Effectiveness enhancement of non-contact vacuum pumps working process

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Abstract. Three options of rotor profiles of Roots vacuum pump are considered: elliptic, circular, and involute. Rotor profiles are drawn in the same housing and are analyzed from point of view of backward leakage minimization through inter-rotor channel and geometric pumping speed increase. It is shown that coefficient of working volume use is only 3% higher for involute profile. Averaged over one revolution conductance of rotor mechanism channels is minimal for elliptic rotor profile. For inter-rotor channel it is 14% less than for involute profile. The presented approach makes it possible to choose the optimal rotor profile of Roots pump for particular purpose.

1. Introduction
In 20-th century two ways of obtaining rough and medium oil free vacuum were used: by oil sealed vacuum pumps with different traps (most often cryogenic) or by dry vacuum pumps (without working fluid in working volume). Dry pumps were tens times more expensive than oil pumps. But with technology development of profiled rotors manufacturing, manufacturing of high-precision ball bearings and other component units it became possible to bring down the price of oil free vacuum, and now oil sealed vacuum pumps (even with traps) are not used for obtaining oil free vacuum. But the problem of effectiveness enhancement of oil free pumps working process has become more urgent.

Oil free forepumps may be divided into two main groups: non-contact pumps (scroll, screw, claw, Roots pumps) and contact pumps (piston, membrane, sliding vane rotary pumps).

Contact pumps have high compression ratio which slightly depends on outlet pressure and work with discharge into atmosphere. But due to frictional contact such pumps do not admit high rotating speed and have limited operating life. Presence of units in frictional contact results in one more disadvantage of contact pumps, that is, penetration of micro particles into vacuum chamber.

Non-contact pumps have high rotating speed due to guaranteed clearances in rotor mechanism but have low pressure ratio due to backward leakage through clearances. Let’s consider, as an example, influence of rotor profile on non-contact machine parameters for one of the most used vacuum pumps - Roots pump.

2. Studied rotor profiles of Roots pumps. Optimization parameters
There are many different rotor profiles of Roots pumps: elliptic, circular, cycloid, involute, with linear parts, and combined.
When choosing rotor profile type and its geometric parameters it is necessary to tend to increase cut-off volume carried by rotors, that is, to increase geometric pumping speed and to lower backward leakage (conductance) of slot channels. The analysis will be carried out for elliptic, circular, and involute profiles which are drawn in the same housing shown in figure 1.

![Figure 1](image1.png)

**Figure 1.** Geometry of rotor profiles of Roots pump: solid line – elliptic profile with $b/a=0.86$, $r/a=0.62$; dashed line – circular profile with $b/a=0.77$, $r/a=0.71$; dashdot line – involute profile with $rb/a=0.646$, $rr/a=0.627$ ($rb$ is basic circle radius of involute; $rr$ is rotor head radius).

It is known that involute rotor profile of Roots pump is the most common case for Roots pump [2]. Circular profile is the special case of involute profile with $r/d=1$. The main geometric dimensions of rotors $a$, $b$, $d$, $r$, which are necessary for drawing of elliptic profile are presented in figure 2.

![Figure 2](image2.png)

**Figure 2.** Elliptic rotor profile of Roots pump.

Three parameters of the presented four parameters may be specified, and it shows a wide degree of freedom in selection of elliptic profile form. It is shown [2] that for elliptical profile minimal backward leakage through inter-rotor channel takes place at $b/a \approx 0.84 \div 0.86$ and $r/a = 0.610 \div 0.64$. That is why let’s take rotor with elliptical profile with $b/a=0.86$, $r/a=0.62$.

Geometric pumping speed [3] of Roots pump is:

$$Q = \frac{V}{t}$$

where $V$ is the volume of the cut-off channel and $t$ is the time it takes for the cut-off channel to fill.

$$V = \pi \left( \frac{b}{2} \right)^2 \left( \frac{r}{2} \right)$$

$$t = \frac{2\pi}{\omega}$$

where $\omega$ is the angular speed of the rotor.
\[ S_G = 2\pi R^2 Ln\chi, \]

where \( R \) and \( L \) are rotor radius and length, respectively; \( n \) is rotating speed; \( \chi \) is coefficient of working volume use:

\[ \chi = 1 - f_R / \pi R^2, \]

where \( f_R \) is rotor cross-section.

Thus, at given \( R \) and \( L \) it is necessary to tend to increase coefficient \( \chi \). This coefficient can vary in a wide range. To find its value it is necessary to find rotor cross section area and area of cylindrical boring of the housing for every pump.

Calculations showed that coefficient of working volume use is equal to 0.4912 for elliptic profile; 0.4972 for circular profile; 0.5061 for involute profile. Thus, involute profile gives higher pumping speed (but only within 3%).

It is known that leakage through rotor mechanism channels influence greatly the characteristics of non-contact pumps, and the main way of effectiveness enhancement of working process is reduction of backward leakage. Backward leakage is connected with rotor profile perfection.

Let’s consider how rotor profile influences backward leakage in Roots pump. The conclusion about slight influence of rotor profile on Roots machine characteristics [1] is true for Roots pressure blowers because their pressure ratio does not exceed 1.5-2. But for machines working in vacuum mode pressure ratio may reach as high as 50-60. As in molecular flow regime backward leakage is proportional to product of pressure ratio and conductance then even slight reduction in conductance of slot channels results in Roots pump characteristics improvement.

In Roots pump leakage occurs through several channels working in parallel: inter-rotor, radial and face channels. Inter-rotor channel gives the most contribution into leakage (up to 60-80%). Moreover, rotor profile has slight influence on leakage through radial and face channels. Their conductance depends mostly on pump dimension, that is why rotor profile optimization should be carried out by minimization of backward leakage through inter-rotor channel.

3. Calculation method

Rotor profile is given by coordinates or equations. Channel conductance in viscous flow regime is calculated by method which in [4, 5] is called as general-purpose method for conductance calculation of slot channels. This method is based on the assumption that inter-rotor and radial channels in Roots pump represent slots with varying cross section along gas flow direction and have the area with minimal clearance. For such channels conductance with sufficient accuracy is defined by this area. Thus, this area giving the main resistance to gas flow has small length, and channel walls may be approximated by convex or concave circle arcs with radii \( R_1 \) and \( R_2 \). Then equations [5] can be used for channel conductance calculation in dependence on flow regime and geometry. Inter-rotor channel conductance was obtained for different rotor rotation angles \( \alpha \) taking into account varying radii of walls curvature at the inlet of the channel \( R_{A1}, R_{B1} \) and at the outlet of the channel \( R_{A2}, R_{B2} \). Indices \( A \) and \( B \) apply to the first and the second wall of the channel. As an example, curvature radii of channel walls and conductance coefficients \( K_C \) for molecular flow regime are presented in table 1. Conductance coefficients were obtained by Monte-Carlo method with the help of specially developed program in software Wolfram Mathematica [6].

Curvature radii of inter-rotor channel walls and conductance coefficients of inter-rotor channel in Roots pump with involute and circle rotor profiles are obtained in the same way. The results of comparison are presented in figure 3.

It can be seen that rotor with elliptic profile gives the least backward leakage through the inter-rotor channel. Conductance coefficient \( K_{CRR}=0.1399 \) averaged over rotor rotation angle is obtained for elliptic profile, \( K_{CRR} \) is equal to 0.1471 for circle profile, \( K_{CRR} \) is equal to 0.1594 for involute profile.
Table 1. Curvature radii of inter-rotor channel walls and conductance coefficients of inter-rotor channel in Roots pump with elliptic rotor profile $K_C$.

| $\alpha^\circ$ | $R_{A1}$ | $R_{B1}$ | $R_{A2}$ | $R_{B2}$ | $K_C$ |
|---------------|---------|---------|---------|---------|--------|
| 0             | -136,76 | 57,87   | -137,85 | 57,97   | 0,1020 |
| 3             | -125,55 | 56,78   | -134,90 | 57,70   | 0,1008 |
| 6             | -107,23 | 54,52   | -120,84 | 56,26   | 0,0976 |
| 9             | -88,49  | 51,28   | -101,40 | 53,64   | 0,0927 |
| 12            | -73,01  | 47,38   | -82,93  | 50,05   | 0,0870 |
| 15            | -62,21  | 43,32   | -68,64  | 45,94   | 0,0826 |
| 18            | -57,30  | 39,77   | -59,75  | 42,01   | 0,0831 |
| 21            | -62,50  | 37,32   | -57,36  | 38,96   | 0,0936 |
| 24            | -107,50 | 36,05   | -64,72  | 37,08   | 0,1168 |
| 27            | 261,06  | 35,60   | -99,81  | 36,11   | 0,1492 |
| 30            | 50,38   | 35,60   | -928,05 | 35,68   | 0,1799 |
| 33            | 31,56   | 35,82   | 97,51   | 35,56   | 0,2017 |
| 36            | 27,41   | 36,16   | 46,37   | 35,62   | 0,2142 |
| 39            | 27,46   | 36,57   | 33,03   | 35,78   | 0,2201 |
| 42            | 29,14   | 37,00   | 28,39   | 36,01   | 0,2216 |
| 45            | 31,06   | 37,42   | 27,14   | 36,29   | 0,2209 |

Figure 3. Conductance coefficients of inter-rotor channel in Roots pump with involute, elliptic and circle rotor profiles.

It should be noted that radial channel conductance characterized by $K_{CRH}$ is minimal for rotors with elliptic profile ($K_{CRH}$ is equal to 0.05712 for elliptic profile, $K_{CRH}$ is equal to 0.0685 for circle profile, $K_{CRH}$ is equal to 0.1146 for involute profile).
4. Conclusion
Thus, the presented method makes it possible to carry out optimization of Roots pump rotor profile with the aim of reducing backward leakage through inter-rotor and radial channels or increasing geometric pumping speed.

References
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