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TWIN SCREW COMPRESSOR PERFORMANCE AND ITS RELATIONSHIP WITH ROTOR CUTTER BLADE SHAPE AND MANUFACTURING COST

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Abstract
By making use of a suite of programs for designing profile geometry, cutter geometry and predicting the thermodynamic performance of a twin screw compressor, this paper investigates techniques of obtaining an optimised rotor cutter blade design. The techniques for using different geometric schemes for setting clearances are explained, and the techniques for optimising main manufacturing parameters for obtaining the optimised blade shapes are presented. The main purpose of using different geometric schemes for setting clearances is to improve the compressor performance, and the main purpose for obtaining the optimised blade shapes is to reduce the manufacturing cost of the compressor.

1 INTRODUCTION

Helical screw compressors contain only two moving parts, a male rotor and a female rotor, the shapes of which are very complex. Along the contact line between them a clearance should exist to allow for gas loading deflections and thermal distortions of the rotors, bearings and housing, and for manufacturing errors and oil film thickness. This paper describes different geometric schemes of providing inter-rotor clearance. The average clearance and the leakage area are calculated and used in a computerised thermodynamic model of the working process of the compressor to determine leakage rates and volumetric and isentropic efficiencies.

The geometric clearance schemes used to calculate cutter blade shapes do not significantly affect the macro geometry of the blade, only the clearance distribution along the contact line of a rotor pair, and as a consequence, the leakage across the contact line, the volumetric efficiency and the indicated isentropic efficiency. The cutter shapes are defined mainly by the profile used in the compressor, and when a profile is chosen certain values of manufacturing parameters such as the offset angle and the angle between the cutter axis and the rotor axis, can require a change in cutter shape with a consequent increase in the manufacturing cost of the rotors. This paper also discusses the optimisation of these manufacturing parameters. The choice of a profile is a separate topic, which also involves the thermodynamic performance of the compressor and the manufacturing cost of the rotors and requires the optimisation of a number of profile parameters.

Although rotors can be manufactured by milling and hobbing, in this paper only milling is considered as milling is used by most manufacturers. However, the results obtained by this paper are also correct for the compressors manufactured by hobbing.

2 COMPUTER PROGRAMS USED

The following computer programs developed by the authors are used for the analysis presented in this paper:
Profile Generation Program This program is a profile library which can generate any profile within the SRM D definition. The profile generation program is the basis of all the research work. It calculates and outputs its calculated results into different data files, which are required by other programs developed by the authors for the compressor geometrical characteristics calculations, cutter blade calculations, etc.

Cutter Blade Calculation Program This program (1) is used to calculate: the zero clearance and real profiles of both the male and female lobes; the zero clearance and real cutter blades for male and female; the variation of the total clearance both normal to the profile and to the helical surface along the length of the contact line. It also gives desirable manufacturing parameters and the average clearance between the male and female rotors, which is required by the working process simulation program of the compressors.

Geometrical Characteristic Calculation Program This program (2) calculates all the required geometrical characteristics and parameters for the working process simulation and for design purposes. Many of the geometrical characteristics are expressed as a function of the male rotor rotation angle, especially those which will be used in the working process simulation program. The start angle is the angle where the cavity volume equals zero.

Working Process Simulation Program This program (3) simulates working processes of a refrigeration twin screw compressor which may run under various conditions, such as partial loading, oil injection, liquid refrigerant injection, gaseous refrigerant superfeeding and different refrigerants. The program calculates the thermodynamic properties in the cavity as a function of the male rotor rotational angle or the cavity volume, and also the derived parameters and efficiencies describing the behaviour of the compressor.

3 INTER-ROTOR CLEARANCE DISTRIBUTION AND TWIN SCREW COMPRESSOR PERFORMANCE

There are in general four geometrical schemes for determining cutter geometry and hence rotor geometry and clearances between rotors to accommodate tolerance build-up, gas force deflections, and the thermal distortions which occur during operation. They are as follows:

1. A zero clearance (perfect) lobe profile is produced in the first instance and then modified according to a chosen geometric scheme to produce a real profile with clearance. In the first scheme considered here which is commonly used by manufacturers, a real profile equidistant from the zero clearance profile in the end plane is proposed. The equidistant profile is constructed by stepping out the same distance along the normal to the tangent at each location point on the zero clearance lobe profile. A suitable cutter geometry is then determined for the equidistant lobe geometry and the given helix angle. This scheme is named the equidistant profile method.

2. Cutter blade geometry capable of manufacturing the zero clearance lobe profile is determined and then a real cutter blade geometry is created by modifying the zero clearance blade according to a chosen geometric scheme. In the scheme considered here a real cutter blade equidistant from the zero clearance blade is created in the same manner as the equidistant lobe profile in method 1. This scheme is named the equidistant helical surface method.

3. A reduced centre distance between cutter and rotor can be used to produce a pair of rotors with a working clearance between them.

4. On assembly, inter-rotor clearance can be created by increasing the centre distance between the rotors.

In this paper method 1 and method 2 are considered with methods 3 and 4 being seen as possible ways of modifying methods 1 and 2 to suit special running conditions in practice.

Each geometric scheme results in its own distinct clearance distribution along the contact line. Fig. 1 shows a graph of the clearance distributions along the contact line obtained using the two clearance schemes subject to the condition that the minimum inter-rotor clearance is the same for both methods. The graph is obtained for the following compressor specification chosen as an illustration:

- Lobe profile—SRM D standard.
- The minimum clearance normal to the helical surface for both methods is 13μm, which is equivalent to 18μm in the plane of the profile, approximately half backlash.
- Male and female rotor diameters (equal): 204mm.
- Male rotor wrap angle: 300°.
- Length/diameter ratio: 1.65.
For the equidistant lobe profile method, the maximum inter-rotor clearance, which equals the uniform distance between the real and the zero clearance end profiles, occurs at the tips and the roots of the rotors, while along the lobe flanks the clearance normal to the helical surface is less than the uniform distance in the end plane. For the equidistant helical surface method the situation is very different. For this case the minimum distance between the real and zero clearance end lobe profiles, which equals the (uniform) clearance normal to the helical surface, occurs at the tips and roots of the rotors. On the lobe flanks of the end profile the distance is larger than the (uniform) inter-rotor clearance normal to the helical surface.

For refrigeration compressors, the temperature of the rotors is slightly higher than the normal atmospheric temperature, which results in a very small thermal expansion in the radial direction, and at the same time the rotor deflection caused by the cavity pressure always tends to separate the rotors, so that the clearances at the tips and the roots of the rotor lobes do not need to be larger than at their flanks. As a result, the inter-rotor clearance distribution obtained by the equidistant helical surface method is to be preferred over that of the equidistant lobe profile method.

The areas under the graphs of the inter-rotor clearances in Fig. 1 represent the leakage areas for gas leaking across the contact line. The equidistant helical surface method results in the same inter-rotor clearance everywhere on the contact line. In magnitude, it is equal to the minimum value resulting from the equidistant lobe profile method so that its leakage area per lobe is only 89 per cent of the equidistant lobe profile method; that is the average inter-rotor clearance of the equidistant lobe profile method is bigger than the equidistant helical surface method by twelve per cent.

The leakage path across the contact line is among the most important of the leakage paths because it has the largest leakage area combined with a short path length in the direction of flow and the largest pressure difference. As a consequence it has a large effect on the performance of the compressor. A leakage analysis (4) conducted by the authors for a refrigeration helical screw compressor shows that the net leakage across the contact line is about 1.3 times the net leakage across the tip sealing lines of the male and female rotors and about 5 times the net leakage rate through the blow holes. As the different geometric schemes result in the different leakage areas across the contact line, they influence compressor performance in different ways. Fig. 2 shows the predictions of the effect of changing from an equidistant lobe profile clearance scheme to an equidistant helical surface clearance scheme. The volumetric and indicated efficiencies are both predicted to improve over the whole range of running conditions. This is as expected since the leakage area across the contact line is smaller for the equidistant helical surface method. Fig. 2 also shows the measured values of volumetric efficiency and total efficiency for the equidistant profile method. The running conditions for Fig. 2 are as follows:
- Refrigerant: R22.

\[ \text{Equidistant helical surface method, normal to helical surface.} \]

\[ \text{Equidistant profile method, normal to end lobe profile.} \]

\[ \text{Equi. helical surface method, normal to end lobe profile} \]

\[ \text{Equidistant helical surface method, normal to helical surface.} \]

Fig. 1 The clearance distributions along the contact line
- Speed of male (driven) rotor: 3000rev/min.
- Condensing temperature: 308.15K.
- Evaporating temperature: 233.15−278.15K (corresponding to a nominal pressure ratio: 12.91−2.32).
- Superheat degrees: 30K.
- Oil and liquid refrigerant injected.

![Efficiencies Graph]

**Efficiencies**
- △ Volumetric efficiency, measured values.
- - Total efficiency, measured values.
- ⋆ Volumetric efficiency, prediction, equidistant lobe profile method.
- ○ Indicated efficiency, prediction, equidistant lobe profile method.
- ☆ Volumetric efficiency, prediction, equidistant helical surface method.
- ✡ Indicated efficiency, prediction, equidistant helical surface method.

![Pressure Ratio vs. Efficiencies Graph]

Fig. 2 Predicted and test results for a compressor with oil and liquid refrigerant injection—two clearance schemes compared

Neither of the schemes described here obtains the optimum inter-rotor clearance distribution. The optimum method requires a combination of a non-equidistant lobe profile method and the equidistant helical surface method (1). The performance of the compressor can be improved further by making use of the optimum method.

4 THE OPTIMISATION OF CUTTER SHAPES

Cutter shapes have an important influence on the manufacturing cost of rotors. If a cutter has a interrupted blade or a sharp point, or the cutter edge has a rapid variation of its radius of curvature, or regions of unusually small radius of curvature, great exactness of the cutter shape is required to produce of a rotor having reasonable tolerances, which would require an increase in manufacturing cost to produce a compressor having a competitive thermodynamic performance. The interrupted blade, the sharp point and the fast variation of the radius of curvature also mean a lower number of rotors produced between resharpening operations of the cutter and restrictions on favourable cutting angles and cutting speeds, again resulting higher manufacturing costs. The angle between the two flanks of the cutter blade, especially the angle at the outer end of the blade where it is a minimum for the male rotor cutter, has an important influence on the manufacturing cost of rotors. If the minimum angle is large, the number of possible resharpening operations of the new blade before it is cut down to its minimum useable size will be large, as the amount of material to be ground away in each operation will be small. The tooling cost can thus be cut down drastically which means a more economical production of rotors.
Cutter shapes are defined mainly by the profile used. Some old profiles have sharp points and can result in interrupted cutter blades; they also have rapid variations of the radius of curvature on the edges. However, modern profiles, such as SRM D, require a cutter which has a shape where the edge follows a continuous curve without abrupt changes of the radius of its curvature. The modern profiles require their cutters to have a large angle between the two flanks of the blade. They permit a wide selection of the angles between the cutting tool and the workpiece axes during the manufacturing operation; which in turn means that the more favourable cutting angles can be chosen, so that the wear of the tool is reduced and simultaneously the possibility of increasing the cutting speed is opened up. In other words the modern profiles open up the possibility of manufacturing a more efficient compressor for a lower cost than is possible when the older profiles are used.

Cutter shapes can of course be changed by changing profile parameters, but usually the optimisation of a cutter shape will not depend solely on changing profile parameters, which are chosen in order to obtain the best thermodynamic performance for the compressor (5). Once the profile parameters are settled according to optimisation procedures to gain the best thermodynamic performance, the cutter shapes can then be calculated. The inter-rotor clearance can be set by the equidistant lobe profile method or the equidistant helical surface method or by a combination of these methods. Thereafter manufacturing parameters such as the offset angle, which is used to rotate the end lobe profile coordinates to a roughly symmetrical position about the line connecting the rotor and cutter centres, and the angle between the cutting tool and the workpiece, influence cutter shapes considerably; the angle between the two flanks of the cutter blades, and the angle between one of the flanks and the line connecting the rotor and cutter centres, are affected significantly.

Fig. 3 shows the influence on the cutter shape of the angle between the cutter and rotor axes. All the blades in Fig. 3 can used to cut the same profile on rotors having the same rotor parameters and the same offset angle, which is −36.72°. Blade 1 is the cutter blade used to cut the male rotor of the compressor mentioned in the last section, and the angle between its cutter axis and the rotor axis is 45°. The angles between the cutter axis and the rotor axis of blades 2 and 3 are 47.5° and 41° respectively. The minimum angles between the two flanks of blade 1, 2 and 3 are 36°, 28° and 50° respectively. The smaller the angle between the cutter axis and the rotor axis, the larger the minimum angle between the two flanks of a cutter blade. The tooling costs of blade 3 are less than those of blades 1 and 2.

Blade 1
Blade 3
Primary flank
Secondary flank

Fig. 3 The influence on cutter shape of the angle between the cutter and rotor axes

Blade 2
Blade 1
Blade 3

Fig. 4 The influence of offset angle on the cutter shape

Fig. 4 shows the influence of the offset angle on the female cutter shape. Blade 1 is the cutter blade used to cut the female rotor of the compressor mentioned in the last section, and its offset angle is 7.5°. Blades 2 and 3 have the same angle between the cutter axis and the rotor axis as has blade 1, which is 45°, but different offset angles, which are 17.5° and −2.5° respectively. The offset angle does not change the basic cutter shape, but changes the minimum angle.
between the primary flank and the line connecting the cutter and rotor centres, which has an important influence
on the number of possible resharpening operations of the cutter for female rotors. For blade 3 the minimum angle
between the primary flank and the connecting line is small, about 5°, which means that a large amount of material
is ground away in each resharpening operation and the number of possible resharpening operations of the new blade
before it is cut down to its minimum size will be small, but the minimum angle between the secondary flank and the
connecting line is large and about 20°. The angles between the primary flank and the connecting line and between
the secondary flank and the connecting line are too dissimilar for good design. A change of the offset angle can
change this arrangement. Blade 1 has 7° and 18°, and blade 2 has 10° and 15° for the minimum angles between
the primary flank and the connecting line and between the secondary flank and the connecting line respectively. For
blade 2, the combination of the angles between the primary flank and the connecting line and between the secondary
flank and the connecting line is much more reasonable than for blades 1 and 3.

It should be mentioned here that another important manufacturing parameter, namely the distance between the
cutter and rotor centres, has no influence on the cutter shape in modern profiles. For old profiles, on which one or
more sharp points exist, the distance is dependent on the angle between the cutter axis and the rotor axis.

5 CONCLUSIONS

1. Of the two geometrical schemes proposed in this paper for determining inter rotor clearances, namely the
equidistant lobe profile method and the equidistant helical surface method, the latter is the superior for refrig-
eration twin screw compressors.

2. The shapes of cutter blades have an important influence on the manufacturing costs of rotors. Some manufac-
turing parameters, such as the offset angle and the angle between the cutter axis and rotor axis, can be used
to optimise the cutter shapes so as to reduce the manufacturing cost of the rotors, especially the tooling cost.

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