1996

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C. X. You
University of Strathclyde

Y. Tang
University of Strathclyde

J. S. Fleming
University of Strathclyde

OPTIMUM ROTOR GEOMETRICAL PARAMETERS IN REFRIGERATION HELICAL TWIN SCREW COMPRESSORS

C X You, Y Tang and J S Fleming
Department of Mechanical Engineering, University of Strathclyde
Glasgow, United Kingdom

ABSTRACT

This paper presents a parameter study for optimum rotor geometrical parameter combinations of a refrigeration helical twin screw compressor with four commonly used lobe combinations and five different length/diameter ratios and wrap angles. The volumetric and indicated efficiencies of the compressor are important. So also are other factors such as rotor deflection, bearing load, bearing life and inter-rotor contact force; any one of which could become a decisive parameter depending on the circumstances. In this paper the influence of rotor geometrical parameters is discussed with respect to all these factors and suggestions on choosing optimum parameter combinations are presented.

NOMENCLATURE

C	Centre distance between the male and female rotors, mm
D	Outer diameter of the male rotor, mm
L	Length of rotors, mm
$\bar{z}_1$, $\bar{z}_2$	Lobe numbers of the male and female rotors, respectively
φ_w	Male rotor wrap angle, deg

1 INTRODUCTION

It is important to choose the best rotor geometrical parameters for a given application of a refrigeration helical twin screw compressor. Rotor geometrical parameters, i.e. lobe combination, length/diameter ratio and wrap angle, influence the performance, size and thus the manufacturing cost of the compressor considerably. After the profile is chosen for a specified application, the skill of the designer lies in choosing an optimum geometrical parameter combination so as to enable the compressor to have the best performance combined with an acceptable size.

The volumetric and indicated efficiencies of the compressor are the most important factors one should consider when choosing the geometrical parameters. However, there are occasions when the influence on the compressor efficiencies of different parameter combinations is small while other factors such as rotor deflection, bearing load and rotor contact force become important for other reasons and sometimes even critical, e.g. when choosing the length/diameter ratio for a high pressure application. Ease of manufacture also requires to be taken into account.

In this paper a parameter study is presented, which makes use of four lobe combinations, i.e. 4+5, 4+6, 5+6, 5+7; five length/diameter ratios ranging from 1.0 to 2.2; and five male rotor wrap angles ranging from 250 to 350. The influence of these geometrical parameters are discussed and suggestions on choosing optimum parameter combinations are presented.

2 COMPRESSOR SPECIFICATIONS AND RUNNING CONDITIONS

The specifications of the compressor used for the calculation are as follows:

- Rotor profile and lobe combination: SRM-D, 4/5, 4/6, 5/6, 5/7
- Outer diameter and centre distance of the rotors: 204, 160 mm
- Length / diameter ratio and male rotor wrap angle: 1.0 to 2.2, 250° to 350°

- Volume ratios for radial and axial discharge: 2.6 and 5.0

The running conditions used for the calculation are listed below:

- Compression medium and male rotor driving speed: *R22*, 3000 rpm
- Evaporating and condensing temperature: -5, 40 °C
- Suction and discharge pressure: 4.21, 15.34 bar
- Oil injection rate and temperature: 150 kg/min, 40 °C
- Compressor real capacity: 275 kg/min

The computer programs used in this paper form a powerful package capable of performance simulation and force analysis for various compressor specifications and running conditions[1-2]. The programs were verified by comparing the predictions with the measured data for the same type of rotor profile and similar compressor specifications and running conditions as those used in this study. Therefore, the authors believe that the simulation results in this study are of the same level of reliability.

To minimize rotor deflection the bearings should be positioned as close to the rotor body as possible. A reasonable distance from the nearest rotor end plane is about $0.3D$ on the suction side and $0.4D$ on the discharge side. It is common to make the shaft diameter outside the rotor body about 13-17 mm smaller than the rotor root diameter[3]. For the compressor considered here, a 17 mm reduction is used. In this study, only female rotor deflection is calculated since the female deflection is several times that of the male.

In addition, the following definitions are used:

$$\text{Input torque} = \text{Male rotor torque} + \frac{\bar{z}_1}{\bar{z}_2}\cdot(\text{Female rotor torque})$$

Maximum Contact Force - The maximum inter-rotor contact force per unit length of the power transmission section of the contact line[2].

3 RESULTS AND DISCUSSION

3.1 Effect of Lobe Combination

The results of the four different rotor combinations are tabulated in Table 1. To obtain the same capacity the dimensions of the compressor have to be different for different lobe combinations, which is revealed by different centre distances.

Table 1 Effect of lobe combinations

Parameters	Lobe combination $\bar{z}_1 + \bar{z}_2$			
	4 + 5	5 + 6	4 + 6	5 + 7
Centre distance C (mm)	151.3	159.0	160.0	173.4
Total rotor weight (kg)	96.7	108.6	104.7	127.2
Volumetric efficiency (%)	92.62	92.91	92.29	92.76
Isentropic indicated efficiency (%)	82.76	82.78	82.41	82.68
Input torque (Nm)	840.0	810.6	101.4	947.0
Maximum contact force (N/mm)	16.3	18.0	15.9	18.8
Max. female rotor deflection (mm)	0.0207	0.0178	0.0123	0.0087
$0.002\ C^{0.5}$ (mm)	0.0246	0.0252	0.0253	0.0263

The volumetric and isentropic indicated efficiencies are virtually unaffected by changing the lobe combination. So also is the maximum rotor contact force. This makes it possible to concentrate attention on other factors.

The 4+5 combination seems to be an excellent choice since it has the smallest size and lowest weight, while the 5+6 combination has the lowest input torque. However, it can be seen that these two combinations have relatively larger deflections than the 4+6 and 5+7 combinations. It is recommended that rotor deflection should be less than $0.002\ C^{0.5}$ mm if good performance and reliability are to be achieved[3]. This criterion is met in Table 1 but for 4+5 and 5+6 combinations an increase in pressure difference may lead to problems.

Table 2 shows the results for a higher discharge pressure of 24.27 bar (condensing temperature 60°). The suction pressure remains unchanged, i.e. 4.21 bar (evaporating temperature -5°). Optimum volumetric ratios for both radial and axial discharges were used which took the values of 3.6 and 5.0, respectively.

Table 2 Different lobe combinations with higher discharge pressure

Parameters	Lobe combination $\bar{z}_1 + \bar{z}_2$			
	4 + 5	5 + 6	4 + 6	5 + 7
Max. female rotor deflection (mm)	0.0295	0.0247	0.0174	0.0119
$0.002\ C^{0.5}$ (mm)	0.0246	0.0252	0.0253	0.0263

For this condition the 4+5 combination may be troubled due to excessive female rotor deflection. It can also be envisaged that for a higher discharge pressure the 5+6 combination may also be troubled by female rotor deflection. Consequently, the 4+6 and 5+7 combinations become the choice in high pressure applications.

High female rotor deflection is mainly a result of the small female rotor shaft diameter, large length/diameter ratio and the necessary distance between the lobe end face and the radial bearing centre at both ends. The female rotor shaft diameter is strongly influenced by the lobe combination and also by the length/diameter ratio. A small length/diameter ratio calls for a larger rotor diameter to keep the displacement volume constant, which may reduce the female rotor deflection significantly. The necessary distance between the lobe end face and the bearing has to be decided according to compressor applications. If the compressor is to be designed for a refrigeration duty but without a slide valve, or for air compression, the distance between the rotor body and bearing can be minimised. It thus becomes possible that the female rotor deflection is small even for very high discharge pressures for the 4+5 and 5+6 combinations.

3.2 Effect of Length / Diameter Ratio

The results of five different length/male rotor diameter ratios ranging from 1.0 to 2.2 are shown in Figs. 1 - 4. From Fig. 1 it can be seen that for the 4+5, 4+6 and 5+6 combinations the volumetric efficiency increases with the increase in length/diameter ratio. This is due to the relatively reduced sealing line length for the cavity. The exception is the 5+7 combination which shows a peak value for a length/diameter ratio of 1.9. Over the entire *L/D* range, the 5+6 combination has the highest volumetric efficiency among the lobe combinations considered.

The 5+6 combination also shows a relatively higher isentropic indicated efficiency for length / diameter ratios up to 1.7 (Fig. 2). For higher length / diameter ratios, the 4+5 combination seems to have better performance but cannot be used due to excessive female rotor deflection. As shown in Fig. 3, the female rotor deflection increases with increasing *L/D* ratio significantly. Also because of this, the 5+6 combination may not be appropriate for higher pressure levels although it shows the next best result in this example. Whilst the 5+7 combination shows a performance very close to the 5+6 combination for *L/D* above 1.7, it's deflections are much smaller as can be seen from Fig. 3. Thus, the 5+7 combination would be more appropriate for *L/D* above 1.7, especially for applications of high pressure level.

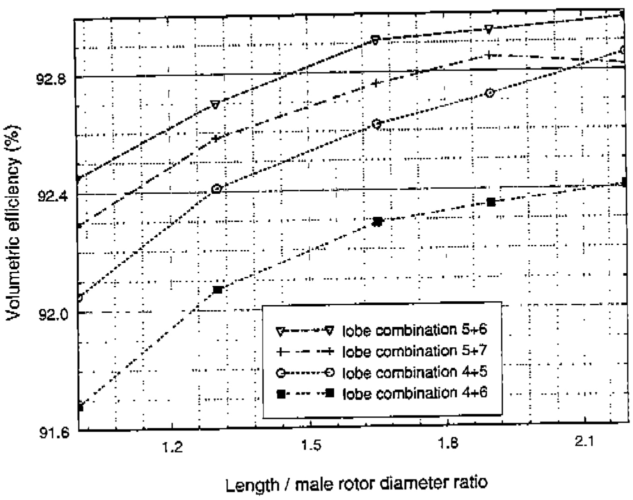

Fig. 1 Volumetric efficiency vs *L/D*

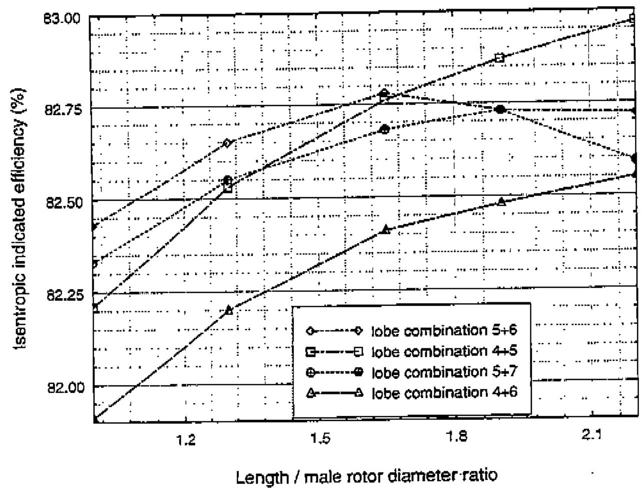

Fig. 2 Isentropic indicated efficiency vs *L/D*

It is noted that for the 5+6 and 5+7 combinations the isentropic indicated efficiencies, instead of increasing with *L/D* as in the case of the 4+5 and 4+6 combinations, peak at *L/D* of 1.65 and 1.9, respectively. This implies that for the 5+6 and 5+7 combinations the length/diameter ratio needs to be optimised for the conditions at which the compressor is to work. In contrast, the choice for the 4+5 and 4+6 combinations is straightforward, the largest *L/D* should always be used provided that the female rotor deflection is within the acceptable level.

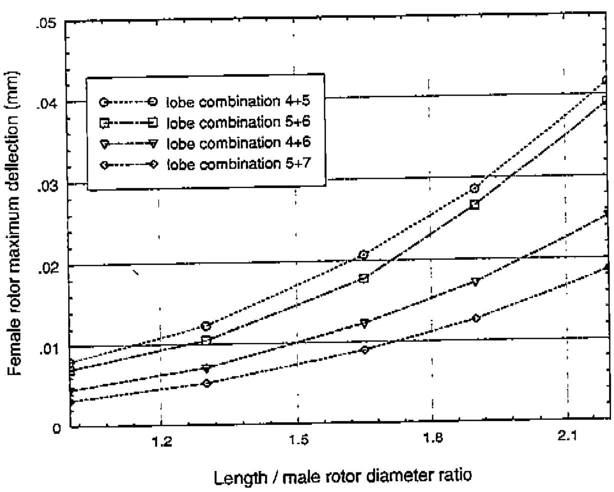

Fig. 3 Female rotor deflection vs *L/D*

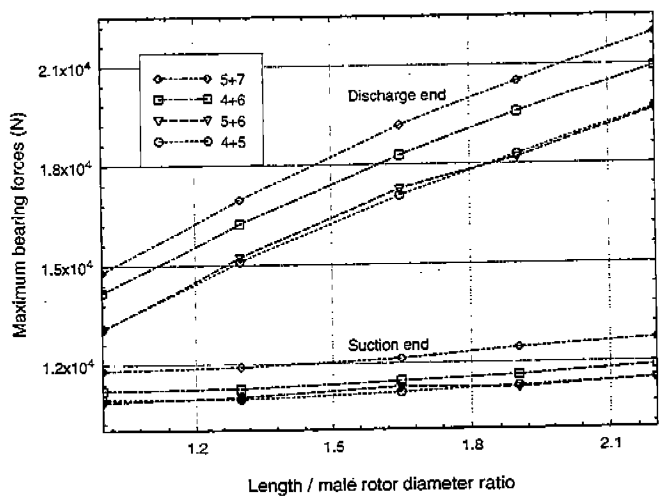

Fig. 4 Female rotor maximum bearing forces vs *L/D*

As shown in Fig. 4, the maximum bearing forces (they occur on the discharge side) increase significantly with increasing *L/D*. However, they remain almost unchanged on the suction side. With the increase in length/diameter ratio from 1.0 to 2.2, the bearing forces on the discharge side increase by about 50 percent for the female rotor and the centre distance of the rotors is necessarily reduced to maintain the same capacity. Consequently, the diameter of the bearings has to be reduced, resulting in a smaller size bearing to meet increased bearing loads. Obviously, this may cause trouble and accordingly, the bearing load and bearing life should be examined if a relatively large *L/D* ratio is used.

The computed results also reveal that the female rotor gas torque and the transmitted torque ratio remain almost unchanged with the increase in length / diameter ratio. Since the length of the power transmission section of the contact line increases somewhat with the increase in length / diameter ratio, the contact force per unit length is reduced slightly (Fig. 5). Thus, from the point of view of obtaining longer rotor life, a higher length/diameter ratio is of advantage.

3.3 Effect of Wrap Angle

Figs. 6 - 9 show the results of five different wrap angles ranging from 250 to 350 degrees. To maintain the same capacity, changes were made to rotor dimensions.

Fig. 6 shows that the volumetric efficiency decreases with increasing wrap angle. This is caused by greater leakage due to an increasing sealing line length. However, as can be seen from Fig. 7, the isentropic indicated efficiency of the compressor increases with increasing wrap angle up to about 325°. This is mainly a result of an increased discharge port area and hence reduced throttling effect. For higher wrap angles the increase in leakage is dominant, resulting in a reduced indicated efficiency. For different running conditions, the peak of the indicated efficiency may vary and the wrap angle should be optimized accordingly.

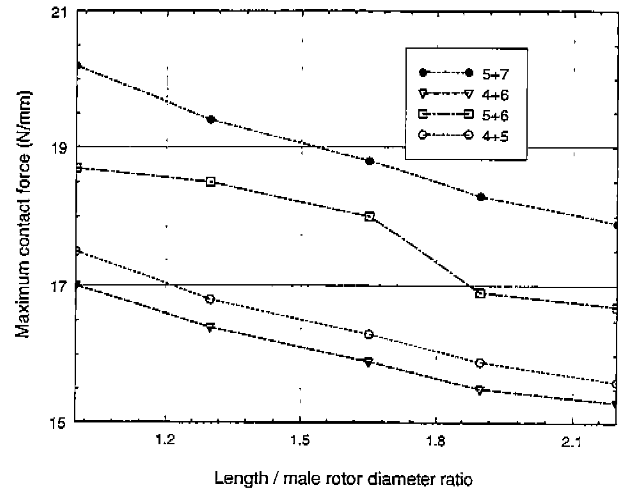

Fig. 5 Rotor contact force vs *L/D*

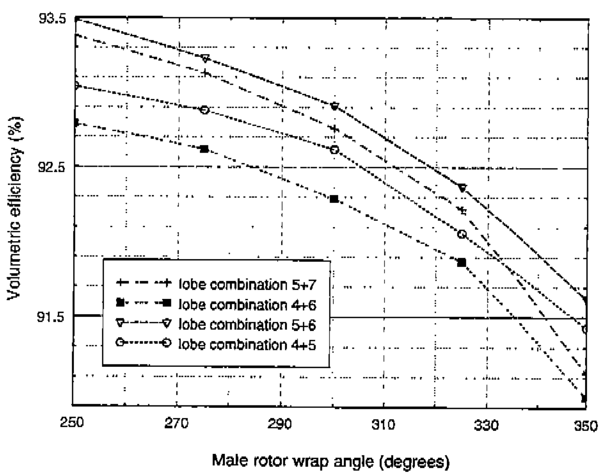

Fig. 6 Volumetric efficiency vs φ_w

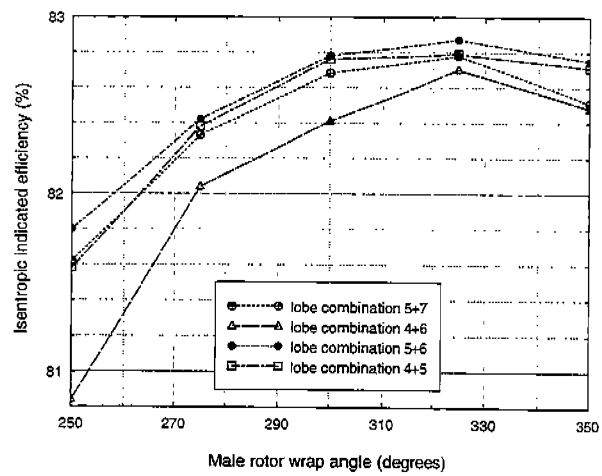

Fig. 7 Isentropic indicated efficiency vs φ_w

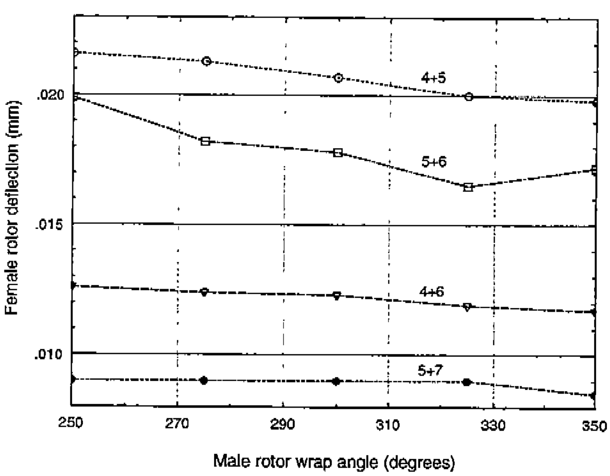

Fig. 8 Female rotor deflection vs φ_w

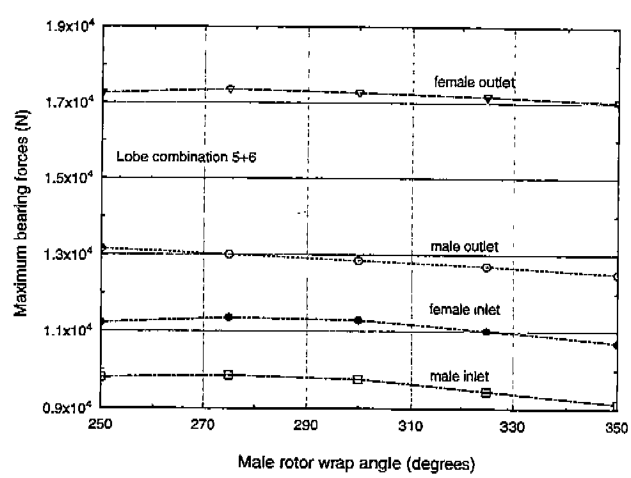

Fig. 9 Maximum bearing forces vs φ_w

The influence of the wrap angle on the female rotor deflection and bearing loads (for the 5+6 combination) are shown in Figs. 8 and 9. It can be seen that the female rotor deflection and bearing forces all decrease somewhat with increasing wrap angle. The extent of these effects is obviously very limited. This is also the case for other lobe combinations and for rotor contact forces. Therefore, for this example the optimum wrap angle should be determined by a decision as to which has the greater importance; volumetric efficiency or indicated efficiency.

4 CONCLUSIONS

For obtaining the optimum rotor geometrical parameter combination, not only the compressor efficiencies, but also the female rotor deflection, bearing loads and rotor contact force should be taken into account.

The 4+5 combination has the smallest dimension and weight among the four combinations considered but can only be used for small *L/D* ratios and low pressure level applications due to poor female rotor stiffness. The 5+6 combination shows the best overall performance within the parameter ranges studied. However, it may also cause trouble if used in high pressure applications due to excessive female rotor deflection. The 5+7 combination, which shows the next best efficiency and the lowest female rotor deflection, would then be the right choice for high length/diameter ratios and high pressure applications. However, the 5+7 combination has the disadvantage of relatively higher bearing loads and rotor contact forces. The 4+6 combination is characterised by relatively lower efficiencies but can be used throughout the parameter ranges studied.

For the 4+5 and 4+6 combinations both volumetric and indicated efficiencies increase with increasing length/diameter ratio. However, this is not the case for the 5+6 and 5+7 combinations, in which there exists a peak value. With the increase in length/diameter ratio, the bearing loads and rotor deflection increase significantly but the bearing size decreases. All these factors should be examined when deciding the length/diameter ratio. The rotor contact forces decrease with increasing *L/D* ratio for all the lobe combinations considered.

For all the four lobe combinations the indicated efficiency peaks at the male rotor wrap angle of 325° for the conditions used. However, the volumetric efficiency decreases with increasing wrap angle. Since the influence of wrap angle on female rotor deflection, bearing load and rotor contact force is relatively small in this example, the choice of wrap angle will mainly depend on which has priority; the volumetric or the indicated efficiency.

Finally it is worth stressing that the discussions in this paper deal with performance and operational considerations. Rotor geometry also influences ease of manufacture which can improve quality (and hence performance). It can also have consequences in the form of higher or lower tooling cost.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the help of Howden Compressors Ltd., especially in supplying the data required.

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