Influence of Profile Parameters on Radial Leakage Line Length of Variable Tooth Thickness Scroll Compressor

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Abstract—In order to accurately calculate the radial length of leak line of scroll compressor of variable tooth thickness, with three sections of circle involute type of scroll line as the research object, according to the type line equation to obtain the geometric model of variable tooth thickness radial leakage line length calculation model was set up, numerical solution, through accurate profile parameters was studied (Base circle radius, Connection point, Turning radius, etc.) on the influence of the length of leak line of change. Results show that the model could accurately describe the radial length of leak line of instantaneous change rule, and got the type line parameter change on the influence of the radial length of leak line of law, and the best control the length of leak line type line parameters, providing theoretical basis for reducing radial leakage scroll compressor, at the same time, the model also applies to other type line leak line length calculation.

1. INTRODUCTION

Scroll compressor is the use of dynamic and static scroll meshing to achieve gas compression. In order to reduce the friction loss, a small gap is usually left in the axial and radial direction of the scroll disc. However, this gap will cause the leakage of gas from the high pressure chamber to the low pressure chamber, which will reduce the exhaust pressure and the repeated compression of gas, resulting in the lower working efficiency of the scroll compressor. In particular, the radial leakage line caused by axial clearance is longer, causing the most serious leakage. Therefore, the research and control of radial leakage caused by axial clearance has become a research hotspot. At present, there are two methods to control the radial leakage: one is to design the axial seal structure by studying the leakage mechanism. The other is to reduce the length of radial leakage line by designing a new vortex line. Liu xingsheng et al. [1] proposed opening labyrinth grooves at the top of the tooth to reduce leakage. Li haisheng et al. [2] proposed to make grooves in the top of the tooth and fill the sealing strip
to achieve axial clearance sealing, in order to reduce radial leakage. LIU Tao[3] proposed a type of scroll teeth with combined lines to reduce leakage by shortening the length of radial leakage lines. Peng bin et al. [4] established a mathematical model of variable section scroll compressor and verified it through experiments. Aiming at the research on the radial leakage mechanism of the vortex compressor, Chen rong [5] established the leakage calculation model based on the principle of fano flow, and wang jun et al. [6-7] established the clearance leakage calculation model based on the finite element method. Kitae[8] measured the temperature change on the scroll teeth through experiments and analyzed the thermal deformation of the scroll teeth, laying a foundation for further research on the influence of thermal deformation on axial clearance. A variety of accurate calculation models have been established for radial leakage in axial clearance, but in all models, the calculation of radial leakage line length is essential, especially for variable cross section scroll compressor, the length of leakage line varies with the spindle Angle. At present, there is no literature on the variation of radial leakage line length of variable section scroll compressor.

Through the above analysis, this paper takes the three-segment circular involute scroll line as an example to establish a radial leakage line length calculation model, and obtains the variation rule of the leakage line length with the spindle Angle, and analyzes the influence of parameters such as base circle radius, turning radius and connection point on the radial leakage line length. It lays a foundation for optimizing profile parameters and calculating leakage quantity accurately. At the same time, the model can also be used to predict the variation rule of leakage line length of other molds.

2. Line equations

2.1. The equation of generatrix

The bus of the vortex line is formed by the smooth connection of the three-segment circular involute. The first segment circular involute and the third segment circular involute have the same radius of the base circle, and the second segment circular involute ACTS as the connection. The tooth head is modified by double arcs, and the geometric model of scroll teeth is shown in figure 1. Then the equations of each section are as follows:

The first equation of the involute of the base circle:
\[
\begin{align*}
  x_1 &= a_1 \cos \varphi + (a_1 + a_1 \varphi \sin \varphi) \\
  y_1 &= a_1 \sin \varphi - (a_1 + a_1 \cos \varphi) (0 \leq \varphi \leq \varphi_1)
\end{align*}
\]

The second part is the involute equation of the base circle:
\[
\begin{align*}
  x_2 &= a_2 \cos \varphi + (a_1 + a_1 \varphi_1 - a_2 \varphi_1 + a_2 \cos \varphi_1) \\
  y_2 &= a_2 \sin \varphi - (a_1 + a_1 \varphi_1 - a_2 \varphi_1 + a_2 \cos \varphi_1) (\varphi_1 \leq \varphi \leq \varphi_2)
\end{align*}
\]

The line equation of the base circle involute in the third section is:
\[
\begin{align*}
  x_3 &= a_3 \cos \varphi + (a_1 + a_1 \varphi_2 + a_2 \cos \varphi_2 - a_2 \varphi_2 - a_2 \cos \varphi_2 + a_3 \varphi_3 + a_3 \cos \varphi_3) \\
  y_3 &= a_3 \sin \varphi - (a_1 + a_1 \varphi_2 + a_2 \cos \varphi_2 - a_2 \varphi_2 - a_2 \cos \varphi_2 + a_3 \varphi_3 + a_3 \cos \varphi_3) (\varphi_2 \leq \varphi \leq \varphi_3)
\end{align*}
\]

According to the principle of normal equidistance, the equation of three-segment circular involute scroll profile is established as follows:The equation of the inner circle of the involute of the first base circle is,
\[
\begin{align*}
  x_1 &= a_1 \cos \varphi + (a_1 + a_1 \varphi + \frac{R}{2}) \sin \varphi \\
  y_1 &= a_1 \sin \varphi - (a_1 + a_1 \varphi + \frac{R}{2}) \cos \varphi (0 \leq \varphi \leq \varphi_1)
\end{align*}
\]
\[
\begin{aligned}
  x_1 &= -a_1 \cos \varphi - (a_1 + a_1 \varphi - \frac{R_{2r}}{2} \sin \varphi) \\
  y_1 &= -a_1 \sin \varphi + (a_1 + a_1 \varphi - \frac{R_{2r}}{2} \cos \varphi) \\
\end{aligned}
\]

\[(0 \leq \varphi \leq \varphi_1)\]

The equation of the inner circle of the second base circle involute is
\[
\begin{aligned}
  x_2 &= a_2 \cos \varphi + (a_1 + a_2 \varphi_1 - a_2 \varphi_1 + a_2 \varphi + \frac{R_{2r}}{2} \sin \varphi) \\
  y_2 &= a_2 \sin \varphi - (a_1 + a_2 \varphi_1 - a_2 \varphi_1 + a_2 \varphi + \frac{R_{2r}}{2} \cos \varphi) \\
\end{aligned}
\]

\[(\varphi_1 \leq \varphi \leq \varphi_2)\]

The equation of the outer circle profile of the involute of the second base circle is
\[
\begin{aligned}
  x_2 &= -a_2 \cos \varphi - (a_1 + a_2 \varphi_1 - a_2 \varphi_1 + a_2 \varphi - \frac{R_{2r}}{2} \sin \varphi) \\
  y_2 &= -a_2 \sin \varphi + (a_1 + a_2 \varphi_1 - a_2 \varphi_1 + a_2 \varphi - \frac{R_{2r}}{2} \cos \varphi) \\
\end{aligned}
\]

\[(\varphi_1 \leq \varphi \leq \varphi_2)\]

The equation of the inner circle of the base circle involute in the third section is
\[
\begin{aligned}
  x_3 &= a_1 \cos \varphi + (a_1 + a_1 \varphi + a_1 \varphi_1 + a_1 \varphi_1 - \frac{R_{2r}}{2} \sin \varphi_1 + (a_1 - a_1) \cos \varphi_1) \\
  y_3 &= a_1 \sin \varphi - (a_1 + a_1 \varphi + a_1 \varphi_1 + a_1 \varphi_1 - \frac{R_{2r}}{2} \cos \varphi_1 + (a_1 - a_1) \sin \varphi_1 + (a_1 - a_1) \cos \varphi_1 + a_1 \varphi - \frac{R_{2r}}{2} \sin \varphi_1 + (a_1 - a_1) \cos \varphi_1) \\
\end{aligned}
\]

\[(\varphi_1 \leq \varphi \leq \varphi_3)\]

The equation of the outer circle profile of the base circle involute in the third section is
\[
\begin{aligned}
  x_3 &= -a_1 \cos \varphi - (a_1 + a_1 \varphi + a_1 \varphi_1 + a_1 \varphi_1 - \frac{R_{2r}}{2} \sin \varphi_1 + (a_1 - a_1) \cos \varphi_1) \\
  y_3 &= -a_1 \sin \varphi + (a_1 + a_1 \varphi + a_1 \varphi_1 + a_1 \varphi_1 - \frac{R_{2r}}{2} \cos \varphi_1 + (a_1 - a_1) \sin \varphi_1 + (a_1 - a_1) \cos \varphi_1) \\
\end{aligned}
\]

\[(\varphi_3 \leq \varphi \leq \varphi_1)\]

Where, \(a_1\) is the base circle radius of the involute of the first base circle; \(a_2\) is the base circle radius of the involute of the second base circle; \(R_{2r}\) is the radius of rotation; \(\varphi_1\) and \(\varphi_2\) are the connection points respectively; \(\varphi\) is the spread Angle of vortex profile.

Fig 1. Geometric model of three - segment circular scroll teeth
2.2. Radial leakage line length calculation model
The dynamic scroll rotates around and each working chamber continuously changes dynamically at the same time. Because of the characteristics of the combined profile, the profile type and length of the radial leakage line change when the gas working chamber meshes from the outer ring to the inner ring. The instantaneous radial leakage line includes leakage from the first working chamber to the second working chamber and leakage from the second working chamber to the third working chamber. Suppose the instantaneous leakage line length from the first working chamber to the second working chamber is \( n_{12} \), and the instantaneous leakage line length from the second working chamber to the third working chamber is \( n_{23} \), then the expression of the instantaneous radial leakage line length is as follows:

When \( 0 \leq \theta \leq \pi \)

\[
L_{n12} = \int_{\phi_2}^{\phi_1} R_{d}d\phi + \int_{\phi_2}^{\phi_1} \sqrt{x_{n1}^2 + y_{n1}^2}d\phi \\
L_{n23} = \int_{\phi_2}^{\phi_1} R_{d}d\phi + \int_{\phi_2}^{\phi_1} \sqrt{x_{n2}^2 + y_{n2}^2}d\phi \\
L_{n23} = \int_{\phi_2}^{\phi_1} R_{d}d\phi + \int_{\phi_2}^{\phi_1} \sqrt{x_{n3}^2 + y_{n3}^2}d\phi \\
\]

When \( \pi \leq \theta \leq \theta_s \)

\[
L_{n12} = \int_{\phi_2}^{\phi_1} R_{d}d\phi + \frac{\pi R_2}{2} \\
L_{n23} = \int_{\phi_2}^{\phi_1} R_{d}d\phi + \frac{\pi R_2}{2} \\
L_{n23} = \int_{\phi_2}^{\phi_1} R_{d}d\phi + \frac{\pi R_2}{2} \\
L_{n23} = \int_{\phi_2}^{\phi_1} R_{d}d\phi + \frac{\pi R_2}{2} \\
\]

When \( \theta_s \leq \theta \leq 2\pi \)

\[
L_{n12} = (\theta - 3\pi + \theta) + \int_{\phi_2}^{\phi_1} \sqrt{x_{n1}^2 + y_{n1}^2}d\phi \\
L_{n12} = \int_{\phi_2}^{\phi_1} \sqrt{x_{n2}^2 + y_{n2}^2}d\phi \\
L_{n23} = \int_{\phi_2}^{\phi_1} \sqrt{x_{n3}^2 + y_{n3}^2}d\phi \\
L_{n23} = \int_{\phi_2}^{\phi_1} \sqrt{x_{n3}^2 + y_{n3}^2}d\phi \\
\]

Replace \( a_1 = 2.885 \); \( a_2 = 4.158 \); \( \phi_1 = 2\pi \); \( \phi_2 = 4\pi \); \( R_{w2} = 5.063 \), Maximum display is \( 6\pi \). The dynamic and static vortex discs mesh to form 3 working cavities. As the spindle rotates, the volume of the working cavity changes. The second month work is studied. Figure 2 shows the leakage area at different spindle angles. The main shaft rotates for one week. The second working cavity leakage line length \( L_{n12} \) and the leakage line length \( L_{n23} \) are:

\[
L_{n2} = \frac{L_{n12} + L_{n23}}{2} \\
L_{n23} = \frac{L_{n23} + L_{n23}}{2} \\
\]
\( \theta \) is the spindle angle; \( n \) is the inner ring line; \( w \) is the outer ring line; \( \theta_s \) is the spindle angle at the end of exhaust; \( \theta_i \) is the spindle angle at the beginning of exhaust.

Fig.2 Leakage area diagram at different spindle angle

3. EFFECT OF LINE PARAMETERS ON LEAKAGE LINE
According to the above analysis, according to the instantaneous calculation model of radial leakage line length, in order to study the variation law of leakage line length and the influencing factors, different type line parameters are selected, as shown in table 1, and the variation of radial leakage line length is analyzed.
Table 1 Type line parameters table

| NO | $a_1$ | $a_2$ | $R_{12}/2$ | $\varphi_1, \varphi_2$ |
|----|-------|-------|------------|-------------------|
| 1  | 2.385 | 4.158 | 2.5315     | $2\pi, 4\pi$     |
| 2  | 2.885 | 4.158 | 2.5315     | $2\pi, 4\pi$     |
| 3  | 3.385 | 4.158 | 2.5315     | $2\pi, 4\pi$     |
| 4  | 2.885 | 4.658 | 2.5315     | $2\pi, 4\pi$     |
| 5  | 2.885 | 5.518 | 2.5315     | $2\pi, 4\pi$     |
| 6  | 2.885 | 4.158 | 2.0315     | $2\pi, 4\pi$     |
| 7  | 2.885 | 4.158 | 3.0315     | $2\pi, 4\pi$     |
| 8  | 2.885 | 4.158 | 2.5315     | $1.5\pi, 3.5\pi$ |
| 9  | 2.885 | 4.158 | 2.5315     | $2.5\pi, 4.5\pi$ |

3.1. Effect of the radius of the base circle

Bring the first to third set of data in table 1 into the leakage line length calculation model, the other parameters are unchanged, and the results are shown in figure 3. It can be seen that $L_{12}$ increases with the increase of $a_1$, but the effect of $a_1$ decreases when approaching the end angle of exhaust. This is because at the end of the scheduling, the leakage zone line is composed of a modified line, independent of $a_1$. After passing through the exhaust angle, the size of $L_{12}$ and $a_1$ is proportional; the size of $a_1$ has a greater effect on $L_{23}$, and the greater the $a_1$, the greater the $L_{23}$. This is because most of the vortex lines that make up the second cavity are composed of the first section of the base circle involute, the larger the radius of the base circle, the larger the rotation diameter of the type line, and the corresponding increase of the leakage line length.

![Fig. 3 Curve of discharge line $L_{12}$ and discharge line $L_{23}$ length under different radius of base circle $a_1$](image_url)
3.2. Effect of base circle radius  $a_2$

The second and fourth and five sets of data in table 1 are brought into the leakage line length calculation model, and the other parameters remain unchanged. The results are shown in figure 4. It can be seen from the diagram that before the end of the exhaust, the size of $a_2$ has little effect on the length L12 of the discharge line. After the end of the scheduling, the effect of $a_2$ is relatively obvious at the beginning of the suction, and the greater the $a_2$, the greater the L12, but the effect gradually disappears as the angle increases; $a_2$ has a great influence on the discharge line length L23, because the discharge line L23-type line is mostly composed of the second base circle involute.

![Fig. 4 Curve of discharge line $L_{12}$ and discharge line $L_{23}$ length under different radius of base circle $a_2$](image)

3.3. Effect of turning radius  $R_{or}$

The second and sixth and seven groups of data in Table 1 are brought into the leakage line length calculation model, and the other parameters remain unchanged, and the results are shown in Figure 5. It can be seen from the diagram that $R_{or}$ has little effect on L12 size and no effect on L23 size.
3.4. Impact of Connection Points $\varphi_1$ and $\varphi_2$

The second and eighth and ninth groups of data in table 1 are brought into the leakage line length calculation model, and the other parameters remain unchanged, the results are shown in figure 5. The connection point has a great influence on $L_{12}$, changing the connection point position, each moving forward $0.5\pi$, the leakage line length is reduced by about 20%. Before the end of the exhaust, the effect on $L_{23}$ is small, but after the end of the scheduling into the inspiratory stage, the impact on $L_{23}$ is greater, no forward shift $0.5\pi$, the leakage line length is reduced by about 40%. The reason for the above phenomenon is that the connection point moves forward, the discharge line is mostly composed of the modified line, and the correction part is independent of the connection point position, so the leakage line length decreases when the connection point moves forward. The discharge line is mainly composed of the second section and the third section base circle involute. When the connection point moves back, the discharge line length is mainly composed of the third section base circle involute and the connecting arc, and the connection arc part has a large circumference, which makes the leakage line length increase obviously.
4. CONCLUSION

(1) The calculation model of leakage line length is established, which not only provides reference for accurate calculation of radial leakage of axial clearance, but also has generality, which can be applied to the calculation of other combined line leakage line length.

(2) The radii of the base circle, the radius of rotation and the position of the connection point all affect the variation of the leakage line length. It is found that the influence of rotation radius \( R_r \) is the least, and when the connection point \( \phi_1 \) increases and the variable tooth thickness section moves back, it has a great influence on the leakage line length.

(3) According to the influence of the type line parameters on the leakage line length, it provides the basis for the design and selection of the type line parameters when considering the leakage control.

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