

Potassium and sodium vapor diffusion pump development for fusion system

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An alkali metal diffusion pump, which can meet many requirements for DT fusion system, was developed based on a commercial oil diffusion pump. Using sodium, potassium, and oil each as a vapor source, their evacuation behaviors were compared. The evacuation rate using potassium was comparable to that by original oil, and operation using sodium was found to require higher temperature. The compression ratio and evacuation of deuterium were also investigated. The diffusion pumping system was operated successfully, making this type of evacuation system a potential candidate for the fusion system.

Keywords: diffusion pump, alkali metal vapor, evacuation rate, compression ratio, sodium, potassium

1. Introduction

The high vacuum system for D-T fusion reactors has many requirements for steady state operation. For example, the vacuum system must be (1) compatible with tritium, (2) compatible with radiation, (3) a low tritium retention component, (4) durable, and (5) easy to maintain, regardless of the confinement type of the fusion system. In the case of magnetic confinement, the system must also be (6) compatible with strong magnetic field and (7) must not release heavy elements into the plasma. Similarly, in the case of inertial confinement, it must be compatible with (8) vapor from elements heavier than He (C, O, Li, Pb or Au in some cases).

Many types of vacuum systems have been developed and commercialized so far; however there is no candidate pump which can meet all the requirements. Turbo molecular pumps are not practical for reasons such as (1: oil contamination), (4), (5), (6), and (8) [1]. Cryo-pumps are not good because of (3), (5), and (8) [1]. Cryogenic diffusion pumps have potential [2-4], while those can also result in high tritium retention (3). Diffusion pumps that transfer the momentum to evacuating gas molecules are often used to achieve high vacuum, however (1), (2), and (8) are thought to be the concerns as long as oil is used as the source of vapor. The diffusion pump using Hg can meet many requirements [1], but Hg backflow to plasma (7) is undesirable. Also, D/T separation systems using a permeation window (Pd) [5] or a noble metal catalyst may be damaged by the foreflow Hg.

The diffusion pump using alkali metal vapor is expected to meet most of the requirements, because no radiation damage is given (1,2) to liquid metal except for the nuclear reaction with neutrons. Alkali metals react especially with oxygen, and with hydrogen isotopes and nitrogen in case of lithium, however many experiments

have been performed for the decomposition of such compound using electrochemical method in molten salt, which is compatible with liquid alkali metal [6,7]. Backflow of the vapor often happens in diffusion pumps, but it can be mitigated using a baffle plate at the pump inlet. However so far, no research has been done to develop the alkali metal vapor diffusion pump. Thus, in this research, a vacuum evacuation system using alkali metal vapor, sodium (Na) and potassium (K), was constructed, and the evacuation rates for several types of gas species were experimentally investigated.

2. Experimental

2.1 Experimental setup

A diffusion pump, ESV-3AC produced by TOKUDA SEISAKUJYO (currently, SHIBAURA ELETEC CORP.) was used as the basic system. A vacuum tank with 0.5 m³ volume (500 L) with JIS150 bottom port (158 mm inner dia.) was connected to the inlet port of the diffusion pump (JIS80, 83 mm inner dia.), through a butterfly-type valve (B-J150 by MIYUKI CO., LTD., minimum inner diameter: 154 mm), a 100 mm-L JIS150 nipple, and a 100 mm-L size-reducing flange (JIS150 to JIS80). Diffusion pump system was equipped with a 500 W heater and an AC cooling fan, whose operation was not adjustable. Because higher temperature was expected to be necessary for the alkali metal, power controller for the heater (up to 900 W) was added. The cooling fan was also replaced by an adjustable DC fan. In addition, several thermocouples (sheathed, type-K) were attached from the outside of the diffusion pump. The positions were at the bottom of the pump, at 3 different heights of the cooling fin, and the inlet flange of the pump where baffle plates were installed, respectively.

The vacuum tank was equipped with a quadrupole mass spectrometer (M-101QA-TDM by CANON ANELVA CORP.), an absolute vacuum gauge (capacitance gauge, M-342DG-1D, by CANON ANELVA CORP.), a rough pumping line, and a gas inlet port. The roughing pump for the diffusion pump (RP-360Z by TOKUDA) was used as-received although it was integrated to the rough vacuum pump for the chamber (GCD-051X by ULVAC Inc.) in the K vapor pumping campaign.

For the K vapor pumping campaign, a Pirani gauge (GP-1G by ULVAC Inc.) was also added roughly at the center position between the outlet of the diffusion pump and the inlet of the rough vacuum pump. The setup is illustrated in figure 1. Because the sensitivity of a Pirani gauge depends on the gas species, the value is calibrated using the absolute gauge in the experimental setup.

As the experimental procedure, evacuating experiments were performed with oil (TS-4) for several gases (H₂, He, CH₄, Ne, N₂, O₂, Ar, and CO₂) at first, then the system was cleaned up, followed by the charging of Na metal. Evacuating experiments with Na for several gases (D₂, He, CH₄, Ne, N₂, and Ar) were also performed and then, a similar replacement to K metal was done, followed by the same evacuation experiment. O₂ and CO₂ were not used in the case of Na and K, because they easily react with the alkali metal. H₂ was also skipped because there was already residual H₂ in the system. The source may be due to the decomposing oil or moisture, or the degassing from the diffusion pump components. All of TS-4 oil, Na, and K were charged for 100 mL at room temperature (oil) or their melting points (Na and K, mass base [8]).

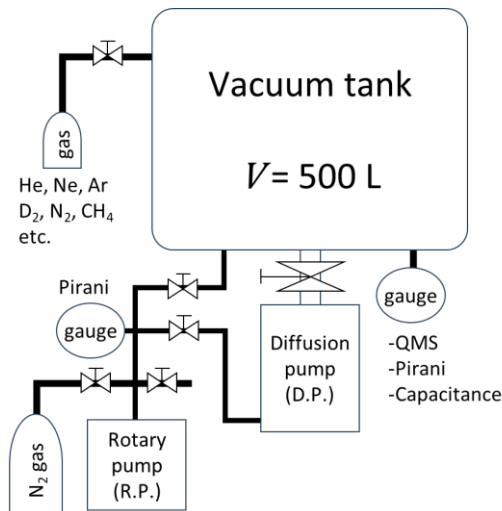


Fig. 1. Experimental setup.

2.2 Estimation of the evacuation rate

The typical outputs of the QMS after the gas introduction are shown in figure 2. The QMS was

operated at 0.1 mA filament current and at 1200 V secondary electron multiplier voltage. The gas was introduced to the chamber to be more than 0.1 Pa. Because the QMS is not designed to work at such high pressure (> 0.1 Pa) conditions, the QMS output for the corresponding ion (e.g. $m/z = 4$ for He), is less than the expected value. As a 2nd Y axis in figure 2, estimated He partial pressure using other gauges is shown. Note that the conversion factor especially in the high-pressure region (~ 0.1 Pa) is not stable as mentioned; the value in Pa can be different from the practical value. Then after several seconds, the gas was evacuated to be below 0.1 Pa where the output of QMS becomes proportional to the partial pressure of the gas. Note that the time in the figure is offset to have the peak around 0 s, so the time does not mean the actual time after the gas injection. The pumping rate S (L/s) is defined in equation 1, using the evacuation volume V (500 L), the time t , the partial pressure of the evacuation gas P (Pa), and system-outgas source Q . In the linear region in figure 2, where the QMS output I is linear to the partial pressure of the corresponding gas, the pumping rate S calculated from equation 1 is the product of $d \ln(P)/dt$ and $-V$, which is also the product of $d \ln(I)/dt$ and $-V$, as shown in equation 2 when Q is negligibly small. Therefore, the vacuum rate was estimated by fitting the linear decrease in the time- $\ln(I)$ diagram.

$$-V \frac{dP}{dt} = SP - Q \quad (1)$$

$$S = -V \frac{d \ln(P)}{dt} = -V \frac{d \ln(I)}{dt} \quad (2)$$

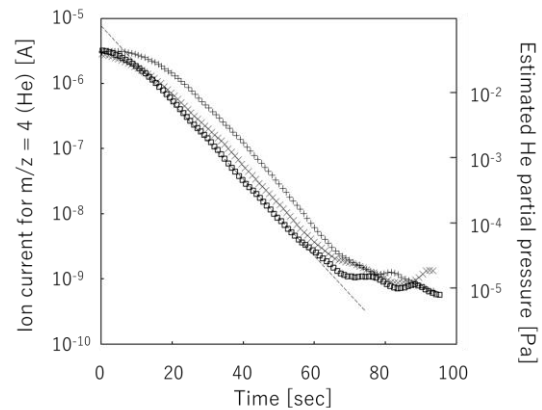


Fig. 2. Example of He evacuation behavior using K vapor.

□: Run 1, ×: Run 2, +: Run 3, dashed line: fitted line for Run 1, indicating an evacuation rate of 69 L/s

3. Results and discussions

3.1 He evacuation

Figure 3 summarizes the evacuation rates of oil, Na and K at different temperatures. Heater power (kW) in each case is also shown in the figure. In case of oil, the temperature at the bottom of the pump was not monitored but it was expected to be below 300°C. It is clear that the

higher the temperature the higher the evacuation rate, for both of Na and K. Comparing the results of Na and K, evacuation by K was capable roughly 150 °C lower than that by Na, which agrees with the vapor pressure difference between Na and K. The diffusion pump requires gas vapor pressure more than 0.1 torr (>13 Pa) [9] and corresponding temperature difference between Na and K is 90 K (260 °C for K and 350 °C for Na) [2]. Considering the heat transport from the bottom to the nozzle inside of the diffusion pump, and radiation heat loss from the nozzle, the required temperature at the bottom will be much higher than that at the nozzle, which explains the reason for each of their operating temperatures (>510 °C for K and >660 °C for Na). The highest evacuation rates (75 L/s for K and 30 L/s for Na) are less than that by oil but are comparable. Note that the values seem to be limited by the heater power (900 W) so by using a heater with more output, or a thermal design to keep the nozzle temperature high, higher evacuation rate could be achievable even with the same geometry.

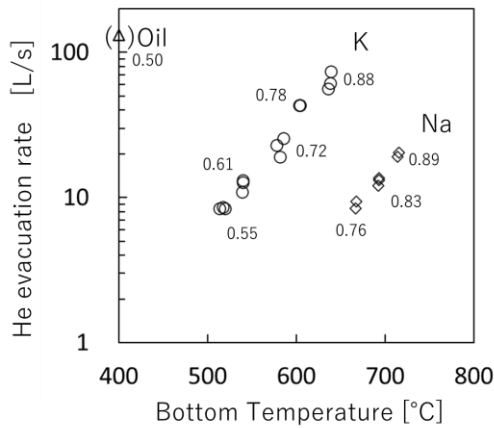


Fig. 3. Evacuation rate of He by the oil, Na and K vapor.

△ :oil (at approximately 300 °C), ◇ :Na, ○ :K, respectively. Numbers next to symbols correspond to heating power in kW.

The dependence on the cooling condition was also investigated in the series using K vapor. When the cooling condition by the DC-fan was changed in constant heater output, the evacuation rate changed as shown in figure 4. The X-axis is the outer surface temperature of the bottom-side cooling rib. It should be noted that most likely because of the heat transfer by the exhausting He gas, the temperature of the cooling rib was often changed (basically, showing an increasing trend) during the evacuation. So, the temperature at the gas introduction was chosen to be shown in the figure. The dependence is not so obvious, but higher temperature (>227°C) and lower temperature (< 216°C) may not be good for the evacuation. The reason will be as follows: (A) If the temperature of the wall is too high, more back diffusion of metal vapor occurs, which also increases the back diffusion of the gas, to achieve less evacuation rate. (B) If

the temperature is too low, more radiation heat loss occurs from the nozzle, which decreases the temperature of the nozzle and vapor pressure of the alkali metal, to reduce the evacuation rate.

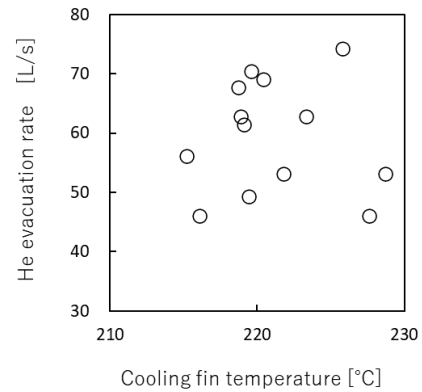


Fig. 4. Evacuation rates at different cooling fin temperatures. Evacuation by K vapor at 0.88 kW heating.

Additionally, to calculate the compression ratio, pressures of the inlet and outlet of the diffusion pump were investigated under a continuously He gas feeding condition. The pressure of the vacuum chamber, monitored by the absolute gauge, was regarded as the inlet pressure. Also, the pressure monitored by the Pirani gauge between the roughing pump and the diffusion pump was regarded as the outlet pressure. Because the Pirani gauge was installed roughly at the middle of the vacuum line (NW25 bellows tube), the actual pressure at the outlet of the diffusion pump may be twice higher than the monitored pressure, that means the compression ratio may also be twice higher. The result of the inlet pressure trend and the compression ratio is shown in figures 5 and 6, respectively. At the time around 0, 200 and 550 s in figure 5, the opening of the gas inlet was changed to change the gas load. The higher the inlet pressure is, the lower the compression ratio is. This behavior is often found in diffusion pumping systems, due to the back diffusion of the evacuated gas [9].

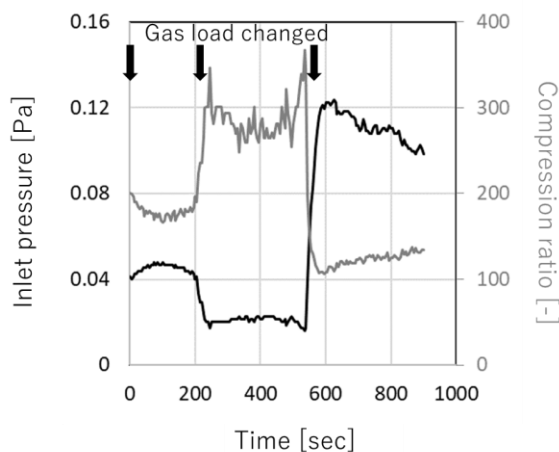


Fig. 5. Temporal change of the inlet pressure and the compression ratio. He gas evacuation by K vapor, 0.78 kW heating.

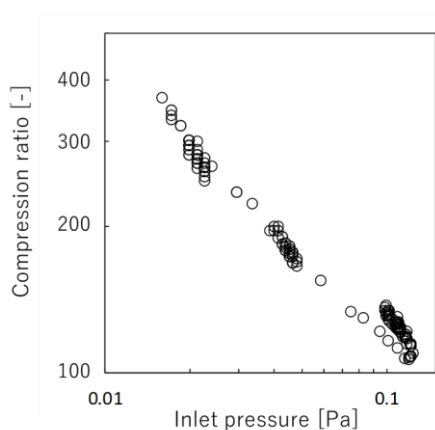


Fig. 6. Compression ratio dependence on the inlet gas pressure. He gas evacuation using K vapor, 0.78 kW heating.

3.2 Evacuation rates of different gas species

Figure 7 shows the evacuation rate of the diffusion pump for several types of gases, summarized in order of increasing mass number. Above mass 16 (CH_4), evacuation ratio becomes smaller for heavier gas. The simplest modelling of the diffusion pump, as a one-way path for gas molecules, shows that evacuation rate for each gas species is linear to the velocity of the gas molecules, which is also linear to the square root of the temperature/mass [9]. The trend above mass 16 has good agreement with the theory. In the case of lighter mass gases, the evacuation rate becomes much smaller, contrary to what is expected from the previous theory. This behavior is also well known (as Ho factor) because of the back diffusion [9]. In the case of alkali metal diffusion pumps, back diffusing gas is more heated than that in oil diffusion pump, to have higher molecular velocity. That might be the reason of the evacuation rate decrease for light gases.

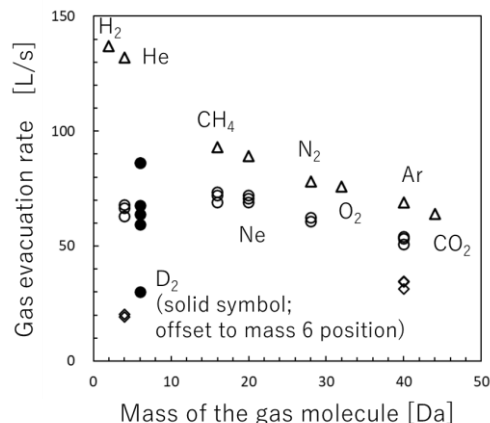


Fig. 7. Evacuation rate dependence on the mass number of the evacuating gas.

Δ : by oil at 0.5 kW heating, $\diamond$: by Na at 0.89 kW, $\circ$: by K at 0.78 kW, respectively. Mass 4 is He for the open symbol $\circ$, and D_2 for the solid symbol $\bullet$, which for better readability has been offset by 2 Da.

3.3 Evacuation of hydrogen isotope

In case of D_2 evacuation, a 2-stage evacuation behavior was often observed, as shown in figure 8. The D_2 gas feeding was done before $t < 0$ s in figure 8 and the time is offset to show the current peak around 20 s. Note that because the sensitivity of QMS decreases at higher pressure (~ 0.1 Pa), Actual pressure around $t < 20$ s is not proportional to the ion current but much higher. The 2-stage behavior is due to the isotope exchange with residual protium in the system, and the formation of alkali metal hydride (NaD , KD). The best evacuation behavior was found at the 1st D_2 evacuation performed at 0.78 kW, as shown in figure 7 (86 L/s). This operation is done as the 1st campaign in the same condition, so the chemical trapping by K might be the reason of the high evacuation rate. Alkali metal hydride is not so stable in high temperature vacuum conditions, while this behavior should be investigated more to assess the tritium inventory in the vacuum system.

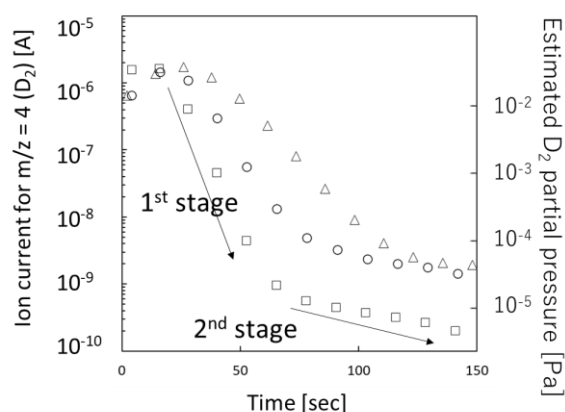


Fig. 8. Evacuation behavior of D₂ using K vapor at 0.78 kW heating

□: Run 1, feeding 0.3 Pa, ○: Run 2, feeding 7.6 Pa, △: Run 3, feeding 1.5 Pa.

4. Conclusion

In this research, a diffusion pump using sodium and potassium vapor was successfully developed, based on a commercial oil diffusion pump. The evacuation rate was increasing with heating power and at the highest available power, comparable to the original oil pump. The compression ratio for He gas was more than 100, even at 0.1 Pa of inlet pressure. The evacuation rates for various gases were also investigated, and for gases no lighter than methane CH₄, the heavier the gas was, the smaller the evacuation rate was. The evacuation of deuterium gas D₂ showed a 2-stage behavior, which may be due to the isotope exchange with residual protium or the decomposition of metal deuteride.

Acknowledgments

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