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Development of Large-And-Small Volume-Switching Rotary Compressor for Residential Multi-Connected Air-Conditioner

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ABSTRACT

Residential Multi-Connected Air-Conditioner(RMAC) are widely used in urban residential in China, but they have low energy efficiency problems in daily use. They are mainly due to the air-conditioning habits of Chinese residents in "part space and part time", Which makes RMAC most of the time only 1-2 indoor units are turned on, and 60% of the operating time is at a low load rate of less than 30%. During low load operation, the compressor's efficiency drops sharply, and there is also the problem of frequent start and stop when the minimum output is too large. In order to solve this problem, a large-and-small volume switching compressor suitable for RMAC is developed. The compressor can choose single-cylinder small-volume operation or twin-cylinder large-volume operation according to the change of system load. The new compressor technology for RMAC improves the energy efficiency by 124% under 10% load, and avoids the problem of frequent start-stops at low loads, making RMAC more energy efficient and more comfortable.

1. INTRODUCTION

Residential Multi-Connected Air-Conditioner (RMAC) refers to Multi-Connected Air-Conditioner used in residences. It consists of one outdoor unit connected to several indoor units. It has the characteristics of small installation space and beautiful decoration, as shown in Figure 1. In recent years, its market share in China has grown rapidly. According to statistical data (HVAC Information), China's RMAC has a compound annual growth rate of 25% in recent years, accounted for more than 27% of the entire central air-conditioning market share. Therefore, its energy consumption level has an increasingly greater impact on building energy efficiency in China, and reducing the actual energy consumption of RMAC is of great significance.

RMAC is designed and selected according to the heat load of the whole house, that is, it has higher energy efficiency when used in "full space". However, due to Chinese residents' "part space, part time" air-conditioning usage habits, most of the time of RMAC is in low load operation. According to big data statistics, see Cheng, J.(2017), RMAC only operates one indoor unit for 60% of the time, which results in 60% of the operating time in the low load range of less than 30%， as shown in Figure 2 and Figure 3.It is mainly because the bedroom area of

Chinese urban residential is small, which makes the heat load small. The demand for one-bedroom cooling load at night in the air-conditioning cooling season is mainly concentrated in 0.8kW ~ 2.4kW. For most RMAC rated capacity of 12-18kW, its minimum output needs to be reduced to about 5% of the rated output. Because most conventional RMAC use variable-frequency rotor compressors, during low-load operation, the operating frequency of the compressor needs to be reduced to reduce the output. However, due to the decrease of the compressor frequency, its efficiency will be greatly reduced, and due to the minimum frequency of the compressor limitation, when the load demand is below 20%, the minimum output of the compressor is too large, which is prone to frequent start and stop, resulting in high power consumption.

In summary, at present, RMAC uses conventional compressor technology, which has the problems of too large minimum output and low energy efficiency at low load operation, resulting in high energy consumption of RMAC in actual use. Therefore, a new large-and-small volume switching compressor technology was developed, which can significantly improve the energy efficiency of compressors operating at low loads below 30% and reduce the minimum output, achieving significant energy saving effects for RMAC.

Figure 1: RMAC installation diagram

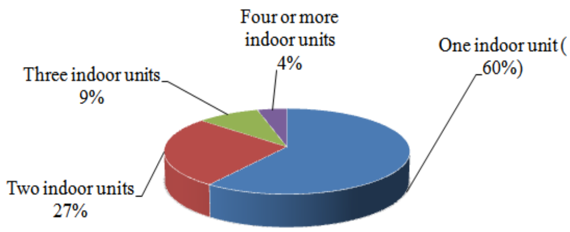

Figure 2: Proportion of indoor unit being turned on

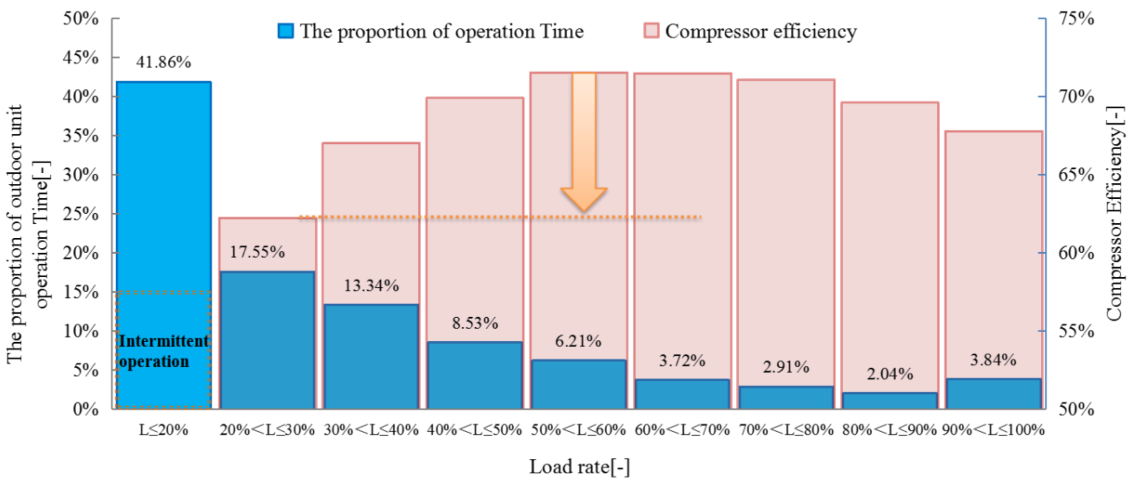

Figure 3: RMAC operation time ratio and corresponding compressor efficiency at different load rate

2. NEW DUAL-EFFICIENCY OPERATING MODE FOR COMPRESSORS

In order to solve the above two major problems of RMAC, a compressor with two modes of small-volume operation and large-volume operation is proposed, which can switch between the two operation modes according to the system load change, as shown in Figure 4 . (a)Small-volume operation(single-cylinder mode) : When RMAC only turns on 1-2 indoor units and is in low-load operation, the compressor operates only with a small-volume cylinder, and a large-volume cylinder is unloaded, and the working volume is reduced by more than

50%. Combined with the reduction of the frequency, the minimum capacity output is greatly reduced, which avoids the frequent start-stop problem caused by the compressor capacity output being too large during low load operation. In addition, due to the reduced operating volume, the compressor's operating frequency at low loads has increased significantly, and the compressor efficiency can be significantly improved. (b)Large-volume operation (Twin-cylinder mode): When multiple indoor units of RMAC are turned on, during medium-high load operation, the small-volume cylinder and large-volume cylinder of the compressor run at the same time to meet the RMAC's high-capacity output and high efficiency demand.

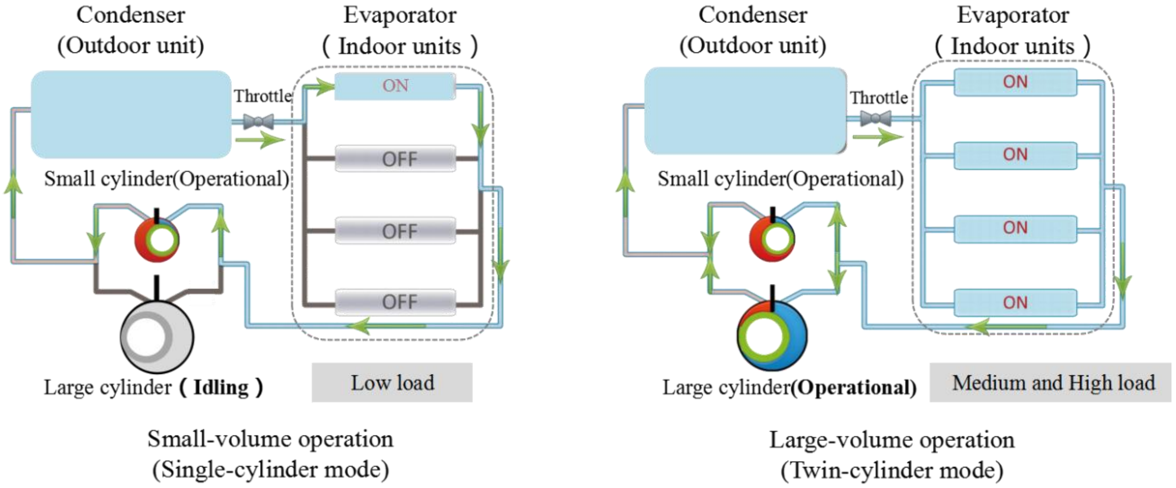

Figure 4: New dual-efficiency operating mode for compressors

3. DEVELOPMENT OF LARGE-AND-SMALL VOLUME SWITCHING COMPRESSOR

3.1 Structure of large-and-small volume switching compressor

The Figure 5 shows a comparison of the compression structure of a conventional twin-rotary compressor and a large-and-small volume switching compressor. Conventional twin-rotary compressor operates with two cylinders of equal volume simultaneously, with a narrow output range. The large-and-small volume switching compressor includes a small-volume cylinder with a volume of V_1, and a large-volume cylinder with a volume of V_2, that is, $V_1 < V_2$. The large-volume cylinder can be switched between operating state and idling state by a vane lock mechanism. That is, a notch is provided on the vane, and a locking mechanism is installed in the lower bearing below the vane. The locking mechanism includes a pin that can move up and down, and a spring at the bottom of the pin.

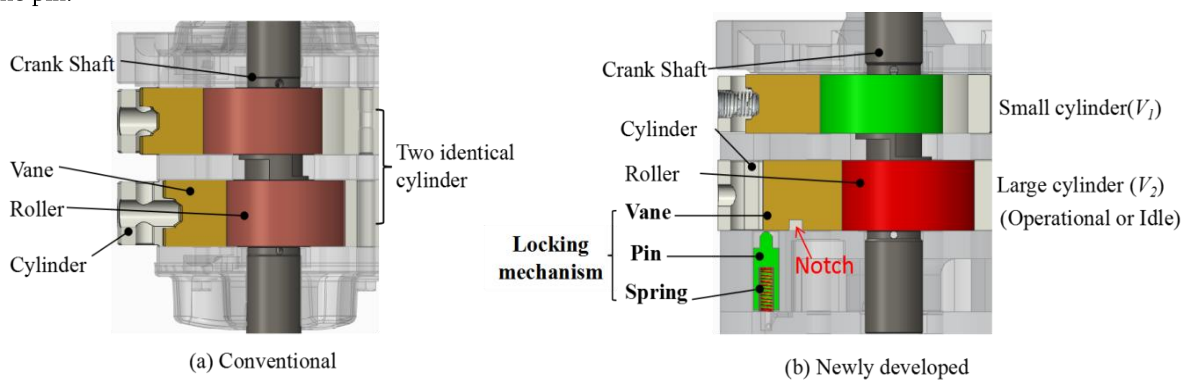

Figure 5: Comparison of compressor structure

3.2 Large and small volume switching principle

In order to achieve the switch between operating state and idling state of the large-volume cylinder, it is realized through the linkage control of the pressure control system and the vane lock mechanism, as shown in the Figure 6.A low-pressure solenoid valve A and a high-pressure solenoid valve B are respectively arranged between the suction port and the exhaust port of the compressor. The two solenoid valves are connected to the sealed cavity at the upper end of the pin through a pressure storage tank, and the lower part of the pin is always connected to the suction low pressure. By opening and closing the two solenoid valves separately, high pressure or low pressure can be applied to the upper end of the pin. The switching process is: (a) the low-pressure solenoid valve A is opened, the high-pressure solenoid valve B is closed, the upper and lower ends of the pin are both low pressure, and the pressure is balanced. The pin is moved upward by the force of a spring force, and the pin locks the vane to separate the vane from the roller. The large-volume cylinder does not compress and realizes idling. (b) The low-pressure solenoid valve A is closed and the high-pressure solenoid valve B is opened. The upper end of the pin is connected with high pressure, and the upper end pressure is higher than the lower end. The pin moves downward against the spring force by the pressure difference between the upper and lower ends, the vane is unlocked, and the sliding blade and the roller fit together, and large-volume cylinder is converted into compression operation.

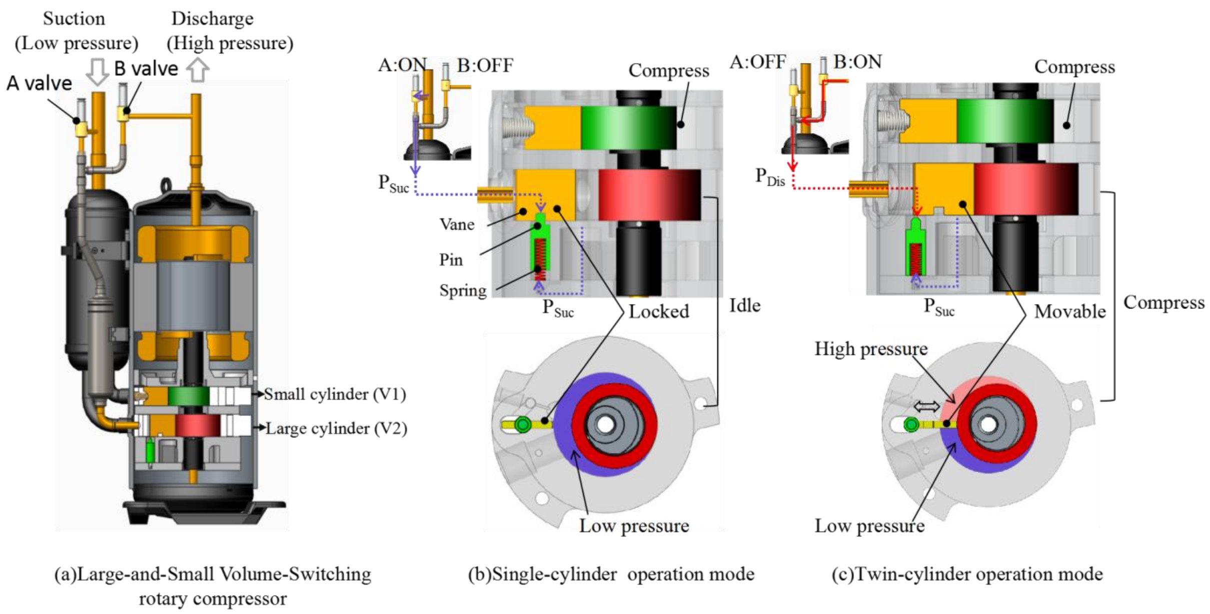

Figure 6: Large-small volume switching principle

3.3 Design of volume distribution ratio of large and small cylinders

Define *K* as the volume ratio of the small volume cylinder(V_1) to the large volume cylinder(V_2), that is, $K = V_1 / V_2$. Through experimental research and theoretical calculations, when the total working volume $(V_1 + V_2)$ is determined, the *K* value has a very significant impact on the minimum cooling capacity, compressor efficiency and operating stability. Therefore, the design of volume distribution ratio is very important.

3.3.1 Impact of the k value on efficiency and minimum output

As mentioned above, 60% of the time for households to be online is to operate at a low load below 30%, and the minimum output needs to be reduced to 5% of the rated output. Therefore, improving the comprehensive energy efficiency of the compressor under 30% low-load operation and reducing the minimum output is the key to ensuring energy saving for RMAC. Through simulation calculations and experimental studies, the efficiency curves of small-volume operation of compressors with different volume distribution ratios *K* are obtained, as shown in Figure 7.In the figure , when K = 1, the load rate corresponding to the highest point of the compressor efficiency is about 40%. Above or below this load rate, the compressor efficiency will drop significantly. The K value decreases, and the compressor's highest efficiency point also decreases. The peak of the efficiency curve moves toward the load reduction direction, and the capacity output range becomes narrower, and the overall efficiency also decreases. This is mainly because when the value of K is decreased, the useless power consumption caused by the large-volume cylinder (V_2) is increased, resulting in a decrease in the compressor efficiency. In order to ensure the overall energy saving effect, it is necessary to focus on ensuring that the compressor in the low-load area with a load rate within 30% has the highest comprehensive operating efficiency, and also needs to reduce the minimum capacity output. As shown in Figure 8, According to the weighted calculation of compressor efficiency and operating time under low load, within the range of volume distribution ratio K= [0.5, 0.7], the comprehensive efficiency of single-cylinder low load compressor can be guaranteed to reach more than 97% of the highest efficiency value, and the minimum output reaches less than 5% of the rated output.

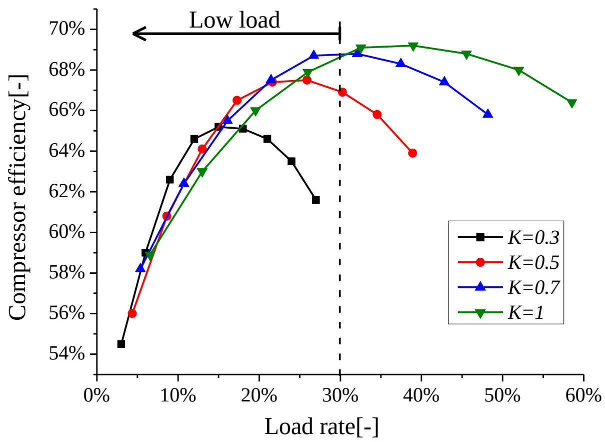

Figure 7: Low-load efficiency of compressor single-cylinder operation with different K values

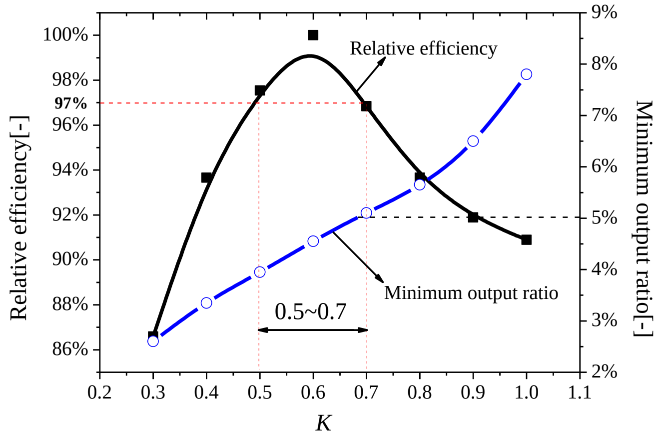

Figure 8: Compressor low load relative efficiency and minimum output ratio at different K values

3.3.2 Impact of the K value on operation stability

For a rolling-rotor compressor, the load torque fluctuates periodically with the rotation angle, and the non-uniformity of torque is the main reason for the low-frequency vibration of the compressor. Because the two cylinders of the large-to-small-volume switching compressor have different volumes, torque fluctuations are large.

Therefore, it is necessary to study the vibration characteristics of different volume distribution ratios *K* in single-cylinder and twin-cylinder modes in order to design a suitable *K* value to ensure the requirements for the stability of the compressor operation. The torque when the compressor is running can be calculated as listed in equation(1)-(3), see Ma et al.（2001） and Miao et al.(2000) . According to the compressor force analysis Figure 9, and the speed fluctuation can be calculated from the equations (4)-(5), see Shen, Y. (2004).

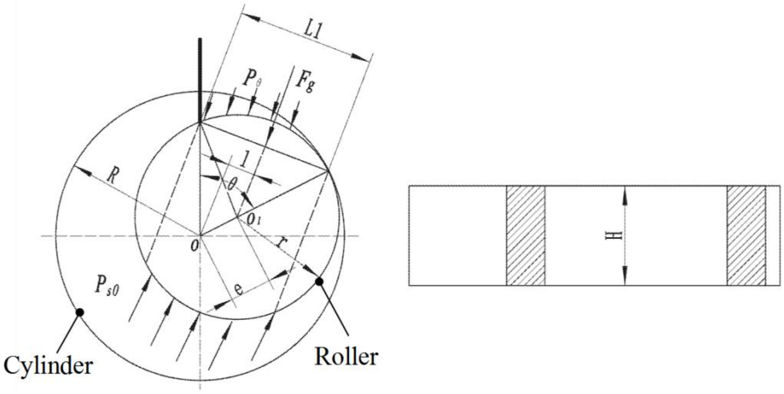

Figure 9 : Compressor force analysis

$$\tau = \frac{e}{R} \tag{1}$$

$$F_g = RH(1-\tau)(p_\theta - p_{s0})\sqrt{2(1-\cos\theta)+\frac{\tau}{1-\tau}(1-\cos 2\theta)} \tag{2}$$

$$M_g = F_g l = \frac{1}{2}R^2 H\tau(1-\tau)(p_\theta - p_{s0})\sqrt{2(1-\cos\theta)+\frac{\tau}{1-\tau}(1-\cos 2\theta)} \tag{3}$$

$$\omega = \sqrt{\omega_0^2 + \frac{2}{J}\left(\int_0^{360} M_d d\varphi - \int_0^{360} M_g d\varphi\right)} \tag{4}$$

$$\xi = \frac{\omega_{\max} - \omega_{\min}}{\omega_m} \tag{5}$$

The calculated load curves for low-frequency operation of the compressor in two-cylinder mode and single-cylinder mode under different volume distribution ratios are shown in Figure 10.From the calculation results: in the single-cylinder mode, only one small-volume cylinder is running. As the volume distribution ratio *K* increases, the volume of the small-volume cylinder increases, and the compressor torque fluctuation gradually increases. In the two-cylinder mode, when two cylinders are running at the same time, the *K* value increases, and the smaller the volume difference between the two cylinders, the smaller the compressor load fluctuations. Therefore, when the single-cylinder mode is operated, the smaller the *K* value is, the more stable the compressor runs; when the twin-cylinder mode is operated, the larger the *K* value, the more stable the operation. According to the calculations of equations (4)-(5), as shown in Figure 11, selecting *K* = [0.5, 0.7] can ensure that the unevenness coefficient of the rotation speed at low frequency is less than 5%, which can meet the low frequency stability of single-cylinder and twin-cylinder modes operational requirements.

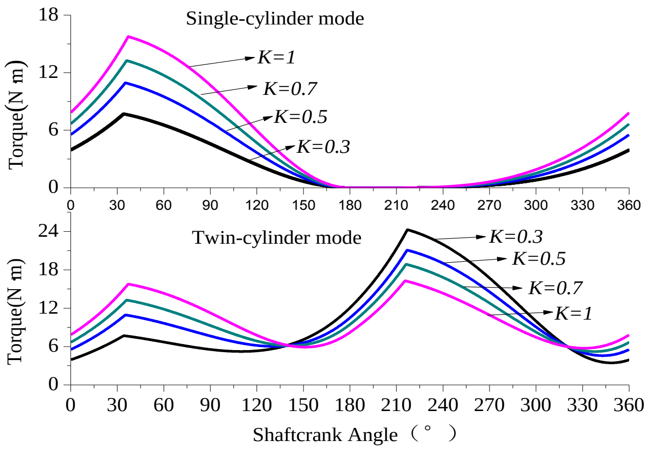

Figure 10: Torque fluctuation with different *K* values

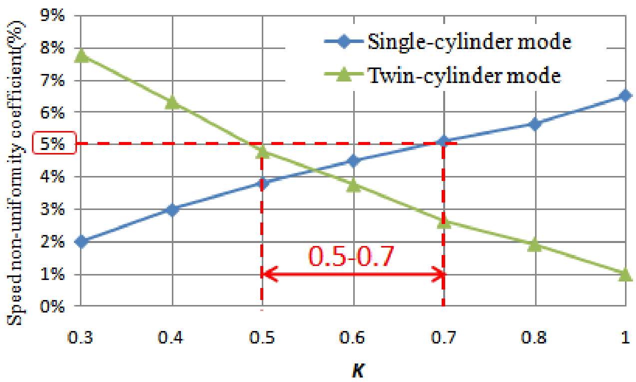

Figure 11: Speed non-uniformity coefficient

Based on the study of the effects of the above-mentioned volume distribution ratio on the compressor's overall efficiency, minimum cooling capacity, and operational stability, it is a better choice to choose a range of compressor volume distribution ratio $K = [0.5, 0.7]$, which can greatly improve the Energy efficiency level of the compressor at low load operation, and can meet the requirements of minimum cooling capacity and operating stability at the same time.

4. COMPRESSOR TEST RESULTS AND APPLICATION IN RMAC

Through the above technology, a 6HP large-and-small volume switching compressor has been developed, and the operating volume of the compressor can be switched between 18cc and 44cc. The compressor energy efficiency test conditions are shown in Table 1**.** The comparison model is a conventional twin-rotary compressor, which uses a fixed volume (V = 42cc) to operate. The test results are shown in the Figure 12. The conventional compressor maintains high energy efficiency at medium and high capacity output, but when the capacity output decreases below 30% of the rated capacity, the compressor frequency must be continuously reduced, energy efficiency drops sharply. The newly developed compressor uses the single-cylinder small-volume operation mode ($V1$ = 18cc) to reduce the minimum capacity output by 52%, and the new compressor's energy efficiency is increased by 45% during low load operation. This is mainly because the compressor speed can be greatly increased by using a small volume operation at low load, thereby achieving the purpose of increasing the compressor motor efficiency and volume efficiency. In addition, when high-capacity output is required, the new compressor uses the twin-cylinder operating mode (($V2$ = 44cc)). The compressor efficiency has also increased by 5%, mainly due to the compressor's optimized compression structure and efficient new motor.

When the 6HP large-and-small volume switching compressor is applied in a 16kW RMAC, the EER value under a 10% load is increased by 124% compared to the use of a conventional compressor. Mainly at low load operation, the energy efficiency of the compressor is greatly improved, and the minimum output of the compressor is reduced, which avoids frequently start and stop of the compressor, and the power consumption of the compressor is greatly reduced. This new compressor technology enables RMAC to achieve extremely significant energy savings.

Table 1: Energy efficiency test conditions for compressor

Compressor	**Conventional compressor**	**Newly developed compressor (single-cylinder mode)**	**Newly developed compressor (twin-cylinder mode)**
Refrigerant	R410A		
Evaporation temp.	7.2℃		
Suction temp.	35℃		
Condensation temp.	54.4℃		
Subcooling temp.	46.1℃		
Ambient temp.	35℃		
working volume	42cc	18cc	44cc
Rotating Speed	10rps-68rps	15rps-70rps	25rps-65rps

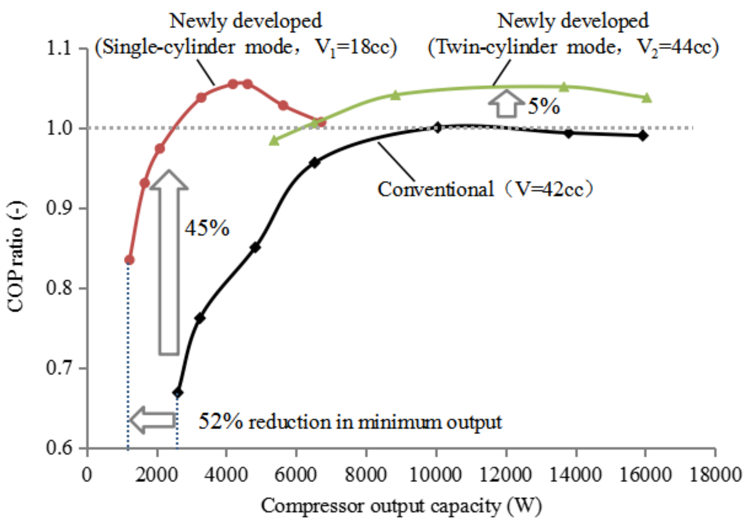

Figure 12: Comparison of compressor energy efficiency

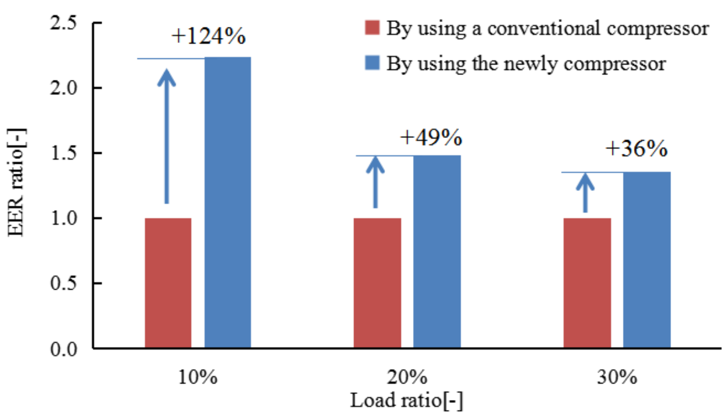

Figure 13: Comparison of energy efficiency at low load with different compressors in 16kW RMAC

5. CONCLUSION

Based on the research on the actual operating load characteristics of RMAC in this paper, it is analyzed that domestic RMAC have problems of excessive minimum cooling capacity and low load energy efficiency when using traditional compressor technology. In order to solve this problem, a high-efficiency large-to-small-volume switching compressor suitable for Chinese households with multiple online connections has been developed.

(1) A new dual high-efficiency operation mode of the compressor is proposed. The compressor can switch the operating volume according to the change of air-conditioning load.

(2) Developed a large-small volume switching compressor, and realized the free switching of two modes of small volume operation and large volume operation in one compressor.

(3) In order to meet the comprehensive requirements of low load energy efficiency, minimum output, and operational stability of the compressor, an optimal volume distribution ratio range of [0.5-0.7] is designed

(4) Compared with traditional compressors, the new compressors developed can improve the low-load energy efficiency by 45%. When it is applied to a 16kW RMAC, the EER value under a 10% load is increased by 124%.

NOMENCLATURE

F_g	gas force	(N)
R	cylinder radius	(m)
L	cylinder height	(m)
E	crankshaft eccentricity	(m)
τ	ratio of the crankshaft eccentricity	(-)
P_θ	compression chamber pressure	(Pa)
P_{s0}	suction pressure	(Pa)
θ	crank angle	(°)
M_g	resistance moment	(N.m)
ω	angular velocity	(rad/s)
ω_0	angular velocity when the crank angle is 0	(rad/s)
M_d	motor output torque	(N.m)
l	arm of force	(m)
J	rotational inertia	(kg·m²)
ξ	speed non-uniformity coefficient	(-)
ω_{max}	maximum angular velocity	(rad/s)
ω_{min}	minimum angular velocity	(rad/s)
ω_m	average angular velocity.	(rad/s)

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