Thermodynamic Prediction Model of Single-stage Gradational Lead Screw Vacuum Pump

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Abstract. As a kind of fluid machinery, screw vacuum pumps are widely used in material engineering and semiconductor industry. Nowadays, new requirements for screw vacuum pumps are put forward on low energy consumption and low manufacture cost. Compared with the constant lead screw (CLS) vacuum pump, the gradational lead screw (GLS) vacuum pump has many advantages. Taking the SGLS vacuum pump as the research object, this paper divides the pumping process into four small stages and proposes a thermodynamic model to analyse the performance. The characteristic curves under diverse operating conditions are drawn and the energy consumptions are illustrated at the end of this paper. The results show that a thermodynamic model can provide a well explanation on the phenomena of pressure pulsation and power consumption, which will help us to understand the outstanding performance of SGLS vacuum pump better.

1. Introduction

The oil-free screw vacuum pump is a kind of positive displacement screw machines to obtain a clean vacuum environment, widely used in the material engineering and semiconductor industry. As a rough vacuum pump, the constant lead screw (CLS) vacuum pump was invented earlier than the gradational lead screw (GLS) vacuum pump (figure 1). The problems of CLS vacuum pump, such as high energy consumption, are also excessive and apparent when the pump system is running. In response to solve these issues, the GLS vacuum pump emerged at the right time [1].

The pitch of GLS rotor is variable along the axis direction. If the pitch of GLS rotor continuously decreases in the axial direction, this kind of rotor is known as a SGLS rotor (figure 2), and the pump comprising the SGLS rotors is referred to as a SGLS vacuum pump. A cylindrical coordinate system can be established to describe the helix of SGLS rotor. In this paper, if we assume that the pitch at outlet is $\lambda$ and the varying pitch coefficient is $\alpha$, the expression of helix and its pitch can be given orderly:

$$z(\theta) = \frac{\lambda}{2\pi} \cdot (\theta + \alpha \theta^2)$$  \hfill (1)

$$\lambda(\theta) = \frac{\lambda}{2\pi} \cdot (1 + 2\alpha \theta)$$  \hfill (2)
Figure 1. The structure diagram of (a) CLS and (b) GLS vacuum pump

Figure 2. The outline of SGLS rotor and its helix

Considerable efforts have been carried out on the gradational screw machines, concerning novel product design [2], structure optimization [3], CFD simulation [4], etc. Although a number of efforts have been concentrated on the area of screw vacuum pump, few studies have been put into the thermodynamic field of SGLS vacuum pump [5]. In this paper, we divide the pumping process into four small stages according to the structure feature of screw rotor, and we establish a thermodynamic model based on the thermodynamics principle to analyze the performance quantitatively. The characteristic curves under diverse operating conditions are drawn and the energy consumptions are illustrated at the end of this paper. The results will help us to understand the outstanding performance of SGLS vacuum pump.

2. Pumping process
As the gas moves along the travel path from inlet side to the outlet side, the pumping process (figure 3(a) to 3(d)) can be split up into four successive stages (sucking, compressing, backlashing and exhausting stage) according to their respective feature. The gas in the said space is marked with the black dot in the drawing.
3. Mathematical model

The thermodynamic model can be established according to the under-mentioned assumption:
(1) The gas is deemed as ideal gas and it is equally distributed in the space at any time
(2) The leak and back-diffusion through the gap are neglected
(3) The outlet pressure is assumed to be constant

3.1 Sucking stage

Owing to the connection between the sucking space and the inlet during this stage, the temperature and pressure of the gas can be seen as isothermal-isobaric process in the interval, thus,

\[ T(t_1) = T_i \]  \hspace{1cm} (3)
\[ P(t_1) = P_i \]  \hspace{1cm} (4)

The volume of sucking space is the product of the length and the cross section area, namely,
\[ V(t_1) = A \cdot l(t_1) = \frac{A \omega \lambda}{2 \pi} \left[ (1 + 2an\pi) t_1 - \alpha \omega t_1^2 \right] \]  \hspace{1cm} (5)

The mass of gas are deduced by the following formula:
\[ M(t_1) = \frac{P_i V(t_1)}{R_i T_i} = \frac{P_i A \omega \lambda}{2 \pi R_i T_0} \left[ (1 + 2an\pi) t_1 - \alpha \omega t_1^2 \right] \]  \hspace{1cm} (6)
3.2 Compressing stage
During compressing stage, volume of gas is lessened and the gas is compressed gradually:

\[ V(t_2) = A \cdot l(t_2) = A \alpha \{1 + 2 \alpha [(n + 1) \pi - \omega t_2]\} \]

(7)

\[ M(t_2) = M_1 = \frac{A \alpha }{R_g T_i} (1 + 2 \alpha \pi - 2 \alpha \pi) \]

(8)

\[ P(t_2) = P_i \left( \frac{V_o}{V(t_2)} \right)^n = P_i \left( \frac{1+2\alpha \pi-2\alpha \pi}{1+2\alpha[(n+1)\pi-\omega t_2]} \right)^n \]

(9)

\[ T(t_2) = T_i \left( \frac{V_o}{V(t_2)} \right)^{n-1} = T_i \left( \frac{1+2\alpha \pi-2\alpha \pi}{1+2\alpha[(n+1)\pi-\omega t_2]} \right)^{n-1} \]

(10)

3.3 Backlashing stage
In view of the backlashing stage is fairly short, it can be treated as an adiabatic process. The gas both in and out of the space conform the ideal gas law, namely,

\[ PV = MR_g T \]

(11)

If the gas flowing back into the space is written as \( M_o \), and the mixture gas in the space is written as \( M_3 \), the mixture mass of gas can be expressed as follow.

\[ M_3 = M_1 + M_o = \frac{V_i P_i}{R_g T_i} + \frac{C_p V_2(P_o-P_2)}{C_p R_g T_o} = \frac{C_p T_o V_i P_i + C_p V_2 T_i (P_o-P_2)}{T_i C_p R_g T_o} \]

(12)

\[ T_3 = \frac{P_o V_2}{M_3 R_g} = \frac{C_p T_o P_i V_2}{C_p T_o V_i P_i + C_p V_2 (P_o-P_2)} \]

(13)

3.4 Exhausting stage
Owing to the connection between the space and the outlet during this stage, the temperature and pressure of the gas can be seen as isothermal-isobaric process in the interval, thus,

\[ P(t_4) = P_o \]

(14)

\[ T(t_4) = T_3 \]

(15)

\[ V(t_4) = A \cdot l(t_4) = A \alpha \{(n + 2)\pi - \omega t_4 + \alpha[(n + 2)\pi - \omega t_4]^2\} \]

(16)

\[ M(t_4) = \frac{P_o V(t_4)}{R_g T_3} = \frac{P_o A \alpha}{2 \pi R_g T_3} \{(n + 2)\pi - \omega t_4 + \alpha[(n + 2)\pi - \omega t_4]^2\} \]

(17)

4. Result and discussion
The above formulas can be used to predict the thermodynamic performance of SGLS vacuum pump. The structure parameters of SGLS vacuum pump are listed in Table 1. Since the inlet pressure and volume ratio are the main factors affecting pumping process, the impacts of these factors will be illustrated in this part.
Figure 4. P-t diagram for various inlet pressures

Figure 5. P-t diagram for various volume ratios
Figure 6. P-V diagram for various inlet pressures

Figure 7. P-V diagram for various volume ratios

Figure 4 reveals the impact of inlet pressure on the pressure changing. The pressure curves in figure 4 can be roughly divided into the under-compression stage and the over-compression stage. The over-compression stage occurs at the initial operation of the pumping system, and later it will transit into the under-compression stage due to the decrease of inlet pressure. Meanwhile, the gas pressure in the space will decline with the decrease of the inlet pressure except the exhausting stage. Figure 5 reveals the effect of volume ratio, which has a visible impact on the pressure especially at the compressing stage. The compressing effect grows with the increase of volume ratio and the pressure can be raised up to a high level, even resulting in the over-compression. Therefore, both the inlet pressure and volume ratio have influences on pressure pulsation.
Table 1. Structure parameters of SGLS vacuum pump with the same discharge volume.

| Structure parameter                        | Dimension                      |
|-------------------------------------------|-------------------------------|
| The total wrap angle                      | $10\pi$                       |
| The varying pitch coefficient             | 0.011, 0.023, 0.037, 0.053     |
| The initial pitch                         | 56.25mm, 52.50mm, 48.75mm, 45.00mm |
| The volume ratio of SGLS vacuum pump      | 1.5, 2, 0, 2.5, 3.0            |

The amount of work can be indicated by the area under the curve in the indicator diagram. Figure 6 reveals the impact of inlet pressure on the work. Since the discharge pressure, the intake volume and discharge volume stay constant, it is obvious that the thermodynamic work descends with the decrease of inlet pressure with the volume ratio of 2. Figure 7 reveals the impact of volume ratio on the work. Owing to the discharge pressure and discharge volume fixed, the compression governs the amount of work. That is to say, the higher volume ratio is, the more compressing work does. Thus, both the inlet pressure and volume ratio have influences on power consumption.

5. Conclusion

In our study, we introduced the structure and four thermodynamic stages of SGLS vacuum pump at first. Then the pumping process was divided into four successive stages a thermodynamic model was established according to the basic physics laws. The characteristic curves of SGLS pump were plotted. The results show that the thermodynamic model can provide a well explanation on the phenomena of pressure pulsation and power consumption, which will help us to understand the outstanding performance of SGLS vacuum pump.

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