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Performance analysis of HCFCs, HFCs and natural refrigerants under different working conditions based on single-stage vapor compression system

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Abstract: *Environmental problems such as the destruction of the ozone layer and global warming force people to choose refrigerants. It has become an inevitable trend to look for refrigerants with low ODP (Ozone Depletion Potential) and GWP (Global Warming Potential) to replace the refrigerants that are harmful to the environment. In addition, we also need to consider the COP (Coefficient Of Performance) and safety of refrigerants. This paper is based on a single-stage vapor compression refrigeration system, The COP of different refrigerants are calculated and analyzed under five different working conditions. After calculation, the COP of R717 is the highest under five working conditions, and its GWP is 0, but its safety level is only B2L.Therefore, it is very difficult to take into account the various properties of refrigerants at the same time.*

Keywords: *GWP, COP, refrigerants, environment, conditions*

1. Introduction

Global warming and ozone layer destruction are the two most important environmental problems faced by human beings all over the world[1].The continuous reduction of the ozone layer will destroy the ecological environment and lead to global warming[2].Studies have shown that the global average temperature increased by 0.85 ℃ between 1900 and 2020.According to the six assessment reports of IPCC (Intergovernmental Panel on Climate Change) [7], if human beings do not take effective action to control the trend of global warming, it is predicted that in the late 21st century, the global temperature will rise by 3.6 ℃ to 4.4 ℃ [2].The increase of temperature will lead to the frequent occurrence of extreme weather such as extreme heat, drought and flood[3].

People were aware of such serious environmental problems in the 1980s. In 1985 and 1987, the international community formulated and signed the Vienna Convention for the Protection of Ozone Layer and the Montreal Protocol Substances at Deplete the Ozone Layer [3], in 1922 signed United Nations Framework Convention on Climate Change and so on [4]. The contents of these conventions contain the controlled time of refrigerants that can cause environmental damage. According to the Kigali amendment to the Montreal Protocol Substances at Deplete the Ozone Layer, Chinese HCFCs will be eliminated by 67.5% in 2025 and 97.5% in 2030, with only 2.5% for maintenance based on the average level of 2009 and 2010. Meanwhile, HFCs (hydrofluorocarbon refrigerants) will be frozen in 2024 and 80% will be eliminated by 2045[5].

The CFCs with high ODP (chlorofluorocarbon refrigerants) were completely eliminated in China in 2007.However, HCFCs are widely used in the refrigeration field in China. The GWP of HCFCs is relatively high, and its service life in the atmosphere is longer[4]. According to the fifth report of IPCC, the GWP of HCFCs refrigerants such as R22 is 1760, and the lifetime in the atmosphere is 11.9 years, so extensive use of these refrigerants will further accelerate the rate of global warming.

Therefore, it has become an irresistible trend to choose refrigerants with low GWP to replace high GWP refrigerants. According to the fifth report of the IPCC, the GWP of R1234yf in HFCs is less than 1, and that of natural refrigerants such as R717 is 0. These refrigerants have low GWP and are environmentally friendly refrigerants. However, GWP can only reflect the effect of global warming directly caused by the emission of greenhouse gases into the atmosphere. But it can not reflect the global warming caused by fossil fuel and other energy consumption in the process of using this kind of gas[4].The refrigeration cycle is a reverse cycle, in which the power consumption is needed to generate the cooling capacity. The refrigeration system has the vapor compression system. This traditional

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system mainly consumes electric energy in the process of operation, and the energy consumption is high. However, due to the high COP, low cost and simple structure, vapor compression system is widely used in China[6].According to the data released by CEC (China Electricity Council) in 2022, from January to February in 2022, fossil fuel based thermal power generation capacity will reach 986.37 billion kilowatts in China. It can be seen that the global warming effect caused by energy consumption generated in its working process can not be ignored. Therefore, in order to alleviate the problem of global warming, it is not enough to consider only the GWP of refrigerant itself, but also the COP of refrigerant in the working process.

At present, the analysis of GWP and COP of refrigeration at home and abroad is based on single-stage vapor compression system. Some literatures have analyzed GWP and COP of R1234yf, R1234a and other refrigerants under 1-2 working conditions[8-12]. However, due to the nature of refrigerants, the refrigeration performance of refrigerants under different working conditions is quite different. In some low or high temperature conditions, many refrigerants are difficult to be applied due to the limitation of evaporation temperature, so it is necessary to select a variety of working conditions for calculation and analysis in performance analysis. Therefore, taking the most widely used single-stage vapor compression system as an example, the GWP and COP of some refrigerants are calculated and analyzed in order to meet the requirements of environmental protection. This paper provides a reference for the selection of refrigerants under different application conditions. The development idea of this paper is shown in Fig. 1.

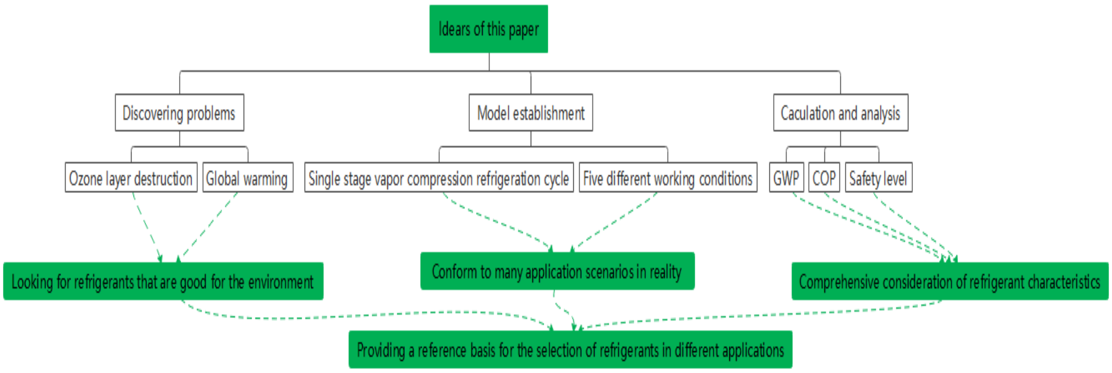

Figure 1: The development idea of the paper

2. Experiment part

This paper takes the single-stage vapor compression system as an example to analyze the performance of the system. The single-stage vapor compression system is shown in Fig. 2. The process 1-3 is the absorption and evaporation of refrigerant in the evaporator, the process 3-5 is the process from the refrigerant leaving the evaporator to the compressor starting to compress, and 5-6 is the compression process of the refrigerant in the compressor,6-8 process is the process before the refrigerant leaves the compressor and starts to cool and condense in the condenser. 8-11 is the cooling and condensation process of refrigerant in the condenser, and 11-1 is the throttling process of refrigerant passing through the throttling element.

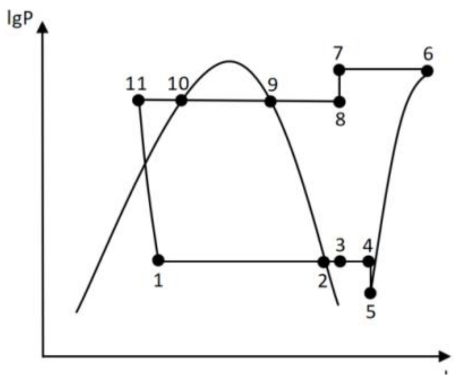

Figure 2: Single-stage vapor compression refrigeration cycle

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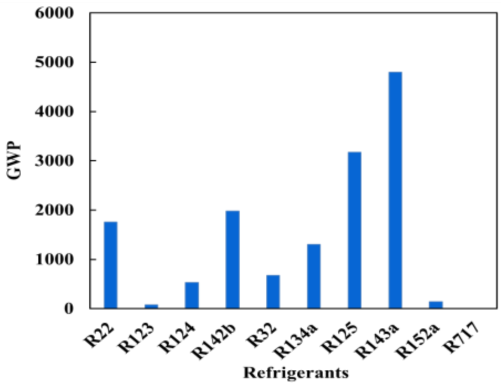

Figure 3: GWP of different refrigerants

In order to be more close to the actual conditions, the following factors are considered in this paper.

1) There are temperature drop and pressure drop of refrigerant in the pipeline from evaporator to compressor inlet.

2) There is temperature rise and pressure drop of refrigerant in the pipeline from compressor outlet to condenser inlet.

3) The enthalpy of refrigerant flowing through the throttling element increases.

At the same time, in order to facilitate the calculation, this paper puts forward the following assumptions:

1) The whole single-stage steam compression system is in stable state.

2) There is no transcritical cycle during the cycle.

3) The pressure drop of refrigerant in evaporator is ignored.

4) The pressure drop of refrigerant in the condenser is ignored.

5) The process of refrigerant from evaporator to compressor, 3-5 is simply considered as 3-4 isobaric superheating process and 4-5 equal enthalpy throttling process.

6) The process of refrigerant leaving the compressor and entering the condenser begins to cool and condense. 6-8 is simply considered as the isobaric cooling process of 6-7 and the equal enthalpy throttling process of 7-8.

7) The pressure drop of 4-5 isoenthalpy throttling process includes the pressure drop of refrigerant in the pipeline from evaporator outlet to compressor inlet and the pressure drop of refrigerant at compressor inlet as well as 7-8.

In order to calculate, some parameters need to be set. The set compressor efficiency, pressure drop, temperature drop and temperature rise are shown in Table 1. Most of the parameters are selected by reference. In AHRI (The Air-Conditioning, Heating, and Refrigeration Institute) 540-2004, AHRI divided the operation conditions of displacement compressor into five nominal conditions: low-temperature refrigeration condition, medium temperature refrigeration condition, high-temperature refrigeration condition, heat pump condition and air-conditioning refrigeration condition. In this draft, the corresponding condensation temperature, evaporation temperature, superheat and subcooling degree corresponding to the five nominal conditions are proposed in the draft, as shown in Table 2. In this paper, the parameters proposed in the draft will be selected for calculation. The refrigerant selected for performance analysis is shown in Table 3, table 4 and table 5. The author will use EES software to program the cycle and calculate its performance under different refrigerants. The indexes to be calculated for performance analysis are as follows. It should be noted that the cooling capacity is a constant value in the calculation process. In addition, the COP calculation formula of low temperature refrigeration condition, medium temperature refrigeration condition, high temperature refrigeration condition, air conditioning refrigeration condition and heat pump heating condition is different. The COP of the first four conditions is recorded as $\mathrm{COP_{cold}}$,the COP of the latter is recorded as $\mathrm{COP_{heat}}$ in order to distinguish:

Power consumption of compressor (kJ/kg)

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$$w = h_6 - h_5 \quad (1)$$

Refrigerating capacity (kJ / kg) and Condensation heat per unit mass (kJ / kg)

$$q_0 = h_2 - h_1 \quad (2)$$

$$q_k = h_8 - h_{11} \quad (3)$$

Refrigeration efficiency $\mathrm{COP_{cold}}$ and heating efficiency $\mathrm{COP_{heat}}$

$$\mathrm{COP_{cold}} = w/q_0 = (h_6 - h_5)/(h_2 - h_1) \quad (4)$$

$$\mathrm{COP_{heat}} = w/q_k = (h_6 - h_5)/(h_8 - h_{11}) \quad (5)$$

Table 1: Compressor efficiency, pressure drop, temperature rise and temperature drop set in calculation

Parameter	value
Isentropic efficiency of compressorηi	0.7
Pressure drop of refrigerant in the pipeline from evaporator outlet to compressor inlet(Δp1)/kPa	5
Pressure drop of refrigerant in the pipeline from compressor outlet to condenser inlet(Δp2)/kPa	10
Pressure drop of refrigerant at compressor inlet(Δp3)/kPa	15
Pressure drop of refrigerant at compressor outlet(Δp4)/kPa	30
Temperature rise of refrigerant in the pipeline from evaporator outlet to compressor inlet(Δt1)/°C	10
Temperature drop of refrigerant in the pipeline from compressor outlet to condenser inlet(Δt2)/°C	10
Enthalpy increase of refrigerant passing through throttling element(Δh)/J/kg	20

Table 2: Different working conditions

Application conditions	Condensation temperature /°C	Evaporation temperature /°C	Superheat/°C	Undercooling degree/°C
Low	40.5	-31.5	11	0
Medium	43.5	-6.5	11	0
High	54.5	7	11	0
Air conditioning	35	-15	11	0
Heat pump	46	10	11	0

Table 3: Calculates the ODP, GWP and safety level of different refrigerants of HCFCs

Cryogen	ODP	GWP	Safety level
R22	0.034	1760	A1
R123	0.01	79	B1
R124	0.02	527	A1
R142b	0.057	1980	A2
R32	0	677	A2L
R134a	0	1300	A1
R125	0	3170	A1
R143a	0	4800	A2L
R152a	0	138	A2
R717	0	1	B2L

3. Results and discussion

The GWP of the 10 refrigerants involved are shown in Fig. 3. On the premise that the refrigeration capacity in the cycle is a constant value, the COP of the 10 refrigerants under high temperature refrigeration condition, the medium temperature refrigeration condition, the high temperature refrigeration condition, the air conditioning refrigeration condition and the heat pump condition of the single-stage vapor compression system are shown in Fig. 4-5. The less power the compressor consumes, the weaker the indirect global warming effect of fossil fuel energy consumed by generating electricity. Therefore, the refrigerant with low GWP and high COP can be selected under different working

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conditions, and the environment-friendly refrigerant can be obtained.

In this paper, the COP of 10 refrigerants under high temperature refrigeration conditions are calculated. As shown in Fig. 4, among all refrigerants, the COP of natural refrigerant R717 is the highest, that of HFCs refrigerant R125 is the lowest. The highest COP of HCFCs is R142b, the lowest COP of HCFCs is R123. The highest COP of HFCs is R152 and the lowest is R125a.The refrigerant R22, which is commonly used on the market in China, is taken as the standard. Among the 10 refrigerants, only R142b, R152a and R717 have higher COP than R22. The COP of these three refrigerants increases by 0.5%, 6.3% and 25.7% respectively compared with R22. The refrigerants with COP less than 10% decrease compared with R22 are R32 and R134a. The COP of R32 decreases by 0.4% compared with R22, while that of R134a decreases by 5.36%. As shown in Fig. 3, the GWP of R142b is 12.5% higher than that of R22, and the GWP of the other four refrigerants is lower than that of R22, but the GWP of R134a is still above 1000.According to ASHRAE 34-1992, four of the five refrigerants are flammable. R142b is A2 and its flammability is flammable. R152a is also A2, and its flammability is low. R32 is A2L and its flammability is weak. R717, with the highest COP, has a safety level of B2L, indicating that it is not only weakly flammable, it is also highly toxic. In terms of the safety of the four refrigerants, we should strictly control the use of these four refrigerants.

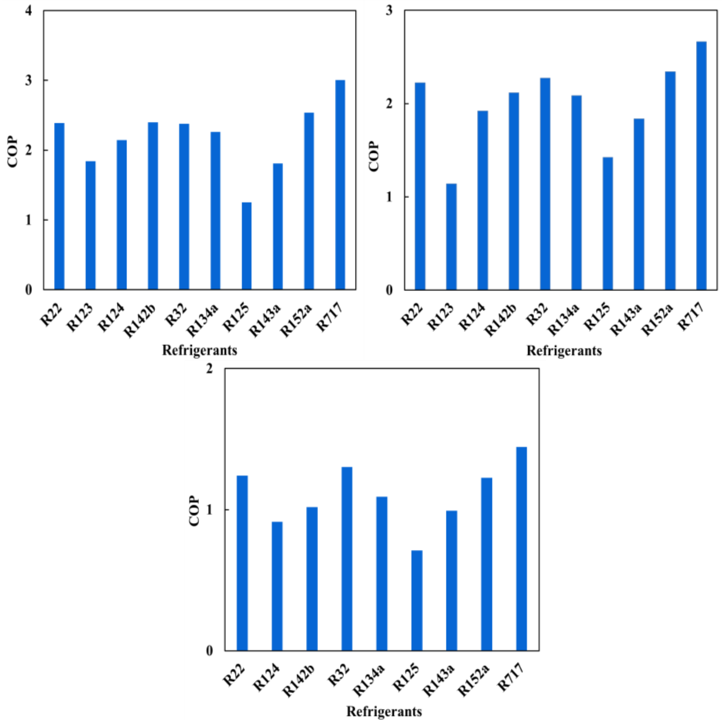

Figure 4: COP of different refrigerants under high, medium, low temperature refrigeration condition

As shown in Fig. 4, under medium temperature refrigeration conditions, the COP of natural refrigerant R717 is the highest that of HCFCs refrigerant R123 is the lowest. The highest COP of HCFCs is R22 and the lowest COP of HCFCs is R123. The highest COP of HFCs is R152a and the lowest is R125.Compared with high temperature refrigeration condition, the COP of each refrigerant under medium temperature refrigeration condition is reduced. Among the three refrigerants with COP higher than R22, only R152a and R717 are still higher than R22, with an increase of 5.3% and 19.8% respectively. The COP of R142b is 4.9% lower than that of R22, while that of R32 with COP lower than R22 in high-temperature refrigeration condition is 2.3% higher than that of R22 under medium temperature. Under medium temperature refrigeration condition, except R142b, the COP of R134a decreases by less than 10% compared with R22, and the decrease rate is 6.3%. This shows that the performance of refrigerants is different under different working conditions, which verifies the necessity of calculating COP in multiple working conditions.

Due to the low evaporation temperature under low temperature refrigeration condition, R123 refrigerant is not suitable for this kind of working condition. There are only 9 kinds of refrigerants for calculation and analysis. As shown in Fig. 4, the COP of natural refrigerant R717 is still the highest that of HFCs refrigerant R125 is the lowest. The highest COP of HCFCs is R32 and the lowest is R124.The highest COP of HFCs is R32 and the lowest is R125.Compared with high temperature and medium temperature refrigeration conditions, the COP of each refrigerant further decreased. Under this condition, only R32 and R717 with COP higher than R22 increased by 4.8% and 16.4% respectively. Under low temperature refrigeration condition, only R152a has a decrease rate of 1.3% compared with R22, but all of the three refrigerants are flammable.

Similarly, due to the low evaporation temperature under the air conditioning refrigertaion condition, R123 refrigerant is also not suitable for this condition, and there are only 9 kinds of refrigerants for calculation and analysis. As shown in Fig. 5, under air conditioning refrigeration condition, the COP of natural refrigerant R717 is still the highest that of HFCs refrigerant R125 is the lowest. The highest COP of HCFCs is R32 and the lowest is R124.The highest COP of HFCs is R32 and the lowest is R125.Compared with high-temperature refrigeration condition, medium temperature refrigeration condition and low-temperature refrigeration condition, the COP of these refrigerants has little difference under air conditioning refrigeration condition. Compared with R717, the COP of the refrigerant with the lowest COP only decreases by 39%, which is less than 58% of the high temperature refrigeration condition, 57% of the medium temperature refrigeration condition and 50% of the low temperature refrigeration condition. Under this condition, the refrigerants with COP higher than R22 are R152a, R32 and R7173, which increase by 2.8%, 3.5% and 15.8% respectively. The COP of R142b and R134a is reduced by 9.3% and 6.9% when compared with R22.

Ten kinds of refrigerants were calculated and analyzed under heat pump condition. As shown in Fig. 5, under heat pump condition, the COP of natural refrigerant R717 is still the highest that of HCFCs refrigerant R123 is the lowest. The highest COP of HCFCs is R22 and the lowest is R123.The highest COP of HFCs is R152a and the lowest is R125.Compared with the first four working conditions, the COP levels of these 10 refrigerants are higher under air conditioning refrigeration condition, and the difference is small. The COP of R123 is only 26% lower than that of R717. Under this condition, only R152a and R717 with COP higher than R22 are R152a and R717, with an increase of 0.6% and 6.1% respectively. Under heat pump condition, the COP of r124, R142b, R32 and R134a are reduced by 4.2%, 3.0%, 2.6% and 2.4% respectively.

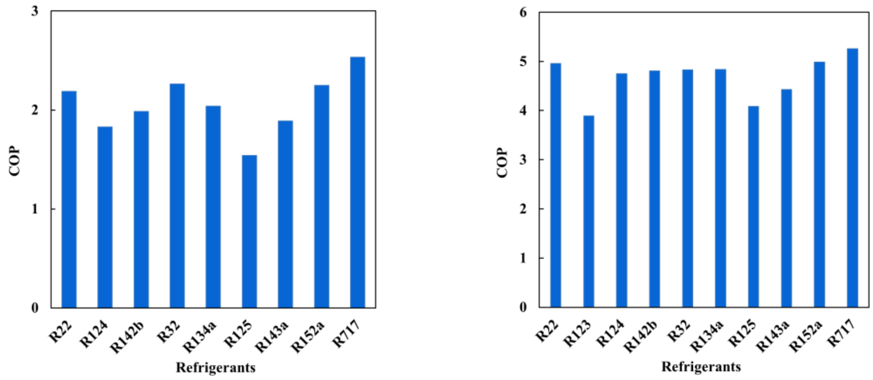

Figure 5: COP of different refrigerants under air conditioning refrigeration, heat pump condition

4. Conclusion

Through comprehensive analysis of COP of 10 refrigerants under five different working conditions, it can be found that the COP of natural refrigerant R717 is the highest under five different working conditions, and the COP of R134a, R32, R22, R152a and R142b are relatively good, while the COP of R123 of HCFCs and R125 of HFCs are lower under five working conditions. Among the six refrigerants with high COP, R22 and R142b belong to HCFCs which will be eliminated soon. In the remaining four refrigerants, only R134a has a safety level of A1, but its GWP is still above 1000, and the safety level of R717 which with the highest COP is B2L. It can be seen that the refrigerant is difficult to meet the safety level of low GWP, high COP and A1 at the same time. Therefore, in order to slow down the global warming effect, when using refrigerants with low GWP and high COP, it is necessary for enterprises to put safety issues in the first place and strictly control the operation problems of employees and the safety problems of equipment.

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