbine to decrease the pressure and temperature (3~4) by expanding adiabatically. Then the air with low pressure and temperature enters the room to absorb the heat (4~1). At last the air enters the compressor again to recycles.

Because in general atmosphere condition, the ratio of water vapor in the wet air is very small (<2%), it is not need to think about the probable condensation of small water vapor in processes (2~3 and 3~4). (But the article considers the influence of water vapor in the thermodynamic processes in the calculation in order to make the result more precise.) The whole cycle works in single phase, so the processes of 2~3 and 4~1 can not become the state of equal-temperature. It is different with Freon steam compression refrigeration cycle. The latter has steam-liquid phase, so has the process with equal temperature.

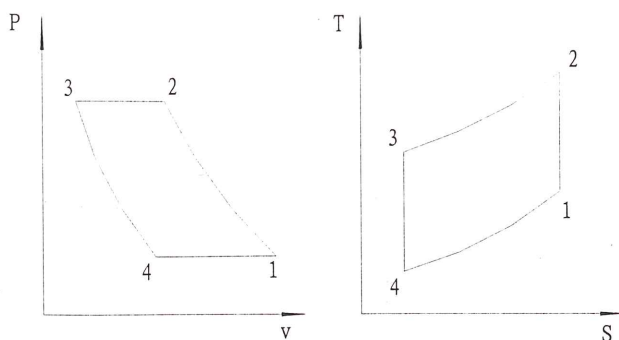


Fig. 1: Thermodynamic processes of air compression refrigeration system

3. The performance calculation as air conditioning system for the purpose of comfort

3.1 The performance calculation of air compression refrigeration system

3.1.1 Calculation conditions

In terms of our national design criterion of heating and ventilation and air conditioning (4), assume the typical air parameters in and out of the air conditioning room as following: the summer air temperature out of the air conditioning room $t_{out}=32^{\circ}\text{C}$, air temperature in the air conditioning room $t_1=26^{\circ}\text{C}$, relative humidity in the room $\phi_1=50\%$. According to specific criterion (4), for air cooling style, the difference in cooling temperature of cooler is about 15°C . So the cooling temperature $t_3=47^{\circ}\text{C}$. The range of compression ratio of air compressor is $1.5 \sim 3$.

3.1.2 Calculation model and result

As shown in Fig. 1, $t_1=26^{\circ}\text{C}$, $\phi_1=50\%$, $P_1=1.01 \times 10^5 \text{ Pa}$, $t_3=3^{\circ}\text{C} \sim 50^{\circ}\text{C}$, $P_2/P_1=1.5 \sim 3$.

In assumed range of t_3 and P_2/P_1 , according to $T_2/T_1=T_3/T_4=(P_2/P_1)^{k-1/k}$ ($k=1.4$), work out T_2 and T_4 , so get t_2 and t_4 . And calculate the unit refrigeration capacity (q_v) and refrigeration coefficient (ϵ) corresponding to different compression ratio (P_2/P_1) and cooling temperature (t_3), according to the following equations:

$$q_m = h_1 - h_4 + q_q \quad q_v = q_m \cdot \rho_1$$

$$\rho_1 = \frac{0.0348 \cdot B}{T_1} - \frac{0.00134 \phi_1 \cdot p_{qb}}{T_1}$$

$$h = 1.005t + \frac{d \cdot (2500 + 1.84 \cdot t)}{1000}$$

$$w_c = h_2 - h_1, \quad w_e = h_3 - h_4 - q_q$$

$$\epsilon = \frac{q_m}{\frac{w_c}{0.75} - w_e \cdot 0.8}, \quad q_m = h_1 - h_4 + q_q$$

where B is standard air pressure, 0.75 is the compression efficiency, and 0.85 is the expansion efficiency.

The effect of water vapor on thermodynamic recycle has been considered in the calculation above.

According to calculation data, draw the curve indicating the relation of ϵ and P_2/P_1 , as shown in Fig. 2.

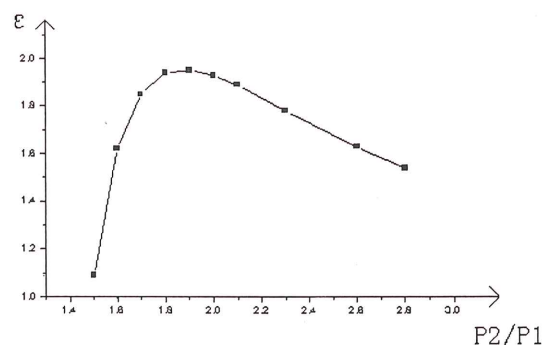


Fig. 2 The relation of ϵ and P_2/P_1 when t_3 is 47°C

Associated with the assumed conditions ($t_1=26^{\circ}\text{C}$, $\phi_1=50\%$) and calculation data, get the maximum of refrigeration coefficient (ϵ) which is 1.59, and the corresponding compression ratio (P_2/P_1) is 1.9 and unit refrigeration capacity (q_v) is 87.84 kJ/m^3 and the temperature (t_4) at the end of expansion is -6.64°C .

3.2 The performance calculation of steam compression refrigeration system

As shown in Fig. 3, use R22 as the refrigerant and take the same calculation conditions as that shown in 2.1.1. According to Standard HB68-88, the temperature of super-cooling liquid (t_3) is 46.1°C , evaporation temperature (t_4) is 7.2°C and the inhaling temperature of compressor (t_1) is 15°C .

According to lgp-h diagram of R22, get the parameters shown as following:

$$h_4=h_3=256.80 \text{ kJ/kg}, \quad h_1=409.75 \text{ kJ/kg},$$

$$h_2=434 \text{ kJ/kg}, \quad \rho_1=26.44 \text{ kg/m}^3$$

According to equations:

$$q_v = (h_1 - h_4) \cdot \rho_1 \quad \text{and} \quad \epsilon = (h_1 - h_4) / (h_2 - h_1)$$

work out:

$$\text{unit refrigeration capacity } q_v = 4044 \text{ kJ/m}^3,$$

$$\text{refrigeration coefficient } \epsilon = 6.31$$

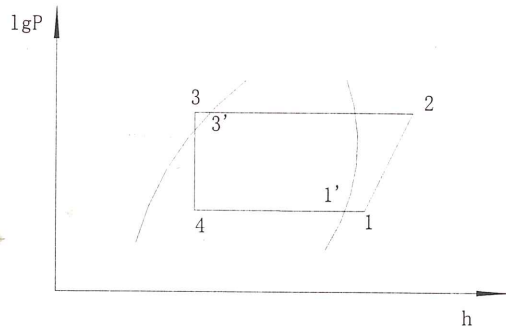


Fig.3: Lgp-h diagram of steam compression system

3.3 The performance comparison of two refrigeration systems

Comparing the values of q_v and ε in 2.1.2 and 2.2, the q_v and ε of air compression refrigeration system are both much smaller. If increase the value of compression ratio (P_2/P_1) in the calculation of 2.1.2, the unit refrigeration capacity will be improved, but ε and t_4 will both decrease. It will increase energy consumption and not meet the wind sending requirements of comfort-aim air conditioning system.

So, used as comfort-aim air conditioning system, except for special requirements, air compression refrigeration system has no practicability.

4. The performance calculation and analysis as air conditioning system used in field needing temperature below zero degree

4.1 Performance calculation of steam compression refrigeration system

To make it convenient to compare the change of performance parameters, according to the conditions in 2.1.1, still assume t_{out} is 32°C and t_3 is 47°C (do not consider the super-cooling temperature for the purpose of convenience of calculation). In terms of Standard GB10874-89, assume inhaling temperature of compressor (t_1) is 5°C , and think the temperature of refrigerant keep almost constant before and after evaporation. In the conditions above, consider the performance change of the system when evaporation temperature (t_4) changes between $0^\circ\text{C} \sim -30^\circ\text{C}$.

In terms of Lgp-h diagram of R22 and equations in 2.2, work out the result (shown in Table 1).

Table 1 Performance of steam compression system

$t_1=t_4(^{\circ}\text{C})$	0	-5	-10	-20	-30
$q_v/(\text{kJ}/\text{m}^3)$	3183	2736	2335	1663	1147
ε	4.41	3.62	3.06	2.60	2.31

The data of the result indicates that as evaporation temperature drops, the unit refrigeration capacity and the refrigeration coefficient of steam compression refrigeration system both decrease.

4.2 Performance calculation of air compression refrigeration system

Referring to the conditions in 2.1.1, consider the humidity in the air below 0°C is very small, so neglect the effect of condensation of water vapor and calculate according to the equations as follows.

$$T_2/T_1 = T_3/T_4 = (P_2/P_1)^{k-1/k} \quad (k=1.4)$$

$$q_m = h_1 - h_4 \quad q_v = q_m \cdot \rho_1$$

$$w_c = h_2 - h_1 \quad w_e = h_3 - h_4$$

$$\varepsilon = \frac{q_m}{w_c - w_e} \quad q_m = h_1 - h_4 \quad (h = 1.01 \cdot T)$$

According to the feature of air compression refrigeration system that inhales air directly from refrigeration room, t_1 is the temperature of refrigeration room. To research the effect of change of compression ratio on refrigeration performance of the system, calculate by different compression ratios. The results are shown in Tables 2 and 3.

Table 2 Performance of air compression system when $P_2/P_1 = 5$

$t_1(^{\circ}\text{C})$	0	-5	-10	-20	-30
$t_4(^{\circ}\text{C})$	-71.01	-71.01	-71.01	-71.01	-71.01
$q_v(\text{kJ}/\text{m}^3)$	93.24	88.01	83.19	71.62	60.06
ε	1.71	1.71	1.71	1.71	1.71

Table 3 Performance of Air compression system when $P_2/P_1 = 7$

$t_1(^{\circ}\text{C})$	0	-5	-10	-20	-30
$t_4(^{\circ}\text{C})$	-89.54	-89.54	-89.54	-89.54	-89.54
$q_v(\text{kJ}/\text{m}^3)$	117.57	112.71	108.45	97.63	87.20
ε	1.34	1.34	1.34	1.34	1.34

The data of the result indicates that as the compression ratio increases, the refrigeration coefficient of air compression refrigeration system drops slightly and the temperature at the end of the expansion also drops, but the unit refrigeration capacity increases obviously.

4.3 The performance comparison of two refrigeration systems

Considering the application of impeller-style compressor with large flow in air compression

refrigeration system, the rotate speed of that compressor is beyond 40000 rpm, which is 10 ~ 30 times as that of the compressor in steam compression refrigeration system. That is to say the flow of air system is 10 ~ 30 times as that of steam system. So in some degree, the factor (R) of rotate speed in the air system increase the total refrigeration capacity, can compensate the flaw of small unit refrigeration capacity of air system (shown in Table 4).

Table4: Comparison of actual capacity in two systems (R=20,
 $P_2/P_1=7$)

$t_1/^\circ\text{C}$	0	-5	-10	-20	-30
$q_{v,s}/(\text{kJ}/\text{m}^3)$	3183	2736	2335	1663	1147
$\varepsilon_{v,s}$	4.41	3.62	3.06	2.60	2.31
$Rq_{v,a}/(\text{kJ}/\text{m}^3)$	2351.4	2254.2	2169	1952	1744
$\varepsilon_{v,a}$	1.34	1.34	1.34	1.34	1.34

According to the analysis above, considering about the energy utilization and actual refrigeration capacity indicated by the data shown in Tables 1 to 4, it is known:

- 1) For the place where refrigeration temperature is required over 0°C , the refrigeration capacity of air compression refrigeration system is obviously less than that of steam system.
- 2) When refrigeration temperature is required between $-5^\circ\text{C} \sim -20^\circ\text{C}$, air compression system has almost the same actual refrigeration capacity as that of steam compression system and less refrigeration coefficient, so it can be applied.
- 3) When refrigeration temperature is required below -20°C , the capacity of air compression system is bigger than that of steam compression system, so it is recommended to be applied.

5. Conclusion

Synthesizing the calculations and analyses above, due to the application of high compression ratio and large flow compressor, the actual refrigeration capacity of air compression refrigeration system is increased evidently. Though the air system is not suitable to be applied in comfort-aim air-conditioning system, its application range has been extended greatly. From the refrigeration performance, the air system can be applied in the places where the temperature below -5°C is needed, especially without the limit of the temperature difference between sending wind and indoor air.

Furthermore, with the development of heat-recycle technique that can make the compression ratio drop by keeping unit refrigeration capacity and refrigeration coefficient constant, the coefficient of energy utilization will be improved further. So it is expected that the air compression refrigeration system will be applied more and more widely in future.

Notations

Symbol	Meaning	Unit
t	temperature	$^\circ\text{C}$
T	thermodynamics temperature	K
φ	air relative humidity	
P	air pressure	Pa
k	air constant	
q	unit refrigeration capacity	kJ/kg
ρ	air density	kg/m^3
h	enthalpy value of wet air	kJ/kg
w	power of system	kJ/kg
ε	refrigeration coefficient	
R	factor of rotate speed in the air system	

Subscript	Meaning
1	Inlet of compressor
2	Outlet of compressor
3	Outlet of air cooler
4	Outlet of turbine or evaporation
m	unit quality
c	compression
e	expansion
v	Unit volume
q	vapor
a	air
s	steam

References

- 1 Qiu L and Lian L. Engineering Thermodynamics. 3rd ed. Beijing: China Architecture Industrial Publishing Company, 1992.
- 2 Yue X and Cheng R. Technique and Application of Refrigeration. 1st ed. Shanghai: Tongji University Publishing Company, 1992.
- 3 Yang L. Principle and Technique of Refrigeration. 1st ed. Beijing: Science Publishing Company, 1988.
- 4 Lu Y. Practical Handbook of Heating Supply and Air Conditioning Design. 1st ed. Beijing: China Architecture Industrial Publishing Company, 1993.