

#### 4. Experimental Objectives

- 1) Measure the density of ambient air by vacuuming method, convert it to the standard value of dry air under standard state (0 °C, one standard atmospheric pressure), and compare it with the theoretical value of the standard state.
- 2) From the ideal gas state equation, derive the expression of universal gas constant under variable pressure. Measure the data of total mass  $m_1$  (air plus container) at gas pressure  $P'$  by the method of reducing pressure step-by-step and plot their relationship curve. Acquire the universal gas constant  $R$  by curve fitting, and compare it with theoretical value.

#### 5. Precautions

- 1) The order of closing the valves must not be wrong, otherwise the oil in the vacuum pump may flow into the pycnometer.
- 2) The process of disconnecting the vacuum tube out from the pycnometer should be carried out slowly to prevent the outside air from suddenly entering the vacuum tube and damaging the pointer of the vacuum gauge.
- 3) It should be ensured that the ambient temperature does not change too much.
- 4) Do not touch the pycnometer with your hands for a long time to prevent the temperature of the gas in the bottle from changing due to heat transfer.

#### 6. Experimental Procedures

- 1) Measure the density of air

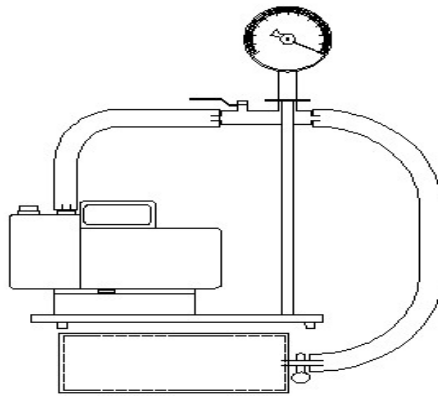


Figure 4 Schematic of experimental setup

- a) Measure the volume of the pycnometer. Use a vernier caliper to measure the outer diameter  $D$ , length  $L$ , upper and lower bottom thicknesses  $\delta_1$  and  $\delta_2$ , and side wall thickness  $\delta_0$  (the side wall thickness should be measured several times and take average) to calculate the volume  $V$  of the pycnometer.
- b) Turn on the pycnometer switch, put it on the electronic physical balance to weigh the total mass  $m_1$  of air and pycnometer, and then lay it down on the table, the bottle mouth is connected to the vacuum tube, refer to Figure 4.

- c) Open the vacuum valve, plug in the power supply of the vacuum pump, and turn on the vacuum pump switch (check whether the oil level of the vacuum pump is in the middle of the oil mark before turning on the switch). Wait until the reading of the vacuum pump close to -0.1 MPa (it needs a few minutes), first turn off the pycnometer switch, then turn off the vacuum valve, and finally turn off the vacuum pump (the sequence must not be wrong, otherwise the oil in the vacuum pump may flow back into the pycnometer).
- d) Disconnect the vacuum tube from the pycnometer. This process should be carried out slowly to prevent outside air from suddenly entering the vacuum tube and damaging the pointer of the vacuum meter.
- e) Place the pycnometer on the electronic physical balance to weigh the pycnometer  $m_0$ , calculate the gas mass, and calculate the ambient air density from the formula  $\rho = \frac{m_1 - m_0}{V}$ .
- f) Read the laboratory temperature  $t$  ( $^{\circ}\text{C}$ ) from the mercury thermometer, and calculate the density of the air in the standard state from the formula  $\rho_n = \rho(1 + \alpha t)$ , and compare it with the theoretical value.
- 2) Determine the universal gas constant  $R$
- a) Measure the ambient temperature  $t_1$  ( $^{\circ}\text{C}$ ) with a mercury thermometer. (This experiment takes a long time, the ambient temperature may change, and the temperature at the beginning and end of the experiment should be measured and averaged).
- b) On the basis of the previous experiment, reconnect the pycnometer and the vacuum tube, turn on the pycnometer switch, the vacuum meter reading changes between -0.1 MPa and -0.09 MPa. Since the interface between the pycnometer and the vacuum tube is not strictly sealed, there is a slow leak, and the pressure of the entire system will slowly drop. When it drops to -0.09 MPa, quickly turn off the pycnometer switch and slowly pull the pycnometer out.
- c) Weigh the mass  $m_1$  of the pycnometer at -0.09 MPa.
- d) Connect the pycnometer to the vacuum tube again, turn on the pycnometer switch, the vacuum gauge reading becomes between -0.09 MPa and -0.08 MPa, and wait until the pressure drops to -0.08 MPa, then slowly pull out the pycnometer and weigh the mass at this time .
- e) Repeat steps a), b), and c), measure the masses at the vacuum gauge readings of -0.07, -0.06, -0.05, -0.04, -0.03, -0.02, -0.01, and 0 MPa respectively.
- f) Measure the temperature of the environment  $t_2$  ( $^{\circ}\text{C}$ ).
- g) Make the graph  $p'-m_1$ , fit the straight line to obtain the slope  $k = \frac{RT}{MV}$ , and calculate the value of the universal gas constant.

## 7. An example of data recording and processing

Note: Following data are for reference only, not the criteria for apparatus performance.

1) Measure the density of air

a) Measure the volume of the pycnometer

Outer diameter  $D = 89.42$  mm, thickness of side wall  $\delta_0 = \frac{1}{2} \times (4.74 + 5.22) \text{ mm}$

(only measured twice here, students can measure more times), get the inner diameter  $d = D - 2 \times \delta_0 = 89.42 - 4.74 - 5.22 = 79.46 \text{ mm}$ .

Total height  $L = 260$  mm, upper bottom thickness  $\delta_1 = 5.50$  mm, lower bottom thickness  $\delta_2 = 5.64$  mm, get the height inside the bottle  $l = L - \delta_1 - \delta_2 = 260 - 5.50 - 5.64 = 248.86 \text{ mm}$ .

Pycnometer volume  $V = \pi \left( \frac{d}{2} \right)^2 l = \pi \left( \frac{79.46}{2} \right)^2 \times 248.86 \times 10^{-3} = 1234.1 \text{ cm}^3$ .

b) Measure the density of air

Total mass of air and pycnometer  $m_1 = 571.33$  g, mass of empty bottle  $m_0 = 569.82$  g, ambient temperature  $t = 13.1$  °C

Laboratory air density  $\rho = \frac{m_1 - m_0}{V} = \frac{571.33 - 569.82}{1234.1} = 1.224 \times 10^{-3} \text{ g/cm}^3 = 1.224 \text{ g/L}$ .

Air density in standard state,  $\rho_n = \rho(1 + \alpha t) = 1.224 \times (1 + 0.003674 \times 13.1) = 1.283 \text{ g/L}$ .

Theoretical value of air density in standard state is  $1.293 \text{ g/L}$ , so the experimental error is  $E = \frac{1.293 - 1.283}{1.293} \times 100\% = 0.8\% < 1\%$ .

2) Determine the universal gas constant  $R$

Ambient temperature  $t_1 = 9.5$  °C,  $t_2 = 9.5$  °C.  $\bar{t} = \frac{1}{2}(t_1 + t_2) = 9.5$  °C.

Table 1: Total mass  $m_1$  of air and pycnometer at different pressures  $p'$

$p' / \text{Pa}$	-90000	-80000	-70000	-60000	-50000	-40000	-30000	-20000	-10000	0
$m_1 / \text{g}$	569.89	570.03	570.17	570.31	570.44	570.60	570.75	570.89	571.06	571.21

Plot  $p'-m_1$  graph as shown in Figure 5.

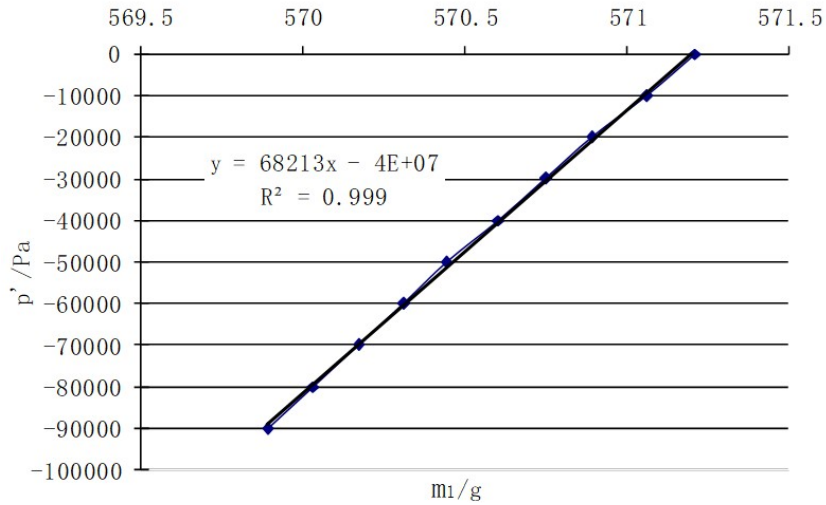


Figure 5 Relationship between vacuum gauge negative pressure  $p'$  and total mass of air and bottle  $m_1$

Do straight line fitting gives the slope  $k = 68213 Pa / g$ .

$$\text{We got } R = \frac{kMV}{T} = \frac{68213 \times 10^3 \times 28.8 \times 10^{-3} \times 1234.1 \times 10^{-6}}{273.15 + 9.5} = 8.58 J / (mol \cdot K)$$

The theoretical value of R is  $8.31 J / (mol \cdot K)$ , so the experimental error is

$$E = \frac{8.58 - 8.31}{8.31} \times 100\% = 3\%$$