Thermodynamics Analysis of Roots Vacuum Pump

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Abstract. As a kind of fluid machinery, the roots vacuum pump is widely used in the metallurgical industry and semiconductor industry. The double-blade roots vacuum pump is widely used in the vacuum system due to its easy manufacture and low cost. The pumping process can be divided into four distinctive processes (i.e. sucking process, transferring process, backlashing process and exhausting process). The characteristics of each process are illustrated sufficiently in this paper. Based on the ideal gas laws, a thermodynamics model of pumping process is established and the influence of gas leakage on the pumping process is taken into consideration. Using this model, quantificational expressions of five gas thermodynamic parameters (volume, mass, pressure, temperature and internal energy) are given. The performance curves are plotted by MATLAB and the pumping characteristics of double-blade roots vacuum pump are discussed at last. This research can provide a theoretical reference on the design of double-blade roots vacuum pump.

1. Introduction
As a kind of fluid machinery, the roots vacuum pump is widely used in the metallurgical industry and semiconductor industry. The pumping components of roots vacuum pump are a pair of intermeshing rotors mounted on the parallel shafts respectively. When the pump is operating, the meshing rotors are rotating in opposite directions in the stator so that the gas can be trapped from the inlet. As a mainstream product of the dry vacuum pump, it has the advantages of high pumping rate, low energy consumption and oil-free compression [1]. The double-blade roots vacuum pump is widely used in the vacuum system due to its easy manufacture and low cost.

In the study of dry vacuum pump, the thermodynamic performance has received an increasing attention. Li Z et al. set up a general model to describe the working process and predict the performance of scroll vacuum pump according to the energy and mass conservation principle [2]. Hesse J et al. describes shows the detail information (such as pressure, velocity, and temperature) of scroll vacuum pump using CFD technology [3]. Burmistrov A et al. established a mathematical model of oil free scroll vacuum pump using differential equations [4]. Zhao F et al. compared and discussed the thermodynamic process in the screw vacuum pump [5].

Although there has been much interest in the research of roots vacuum pump, there have been few studies on the thermodynamic performance of the roots vacuum pump. In this paper, based on the ideal gas laws, a thermodynamics model of pumping process is established and the influence of gas leakage on the pumping process is taken into consideration. Using this model, quantificational expressions of five gas thermodynamic parameters (volume, mass, pressure, temperature and internal energy) are given.
The performance curves are plotted by MATLAB and the pumping characteristics of double-blade roots vacuum pump are discussed at last.

2. Pumping process
The pumping process can be divided into four distinctive processes (i.e. sucking process, transferring process, backlashing process and exhausting process):

2.1. Sucking process
With the rotation of the rotor, the gas volume is increasing, so the gas will constantly be pumped from the air inlet into the working chamber, on the other hand, since some gas continually leaks through the gap between pump chamber and rotors, leading to the temperature and mass of mixed gas are decided by these two parts of gas. Since the pressure in the cavity is equal to the pressure at the inlet, it can be regarded as an isobaric process.

2.2. Transferring process
At this time, the working chamber is closed until it communicates with the outlet. Since the time of this process is very short, the change of thermodynamic parameters can be ignored.

2.3. Backlashing process
When the working chamber is connected with the outlet, the gas in the front pipeline will rush into the working chamber due to the pressure difference. The time of this process is instantaneous, and the pressure in the working chamber will suddenly rise to the pressure in the front pipeline. In addition, because the volume of working chamber is constant, it can be regarded as a constant volume process.

2.4. Exhausting process
With the rotation of the rotor, the volume of the working chamber decreases continuously, and the gas is discharged into the front pipeline. Since the temperature and pressure in the working chamber are uniform and stable, so it can be regarded as an isothermal isobaric process. Part of the gas will be removed by the front stage pump, and the other will leak back into the suction chamber.

3. Model
According to above analysis, a thermodynamics model of pumping process can be established based on the ideal gas laws and the influence of gas leakage on the pumping process is taken into consideration.

3.1. Style and spacing sucking process

\[
P_1(t) = P_{in} \quad (1)
\]

\[
V_1(t) = \frac{V_0}{2} t = \frac{S_{th}}{2} t \quad (2)
\]

\[
m_1(t) = \left(\frac{P_{in} S_{th}}{T_{in}} - \frac{C_L}{T_{out}} \left(\frac{P_{out}}{T_{out}} - P_{in}\right) + \frac{S_F}{T_{out}} \left(1 - T_{out}/T_{in}\right)\right) \frac{\mu t}{2R} \quad (3)
\]

\[
T_1(t) = P_{in} \cdot S_{th} \cdot \left(\frac{P_{in} S_{th}}{T_{in}} - \frac{C_L}{T_{out}} \left(\frac{P_{out}}{T_{out}} - P_{in}\right) + \frac{S_F}{T_{out}} \left(1 - T_{out}/T_{in}\right)\right)^{-1} \quad (4)
\]

\[
U_1(t) = \frac{C_v \mu P_{in} V_0}{R \cdot \tau} t \quad (5)
\]

3.2. Transferring process

\[
V_2 = \frac{S_{th}}{2} \tau \quad (6)
\]

\[
P_2 = P_{in} \quad (7)
\]
Through the calculation of the thermodynamic parameters, the pumping process can be expressed. The calculating parameters and relative values are listed in Table 1.

### Table 1. The calculating parameters and relative values.

| calculating parameters | values                      |
|------------------------|-----------------------------|
| Period $T_z$           | 0.02 s                      |
| Theoretic pumping speed $S_{th}$ | 600 L/s                     |
| Inlet pressure $P_{in}$ | 100 Pa, 10 Pa, 1 Pa         |
| Outlet pressure $P_{out}$ | 390 Pa, 38 Pa, 3 Pa,         |
| Inlet temperature $T_{in}$ | 293 K                      |
| Outlet temperature $T_{out}$ | 313 K, 320 K, 328 K      |
| Gas constant $R_g$     | $287 J \cdot kg^{-1} \cdot K^{-1}$ |
| Specific heat at constant volume $C_v$ | $717 J \cdot kg^{-1} \cdot K^{-1}$ |
| Specific heat at constant pressure $C_p$ | $1004 J \cdot kg^{-1} \cdot K^{-1}$ |
Figure 1. The volume change of gas.

Figure 2. The pressure change of gas.

Figure 3. The mass change of gas.

Figure 4. The temperature change of gas.

Figure 5. The internal energy change of gas.

Figure 6. The P-V chart of gas.

Figure 1 ~ Figure 5 reflect the variation of thermodynamic parameters with time. In the sucking process, with the increase of the volume of working chamber, the mass and internal energy of gas increase. Since the transferring process is very short, the thermodynamic parameters are same with final state of the suction process. In the backlashing process, the pressure, temperature, mass and internal
energy are shapely increased due to the gas mixture. In the exhaust process, with the decrease of the volume of working chamber, the mass and internal energy of gas decrease. Fig. 6 shows the pressure-volume diagram of the gas in the working chamber. It reveals that the power consumption of the double-blade roots vacuum pump decreases with the decrease of inlet pressure. Compared with CFD simulation, the method mentioned in this paper has the advantages of small computation and short running time.

5. Conclusion

In this paper, based on the ideal gas laws, a gas thermodynamics model of double-blade roots vacuum pump is established and the influence of gas leakage on the pumping process is taken into consideration. Using this model, quantification expressions of five gas thermodynamic parameters (volume, mass, pressure, temperature and internal energy) are given. The performance curves are plotted by MATLAB and the pumping characteristics of double-blade roots vacuum pump are discussed at last. This research can provide a theoretical reference on the design of double-blade roots vacuum pump.

6. References

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