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Study on a novel screw rotor with variable cross-section profiles for twin-screw vacuum pumps

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A B S T R A C T

In order to improve the performance of screw rotors, a novel screw rotor with variable cross-section profiles, in which the screw pitch and cross-section profile varying with the helical angle, is proposed for twin-screw vacuum pumps in this paper. The screw pitch of the proposed screw rotor decreases, on the contrary, its screw width increases continuously from the suction side to the discharge side. Equations of its cross-section profile cluster varying with two variables, the angular parameter and helical angle, are derived. The proposed screw rotor is compared with the existing variable pitch screw rotor. The study results show that the proposed screw rotor can realize completely correct meshing, and has better comprehensive performance in terms of the built-in volume ratio, gas sealing and mechanical property. Thus, the screw rotor designed and the data obtained can be applied to the design and optimization of twin-screw vacuum pumps.

1. Introduction

The twin-screw vacuum pump is a positive-displacement pump. It consists of a pair of intermeshing screw rotors rotating in opposite direction about parallel axes in the stator, and it removes gas from a sealed volume in order to leave behind a partial vacuum. The twin-screw vacuum pump is characterized by its simple design, high suction capacity and "dry"-running mode. So, it is widely used in low and medium-low vacuum applications, such as the semiconductor industry, chemical industry and high-technology industry.

The working performances of the twin-screw vacuum pump are determined by the cross-section profile of screw rotor, working chamber volume and gas sealing. In the geometric design of screw rotors, Hsieh et al. [1] presented a profile of claw rotor, which is designed by means of the theory of gearing and the equation of undercutting, and proposed two modified designs to improve gas sealing and reduce carryover. Pfaller et al. [2] performed a simulation of the compression process in the twin-screw vacuum pump, and presented the optimized cross-section profile for screw rotors. Lu et al. [3] proposed a new profile that the arc was added to the trapezoidal profile to obtain the self-conjugate curve. The geometric characters of new profiles were compared with the old ones from view point of area of leakage triangle, length of contact line, area utility coefficient. Ohbayashia et al. [4] established a method of the performance prediction and proposed a way to design the pump that satisfies specific requirements. The leaks flow through clearances between a screw rotor and a stator, and clearances between two meshing rotors were estimated with the results based on the linearised BGK model. Zhang et al. [5] introduced a method for determining the dynamic balance of the single-threaded, fixed-pitch screw rotor. Zhang et al. [6] proposed a novel tilt form grinding method to overcome the undercut problem of concave profile grinding, and gave three numerical examples to validate the method.

The common used screw rotor has the constant screw pitch, constant screw width and constant cross-section profiles [1–3], by which constant working chamber volumes are formed. In the working process of the twin-screw vacuum pump, the quantities of gas are trapped in the sealed working chamber, carried without volume reduction to the discharge port, compressed by backflow from the discharge port, and pushed out of the working chamber. Thus, this screw rotor is characterized by an "isochoric" transport process, and will lead to large power consumption and small ultimate vacuum. Therefore, it is more critical to establish internal compression ratio in the twin-screw vacuum pump.

In order to achieve built-in compression process, the working chambers with volume reduction formed by two intermeshing

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screw rotors are desirable. Im [7]. designed a new screw vacuum pump, wherein the pitch of the screw members decreased continuously from the suction side to the discharge side to cause compression of the gas being delivered. Becher [8] proposed a screw rotor with variable pitch and without profile variation in order to increase compression ratio, and also proposed the technical solutions for balancing screw rotors with variable pitch and eccentric position of the cross-section profile center of gravity. Inagaki et al. [9] proposed a screw pump with increased volume of fluid to be transferred, volume of the pump space is set smaller than the maximum volume of the inlet space by setting the lead angle of the first portions. Stosic et al. [10] gave the results of an investigation of how their performance was affected by changing the screw pitch from a constant value to a variable one. North et al. [11] presented a pair of tapered rotors, mounted on respective shafts and adapted for counter-rotation within the stator to compress fluid passing from the suction to the discharge.

However, these variable pitch screw rotors [7–10] exist the following drawbacks. The screw width and screw pitch decrease from the suction side to the discharge side, and the changing rule of the screw width can not be controlled. The pressure of gases in the working chamber near the discharge side is higher than that near the suction side in the working process. The screw pitch near the discharge is small leading to small working chamber volume, which is conducive to the compression process, but the screw width near the discharge is also small, which is not conducive to the strength and gas sealing of the screw rotor; in the same situation, the screw width near the suction is large, which is not conducive to the suction capacity and pumping speed. The reason is that the cross-section profile is constant from the suction side to the discharge side, which causes that the changing rule of the screw width does not accord with that of the working chamber volume. These variable pitch screw rotors are not benefitial to further improve the pumping speed and ultimate vacuum of the twin-screw vacuum pump.

Aiming to solve the above problems, the authors put forward a novel screw rotor with variable cross-section profiles for the twin-screw vacuum pump, elaborate the design process and analyze the comprehensive performance in this paper.

2. The screw rotor with constant cross-section profiles

The screw rotor is formed by sweeping the constant cross-section profile along the cylindrical helix from the suction side to the discharge side. When the constant pitch helix is employed, the constant pitch screw rotor is obtained; when the variable pitch helix is employed, the variable pitch screw rotor is obtained. Both of them have the unchanged cross-section profile in the arbitrary axial position of the screw rotor.

2.1. Generation process of the constant pitch screw rotor

The helix can be either right-handed or left-handed, as shown in Fig. 1. With the line of sight along the axial direction, if a clockwise screwing motion moves the helix away from the observer, then it is called a right-handed helix; if a counter-clockwise screwing motion, then it is called a left-handed helix.

The parametric equation of the constant pitch helix in Cartesian coordinates can be represented as follows:

$$\begin{cases} x(\tau) = R_1 \cos(\tau) \\ y(\tau) = \pm R_1 \sin(\tau), \quad 0 \le \tau \le 2n\pi \\ z(\tau) = \dfrac{h}{2\pi}\tau \end{cases} \tag{1}$$

Where, τ is helical angle; R_1 is radius; n is turns of the helix; h is pitch of the helix; the sign plus means right-handed helix, and the sign minus means left-handed helix.

When the constant cross-section profile is sweeping along the constant pitch helix, the constant pitch screw rotor is generated. When the right-handed helix is employed, the right-handed screw rotor is obtained, as shown in Fig. 2; when the left-handed helix is employed, the left-handed screw rotor is obtained. The right-handed and the left-handed screw rotors have the same cross-section profile, and can mesh correctly in the working process.

The constant pitch screw rotor has constant cross-section profile, constant screw pitch h and the constant screw width B in arbitrary axial position. B can be represented as follows:

$$B = h\frac{\theta}{2\pi} \tag{2}$$

Where, θ is central angle of the head circular arc.

2.2. Generation process of the variable pitch screw rotor

The pitch $h(\tau)$ of the variable pitch helix varies with the helical angle τ, as shown in Fig. 3.

In this design, the screw pitch $h(\tau)$ is linearly decreased with τ, and can be represented as follows:

$$h(\tau) = h_1(1 - 2\lambda\tau) \tag{3}$$

The relationship between the $h(\tau)$ and $z(\tau)$ can be represented as follows:

$$h(\tau) = \frac{dz(\tau)}{d\tau} \tag{4}$$

Hence, the equation of the variable pitch helix can be obtained as follows:

$$\begin{cases} x(\tau) = R_1 \cos(\tau) \\ y(\tau) = \pm R_1 \sin(\tau), \quad 0 \le \tau \le 2n\pi \\ z(\tau) = \dfrac{h_1}{2\pi}\left(\tau - \lambda\tau^2\right) \end{cases} \tag{5}$$

Where, h_1 is initial pitch, and λ is coefficient of variable pitch.

The variable pitch helix used to form the screw rotor is continuous and smooth curve, and its equation satisfies the following conditions.

$$\begin{cases} z(0) = 0 \\ \dfrac{d}{d\tau}z(\tau) > 0 \\ \dfrac{d^2}{d\tau^2}z(\tau) < 0 \end{cases} \tag{6}$$

The variable pitch screw rotor is generated by sweeping the constant cross-section profile along the variable pitch helix, as shown in Fig. 4. The cross-section profile is unchanged in different axial postion. The screw pitch $h(\tau)$ and screw width $B(\tau)$ both decrease from the suction side to the discharge side.

The screw width $B(\tau)$ varies with τ, and can be derived as