Analysis of APF Standard of Japan and China and Research of R32 Inverter Compressor with High Efficiency

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ABSTRACT

In this paper, the differences between APF (Annual Performance Factor) of Japanese and Chinese standards were analyzed. In the APF standard of Japanese, the intermediate condition had the greatest influence on APF. Therefore, in the process of researching compressors for the Japanese market, it was necessary to focus on improving the energy efficiency level of middle and low frequency. Some ideas for the development of high-efficiency compressor was also provided. With the improvement of energy efficiency of air conditioning, compressor design should dare to innovate and dare to break through the routine. Based on innovative technologies such as rocker blade, high-efficiency technology of eccentric part of crankshaft and breakthrough of motor, the energy efficiency of compressor was greatly improved compared with the base compressor, and the improvement rate of intermediate cooling condition was 9%, and the improvement rate of other conditions was about 5%. Equipped with Japan's high-efficiency air conditioning system, the APF was reaching a higher level in the industry.

1. INTRODUCTION

In 2023, china household electrical appliances association released the white paper on the dual carbon action plan for the Chinese household appliance industry before 2030, which mentioned the need to continuously improve product energy efficiency levels. By 2030, the average level of product energy efficiency will increase by 20%. Therefore, with the increasing demand for energy conservation, high-efficiency air conditioning will become a future industry trend.

One of the evaluation indicators for household air conditioning is APF (Annual Performance Factor), which was first proposed by Japan and implemented in 2010. Japan began implementing the "Leader" program in 1998. The "Leader" plan is different from the minimum energy efficiency standard, which sets the highest energy efficiency level in the current market as the energy efficiency target of the product. When the target is reached, the new target energy efficiency value will be reset. Under the guidance of the "Leader" program, Japan has now become the global benchmark market for household air conditioning energy efficiency.

Based on the above, this article takes the mainstream capacity below 7.1 kW as an example, analyzes the differences in APF evaluation methods between Japan and China, and provides design ideas for high-efficiency compressors, which has certain reference significance for understanding APF standards and developing high-energy efficiency products.

2. ANALYSIS OF APF STANDARD OF JAPAN AND CHINA

APF comprehensively considers the energy efficiency of inverter air-conditioner in the cooling and heating seasons, which is related to the occurrence time, load design, etc.

2.1 Using Time

The APF standards in Japan and China stipulate that the ambient temperature and annual time for air conditioning use are consistent. The cooling time of the air conditioner is from June 2nd to September 21st, between 6:00 and 24:00 every day, when the ambient temperature is 24 ℃ or above; The heating time is from October 28th to April 14th of the following year, between 6:00 and 24:00 every day, with an ambient temperature of 16 ℃ or below.
There are two ways to count using time in the APF standard. One is based on typical city, and another is based on the nationwide. The typical city in Japan is Tokyo, and in China is Nanjing.
But in the calculation of APF, Japan uses the typical city-Tokyo, while China uses the average time of temperature occurrence nationwide. As shown in Figure 1, the total usage time of air conditioning in Japan is 4276 hours, while in China it is 1569 hours. The total usage time of air conditioning in Japan far exceeds that in China, reaching up to 2700 hours, which puts higher requirements on the reliability of compressors.
Secondly, the heating time of air conditioning in Japan is longer than the cooling time, while in China it is the opposite. This also shows that the two countries focus on different working conditions, with Japan focusing on heating and China on cooling.

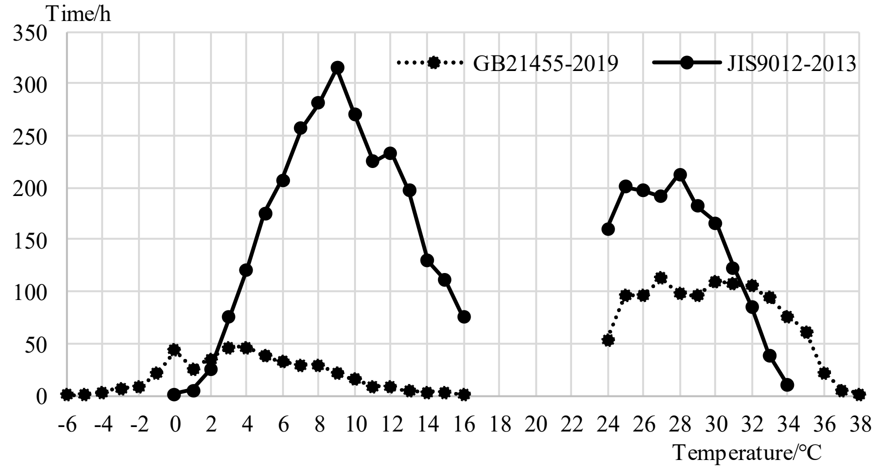


Figure 1: Comparison of using time between China and Japanese APF standard

2.2 Testing Condition

When calculating APF, energy efficiency in several conditions is required. The standard specifies the test conditions, and interpolation calculations can be performed on other conditions based on the experimental results of the test results. For the capacity range below 7.1 kW, both Japan and China can use the 5-point method for testing, and the 5-point method has the same testing conditions. The testing conditions are shown in Table 1:

Table 1: Test conditions

	Indoor temperature (Dry bulb /Wet bulb)	Outdoor temperature (Dry bulb /Wet bulb)
Rated cooling	27/19	35/24
Intermediate cooling	↑	↑
Rated heating	20/15(MAX)	7/6
Intermediate heating	↑	↑
Low temperature heating	20/15(MAX)	2/1

2.3 Load Design

In the latest APF standards GB21455-2019 and JIS9612-2013 in China and Japan, the load design concept is consistent [3], as shown in Table 2. Interpolate and calculate the capacity, power, and energy efficiency under different modes, and finally combine them with operating time to obtain CSTL (cooling seasonal total load), HSTL (heating seasonal total load), CSTE (cooling seasonal total energy), and HSTE (heating seasonal total energy), and obtain the APF result. The APF calculation formula is shown in equation (1).

$$APF = \frac{CSTL + HSTL}{CSTE + HSTE} \tag{1}$$

Table 2: Compassion of load design between Japan and China

Standard	Cooling load	Heating load
JIS9612-2013	The cooling capacity at an outdoor temperature of 35 ℃ is used as the cooling building load, and the straight line connecting this point to the point where 23 ℃ is zero load is used	The heating load (cooling capacity x 1.25 x 0.82) at an outdoor temperature of 0 ℃, connected by a straight line to the point where the outdoor temperature of 17 ℃ is 0 load
GB21455-2019	↑	↑

However, due to the inconsistency in the labeling value for rated capacity between the two countries, Japan has set the labeling values for rated capacity. When labeling products, they can only be selected from Table 3 below, and China has no specified value requirements, resulting in differences in the load lines used in calculations. Furthermore, there is a temperature difference at the intersection of the load line and the air conditioning operating capacity line, which ultimately affects the APF results.

Table 3: Japanese rated refrigeration capacity identification value

1.0	1.1	1.2	1.4	1.6	1.8	2.0
2.2	2.5	2.8	3.2	3.6	4.0	4.5
5.0	5.6	6.3	7.1	8.0	9.0	10.0

2.4 Efficiency grade

Table 4 shows the energy efficiency grades of Chinese APF, which are divided into 5 levels. For heat pump air conditioners with inverter compressors, the APF should be greater than or equal to grade 3.

Table 4: Energy efficiency grade of China

Rated cooling capacity (W)	APF				
	Energy efficiency grade				
	1级	2级	3级	4级	5级
CC≤4500	5.0	4.5	4.0	3.5	3.3
4500<CC≤7100	4.5	4.0	3.5	3.3	3.2
7100<CC≤14000	4.2	3.7	3.3	3.2	3.1

Different from Chinese APF standard, considering the small building area in Japan, air conditioners with cooling capacity below 4.0 kW have two categories: specified size and free size. The specified size limits the indoor unit width to below 800 mm and height to below 295 mm. There is no size limit for free size, but the target benchmark value is higher, resulting in a significant increase in cost and selling price under the same grade. Therefore, user choices are limited.

Driven by the Energy Efficiency Leader Program, the energy efficiency of room air conditioners in Japan is gradually improving, and the APF benchmark value for 2027 will be changed. Table 5 shows the APF admission values for products with specified sizes before and after 2027, with significant improvements in each capability segment, ranging from 13.8% to 34.7%.

Table 5: APF admission values for Japanese specified size products

Cooling capacity/kW	Before 2027	After 2027	Improvement ration
＜3.6	5.8	6.6	13.8%
＜4.0	4.9	6.6	34.7%
＜5.6	5.0	6.3	26.0%
＜6.3	5.0	6.1	22.0%
＜7.1	4.5	6.0	33.3%

Japan's energy efficiency grades are divided based on the achievement rate of energy-saving standards as Table 6, which is defined as the ratio of the APF identification value to the APF admission value. Therefore, unlike China, Japanese air conditioning products generally do not indicate energy efficiency star ratings, but rather indicate energy-saving benchmark achievement rates.

Table 6: Energy efficiency grade of Japan

Grade	Energy saving benchmark achievement rate
★★★★★	＞121%
★★★★	＞114%
★★★	＞107%
★★	＞100%
★	＜100%

In addition, it should be noted that Chinese air conditioning require the measured energy efficiency value to be no less than 95% of the labeled value, while Japan requires the measured energy efficiency value of air conditioning products to be greater than the labeled value, which is equivalent to higher requirements for product energy efficiency.

2.5 Proportion of operating conditions

Based on the analysis of the APF standards above, due to the same testing methods, Chinese and Japanese air conditioners were selected, and GB21455-2019 and JIS9612-2013 standards were used for calculation. The APF values of air conditioners under different evaluation standards were analyzed, and the results are shown in Table 7. Compared with result of GB21455-2019, the result of JIS9612-2013 is about 10% higher;

Table 7: Comparison of APF under different air conditioning standards between China and Japan

	Standard	Chinese air conditioning	Japanese air conditioning
C	JISC9612-2013	/	/
A	GB21455-2019	C/A -1= 8.8%	C/A -1= 11.3%

Analyzing the proportion of each condition in different standards, as shown in Table 8, GB21455-2019 standard slightly focuses on refrigeration conditions. The proportion of intermediate cooling and rated cooling is the highest, with a sum of nearly 50%. The proportion of rated heating and intermediate heating is about 45%, and there is also a certain proportion of low-temperature heating, about 5%. Meanwhile, the proportion of intermediate and rated operating conditions is basically equivalent.

The Japanese APF standard focuses more on heating conditions and intermediate conditions. Only one intermediate heating condition accounts for over 50%, followed by intermediate cooling and rated heating conditions, with rated cooling conditions accounting for only about 5%. Low temperature heating conditions have little impact on the APF calculation results. However, it should be noted that Japanese air conditioning products need to indicate their low-temperature heating capacity on their nameplate markings. Although the energy efficiency of low-temperature heating conditions may not be high, it is necessary to ensure that the low-temperature capacity meets the requirements.

Table 8: The proportion of APF standard in each operating conditions

(a)Chinese air conditioning

	Standard	Rated cooling	Intermediate cooling	Rated heating	Intermediate heating	Low temperature heating
A	GB21455-2019	16.3	32.4	27.5	18.8	5.0
C	JIS9612-2013	3.9	24.6	9.6	61.9	0.00
	C-A	-12.2	-7.8	-20.9	43.1	-5.0

(b)Japanese air conditioning

	Standard	Rated cooling	Intermediate cooling	Rated heating	Intermediate heating	Low temperature heating
A	GB21455-2019	17.2	34.1	32.3	13.8	5.1
C	JIS9612-2013	4.8	23.9	12.8	58.5	0.01
	C-A	-12.4	-10.2	-19.5	44.7	-5.1

3. Research of High Efficiency Compressor

Based on the above analysis, in the Japanese APF standard, intermediate operating conditions have the greatest impact on the APF, followed by intermediate cooling and rated heating conditions. Therefore, in the process of researching compressors for the Japan, it is necessary to focus on improving the energy efficiency level in the mid and low frequency. At the same time, to ensure low-temperature heating capacity, the maximum operating frequency of the compressor needs to meet requirements.

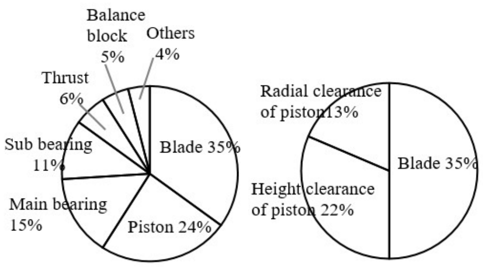
This article takes the development process of a high-efficiency compressor an example to introduce. There are four performance indicators for rotary compressors, including volumetric efficiency, indicated efficiency, mechanical efficiency, and motor efficiency. The factors that affect volumetric efficiency and indicated efficiency include clearance volume, suction and exhaust pressure losses, gas heating losses, leakage losses, reflux losses, etc. Conventional solutions, such as exhaust path optimization, clearance optimization, and exhaust valve plate optimization have become mature technologies in the industry. We will not elaborate on them here, but mainly introduce some new technical points in improving mechanical efficiency and motor efficiency.

3.1 Improvement of Mechanical efficiency

Mechanical efficiency reflects the magnitude of mechanical friction losses, mainly including: friction losses between the main bearing and the crankshaft, the sub bearing and the crankshaft, the tip of the blade and the crankshaft and so on. Improving the mechanical efficiency is to find ways to reduce the friction between the above-mentioned friction amplitudes [4]. This article mainly introduces the high-efficiency technology of rocker blade and crankshaft eccentric part.

3.1.1 Rocker Blade

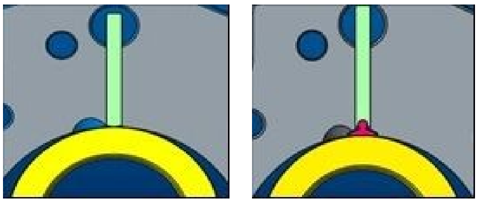
Figure 2 shows the proportion of friction power loss and pump leakage loss in a rotary compressor. It can be seen from the figure that the proportion of friction power loss and leakage loss of the blade are both the highest. Based on this, a low friction and low leakage technology – rocker blade- was proposed to solve this problem.



(a) frictional power loss (b) leakage loss

Figure 2: Proportion of frictional power loss and leakage loss in the pump body

Figure 3 is a schematic diagram of the comparison between the rocker blade and the traditional blade. A component named "rocker" is added between the tip of the blade and the piston; A circular is designed at the tip of the blade, and one end of the rocker hinged and embedded in the opening groove, which can swing left and right at a certain angle. The other end of the rocker block is a circular arc, which freely contacts the outer circular surface of the piston. The rocker blade swings back and forth in the opening groove at the front end of the blade under the driving force of the piston rotation, while the blade moves back and forth. The piston completes one cycle of suction and exhaust process.



(a)Traditional blade (b)Rocker blade

Figure 3: Schematic diagram of traditional blade and rocker blade

According to the Streibeck curve, lubrication states can be divided into four types: fluid dynamic pressure lubrication, elastic fluid dynamic pressure lubrication, mixed lubrication, and boundary lubrication [5]. The friction pair formed between the blade and the piston in traditional rotary compressors belongs to a typical boundary lubrication state, which causes much power consumption. According to the contact form of the friction pair, there are mainly three forms: point, line, and surface. The contact stress of these three forms is in descending order. The higher the stress, the greater the probability of contact fatigue wear occurring.

The blade in traditional rotary compressors is in line contact with the piston, resulting in high contact stress and easy fatigue wear, increased leakage, and reduced compressor energy efficiency; The rocker blade transforms the line contact to approximate surface contact, greatly reducing the contact stress. Moreover, the friction pair formed by the rocker, blade and piston belongs to a typical bearing model, which can form a dynamic pressure oil film. The friction coefficient in the boundary lubrication state is 0.1, while in the fluid lubrication state it is 0.001. The friction coefficient and wear of the rocker blade are significantly reduced.

Furthermore, calculate the stress of the friction pairs of the two structures. The problem of line contact can be approximated by the contact of two cylinders with the same curvature radius as the contact point. The contact stress between the tip of the blade and the piston, as well as the friction pair formed by the rocker and the blade and piston respectively, can be calculated using Hertz contact theory:

$$\sigma_H = \sqrt{\frac{p}{\pi l} * \frac{\frac{1}{R_1} + \frac{1}{R_2}}{\frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2}}} \qquad (2)$$

Among them: R1 and R2 are the radii of the cylinder; E1 and E2 are the elastic moduli of the cylinder; μ 1 and μ 2 is the Poisson's ratio of a cylinder; P is the normal outward pressure; L is the contact length;

Using the above formula for theoretical calculation, the contact stress of the traditional compressor at the blade and the piston is 320MPa; In the rocker blade, the contact stress between the rocker and the blade is 50MPa, and the contact stress between the rocker and the is 4MPa. The use of a rocker blade significantly reduces the stress at the tip of the blade. Therefore, under the same operating conditions, the wear resistance of the rocker blade is significantly better than that of the traditional blade. At the same time, the large arc of the blocker is in approximate surface contact with the piston. Compared with the previous linear contact between the blade and the piston, the leakage at the tip of the blade is smaller, further improving the energy efficiency of the compressor.

As Figure 4 shows, the use of blade improves energy efficiency, about 1% to 2%, manifested with cooling capacity increasing by about 1% and power decreasing by about 1-2%.

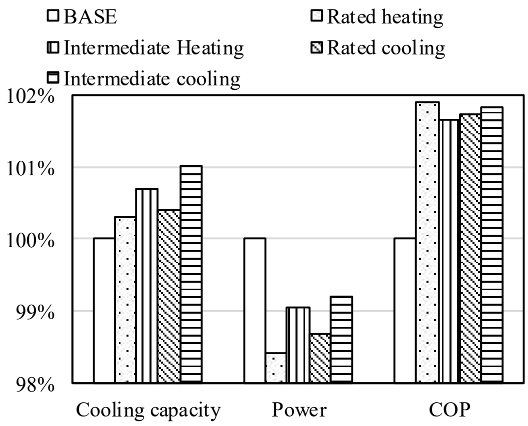
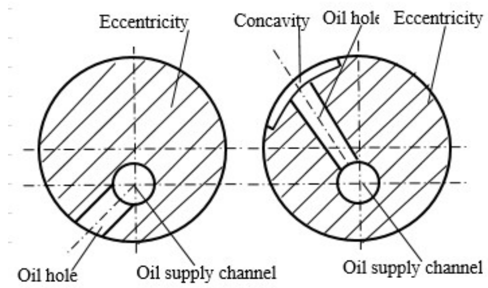


Figure 4: Improvement of energy efficiency of rocker blade

3.1.2 Efficient Technology for Crankshaft Eccentricity

During the operation of the rotary compressor, the piston bears the high and low pressure differential pneumatic force, which is transmitted to the eccentric part through the oil film between the piston and the eccentric part. Due to the varying load-bearing sizes on the outer circumference of the eccentric part in different regions, the position of the oil hole can affect the distribution of the oil film and even damage its load-bearing capacity, resulting in abnormal wear. In addition, due to the friction loss caused by the eccentric part driving the piston to rotate, the working load of the rotary compressor increases. Therefore, it is possible to reduce compressor power consumption and solve abnormal crankshaft wear by rationalizing the design of oil hole positions.

Figure 5 shows the final design of the eccentric oil hole position and the optimization of the crankshaft eccentric oil outlet position, effectively ensuring lubrication and load-bearing between the eccentric part and the piston, and reducing the friction power consumption of the eccentric bearing. At the same time, a concave part is set up near the design range of the oil hole. Through the opening of the concave part, the contact area between the eccentric part of the crankshaft and the piston is reduced, and the friction loss is reduced; Secondly, the velocity gradient of the non bearing oil film is reduced, thereby reducing shear force and power consumption; At the same time, the axis trajectory of the eccentric part of the crankshaft was optimized, reducing the total radial clearance leakage and improving the cooling capacity.



(a)Traditional structure (b)New structure

Figure 5: Schematic diagram of crankshaft eccentricity

The experimental result is shown in Figure 6, and the high-efficiency technology of the crankshaft eccentric part can improve energy efficiency by about 1%. The improvement in energy efficiency is manifested by an increase in cooling capacity and a decrease in input, with cooling capacity increasing by about 1-2% and input decreasing by about 1%.

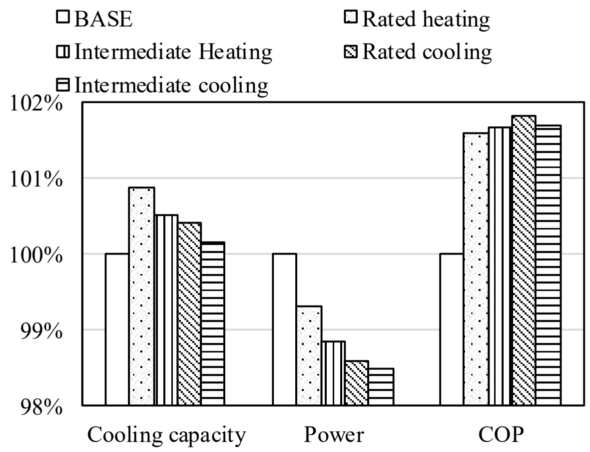


Figure 6: Improvement of efficient technology for crankshaft eccentricity

3.2 Improvement of Motor Efficiency

To meet Japan's high energy efficiency needs, it is necessary to improve the efficiency of the motor; At the same time, to ensure low-temperature heating, the maximum operating frequency of the motor must meet certain requirements. In addition to conventional techniques such as increasing thickness, increasing outer diameter, and optimizing back electromotive force, this product has made breakthroughs and innovations in materials and processes.

For example, using ultra-thin silicon steel plates as high-performance materials can effectively reduce iron loss and improve power density, which helps to improve motor efficiency; Improving the slot filling rate of the coil has a direct impact on the efficiency of the motor. However, the higher the slot filling rate, the more difficult it is for the coil to be automatically wound and embedded. This product has made a technological breakthrough to increase the slot filling rate to a higher level; By using stator laser welding technology, the retention force of the stator inside the shell is ensured while reducing the deformation of the stator core, further reducing iron loss, and improving the overall efficiency of the motor.

Based on the above, the improvement effect of motor efficiency is shown in Table 9. Under all operating conditions, the efficiency of the motor has been improved, especially in the intermediate operating conditions with a significant proportion. The intermediate refrigeration operating condition has increased by 1.6%, and the intermediate heating operating condition has increased by 0.9%.

Table 9: Improvement of motor efficiency

Condition	Rated cooling	Intermediate cooling	Rated heating	Intermediate heating
Improvement	0.7%	1.6%	0.6%	0.9%

3.3 Improvement of Compressor Efficiency

Based on the high-efficiency technology - rocker blade and crankshaft eccentric part, as well as breakthroughs in motor technology and materials, and other conventional optimization methods, the energy efficiency of the compressor has been significantly improved, as shown in Figure 7. The intermediate refrigeration condition has an improvement of 9%, while the other working conditions have an improvement of about 5%

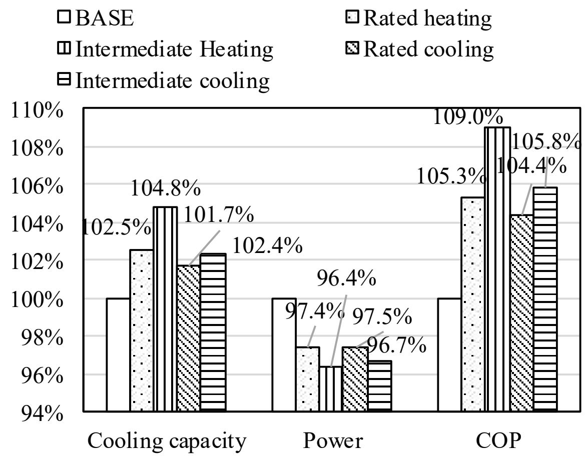


Figure 7: Improvement of compressor COP

This high-efficiency compressor is equipped with a Japanese high-efficiency air conditioning system, which meets the high APF requirements of the Japanese market and reaches a high level in the industry.

4. CONCLUSION

With the increasing demand for energy conservation and emission reduction, high-efficiency air conditioning will become a future industry trend. Japan is the global benchmark market for household air conditioning energy efficiency, and its high energy efficiency products represent the highest energy efficiency level in the industry. This article takes the capacity range of 7.1 kW and below frequency conversion models as an example to analyze the Japanese APF standards JIS9612-2013 and Chinese APF standards GB21455-2019, and provides some development ideas for efficient compressors. The conclusion is as follows:

- The using time is different: the total usage time in Japan is about 2700 hours longer than that in China, which requires higher reliability of the compressor; The heating usage time in Japan is longer than the cooling usage time, while in China it is the opposite.
- The testing method is the same: for the capacity range below 7.1kW, both Japan and China can use the 5-point method, and the testing conditions for the 5-point method are the same;
- The load design is the same, but the load lines are different: when Japanese products indicate the rated cooling capacity, they can only be selected from the specified values, and China does not have this regulation, resulting in differences in the load lines during calculation;
- Energy efficiency level: The energy efficiency grade in Japan is gradually improving, with an increase of 13.8% to 34.7% in APF after 2027;
- Proportion analysis: China focuses on refrigeration conditions, and low-temperature heating also accounts for a certain proportion, about 5%; The Japanese APF standard focuses more on heating and intermediate conditions, with intermediate heating alone accounting for over 50% of the total. Low temperature heating conditions have little impact on APF;
- Research and development of high efficient compressors: With the increasing demand for energy efficiency in air conditioning, compressor design should dare to innovate and break through conventions. This product is based on breakthrough technologies such as rocker blade, crankshaft eccentricity, and breakthroughs in motor technology and materials. Ultimately, it achieves a significant improvement in compressor energy efficiency, with an increase of 9% in intermediate refrigeration conditions and around 5% in other conditions. Equipped with a high-efficiency air conditioning system from Japan, it meets the high APF requirements of the Japanese market.

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