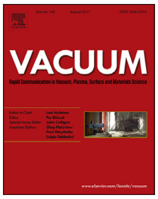
Vacuum 143 (2017) 174–184

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum



Geometric design and performance analysis of a novel smooth rotor profile of claw vacuum pumps

Jun Wang*, Dong Cui, Xiaofeng Pang, Haozhi Feng, Zengli Wang

College of Chemical Engineering, China University of Petroleum (East China), Qingdao, Shandong 266580, China

A R T I C L E I N F O

Article history:
Received 25 May 2017
Received in revised form
1 June 2017
Accepted 4 June 2017
Available online 7 June 2017

Keywords:
Claw vacuum pump
Smooth rotor profile
Equidistant curve
Epicycloid
Numerical simulation

A B S T R A C T

In view of the problems that the existing rotor profiles of claw vacuum pumps contain non-smooth connection points, a novel smooth rotor profile was proposed in this paper. The proposed profile, which can achieve correct meshing, is composed of 6 circular arcs and 3 equidistant curves of epicycloid, and its design procedures as well as equations were given. The effects of geometric parameters on the shape and performances of the claw rotor were analyzed. Besides, 3D numerical simulations of the entire working process of the claw vacuum pump with the proposed rotor profile were performed, and its performances were analyzed. The study results indicate that the proposed rotor profile of claw vacuum pumps, compared with the existing rotor profiles, has remarkable advantages of better meshing performance, smaller carryover and better mechanical properties. Thus, the new rotor profile designed and the data obtained can be applied to the design and optimization of claw vacuum pumps.

1. Introduction

The claw vacuum pump is a rotary positive-displacement pump with built-in compression. Because of its many advantages such as high reliability, compact structure, oil-free and simple manufacture, the claw vacuum pump has been widely applied in many industries including microelectronics, aerospace and medical equipment, etc. In the working process of the claw vacuum pump, two claw rotors rotate in opposite directions about their axes and are synchronized by a pair of gears, and the formed volumes of working chambers are periodically changed to complete the cyclical process of suction, compression and discharge. Hence, the cross-section profiles of the claw rotor, or called the rotor profiles, have an important influence on the performances of the claw vacuum pump.

With regard to rotor profile research of claw vacuum pumps, Hsieh [1] presented a simple mathematical model for the geometric design of a claw type pump, and discussed the design of gas port and fluid carryover. Hsieh et al. [2] designed profile of claw type rotor by means of the theory of gearing. Giuffrida [3] presented the working principles of claw rotor compressor, and reported basic thermodynamic considerations leading the formulation of volumetric efficiency. Giuffrida [4] proposed a rotor profile of the claw-type mechanism which include circular arcs and epitrochoidal arcs, and indicated the profile geometry; additionally the author compared compressor different performances by changing design parameters and proposed a preferable one. Wang et al. [5] established an analytical model of rotor profile of claw vacuum pumps, which includes profile equations, design methods and geometric theories, and revealed the particular gas mixing process for claw vacuum pumps. Wang et al. [6] proposed a type of circular arc rotor profile of claw vacuum pumps, and obtained the changing rules of rotor profile of claw vacuum pumps varied with the value of circular arc radius. However this circular arc rotor profile still has two unsolved cusps (or non-smooth connection points) in the pitch circular arc.

Ioffe et al. [7] developed a model based on algebraic and differential equations that includes volume variation, gas flow between stages, leakage within and between stages, gas mixing, and heat exchange to describe pressure and temperature time dependence for a multistage claw rotor vacuum pump. Peng et al. [8] constructed a tooth compressor mathematical model that allows for gas leakage as well as the main flow into and out of the working chamber to simulate the thermodynamic processes and predict its performance, and described the volumetric efficiency of the prototype compressor at various discharge pressures and rotating speed and the adiabatic efficiency at various operating conditions. Aiming at the tooth compressor, Voorde et al. [9] presented the mesh manipulation algorithm that replaces nodes of the mesh based on the solution of the Laplace potential equation, which is

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* Corresponding author.
E-mail address: wangjun@upc.edu.cn (J. Wang).

http://dx.doi.org/10.1016/j.vacuum.2017.06.006
0042-207X/

capable of setting up block-structured meshes for Arbitrary Lagrangian-Eulerian (ALE) computations of the internal flow in rotary volumetric pumps and compressors. Salikeev et al. [10] calculated the laminar gas flow through channels of roots, claw and scroll pumps at arbitrary pressure difference.

However, the presented rotor profiles of claw vacuum pumps in the above literatures [1–10] still contain non-smooth connection points, or called cusps. In the position of the cusp during the working process of the claw vacuum pump, the leakage, deformation and damage are prone to occur, which decreases the mechanical and sealing performances of the claw rotors. In order to solve this problem, a novel smooth rotor profile of claw vacuum pumps is proposed in this paper, which can realize the smooth connection and correct meshing between the two rotor profiles, improve the mechanical and sealing performances, and enrich the type of the claw rotors. The proposed smooth rotor profiles are of great significance for the development of claw vacuum pumps.

2. Geometric design of a novel smooth rotor profile

2.1. The existing rotor profile of claw vacuum pumps

The existing and normal rotor profiles [1,5,7] of claw vacuum pumps consist of six curves, followed by extended epicycloid curve *ab*, claw head circular arc *bc*, epicycloid curve *cd*, pitch circular arc *de*, extended epicycloid curve *ef* and claw bottom circular arc *fa*, as shown in Fig. 1. Because of the advantages of the simple structure, this rotor profile is widely used. But its drawback is that it contains four non-smooth connection points, or called cusps, respectively, points *b*, *c*, *d* and *e*. Adjacent curves of this rotor profile cannot be connected smoothly at points *b*, *c*, *d* and *e;* and in the working process these points mesh with curves. These non-smooth connection points, however, have very important influences on the working efficiency of claw vacuum pumps, resulting in serious leakage and deformation.

2.2. A model for calculating the conjugate envelope curve of the circular arc

In order to eliminate influences of non-smooth points, circular arcs and their conjugate envelope curves are employed instead of point and epicycloid to generate the rotor profile of claw vacuum pumps. Thus, it is necessary to set up a model for deriving the conjugate envelope curve of a circular arc of the claw vacuum pump.

In the working process of the claw vacuum pump, the left and right claw rotors rotate at same angular speed and in opposite directions about their axes. The moving relationship between two claw rotors during the working process is transformed into an equivalent motion as follows. The left rotor is fixed; the right rotor rotates about its own axis, and also rotates about the axis of the left rotor in the same direction and with the same angular speed. In other words, the right rotor is rolling on the left rotor.

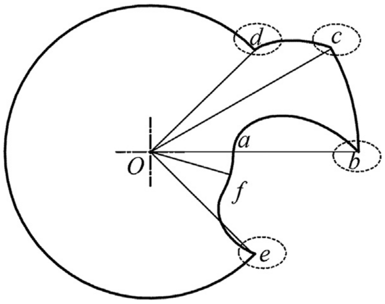

Fig. 1. The existing rotor profile of claw vacuum pumps.

As shown in Fig. 2, circles centered with O_1 and O_2 represent the two claw rotors, respectively. The radii of two circles are R_2. When point M is located outside the circle O_2, i.e., $a > R_2$, the conjugate curve of the point M is the extended epicycloid (Fig. 2a). The meshing relationship is point and curve. In this situation point M and the extended epicycloid 1 can realize correct meshing. Where, a is the distance between point M and point O_2.

In order to eliminate the non-connection point, the point M is replaced by a circle centered M with radius r. The conjugate envelope curve of the circle centered M is the equidistant curve of extended epicycloid 2. Therefore, two curves, the circular arc centered M and the equidistant curve of extended epicycloid 2, can realize correct meshing.

When point M is located inside the circle O_2, i.e., $a < R_2$, its conjugate curve is shortened epicycloid (Fig. 2b). The same method is employed, and the equidistant curve of shortened epicycloid 4 is obtained. Therefore, the circular arc and the equidistant curve of shortened epicycloid 4 can also realize correct meshing.

The equations of the extended epicycloid 1 are as follows.

$$\mathbf{r}_1 = \begin{bmatrix} x_1(t) \\ y_1(t) \\ 1 \end{bmatrix} = \begin{bmatrix} -\cos(2t) & -\sin(2t) & 2R_2\cos(t) \\ -\sin(2t) & \cos(2t) & 2R_2\sin(t) \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ 0 \\ 1 \end{bmatrix} \tag{1}$$

The equidistant curve of extended epicycloid 2 is the parallel curve in normal direction with distance r of the extended epicycloid 1. Thus, the equations of the outer equidistant curve of extended epicycloid 2 are:

$$\begin{aligned} x_2(t) &= x_1(t) + \frac{r y'_1(t)}{\sqrt{x'_1(t)^2 + y'_1(t)^2}} \\ y_2(t) &= y_1(t) - \frac{r x'_1(t)}{\sqrt{x'_1(t)^2 + y'_1(t)^2}} \end{aligned} \tag{2}$$

The equations of the inner equidistant curve of the extended epicycloid can also be derived by replacing $-r$ with r in Eq. (2).

In the same method, the equations of the shortened epicycloid 3, the inner and outer equidistant curve of shortened epicycloid 4 can also be obtained.

2.3. A novel smooth rotor profile

According to the model in Section 2.2, a novel smooth profile of the claw rotor is proposed and obtained, as shown in Fig. 3. The proposed rotor profile is composed of 6 circular arcs, 2 equidistant curves of extended epicycloid and 1 equidistant curve of shortened epicycloid, followed by equidistant curve of extended epicycloid *ab*, circular arc *bc*, claw head circular arc *cd*, circular arc *de*, equidistant curve of shortened epicycloid *ef*, pitch circular arc *fg*, circular arc *gh*, equidistant curves of extended epicycloid *hi*, claw bottom circular arc *ia*. It can be seen that the proposed rotor profile doesn't contain non-connection points, and is continuous and smooth. All the adjacent curves connect smoothly.

Where, R_1 is the radius of claw head circular arc *cd*, R_2 is the radius of pitch circular arc *fg*, R_3 is the radius of claw bottom circular arc *ia*, R_4 is the radius of circular arcs *bc* and *de*, R_5 is the radius of circular arc *gh*, α is the central angle of claw head circular arc *cd* and claw bottom circular arc *ia*, β and γ are angles.

2.3.1. Relationships between geometric parameters

The proposed rotor profile of claw vacuum pumps has the geometric parameters: R_1, R_2, R_3, R_4, R_5, α, β, γ, etc. Among them, five geometric parameters, R_1, R_2, R_4, R_5, α, are independent. Other geometric parameters R_3, β, γ can be calculated.