Research for a clean and large throughput differential pumping system

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Abstract. The research is to design a differential pumping system not only to achieve the pressure transition with a large throughput, but also to achieve a clean system without oil vapour contamination. In the paper, the pressure in differential stages are calculated; the differential pumping system design and equipment choice are introduced; the tests of MBP, a new kind of molecular-drag pump with large throughout and clean vacuum are described and the system experiment result and analysis is presented.

1. Introduction

The Gas-filled Recoil Separator built in Heavy Ion Research Facility in Lanzhou (HIRFL) needs to be filled with helium by a pressure of 100 Pa as a support medium when it works. The working pressure in the beam line connected with the device is 10⁻⁵~10⁻⁶ Pa. There are 7-8 orders of magnitude of pressure difference between them. The beam passage in the system is in a shape of a taper with a length of 2 m and diameter of 10 mm in one side and 30 mm in another side (see figure 1). Hence, the traditional differential methods of increasing length and reducing aperture diameter (such as capillary) of the passage are not fit to the system. On the other hand, the device is close to the vacuum system of the Cooler Storage Ring (CSR) which has a working pressure of less than 10⁻⁹ Pa and need to be protected from contamination of any oil vapour. The research is not only to design a differential pumping system to achieve the pressure transition with a large throughput, but also to achieve a clean system without oil vapour contamination.

The working pressure of this differential pumping system covers the whole pressure ranges. In viscous flow and molecular flow ranges, dry mechanical pump and turbo-molecular pump (TMP) can be used respectively to keep the system clean. Nevertheless, they can not work well in intermediate flow range (10⁻⁵~10⁻³ Pa). Pumping speed and compression ratio of TMP will be reduced sharply in the range. Furthermore, TMP will be damaged by the high temperature caused by internal viscosity. Dry pump can work in intermediate flow range continuously, but the price is high and the pumping speed is too small (less than 10 l/s) to establish a differential pumping ratio, especially in a large throughput differential pumping system.

Therefore, Roots pump unit is being used in intermediate flow range for most of differential pumping system [1-3]. However, Roots pump has a big problem of back-streaming of its backing.
pump oil. To reduce the contamination, the cold trap or other device has to be adopted. In this case the cost is higher and the operation is more complex, but the oil vapour cannot be eliminated completely.

In our research, Molecular/Booster Pump (MBP), a special kind of molecular-drag pump [4] is adopted to replace the Roots pump unit. The new pump can operate continuously in intermediate flow range with large throughput as that of Roots pump unit and low contamination as that of normal TMP. As a result, a clean and large throughputs differential pumping system will be set up.

2. Pressure calculation for differential pumping stages

The schematic diagram of the differential pumping system is shown in figure 1.

Figure 1. Schematic diagram of the differential pumping system.

It is supposed there are \( n \) stage of differential pipes (here 5 stages). \( S_i \) and \( C_i \) \((i=0,1,2...n)\) are pumping speed and pipe’s conductance of the stage \( i \). If the outgassing of the pipes is ignored, the pump in every stage is mainly used to exhaust the gas flow from up stage, and a part of gas flow will pass to next stage. According to the conservation of mass, the equation is given for stage \( i \) [5]:

\[
S_i \cdot P_i = C_i (P_{i+1} - P_i) - C_{i+1} (P_i - P_{i+1})
\]

For \( n \) stage, \( n \) equations can be listed and the follow equation can be deduced:

\[
P_i = \lambda_i \times P_{i+1} \quad (i=1,2,3...n)
\]

Where \( \lambda_i \) is differential ratio of stage:

\[
\lambda_i = \frac{C_i}{C_i + S_i + C_{i+1} - \lambda_{i+1} \times C_{i+1}}
\]

According to the parameters of pipes and pumping speed of stages, the conductance \( C_i \) and differential ratio \( \lambda_i \) are calculated, then the pressure \( P_i \) in each stage, both for \( \text{N}_2 \) and \( \text{He} \), can be obtained (see table 1 in paragraph 5).

3. The differential pumping system design

3.1. Differential chambers

The differential length of 2 m is divided into equal parts for 4 differential chambers (HIRFL beam line is as stage 5, see figure 1). There is a flange with an orifice between every two chambers. The diameters of the orifices are from 10mm to 30mm according to the beam passage. In order to reduce conductance, a pipe with a length of 100–120mm and a diameter of 10–30mm is welded to each orifice (figure 2). The chambers and differential flanges are made of AISI 304 stainless steel. All components are chemical cleaned and degassed before installation to reduce the outgassing.
3.2. Pumping and measuring equipment

Two Molecular/Booster pumps (MBP, shown in figure 3), developed by professor J G Chu of Shenzhen University of China, are used in stage 1 and 2. MBP (nominal pumping speed: 800 l/s) can operate continuously in pressure range of $10^2$–$10^{-3}$Pa. Three turbo-molecular pumps (KYKY, China, nominal pumping speed: 600 l/s) with an ultimate pressure of $1 \times 10^{-5}$ Pa (without bake-out) are used in stage 3–4 and the beam line which connected with the differential system. Five rotary-vane pumps (Leybold, Germany, pumping speed: 8 l/s) are adopted as backing pumps.

One rough vacuum gauge DM 12 with a Pirani sensor TTR 301 (measure range $10^{-1}$–$10^5$ Pa) and two high vacuum gauges Center Two with 4 PTR 237 cold cathode ionization sensors (measure range $1 \times 10^{-7}$–1Pa, both from Leybold, Germany) are adopted for high pressure and low pressure measurement respectively.

4. Performance tests of MBP

4.1. Test of ultimate pressure

A standard ultimate pressure test dome was installed on the DN 200 MBP. The dome and MBP were baked-out to 150°C and 85°C respectively for 24h. Another 24h later, the pressure of $5 \times 10^{-6}$ Pa was obtained. The mass spectra obtained after bake-out (figure 4) shows the system very clean.

4.2. Test of pumping speed

The tube-flow-meter method was applied to test the pumping speed. The pumping speeds in different pressure ranges can be calculated by formula [6]:

$$S = \frac{Kh}{Pt}$$

Where $S$ is pumping speed (l/s); $K$ is the tube constant; $P$ is pressure reading, $h$ is the oil height risen in the measuring tube and $t$ is the time needed when the oil rise.

Figure 5 shows the pumping speed curves of N$_2$ and He in pressure range of $10^2$–100Pa.

![Figure 5. Pumping speed curves of N$_2$ and He.](image)

![Figure 6. Test site of the differential pumping system (without connected with the beam line).](image)

The pumping speed of N$_2$ is 1.4–1.6 times larger than that of He when pressure is lower than 1 Pa. In the pressure of 1–10 Pa, the difference of the pumping speed of two gases gets small with the pressure increasing. When the pressure is higher than 10 Pa, their pumping speeds are almost equal.

5. Experiment and analysis of the differential pumping system

The experimental test of the differential pumping system was done in our laboratory (figure 6). In the experiment, beam line (stage 5) was not connected, so only 4 differential stages were tested. Four pump units were started simultaneously, pumped the stages to their ultimate pressures. Then N$_2$ and He were sent into the target chamber respectively. 3 pressure points were recorded for every pressure
magnitude until 100 Pa. The pressure curves of N$_2$ and He in each differential stage versus the pressure of the target chamber are shown in figures 7–8. The pressures in each stage obtained from calculation and experiment with the target chamber pressure of 100 Pa are listed in table 1.

![Figure 7. Pressure in each stage vs. the pressure in target chamber (N$_2$).](image1)

![Figure 8. Pressure in each stage vs. the pressure in target chamber (He).](image2)

| Gas    | Unit | Target chamber | Stage 1 | Stage 2 | Stage 3 | Stage 4 | Stage 5 |
|--------|------|----------------|---------|---------|---------|---------|---------|
| N$_2$  | Pa   | Cal. 100       | 3.2     | 1.4$\times$10$^{-2}$ | 1.6$\times$10$^{-4}$ | 2.8$\times$10$^{-6}$ | 1$\times$10$^{-7}$ |
|        |      | Exp. 100       | 4.5     | 1$\times$10$^{-2}$ | 2.5$\times$10$^{-4}$ | 3.5$\times$10$^{-5}$ |
| He     | Pa   | Cal. 100       | 4.1     | 8.6$\times$10$^{-2}$ | 3.4$\times$10$^{-3}$ | 1.9$\times$10$^{-4}$ | 2.1$\times$10$^{-5}$ |
|        | (N$_2$ equivalent) | Exp. 100 | 7.4     | 3.2$\times$10$^{-2}$ | 1.9$\times$10$^{-3}$ | 2.4$\times$10$^{-4}$ |

In stage 4, the experimental pressure (N$_2$) is higher than calculated ones. The reasons are: 1) in the larger diameter of the differential pipes, a part of gas will pass through the pipes without impact in the molecular flow range. As a result, the gasload will be increased in the later stages [7]; 2) the outgassing and the leakage of the chambers was not taken into account in the calculation; 3) the pressure is restricted by the ultimate pressure of the turbo-molecular pump used in stage 4. If a pump with lower ultimate pressure is used, the pressure in this stage will be lower; 4) when the system connects with the beam line (stage 5), the pressure of 10$^{-5}$–10$^{-6}$ Pa will be obtained in this stage with a more TMP.

6. Conclusion
Although the differential distance is short and the diameter of the beam passage is big, the pressure transition from 100 Pa to 10$^{-5}$–10$^{-6}$ Pa can be achieved by a reasonable structure design; MBP, a new kind of molecular-drag pump with a small volume and without oil vapour contamination, can replace Roots pump unit to operate in intermediate flow range.

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