Stress and Deformation Analysis of Oil-Free Air Scroll Compressor

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Abstract. This paper examined the deformation and the distribution of von-mises stress on the fixed and orbiting scroll. The stress and deformation of the scroll plate has been achieved under thermal load, structural load and thermo-static load. The full process of compression is achieved by the meshing operation of the moving and fixed scroll during the compression process of the scroll compressor. In this process, the teeth of the scrolls are mainly subjected to the combined effect of temperature and gas force resulting in stress and deformation. The performance of the scroll compressor can be affected by the high stress and deformation of the scroll, so it is important to research the scrolls under different field conditions. In this paper we presented the scrolls specification and deformation of oil-free scroll compressor. This study will enable the researcher and designers to improve the workability of the scroll compressor, resulting in a good performance prototype.

1. Introduction

Oil-free scroll compressors are widely used in refrigeration equipment, air-conditioning systems and various gas compression applications due to the advantages of light weight, small size, low sound, operational stability, high volume efficiency and a simple structure [1]. In the development of refrigeration, Le Wang designed and developed oil-free scroll compressor for aerospace applications, also developed a thermodynamic model and evaluated the prototype performance [2]. A thermodynamic model based on pressurization changes in the working cavity in the scroll compressor was analyzed and developed by Qiang Jianguo et al. Via analysis of the thermodynamic model, the law of temperature change on the scroll was obtained [3,4]. Experts, scholars as well as several other scientists have also done a lot of research in the field of oil-free scroll compressor. Lai Ching-Feng conducted a detailed study of the oil-free scroll compressor on electric vehicles, and the leakage model is very important to the efficiency of the oil-free scroll compressor [5]. Scroll compressor is a rotating compressor, with two spiral shaped scrolls; one is fixed and the other rotates, which creates compression in the chamber [6]. Le Wang has developed an oil-free scroll air compressor prototype suitable for aviation through continuous study, conducted a detailed assessment of its performance, and etc. By analyzing data, the compressor is found to perform well. There is a high degree of practicality and reliability [7]. The scroll disc deformation is studied under single load in all existing research studies [8]. The thermodynamics model and leakage model in the oil-free scroll cavity has been researched extensively by Peng Bin et al. and a mathematical model for the working
phase has been tested by the built test platform [9,10]. In the thermodynamic model analysis for oil-free scroll compressors there are several scholars in the related research. Zhao is renowned for its fuel cell vehicle spray oil-free scroll compressor for comprehensive performance analysis and research [11]. Fang Shiyi ignored the gas and scroll wrap heat exchange case for calculating the new oil-free scroll compressor thermodynamic operation [12]. Poi and Zhu Research the scroll plate heat transfer model with the 2D models [13]. The volumetric efficiency of oil-free Scroll Compressors has been analyzed in detail by Yanagisawa [14]. In the simulated analysis, the compression mechanism of a car air conditioning scroll compressor has been simulated by Yi et al. and the results has been tested experimentally [15,16].

2. Geometric Model:
The Figure 1, demonstrates the components of oil free scroll compressor, were designed in solid works software.

![Figure 1. Oil-free scroll compressor model](image)

1. Drive pulley; 2. Housing; 3. Colling wind wheel; 4. Fan shroud; 5. Air circulation channel; 6. Shaft; 7. Crank pin; 8. Counter weight; 9. Driving plate; 10. Orbiting scroll; 11. Fixed scroll

The circle involute equation is used to deduce the spiral equation of the scroll plate, the circle involute baseline equation is:

\[
\begin{align*}
x &= r_b \cos \varphi + r_2 \varphi \sin \varphi \\
y &= r_b \sin \varphi + r_2 \varphi \cos \varphi
\end{align*}
\]

(1)

The basic parameters of the oil-free scroll compressor as illustrated in Table. 1, the inner and outer profile wall lines of the scroll teeth are drawn in 2D software by baseline method, as shown in Figure. 2(a). According to the inner and outer ring profiles of the generated scroll teeth, the line equation is drawn by solid work software to draw the 3D model of the orbiting scroll as shown in Figure 2(b).

![Figure 2](image)

(a). Scroll profile and (b) 3D model of orbiting scroll
Table 1. Geometric parameters of scroll compressor

| Parameters         | Symbols | Description  |
|--------------------|---------|--------------|
| Base circle radius | r_b     | 3.675 mm     |
| Thickness          | t       | 5.8 mm       |
| Height             | h       | 36 mm        |
| Cylinderumber      | N       | 4.25         |
| Pitch of scroll    | p       | 23.0907 mm   |
| Offset distance    | R_o     | 5.74 mm      |

3. The procedure of Finite Element Analysis

Finite Element Analysis is a computational way to solve design problems. Finite Element Research uses building models to minimize the number and carry out simulated testing to refine designs.

3.1 Material Selection and Mesh generation

To carry out the simulations, select a material and boundary conditions to get accurate results. Cast iron where selected and some of its properties and their values as described in Table 2. In order to obtain efficient results, triangular and fine mesh is used. The fixed and orbiting scroll meshing is shown in Figure 3. The meshing of fixed part has about 195749 elements and 337994 nodes. Coarse and triangular mesh is being used for orbiting part. The meshing of orbiting part has around 11030 elements and 22004 nodes. There are three sections in the boundary conditions: working pressure of chamber fluid, inlet and outlet of the compressor temperature, and physical constraints. The estimated thermal analysis chamber pressure and thermal analysis temperatures are also measured. The physical limitations are determined by the operational action.

Table 2. The parametric of geometry

| Material characteristics | Notation | Fe            |
|--------------------------|----------|---------------|
| Young modulus            | E        | 1.1E+05 MPa   |
| Poisson Ratio            | µ        | 0.28          |
| Bulk modulus             | K        | 8.3E+10 Pa    |
| Coefficient Expansion    | α        | 1.1E-05 C^-1  |
| Ultimate Tensile Strength| σ_u     | 240 MPa       |
| Modulus of rigidity      | G        | 4.29E+10 Pa   |
| Density                  | ρ        | 7200 Kg m^-3  |
| Ultimate Compressive Strength | σ_cu | 820 MPa       |
| Thermal Conductivity     | λ        | 52 W m^-1C^-1 |
There are two main parts of the scroll compressor; one of them is fixed and the other is orbiting. Both are built by Solid Works software. The aim of this study is to analyze different parameters and enhance their performance on the scroll compressor. Three types of analysis are performed: thermal analysis; thermal loads only applied such as temperature, structural analysis; force applied to various surfaces, thermo-static analysis; thermal and statistic loads both are applied in order to achieve stress and deformation in fixed and orbiting scroll. In addition, the stress and deformation of scrolls directly influences the compressor’s output.

4.1 Analysis of pressure and temperature field

The pressure and temperature curve changes in the scroll compressor’s working chamber with the rotation angle of main shaft as shown in Figure. 4 and 5 respectively. As the gas enters the vacuum chamber through the suction opening, the preheating effect of the suction pipe allows the gas to heat up by 2 to 3 degrees. The working gas in the cavity is being continually compressed which causes its temperature to rise and, as a result, the pressure of the gas in the cavity increases. During the exhausting process, the pressure and temperature begin to increase first, then decrease slowly and eventually stay stable. This is because once the main shaft angle reaches the exhaust angle and the exhaust port is released, the gas in the cavity can’t diffuse in time, resulting in an instantaneous rise in pressure and temperature and the maximum temperature can reach 160°C. As the main shaft angle continues to increase, the exhaust port is completely opened, and the pressure and temperature remains relatively stable.
4.2 Stress and deformation analysis of fixed and orbiting scroll

4.2.1 Stress and deformation analysis of scrolls under thermal load. The thermal distribution on the surface of fixed and orbiting scroll is shown in Figure. 6. The figure shows that from the intake zone to the central area the temperature rises and the temperature rates in the working chamber are not sufficiently uniform. The intake area has a low temperature value, this is because the gas has just been compressed from the intake area. The temperature in the compression chamber is considerably higher over time with the orbiting scroll rotating. The reddish area on the fixed and orbiting scroll surface shows maximum temperature while the blue area displays minimum temperature.

Figure 6. Temperature distribution on surface of fixed & orbiting scroll

The stress and deformation of the scrolls under temperature load are displayed in Figure. 7 and 8. Figures show that the stress value for the scrolls is [0.0016231MPa, 801.64MPa] under the temperature load action of the scrolls, and the maximum stress value is at the fixed scroll. The deformation is high at high temperature under the effect of temperature load. Which shows that the temperature has a greater impact on the deformation of the scroll compressor.
4.2.2 Stress and Deformation Analysis of scrolls under structural load. In the structural analysis conditions, force is applied to the fixed and rotating scroll in two directions. Force 1675.2N, 780.11N is applied in X and Z directions respectively. The structural analysis results are in the form of total deformation and stress. Figure 9 indicate the cloud distribution of Von misses and the distribution of deformations is shown in Figure 10. At a fixed scroll, the maximum equivalent von misses stress is 9.5173MPa. The deformation picture illustrates that the deformation in scrolls close to the fixture is minimal (shown in blue region).
Figure 9. Equivalent (Von-misses) stress in fixed & orbiting scroll

Figure 10. Total deformation under structural load of fixed scroll & orbiting scroll

4.2.3 Stress and Deformation Analysis of scrolls under thermo-Static load. In the actual function of the scroll compressor, the pressure, force and temperature loads influence the scroll teeth, so that the deformation and stress of the scroll are more in keeping with the actual working conditions under the relation between the temperature and force. The stress and deformation of moving and static scroll under the combination of force and temperature load are shown in Figure. 11 and 12. The stress on the scroll teeth is relatively small from the stress cloud diagram, the root of the scroll teeth head is where the stress of the entire scroll teeth is higher, and the highest stress is 801.65MPa. In the deformation graph, 0.16758mm and 0.067401mm respectively are the maximum deformation of the fixed and orbiting scroll. The deformation of the static scroll occurs predominantly on the scroll's wall surface.
5. Conclusion
This paper analyzes in detail the compressor pressure field, temperature and force field distribution. The pressure load, force load and temperature load of the meshing scrolls are evaluated after the analysis results have been obtained. Detailed analysis is done of the stress and deformation under the coupled field. The simulation results can be considered as primary references for further optimization of oil free scroll compressors. The following conclusions can be drawn:

(1) It is visually and intuitively shown by the study of the distinct field load flow in the compression chamber. The fluid motion can be seen to be consistent with the rotational direction of the scroll teeth, but from the high to low pressure cavity, there will be a slight amount of backflow. It
indicates that there is a small amount of leakage, and in the middle exhaust region and the suction chamber, the vortex phenomenon of fluid will appear. By analyzing the pressure field, the pressure in the compression chamber is found to be relatively uniform, the pressure from outside to inside increases and the greater pressure close to the center. The temperature shows an upward trend from the intake region to the central area by examining the temperature field.

(2) In the study of the stress and deformation of the meshed scrolls, the temperature load has a greater effect in the analyzed stress and deformation of the scroll teeth. The stress value of scrolls [0.0016231MPa and 801.64MPa] is measured separately, the root of the scroll teeth is the highest stress, and the maximum deformation in the fixed scroll is 0.167 mm and 0.067 on the rotating scroll teeth. The maximum deformation occurred at the top of the moving scroll along the direction from the head to the tail. The results show that the load of the temperature field has a very massive effect on the scrolls, which must be considered when evaluating the stress and deformation of the scroll teeth. In addition, the stress value of the coupling field is below the material yield strength which shows that the scroll in practical applications is safe and reliable.

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6. References
[1] Peng Bin, Arnaud Legros, Vincent Lemort, Xie Xiaozheng, Gong Haifeng (2016). Recent Advances on the oil-free Scroll Compressor. Recent Patents on Mechanical Engineering, 9(1): 37-47.
[2] L Wang, Y Zhao, L Li, G Bu, etc. Research on oil-free hermetic refrigeration scroll compressor [J]. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 2007, 221(7): 1049-1056.
[3] Jianguo Qiang, Tao Wen. Numerical modeling of temperature distribution for orbiting scroll wrap in an air scroll compressor[J]. International Journal of Heat and Mass Transfer, 2013, 67(12): 678-689.
[4] Jianguo Qiang, Bin Peng, Zhenquan Liu. Dynamic model for the orbiting scroll based on the pressures in scroll chambers—Part I: Analytical modeling [J]. International Journal of Refrigeration, 2013, 36(7): 1830-1849.
[5] Lai Ching-Feng, Ann-Huang, Liang Kun-I. The development of oil-less scroll compressors used for fuel cells[C]. In: The 4th International Conference on Compressor and Refrigeration (ICCR), Xi’an Jiaotong University, Xi’an, China, 2003: 241-249
[6] Cardone, M.; Gargiulo, B. Numerical simulation and experimental validation of an oil free scroll compressor. Energies 2020, 13, 5863; doi: 10.3390/en13225863.
[7] L Wang, Y Zhao, L Li, G Bu, etc. Research on oil-free hermetic refrigeration scroll compressor[J]. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 2007, 221(7): 1049-1056.
[8] Fadiga, E.; Casari, N.; Suman, A.; Pinelli, M. Structured mesh generation and numerical analysis of a scroll expander in an open-source environment. Energies 2020, 13, 666.
[9] PENG Bin, ZHAO ShengXian, Li YaoHong. Performance Analysis of New Oil- free Scroll Compressor[C]. In: The 8th International Conference on Compressors and Refrigeration at Xi’an, July 20-22, 2017: L51:1-16.
[10] PENG Bin, ZHAO ShengXian, Li YaoHong. Thermodynamic Model and Experimental Study of Oil-free Scroll Compressor[C]. In: 2017 International Conference on Fluid Mechanics and Industrial Applications at Tai Yuan, October 21-22, 2017: 1-12.
[11] Yuanyang Zhao, Liansheng Li, Huagen Wu, etc. Theoretical and Experimental Studies of Water injection Scroll Compressor in Automotive Fuel cell Systems[J]. Energy Conversion and Management, 2005, 46(9-10): 1379–1392.

[12] FANG Shiyi, LI Liansheng, SHU Pengcheng, et al. Study on working process of oil-free scrolltype air compressor [J]. China Mechanical Engineering, 2005, 16(2): 123-127

[13] K. T. Ooi, J. Zhu, Convective heat transfer in a scroll compressor chamber: a 2-D simulation, Int J Therm Sci 43(7): 2004, 677-688.

[14] Yanagisawa T, Fukuta, Y Ogi. Performance of an oil-free scroll-type air compressor[C]. In: International Conference on Compressors and their Systems, City university, Londen, England, 1999: 279-287.

[15] F. Yi, E.A. Groll, J.E. Braun, Modeling and Testing of an Automobile AC Scroll Compressor. Part I. Model Development, Proceedings of 2004 International Compressor Engineering Conference at Purdue University, 2004, p. 1–8 (C082).

[16] F. Yi, E.A. Groll, J.E. Braun, Modeling and Testing of an Automobile AC Scroll Compressor. Part II. Model Validation Proceedings of 2004 International Compressor Engineering Conference at Purdue University, 2004, p. 1–8 (C083).