3. Theory

1) Vacuum

A space where the air pressure is lower than one atmosphere pressure (about 10^5 *Pa*) is collectively called a vacuum. Among them, according to the level of air pressure, it can usually be divided into five segments: rough vacuum ($10^5 \sim 10^3$ *Pa*), low vacuum ($10^3 \sim 10^{-1}$ *Pa*), high vacuum ($10^{-1} \sim 10^{-6}$ *Pa*), ultra high vacuum ($10^{-6} \sim 10^{-12}$ *Pa*) and very high vacuum ($< 10^{-12}$ *Pa*). In physical experiments and research work, low vacuum, high vacuum and ultra high vacuum are often used.

The equipment used to obtain vacuum is generally called vacuum system. The common equipment used to obtain low vacuum is a mechanical pump. The common devices used to measure low vacuum are thermocouple gauges and vacuum gauges.

2) Vacuum gauge

Atmospheric pressure: the pressure of the air column on the earth's surface due to gravity. It is related to the altitude, latitude and weather conditions.

Differential pressure: the relative difference between two pressures.

Absolute pressure: all pressures in the space where the medium (liquid, gas or steam) is located.

Negative pressure (vacuum gauge pressure): If the difference between absolute pressure and atmospheric pressure is a negative value, this negative value is negative pressure, i.e., negative pressure = absolute pressure-atmospheric pressure < 0.

3) Working principle of rotary vane mechanical pump

The main parts of a rotary vane vacuum pump are cylindrical stator, eccentric rotor and rotary vane. Figure 2 shows the structure diagram.

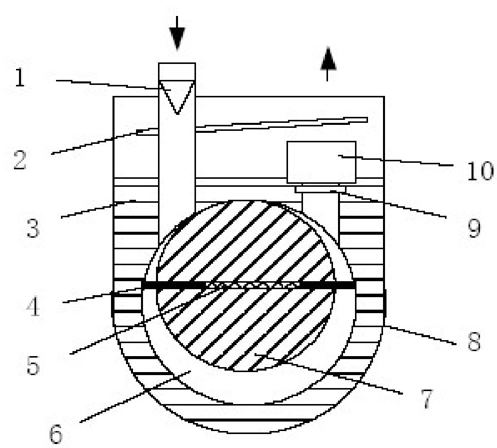

Figure 2 Structure diagram of rotary vane vacuum pump

1. Filter, 2. Oil retaining plate, 3. Vacuum pump oil, 4. Rotating vane, 5. Rotating vane spring, 6. Cavity, 7. Rotor, 8. Oil container, 9. Exhaust valve, 10. Spring plate.

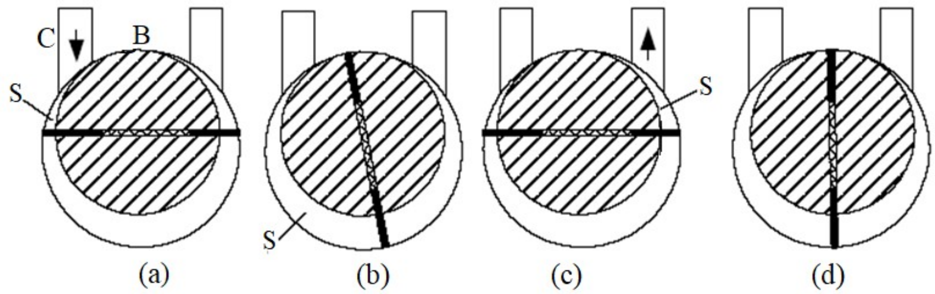

Figure 3 Working principle of rotary vane vacuum pump

The eccentric rotor rotates counterclockwise around its own central axis. During the rotation, the stator and rotor maintain contact at B, and the two rotating vanes always contact the stator by the action of a spring. The rotating vanes divide the space between the rotor and the stator into two parts. The air inlet C connects with the container to be pumped. The outlet port is equipped with a check valve. When the rotor changes from the state of Figure 3(a) to the state of Figure 3(b), the space S continues to expand and the gas is sucked through the air inlet; the rotor turns to the position of Figure 3(c), the space S is separated from the air inlet; After the position Figure 3(d), the gas is compressed and the pressure rises until the check valve of the gas outlet is opened, and the gas is discharged out of the pump. The rotor continuously rotates, and these processes are repeated continuously, so as to continuously draw out the gas in the container connected to the air inlet and reach a vacuum state.

4) **Air density**

The density ρ of air is obtained by the formula $\rho = \frac{\mathrm{m}}{\mathrm{V}}$, where *m* is the mass of air and *V* is the corresponding volume. Take a pycnometer, suppose the mass is m_1 when there is air in the bottle, and the mass is m_0 when the pycnometer is evacuated to vacuum. Then the mass of air in the bottle is $m = m_1 - m_0$.

If the volume of the pycnometer is *V*, then we have $\rho = \frac{m_1 - m_0}{V}$. Since the density of air is related to factors such as atmospheric pressure, temperature and absolute humidity, the measured air density value is under the laboratory conditions at that time. Use the following formula, the measured air density can be converted to the value of dry air in the standard state (0 °C and one standard atmospheric pressure):

$$\rho_n = \rho \frac{p_n}{p}(1 + \alpha t)(1 + \frac{3}{8}\frac{p_\omega}{p}), \tag{1}$$

where ρ_n is the density of dry air in the standard state; ρ is the air density measured under the experimental conditions at that time; p_n is the standard atmospheric pressure; p is the atmospheric pressure under the experimental conditions; α is the pressure coefficient of the air (0.003674 °C^{-1}); t is the temperature of the air (°C); p_ω is the partial pressure of the water vapor contained in the air (i.e. the absolute humidity value) and p_ω = relative humidity × $p_{\omega 0}$ with $p_{\omega 0}$ the saturated water vapor pressure at this temperature. Under normal laboratory conditions, the air is relatively dry, and the ratio of standard atmospheric pressure to atmospheric pressure is close to 1, and equation (1) is approximately:

$$\rho_n = \rho(1+\alpha t)\,. \tag{2}$$

5) **Measurement of universal gas constant**

The ideal gas state equation is:

$$pV = \frac{m}{M}RT\,, \tag{3}$$

where p is the pressure of the gas, V is the volume of the gas, m is the total mass of the gas, M is the molar mass of the gas, T is the thermodynamic temperature of the gas, and its value is $T = 273.15 + t$. R is called the universal constant of ideal gas, also known as the molar gas constant, theoretical value is $R = 8.31 J/(mol \cdot K)$.

All kinds of actual gases generally follow this equation under conditions of usual pressure and not too low temperature. The lower the pressure is, the higher the degree of approximation.

This experiment uses air as the test gas. The average molar mass M of air is 28.8 g/mol. (Nitrogen in the air accounts for about 80% and the molar mass of nitrogen is 28.0 g/mol; oxygen accounts for about 20% and the molar mass of oxygen is 32.0 g /mol.)

Take a pycnometer, suppose the total mass is m_1 when the bottle is filled with air, and the mass of the bottle is m_0, then the air mass in the bottle is $m = m_1 - m_0$. The pressure of the air in the bottle is p, the thermodynamic temperature is T, the volume is V. The ideal gas state equation can be rewritten as:

$$p = \frac{mT}{MV}R, \quad \text{i.e. } p = \frac{m_1 T}{MV}R + C' \quad \left(C' = -\frac{m_0 T}{MV}, \text{ a constant}\right). \tag{4}$$

If the pressure in the laboratory environment is p_0 and the reading of the vacuum meter is p', then $p' = p - p_0 < 0$. Formula (4) can be rewritten as:

$$p' = \frac{m_1 T}{MV}R + C' - p_0 = \frac{m_1 T}{MV}R + C \quad (C \text{ is a constant}). \tag{5}$$

In equation (5), $C = C' - p_0$. Measure the value m_1 under different vacuum gauge negative pressure readings p', and then make the relationship diagram $p' - m_1$, find the slope of the straight line $k = \frac{RT}{MV}$, the value of the universal gas constant can be derived.