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3D Modeling and Simulation Based Design of a Split Cylinder Block for Refrigerator Compressors

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Abstract: As the pivotal component of refrigeration systems, the performance of refrigerator compressors directly determines the overall energy efficiency, reliability, and lifespan of refrigerators. The cylinder block, a critical element of compressors, significantly influences operational efficiency, mechanical losses, and noise control. Traditional compressors typically employ integrally molded cylinder blocks, which suffer from constrained machining accuracy, high manufacturing costs, and complex assembly processes. Split-type cylinder block designs are increasingly gaining attention for their modular structure, which optimizes manufacturing and assembly while enhancing overall compressor performance. This study investigates the impact of split cylinder block structural characteristics on refrigerator compressor performance through three key aspects: Comparative analysis of design differences between split-type and monolithic cylinder blocks, highlighting advantages in machining precision, material utilization efficiency, and assembly convenience. Examination of mechanical stress distribution during compressor operation using finite element analysis (FEA) to validate structural reliability. Experimental results demonstrate that split-type blocks improve component fit accuracy and reduce frictional losses, thereby enhancing operational efficiency. Identification of modular design's critical role in reducing production costs, increasing part interchangeability, and improving maintenance accessibility. In conclusion, split-type cylinder blocks exhibit significant advantages in improving compressor performance, reducing manufacturing expenses, and boosting assembly efficiency, demonstrating broad application potential. This research provides a theoretical foundation for structural optimization of refrigerator compressors.

Keywords: Refrigerator compressor; Split-type design; Cylinder block; 3D modeling; Simulation

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1 Introduction

The cylinder block, a core component of refrigerator compressors, functions primarily to compress and circulate refrigerant between the evaporator and condenser, enabling refrigeration[1]. Its performance characteristics—including efficiency, noise levels, and structural integrity—critically influence the overall functionality of refrigerators[2].

As the "heart" of refrigeration systems, compressor production volumes and technological advancements reflect a nation's mechanical manufacturing capabilities. China initiated replication of

Soviet-era piston refrigeration compressors in 1958[3]. By the 1960s, the country established its first series standard for small piston compressors. Subsequent economic reforms and rising living standards spurred extensive adoption of foreign manufacturing technologies[4]. Today, China's compressor technology not only meets domestic demand but also competes globally. The cylinder block—serving as the compressor's foundation—is widely used in refrigeration compressors due to its compact structure, high load capacity, and superior sealing properties[5]. Amid increasing diversification of refrigeration equipment, innovation and optimization of cylinder blocks remain pivotal to technological progress.

In the late 1980s, companies such as Haier and Midea pioneered the use of aluminum alloys and composite materials for cylinder block manufacturing[6]. Design paradigms gradually shifted from traditional monolithic structures toward modular approaches. Domestic manufacturers adopted split-type designs, segmenting cylinder blocks into multiple components to enhance heat dissipation, reduce weight, lower part replacement costs, and improve maintainability[7]. Researchers at Xi'an Jiaotong University investigated deformation optimization of cylinder bores, analyzing correlations between bolt preload force and bore distortion[8]. Wang Zhongsu et al. explored bolt-connected contact mechanics via finite element analysis (FEA), validating the reliability of split-type cylinder block assemblies. Through sustained research, data analysis, and patents, Chinese scholars have achieved significant noise reduction and cooling efficiency improvements in split-type compressors, cementing China's competitive position in the global market[9].

Since the mid-20th century, foreign countries have carried out research and development work on cylinder block technology for refrigerator refrigeration compressors[10]. The split-type cylinder blocks of foreign refrigerator compressors have evolved from traditional integral designs to modular, high-precision, and lightweight designs. In the future, they will further develop towards higher energy efficiency, energy conservation, and intelligentization, combining advanced materials and precision manufacturing technologies to meet the requirements of environmental protection and energy conservation[11].

In the 1950s and 1960s, the research and development team of General Electric (GE) in the United States selected high-strength cast iron alloys and copper-based coating materials, enabling the cylinder blocks to operate stably under high temperature and pressure conditions[12]. The copper-based coating improved the wear resistance of the cylinder blocks, reduced friction with pistons, thereby enhancing compressor efficiency and service life. GE significantly improved the precision machining of cylinder blocks to ensure their surface flatness and sealing performance, reducing gas leakage. According to GE's report, this precision machining process increased the overall efficiency of the compressor by more than 15% and reduced the failure rate by more than 30%[13].

In the mid-20th century, Whirlpool Corporation[14] of the United States developed innovative sealing technologies, adopting new rubber sealing rings and a dual sealing system, which improved the sealing performance of cylinder blocks during operation, prevented refrigerant leakage, and increased the energy efficiency of refrigerators by approximately 20% compared with the previous generation.

Clement of Italy adopted improved cylinder block designs for compressors, which reduced the leakage rate of compressors by more than 50%[15]. According to test data, the refrigerant leakage rate of compressors using the new cylinder blocks within 2000 hours was only over 40% of that of the traditional design. This innovation brought the refrigerator compressors to a new technical level in the mid-20th century, ultimately promoting the widespread popularization of refrigerator products and the growth of market demand[16].

Danfoss conducted vibration tests on modular split cylinder blocks, using a laser interferometer vibrometer to measure vibration amplitude, testing noise and vibration under standard operating conditions,

and carrying out experiments by simulating stress distribution through finite element analysis[17]. The experimental results showed that the vibration amplitude was reduced by 12%, and the fatigue life of the cylinder block material was extended by 10%[18].

2 Working Principle of Refrigerator Compressors

For a refrigeration compressor, the calculation formula of refrigeration capacity is as follows[19]:

$$\mathrm{COP} = \frac{q_0}{W_0} \times \eta_i \times \eta_m \times \eta_{ma} \tag{1}$$

Where: q_0— refrigerating capacity per unit mass (*kJ/kg*); W_0— theoretical compression work per unit mass (*kJ/kg*); η_i— compression efficiency; η_m— mechanical efficiency; η_{ma}— motor efficiency.

For a given working condition and refrigerant, and are fixed, and the factors affecting the COP value are compression efficiency, mechanical efficiency, and motor efficiency.

It can be known from the thermodynamic calculation of the compressor that the theoretical volumetric gas delivery rate is[20]:

$$V_h = \frac{\pi}{4 \cdot D^2 \cdot S \cdot n \cdot 60} \tag{2}$$

Where: D — cylinder diameter (*m*); S — piston stroke (*m*); n — rotational speed (*r/min*).

The actual mass flow rate is[21]:

$$Ca = \frac{\lambda V_h}{v_1} \tag{3}$$

Where: v_1— specific volume of gas at suction state (m^3/kg); λ— gas delivery coefficient.

$$\lambda = \lambda_v \lambda_T \lambda_l \lambda_P \tag{4}$$

Where: λ_v— volumetric coefficient; λ_T— temperature coefficient; λ_l— leakage coefficient; λ_P— pressure coefficient.

It can be seen from formula (3) that the value of the gas delivery coefficient directly affects the actual gas delivery rate of the compressor. Therefore, it is crucial to improve λ_v, λ_T, λ_l and λ_P[22].

In the design process, it should be considered that objects made of solid materials with relatively fixed shapes will deform under certain specific conditions (such as external force, displacement, temperature, and constraint). The mechanical basis of finite element analysis is elastic mechanics. When analyzing any elastic mechanics problem, three aspects should be considered: statics, geometry, and physics. For a deformable body of any shape under force, in any tiny volume element *dx, dy, dz*, three types of basic mechanical equations can be established based on three types of variables: displacement, strain, and stress[23].

(1) Equilibrium equations[24]

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z} = 0 \tag{5}$$

$$\frac{\partial \sigma_{yx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} = 0 \tag{6}$$

$$\frac{\partial \sigma_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} = 0 \tag{7}$$

(2) Geometric equations[25]

$$\varepsilon_x = \frac{\partial u}{\partial x} \quad \varepsilon_y = \frac{\partial u}{\partial y} \quad \varepsilon_z = \frac{\partial u}{\partial z} \tag{8}$$

$$\gamma_{xy} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \tag{9}$$

$$\gamma_{yz} = \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \tag{10}$$

$$\gamma_{zx} = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \tag{11}$$

(3) Physical equations[26]

$$\varepsilon_{xx} = \frac{1}{E}\left[\sigma_{xx} - \mu\left(\sigma_{yy} + \sigma_{zz}\right)\right] \tag{12}$$

$$\varepsilon_{yy} = \frac{1}{E}\left[\sigma_{yy} - \mu(\sigma_{xx} + \sigma_{zz})\right] \tag{13}$$

$$\varepsilon_{zz} = \frac{1}{E}\left[\sigma_{z} - \mu\left(\sigma_{xx} + \sigma_{yy}\right)\right] \tag{14}$$

$$\gamma_{xy} = \frac{1}{G}\tau_{xy} \ , \ \gamma_{yz} = \frac{1}{G}\tau_{yz} \ , \ \gamma_{zx} = \frac{1}{G}\tau_{zx} \tag{15}$$

Among the above three types of variables: *x, y, z* — Cartesian coordinates; σ— normal stress; *u, v, w* — displacement components in Cartesian coordinates; γ— tangential strain; ε — linear strain; *E* — elastic modulus; *G* — shear modulus; μ — Poisson's ratio; τ— shear strain.

3 Structural Modeling of Split-type Cylinder Block

3.1 Overall Structural Modeling of Cylinder Block

This paper innovatively proposes a split-type high-efficiency compressor cylinder block, which is detachable. The selection of split-type cylinder block design aims to solve the traditional problems of the "crescent groove". Through structural optimization, it is expected to improve the refrigeration efficiency of the compressor and enhance its performance. To achieve these goals, the following technical solutions are adopted:

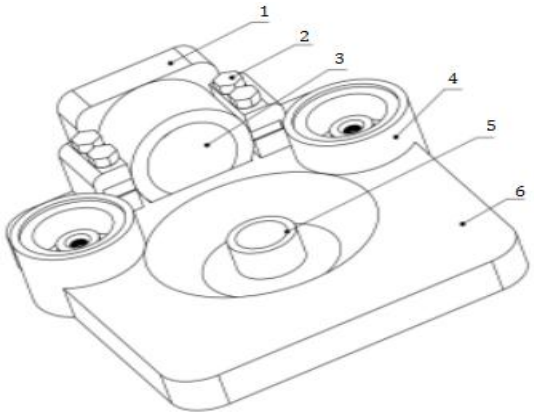
(1) Determine the structural form of the cylinder block: According to the operating environment of the refrigerator compressor and its performance requirements, the external dimensions and internal structure of the cylinder block are determined, and it is designed as a split-type and detachable cylinder block.

(2) Optimize the structure of the cylinder block: Considering that the cylinder block must have rigidity, sealing performance and heat dissipation performance, its structure is optimized through methods such as finite element analysis to improve the performance of the cylinder block.

(3) Design the connection mode of the cylinder block: The connection mode between the cylinder block and other components is designed to ensure a firm and reliable connection. In this paper, bolt connection is selected, which can not only ensure the connection strength, but also reduce the replacement cost and improve the adaptability of the cylinder base, as shown in Figure 1.

The split-type cylinder block consists of two parts: the lower base and the cylinder body. With the lower base unchanged, the size of the cylinder body can be adjusted according to the piston size. In addition, the fixed position of the bolts in the threaded holes can be adjusted according to the different crankshaft feed amounts, thereby changing the installation position of the cylinder body. This design has good flexibility, which can flexibly adjust the cylinder size according to different compressor models, and can also carry out targeted design on the connection part between the cylinder and the cylinder block according to the stress condition and working state of the compressor If the stress is large, the thickness can be appropriately increased; if the stress is small, the size can be reduced. Bolts of different models can also

be selected according to the actual stress to ensure a stable connection. The muffler cavity can be optimized and improved according to the operating noise of different compressors, so as to effectively reduce the operating noise. The bottom shaft hole corresponds to the cylinder, and its position cannot be changed at will, but the size of the shaft hole can be adjusted according to the piston size to ensure precise adaptation between the two.



1-Cylinder; 2-Bolt; 3-Piston cylinder; 4-Muffler cavity; 5-Shaft hole; 6-Cylinder block

Fig.1 Assembly drawing of cylinder block

3.2 Split-type Modeling of Cylinder Block

Design the connection part between the cylinder and the cylinder block: This is the key innovation point of the cylinder block design. The connection effect directly affects the performance of the compressor, the noise level, and whether the cylinder block will shake. It should be particularly noted that space for cylinder sinking should be reserved on the cylinder base. Finally, threaded holes are drawn at appropriate positions, and thread lines are added at the positions of the threaded holes, thus completing the design of the connection part between the cylinder and the cylinder block.

Muffler cavity design: The appropriate position is selected for the sketch design of the muffler cavity. The size and position of the muffler cavity can be changed according to specific requirements, and then a basic cylinder block base is obtained by stretching and cutting, as shown in Figure 2.

Cylinder modeling: Finally, the modeling of the cylinder part is carried out. First, the sketch of the cylinder piston cylinder is constructed, and the size of the piston cylinder must correspond to the actual piston size accurately. Then, the part for fixing the cylinder is drawn at an appropriate position, stretched to form, and finally, the boss sketch is drawn in front of the piston cylinder and then stretched to obtain a complete cylinder, as shown in Figure 3.

Split-type assembly of cylinder block: Insert components such as cylinder block, cylinder and bolts. First, assemble the cylinder and the cylinder block, then install four bolts of appropriate size correctly, and install bolts at the threaded holes for fixation, thus completing a complete split-type cylinder block, as shown in Figure 4.

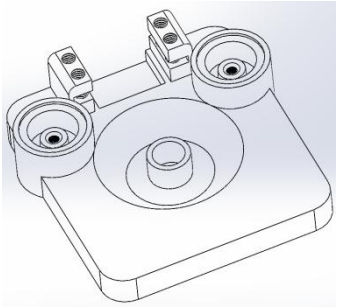


Fig.2 Structural design of muffler cavity

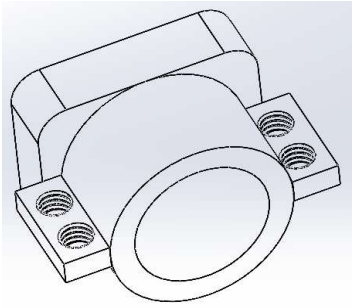


Fig.3 Structural design of cylinder

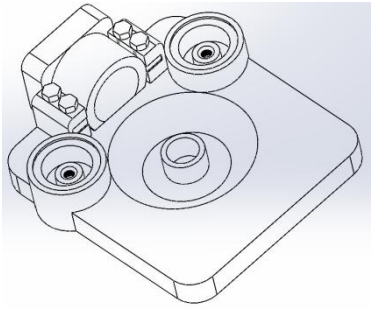


Fig.4 Split-type structural design

3.3 Stress Analysis of Split-type Cylinder Block

Under the actual stress condition of the split-type cylinder block, the internal pressure of the cylinder acts on the cylinder wall, generating circumferential stress (σ_1) and axial stress (σ_2). Circumferential stress is usually the main stress of thin-walled cylinders, which controls the strength of the cylinder block. Axial stress is relatively small, but it also needs to be considered in the design, especially in high-pressure cylinders. The piston exerts an axial force on the cylinder block during movement. In addition, due to different installation methods, the cylinder block may bear bending moment (M) and torque (T). Therefore, when applying loads, the focus is on whether the bolt connection part can meet the actual use requirements under the stress state of the cylinder barrel.

According to the thin-walled cylinder theory, the circumferential stress and axial stress of the cylinder block are calculated as follows[27]:

$$\sigma_1 = \frac{PD}{2t} \quad , \quad \sigma_2 = \frac{PD}{4t} \tag{16}$$

In formulas (16), P is the working pressure (MPa); D is the inner diameter of the cylinder block (mm); t is the wall thickness of the cylinder block (mm).

The radial expansion of the cylinder block is proportional to the internal pressure, and the calculation formula is[28]:

$$\Delta D = \frac{PD^2}{4Et} \tag{17}$$

In formula (17), E is the elastic modulus of the material. This formula is used to evaluate the deformation of the cylinder block under working conditions, so as to ensure that it does not exceed the allowable deformation range in the design.

The split-type cylinder block is connected by bolts, and the bolts need to bear the axial force caused by the working pressure. The calculation formula of bolt preload is as follows[29]:

$$F_b = \frac{\pi PD^2}{4n} \tag{18}$$

In formula (18), F_b is the preload of a single bolt (N); n is the number of bolts. By calculating the bolt preload, it can ensure that the cylinder block maintains sufficient fastening force during installation, so as to avoid structural loosening or leakage.

During the operation of the compressor, the cylinder is the key mission of compressing air and working together with the piston connecting rod, and its actual stress condition is extremely complex. To conduct in-depth research on this situation, simulation methods can be used to simulate the stress state of the cylinder inner wall and the piston during operation. The formula followed for applying force in a specific direction to the cylinder inner wall is[30]:

$$\sigma = \frac{F}{A} \tag{19}$$

In formula (19), σ is the stress, F is the force on the inner wall of the cylinder, and A is the area of the inner wall of the cylinder. A leftward friction force of 100N is applied to the inner wall of the cylinder, and at this time, the four bolts will be subjected to force. Through ANSYS, the maximum stress at this time is calculated to be 200.28 *MPa*. Under this condition, it is necessary to analyze the deformation degree of the cylinder under stress to determine whether the design is qualified. The formula used at this time is:

$$\varepsilon = \frac{\triangle L}{L} \tag{20}$$

In formula (20), ε is the strain, is the length change of the cylinder after being stressed, and L is the original length of the cylinder. When the piston reciprocates in the cylinder, the cylinder is subjected to force, and the maximum strain generated is 0.00085627*mm*.

4 Simulation Experiment of Split-type Cylinder Block

4.1 ANSYS Finite Element Analysis

The 3D modeling of the split-type cylinder block is completed in SolidWorks software to create an accurate 3D model of the split-type cylinder block. The model is imported into ANSYS software, and Workbench is used to perform static structural analysis on the split-type cylinder block. Then, according to the actual material used for the cylinder block, its material properties such as elastic modulus, Poisson's ratio, and density are defined. The final pre-processing step is meshing. An appropriate element type is selected, and to ensure calculation accuracy, a smaller mesh size can be adopted in key parts (bolt connection parts) for mesh refinement.

(1) Model Creation

The cylinder block assembly pre-drawn in SolidWorks is imported into the "geometric model" of static structure using the "import" command, and the material of the split-type cylinder block is configured as cast carbon steel in the "engineering data" of the unit command. Its material property parameters are shown in Table 1.

Table 1 Material Parameters of Cast Carbon Steel

Density (kg/m³)	Elastic Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)
7850	200	0.3	250

(2) Meshing

The system's default tetrahedral meshing is adopted for the research object, and the mesh resolution is set to 3 according to the actual situation. The geometric size adjustment is set for the four bolts, with the element size set to 2mm. The effect diagram after meshing is shown in Figure 5, thus generating a relatively reasonable mesh element model with 57,105 elements and 98,012 nodes.

(3) Boundary Condition Setting

A) The first type is to add "fixed support" to the bottom surface of the cylinder block according to the working state of the part, and add "bolt preload" to the four bolts. According to the working condition of the cylinder block, a rightward force of 100*N* is applied to the bolts on the left end of the part, and a leftward force of 100*N* is applied to the bolts on the right end, as shown in Figure 6.

B) The second type is to analyze the impact on the four bolts when the connection between the cylinder and the cylinder base moves at the bolt connection during the operation of the piston and the

cylinder. First, "fixed support" is applied to the cylinder base, and then "forces" are added to both sides of the cylinder, with the force magnitude being 100*N*, as shown in Figure 7.

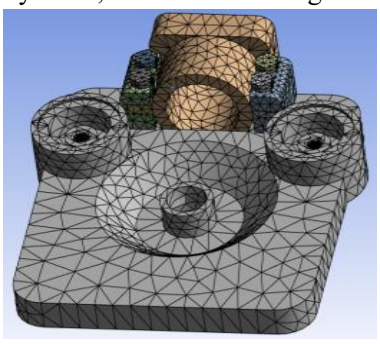


Fig. 5 Meshing

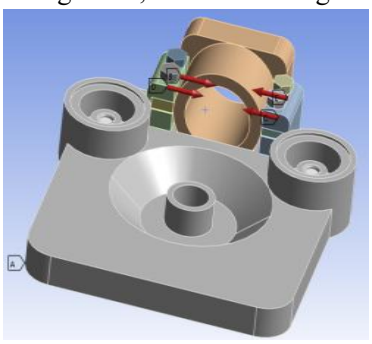


Fig.6 Boundary Condition Setting 1

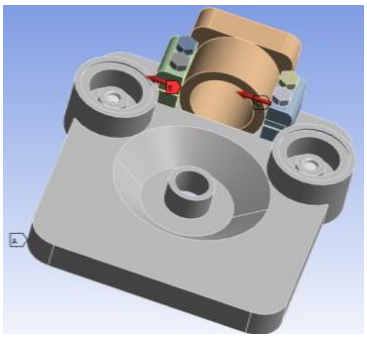


Fig.7 Boundary Condition Setting 2

4.2 Equivalent Stress Simulation Experiment

The simulation results of total deformation and equivalent stress analysis under the two boundary condition settings are solved, as shown in Figures 8 and 9. It can be seen that the maximum total deformation of the split-type cylinder block is 0.00085627*mm*, and the maximum equivalent stress is 200.28M*Pa*, while the average equivalent stress is 4.653*MPa*, which are reliable simulation data.

As shown in Figures 10 and 11, which are the equivalent stress simulation analyses under the second boundary condition setting, the simulation experiment data of the split-type cylinder block are: the maximum total deformation is 0.00020268*mm*, and the maximum equivalent stress is 4.1589*MPa*. Compared with the first boundary condition, these data are more reliable.

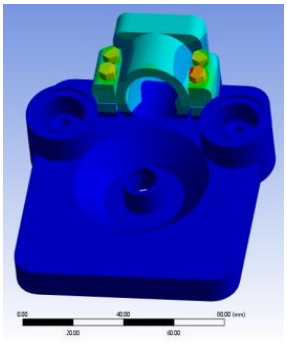


Fig.8 Total Deformation 1

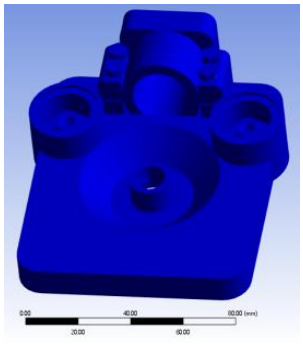


Fig.9 Equivalent Stress 1

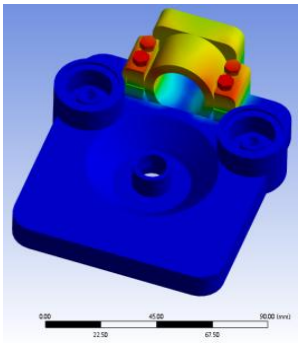


Fig.10 Total Deformation 2

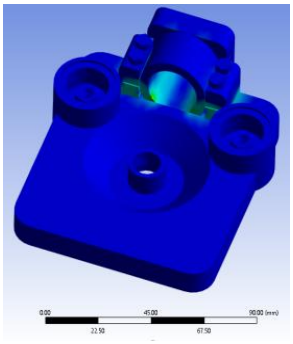


Fig.11 Equivalent Stress 2

4.3 Simulation Experiment Results

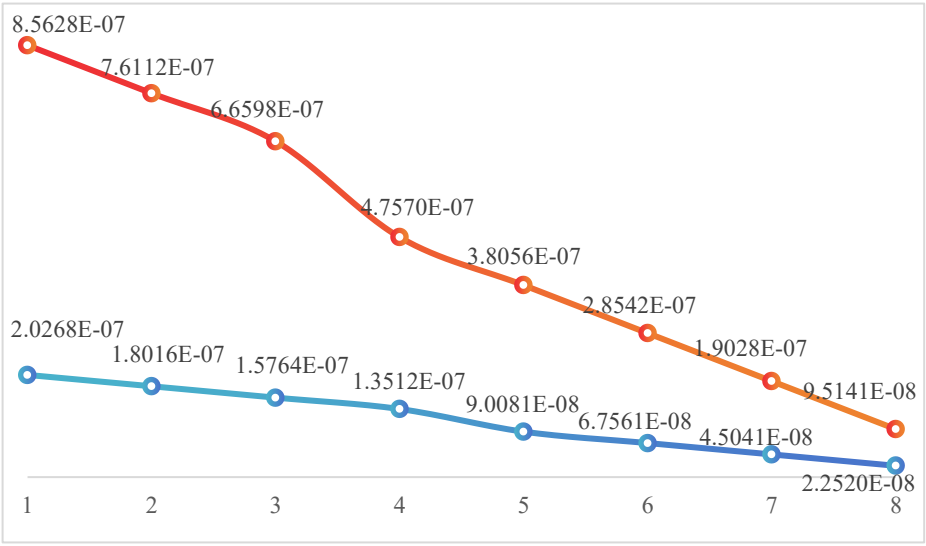
Among the most effective data, the data of 8 different reference points are exported, as shown in Table 2. It is undoubtedly concluded from the table that the data of point 1 in displacement value 1 is the maximum, which is 2.0268e-7m. Similarly, the maximum value of displacement value 2 is 8.5628e-7m, both located in the red area on the four bolts in the total deformation diagram. Among the 8 data points, the data of point 8 in displacement value 1 is the minimum, which is 2.252e-8m. Similarly, the minimum value of displacement value 2 is 1.9028e-8m, located in most of the blue area of the cylinder base in the diagram. It is easy to see that when the external force on the cylinder is larger, the force borne by the part close to the bolts is larger, and the displacement is larger.

Table 2 Distribution Data of Force-Displacement Experiment

Reference Point	Displacement Value 1 (m)	Displacement Value 2 (m)	Component

1	$2.0268e^{-7}$	$8.5628e^{-7}$	Fixed Boss
2	$1.8016e^{-7}$	$7.6112e^{-7}$	Fixed Boss
3	$1.5764e^{-7}$	$6.6598e^{-7}$	Fixed Boss
4	$1.3512e^{-7}$	$4.757e^{-7}$	Fixed Boss
5	$9.0081e^{-8}$	$3.8056e^{-7}$	Fixed Boss
6	$6.7561e^{-8}$	$2.8542e^{-7}$	Fixed Boss
7	$4.5041e^{-8}$	$1.9028e^{-8}$	Fixed Boss
8	$2.252e^{-8}$	$9.5141e^{-8}$	Fixed Boss

The distribution of force-displacement experiment data in Table 2 is plotted as shown in Figure 12, which can more intuitively show the displacement distribution and trend.



Blue Line;Displacement Value 1; Red Line:; Displacement Value 2

Fig.12 Distribution of Force-Displacement Data

When the piston and the cylinder operate normally, after carefully analyzing the displacement distribution diagrams of each cylinder, it can be determined that the maximum displacements are 0.00085627*mm* and 0.00020268*mm*, respectively, both of which are much smaller than the standard specified 40*mm*. Further observation of the stress distribution diagrams shows that under the first working condition, the maximum stress is 200.28*MPa*, which, although still within the safe range of the 250*MPa* yield limit, is not feasible in practical applications. As for the second working condition, the maximum stress is as low as 4.1589*MPa*, which provides the most reliable data support.

Based on the above analysis, under both working conditions, the stress borne by the cylinder block is lower than the yield strength of cast carbon steel, and the corresponding deformation is extremely small, which fully meets all the standards set in this study.

5 Conclusions

This study conducts a systematic investigation and analysis on the structural characteristics, manufacturing processes of the split-type cylinder block of refrigerator compressors, and its impact on compressor performance. By comparing the design differences between integral and split-type cylinder blocks, it is found that split-type cylinder blocks have obvious advantages in terms of manufacturing

accuracy, assembly convenience, and cost control. According to experimental tests and finite element analysis, the split-type cylinder block can effectively improve the fitting accuracy between the cylinder and the piston, reduce friction loss, lower vibration and noise, thereby enhancing the operating efficiency and stability of the compressor. Its modular design not only improves the universality of components but also reduces manufacturing and maintenance costs, making it have good application prospects in industrial production.

The split-type cylinder block is an important direction for structural optimization of refrigerator compressors, playing a significant role in improving performance, reducing costs, and increasing production efficiency. With the continuous advancement of manufacturing technology and materials science, the application prospect of split-type cylinder blocks will become better and better. Future research can further mature this technology, realize industrial application, and provide better solutions for improving the performance of refrigerator compressors.

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