<<Research Paper>> Journal of the Korean Vacuum Society Vol.15 No.1, January 2006, pp.14~23

# Hydrogen Pumping Characteristics of a Scroll Pump

S. R. In*

*Nuclear Fusion Research Lab. Korea Atomic Energy Research Institute, Daejeon 305-600*

(Received December 19, 2005)

The scroll pump is widely used in ultra clean vacuum systems. However, there is no commonly available information on the hydrogen pumping characteristics of this pump, which creates a difficulty in determining whether the scroll pump can be used or not in a fusion experiment system where hydrogen is the main working gas. In this paper the experimental setup, measurement procedures, experimental results, and discussions on the pumping speed, the maximum compression ratio and the back-streaming properties of the scroll pump, especially for the hydrogen gas, are reported.

Keywords : Scroll pump, Pumping speed, Maximum compression ratio, Hydrogen

## I. Introduction

The scroll pump is widely used as the main pump in a low vacuum system or the backing pump of the turbo-molecular pump (TMP) in a high vacuum system because of its cleanness, medium size, simple construction, light weight, low ultimate pressure, low vibration and noise level, and so on. There are two kinds of operating mechanisms of the scroll pump depending on the moving pattern of the rotor; orbiting type and rotating type. [1,2] Figure 1 shows the sequential diagram of the scrolls for the orbiting and rotating types when the pumping is going on. For both types, the sweeping speed of the scroll is about a fifth of that for a conventional rotary pump of the similar size, because the orbit radius is only a small fraction of the scroll size in the orbiting type, and the relative speed between two scrolls is much lower in the rotating type. A slow sweeping speed may provide a longer life of the scrolls.

In any type of scroll pump several serial quasi-isolated pumping pockets resembling a crescent are formed in two parallel rows be-

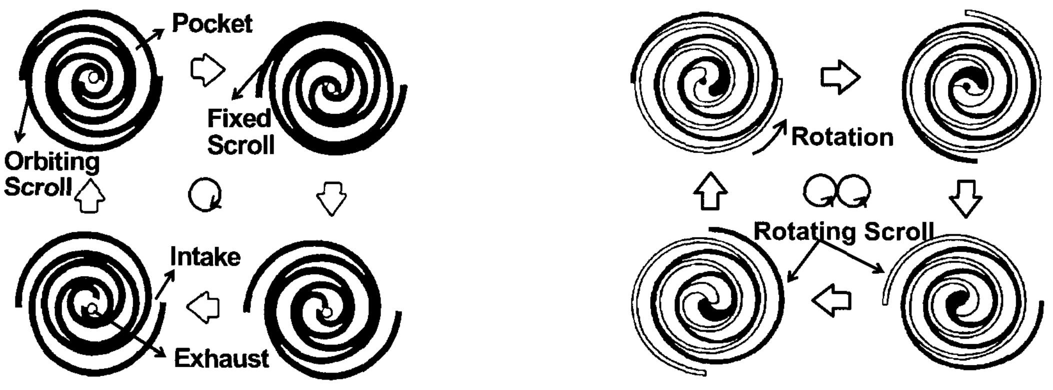


Fig. 1. Evolution of scrolls in a) orbiting and b) rotating type scroll pumps.

* [E-mail] srin@kaeri.re.kr

tween two scrolls. Pumping of the scroll pump starts when the mouth of the outermost pocket opens. Then, the pocket is promptly filled with gas and the mouth is closed after one revolution of the scroll. The pocket which has just closed continues to move along the spiral line up to the scroll center as being simultaneously constricted and compressed. The trapped gas in the pocket reaches the exhaust port after a few revolutions depending on the number of the serial pockets. Note that the moving speed of the pocket (or the sweeping speed of the scroll) is inversely proportional to the number of pockets. There must be an optimum design to create both a large pumping speed and a low ultimate pressure at a given size.

The pumping speed of a vacuum pump is the net amount of the forward volume flow rate determined by subtracting the back-streaming flow from the intake flow. The back-streaming performance of the scroll pump is strongly influenced by a leakage from the downstream pocket through the minute gap between two successive pockets. [3] It is apparent that the leakage through a dry (non-oily) passage becomes larger for a lighter gas. Therefore, the scroll pump would have a low pumping speed for hydrogen or helium, the most mobile gases.

If the pumping speed of a scroll pump backing up a TMP for hydrogen is not high enough to maintain the foreline pressure below a certain limit (namely, the allowable backing pressure of TMP), the TMP could not be operated normally in a fusion experiment system where hydrogen is the main fuel gas. Accurate information about hydrogen pumping characteristics is necessary to judge whether the scroll pump can be used or not in the above application. Unfortunately, there is very scant data for the hydrogen pumping performance of dry pumps, including the scroll type, with a few exceptions. [4-6]

In this paper the experimental setup, the measuring procedure, experimental results, and discussions on the pumping characteristics, such as the pumping speed, the maximum compression ratio and the back-streaming properties for hydrogen, helium, nitrogen, and argon, of the scroll pump of the orbiting type are reported.

# II. Experiment

## 2.1 Device

Fig. 2 shows the experimental setup for measuring the pumping speed and the maximum compression ratio of the scroll pump (Edwards XDS-35i, 10 L/s, 1 Pa). Most components, connections, and fittings used in constructing the system are of the ISO KF type. A TMP (Alcatel ATH 31, 30 L/s) is used to attain quickly the base pressure by conditioning the whole system, and for zeroing the vacuum gauges at a sufficiently low pressure. Sometimes, a diaphragm pump (Pfeiffer MVP 055-3, 1 L/s, 200 Pa) is used to lower the backing pressure of the scroll pump below the atmospheric pressure.

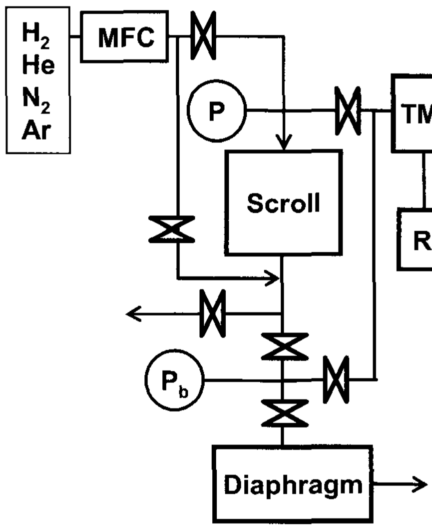


Fig. 2. Experimental setup for measuring the pumping characteristics of the scroll pump.

Two capacitance diaphragm gauges (CDG, MKS Baratron 626A, 0.001~10 Torr/ 722A, 0.002~20 Torr), a Pirani gauge (Varian HV 100, 0.00001~0.1 mbar) and a Bourdon gauge (Ashcroft, 0~3 atm) are used to measure the pressures of the inlet and outlet of the pump. The gas flow is regulated by two mass flow controllers (MFC, MKS 1179A, 100 sccm/ 2179A, 5000 sccm).

In this experiment, a test dome, recommended in the standards for testing positive displacement vacuum pumps [7], is not adapted. The gas port is 60 mm apart from the pump inlet, and the gauges are installed at the upstream side 120 mm further on.

There is, as usual in the case of a pump exhausted to the atmosphere, a check valve at the exhausting port of the scroll pump. The operating differential pressure ΔP of the valve is measured to be about 4000 Pa. Therefore, the practical backing pressure of the scroll pump is slightly higher than the atmospheric pressure or the inlet pressure of the diaphragm pump, depending on the experimental mode. Note that the minimum backing pressure of the scroll pump, even when the gauge pressure is sufficiently low, is practically 4000 Pa.

## 2.2 Procedure

The pumping characteristics of the scroll pump are measured not only for hydrogen, but also for nitrogen, helium and argon to investigate the effects of the mass of the pumped gas. Before starting the next experiment with different gas, the system is lightly baked at the temperature below 100℃, and the base pressure, when isolating the system from the TMP, is in the lower range of $10^{-2}$ Pa.

The pumping speed of the scroll pump is measured when introducing a gas into the pump inlet after closing the valve to the TMP and reaching the base pressure. The pressures at the pump inlet and the outlet are recorded by capacitance diaphragm gauges and pirani gauges as increasing the gas flow rate at a regular step from 1 sccm (~0.0017 Pa·m$^3$/s at 20℃) to 5000 sccm by using two MFC's. Then, the pumping speed is calculated by dividing the gas flow rate with the pressure rise at the inlet.

There are two experimental modes for measuring the pumping speed; 1) exhausting directly to the atmosphere (1 atm) and 2) indirectly through a diaphragm pump. In the latter case, as a by-product, the pumping speed of the diaphragm pump is obtained from the foreline pressure of the scroll pump.

The maximum compression ratio is measured when introducing the gas into the outlet of the scroll pump after isolating the inlet of the scroll pump from the TMP and reaching the base pressure. Then, the maximum compression ratio is given by dividing the outlet pressure with the pressure rise at the inlet when there is no net gas flow through the pump (no external gas supply). In this case the pressure rise is assumed to be maintained by only the gas penetrating through the rotating scrolls. Because the back-streaming rate is very low when compared with the case of the TMP, it takes a much long time to reach a fully developed pressure profile at a certain outlet pressure. Therefore, to proceed with the measurement in a practical time frame, the outlet pressure is gradually increased from the base pressure to the atmospheric pressure for a few hours, and then held at that pressure till attaining the ultimate inlet pressure.

The back-streaming rate is roughly measured when opening the valve connected to the TMP, to pump out the upstream side of the scroll pump, with a known pumping speed, and introducing the gas at the outlet like in the measurement of the maximum compression ratio.

## III. Results

Fig. 3 shows the pumping speed curves of the scroll pump for hydrogen, helium, nitrogen, and argon, obtained at two exhausting modes. The reduction of the pumping speed in the lower pressure range, which is the general trend found in all the results regardless of the kind of gas, is probably due to the relative increase of the back-flow of the gas from the high pressure side. When the scroll pump is exhausted to the atmosphere, the pumping speed has approximately the same pressure dependency for all the gases except for hydrogen. At the medium pressure, 5~200 Pa, the lighter gas has a slightly but apparently higher pumping speed. However, at a sufficiently low pressure, a reduction of the pumping speed for helium is clearly found. In Fig. 3a the pumping speed for hydrogen has a maximum at 5.5 L/s and decreases very fast when approaching 100 Pa. The maximum pumping speed is 9.8 L/s for helium, 10.5 L/s for nitrogen, and 11.2 L/s for argon. The pumping speed curve for nitrogen in the pressure range of the experiment agrees well with recommended one by the maker.

For heavy gases the effect of backing up the scroll pump with the diaphragm pump is not much large, because the back-streaming rate is intrinsically low. However, the pumping speed for hydrogen is considerably increased by reducing the backing pressure of the scroll pump. The maximum pumping speed in this case has nearly the same value for all the gases, though the heavier gases have a higher maximum pumping speed; 9.9 ($\Delta$=4.4) L/s for hydrogen, 10.4 ($\Delta$=0.6) L/s for helium, 11 ($\Delta$=0.5) L/s for nitrogen, and 11.6 ($\Delta$=0.4) L/s for argon, where $\Delta$ means the increment of the pumping speed by exhausting through the diaphragm pump. In Fig. 3b, below about 200 Pa, the pumping speed has a higher value for the lighter gases, as shown in Fig. 3a too, however more obviously in this case.

Fig. 4 is the pumping speed of the diaphragm pump for hydrogen, helium, nitrogen and argon. There is basically no great difference in the pumping speed for the different gases, which is the reason why this pump is selected for backing up the scroll pump. The pumping speed for the lighter gases is even larger than those for the heavier gases.

Two graphs for the maximum compression ratio of the scroll pump as functions of the outlet pressure and gas feeding time, respectively, are shown in Fig. 5. For all the gases the maximum compression ratio decreases gradually with an increase of the outlet pressure, and this trend continues even after maintaining the outlet pressure at 1 atm. The temporal evolution of the maximum

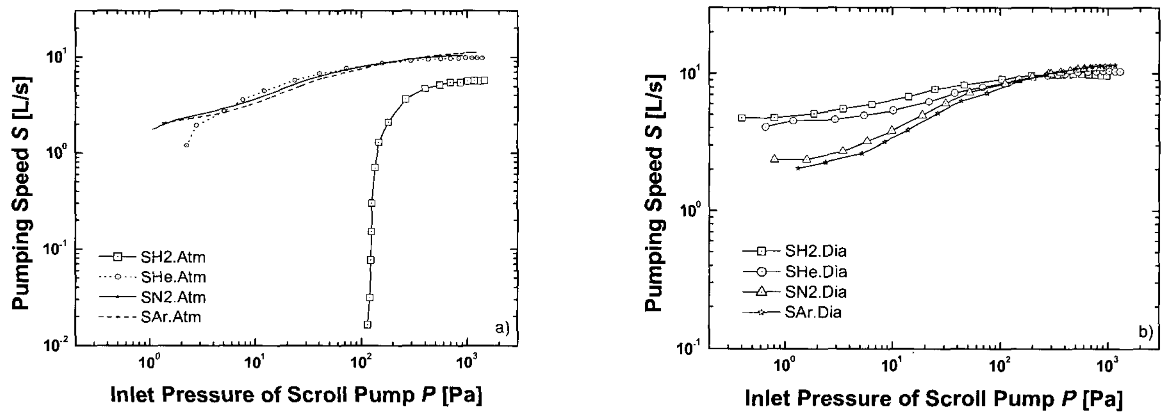


Fig. 3. Pumping speed curves of the scroll pump when exhausting a) to the atmosphere and b) through a diaphragm pump.

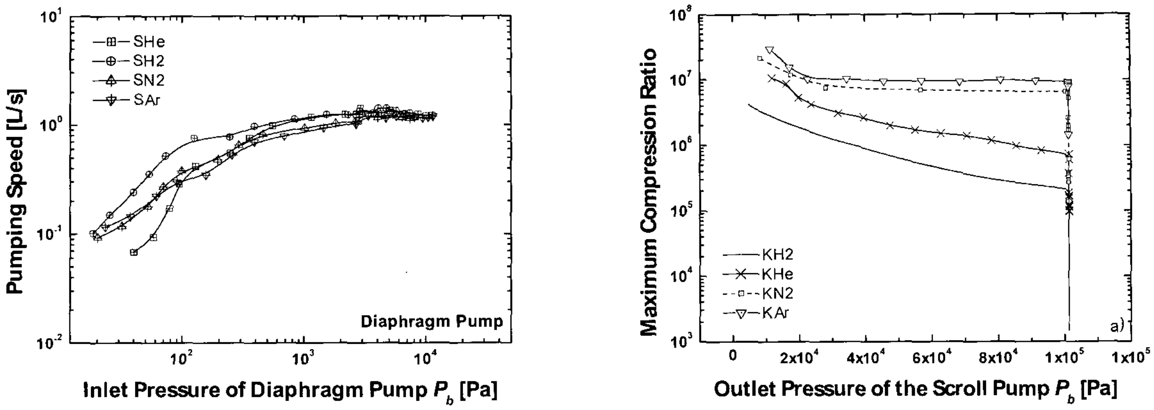


Fig. 4. Pumping speed curves of the diaphragm pump.

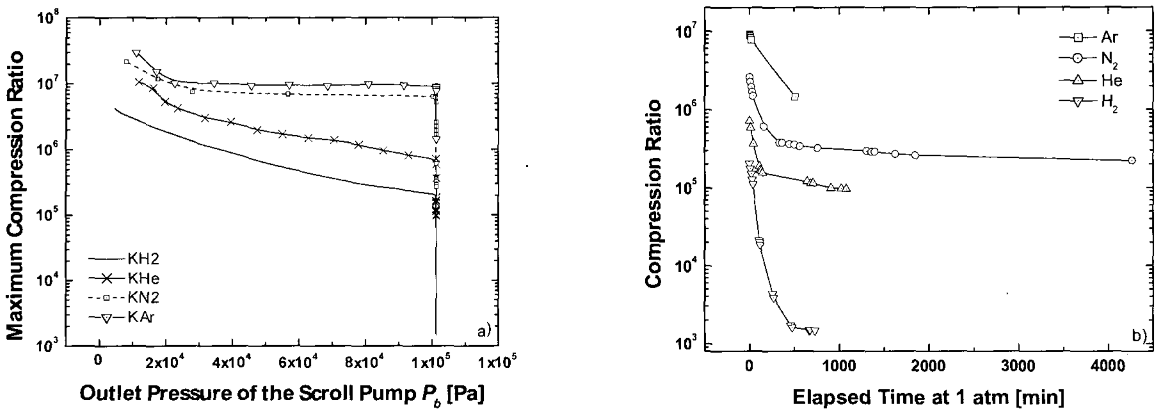


Fig. 5. Variations of the maximum compression ratio as functions of a) the outlet pressure and b) elapsed time, maintained at 1 atm.

compression ratio at the outlet pressure of 1 atm (Fig. 5b) indicates clearly a saturation of the parameter after several hundred hours. The maximum compression ratio for hydrogen at 1 atm initially reaches $2.1x10^5$ and the final value of about 1500 after more than 12 hours, for helium initially $7\times10^5$ and finally $9.5\times10^4$ after 20 hrs, for nitrogen initially $6.5\times10^6$ and finally $2.2\times10^5$ after 70 hrs, and for argon initially $1\times10^7$ (final value was not tried).

Fig. 6 is the back-streaming rate as a function of the backing pressure when the scroll pump is operating. The final values when maintaining the pressure at 1 atm are about $1.25\times10^{-4}$ Pa·m$^3$/s for hydrogen and $2\times10^{-6}$ Pa·m$^3$/s for nitrogen. Figure 7 shows the leak rate measured when the scroll pump is stoped and the outlet pressure is main- tained at 1 atm. Just after stopping the pump,

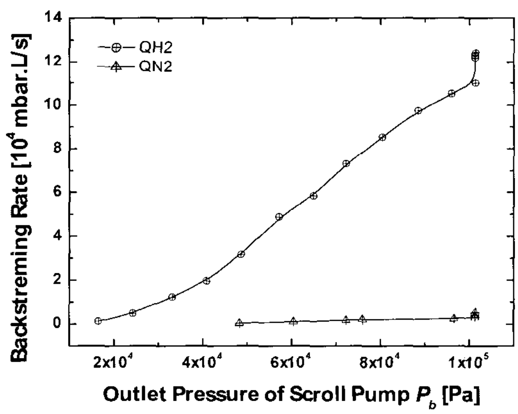


Fig. 6. Back-streaming rate of the scroll pump operated normally.

the leak rate becomes very high due to the prompt back-flow from near pockets. And then, the leak rate decreases and becomes quickly saturated. The saturated values are $4\times10^{-4}$ and $8\times10^{-5}$ Pa·m$^3$/s for hydrogen and nitrogen, respectively, which are much larger than those

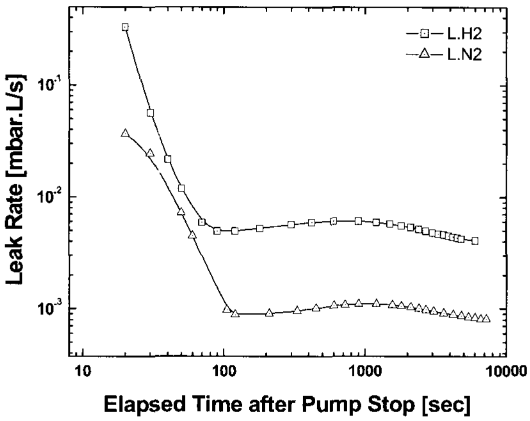


Fig. 7. Leak rate of the scroll pump when stopped completely.

of the back-streaming rate measured when the scroll is orbiting.

## IV. Discussion

The pumping speed of the scroll pump, $S$, measured by a gauge, can be expressed as follows;

$$Q = PS = PS_0 - P_b S_b \rightarrow \qquad (1)$$
$$S = S_0 - \frac{Q_b}{P} = S_0 - S_b \frac{P_b}{P} \equiv S_0 - S_{beff}$$

where $Q$ is the throughput (net flow rate), $S_0$ is the intrinsic forward pumping speed, $P$ is the inlet pressure (more exactly, the pressure rise compensated with the base pressure), $P_b$ is the backing (or outlet) pressure, $Q_b$ is the back-streaming rate, $S_b$ is the back-streaming speed, and $S_{beff}$ is the effective back-streaming speed felt at the inlet.

$S_0$, which theoretically represents the maximum performance, can be obtained when $Q_b$=0. Parameters related with $S_0$ are the volume displacement rate $S_{0V}$ of the rotor and the transfer rate $S_{0t}$ composed of the conductance from the gauge to the pumping pocket and the in-rush speed of the gas to the inside of the pocket. Therefore, the relation $S_0 = S_{0v}S_{0t}/(S_{0v}+S_{0t})$ is obtained. If $S_{0v} \ll S_{0t}$, $S_0 \approx S_{0v}$, and vice versa. At a high pressure the term $S_{0t}$ can be neglected because the passage conductance is very high and the pocket is open long enough during one revolution, for example, longer than 30 msec at 1750 rpm, for any gas to expand fully into the pocket. Therefore, in this case, $S_0$ can be assumed to be constant and approximately equal to $S_{0v}$ for most gases. It is reasonable to say that $S_{0v}$ depends only on the intake volume of the pocket $V$ and the rotational speed $N$, namely $S_{0v}=2NV$, where 2 indicates that there are two inlets for one scroll set. $V$ is given by the following equation.

$$V = h\delta R_{OR}(2\Phi_m - 3\pi)/2 \qquad (2)$$

Here, $h$, $\delta$, $R_{OR}$, and $\Phi_m$ are the height of the involuted wrap, the pitch of the convolution, the orbiting radius, and the accumulated angle of the end of the scroll at the entrance of the outermost pocket, respectively. $R_{OR}$ is given by $\delta/2-t$ where $t$ is the thickness of the scroll wrap, and the area of the outermost crescent, $\delta R_{OR}(2\Phi_m-3\pi)/2$, is easily derived by a surface integration or by using the average radius of the spiral lines forming a crescent. In the above condition ($S_0 \approx S_{0v}$), $S_0$ does not depend on the mass of the gas and can be estimated from the pumping speed curves for heavy gases, which do not receive a large influence from the back-streaming. Then, $S_0$ must be larger than at least 11.6 L/s (maximum value in Fig. 3b).

However, at a low pressure the conductance and the in-rush speed may be influenced by the mass of the gas, which results in a heavier gas with a lower $S_0$. This may be one of the reasons why the pumping speed in the pressure range below 200 Pa has a larger value for the lighter gases in both Fig. 3a and 3b.

As a summary, $S_0$ can be considered as a slight increasing function of the inlet pressure, of which the change is larger for the lighter gas, and has the same maximum value regardless of the mass of the gas. The pumping speed curves in Fig. 3b may be assumed as those of $S_0$ at least below 100 Pa, and show, as a whole, the mass dependency of $S_0$. The pumping speed above 100 Pa is strongly influenced by another factor, probably $S_b$.

$S_b$ includes all the contributions to the backward flow in the scroll pump including a return fraction of the intake flow in the way to the exhaust port, and a leak from the outlet, though they are not distinguishable from each other. It is plausible to consider $S_b$ as the overall leak speed seen from the pump outlet determined by successive leaks from a pocket to the just upstream pocket at a fully developed pressure profile. Therefore, $S_b$ depends on the total conductance of the serial gaps between two scrolls, and consequently on the mass of the gas. It is safe to assume that the conductance of a single gap has nearly the same trend as that of a simple conduit. Then, a single conductance is constant at a very low pressure, and, above a transition pressure, proportional to the average pressure of the gap. If the end gap of a pocket is 0.1 mm, the transition pressure is about 700 Pa in nitrogen, and 1200 Pa in hydrogen.

The leak flow experiences a wide range of the flow regime from a viscous (high pressure) to a molecular flow (low pressure), depending on the position. The final $S_b$ is mainly governed by the smallest conductance which would be that of the most upstream element which is at the lowest pressure. It should be noted that the impact of $S_b$ exerted on the inlet pressure of the scroll pump, denoted as $S_{beff}$, is multiplied by the compression ratio $P_b/P$.

When $P_b$ is fixed at the atmospheric pressure, and the inlet pressure of the scroll pump is at a low level, where the gap conductance is rearly constant, $S_{beff}$ ($\propto S_b/P$) in Eq. (1) is drastically increased until a balanced inlet pressure, equivalent to the ultimate pressure, is reached at a given backing pressure, and $S$ becomes zero. As the inlet pressure increases, $S_{beff}$ decreases inversely proportional to the inlet pressure, and $S$ increases up to the maximum.

If $P_b$ is decreased considerably, when the scroll pump is backed up by a fore pump, $S_{beff}$ is also lowered and the reduction of $S$ at a lower pressure is moderated. If the pumping speed of the fore pump is $S_p$, Eq. (1) can be modified to Eq. (3).

$$Q = PS = PS_0 - P_b S_b = P_b S_p \rightarrow S = \frac{S_0}{1 + S_b/S_p} \quad (3)$$

In Eq. (3), the higher $S_p$ the larger $S$ is. If $S_p$ is much larger than $S_b$, $S$ is always nearly equal to $S_0$. If $S_p$ is an increasing function of the backing pressure $P_b$, and $S_b$ is constant, which is simultaneously satisfied at a low throughput, $S$ increases too. Inversely, if $S_b$ becomes proportional to the pressure $P_b$ and $S_p$ becomes saturated at a large throughput, $S$ begins to decrease.

As an order estimation, $S_b$ is roughly calculated using the relation $S_b=(S_0-S)P/P_b$ and assuming $S_0$ to be 12 L/s when the inlet pressure is high enough to neglect the mass-dependent term of $S_0$ (that is $S_{0t}$). $S_b$ is about 0.007 and 0.2 L/s for nitrogen and hydrogen, respectively, at the inlet pressure of 1000 Pa and at the outlet pressure of 1 atm. We can obtain full trends of $S_b$ for a gas from Fig. 3a by assuming a graph of Fig. 3b as a reference of $S_0$. Fig. 8 shows the variations of the calculated $S_b$ for hydrogen and nitrogen. In the pressure range below 100 Pa, the condition $S_b \ll S_p$ is satisfied even for hydrogen, and the above assumption for $S_0$ can be justified.

The ultimate pressure is theoretically the attainable pressure at the pump inlet side determined by only an intrinsic back-streaming of the pump without any positive gas flow nor an outgassing from the chamber wall, which is the same situation with the maximum compression ratio measurement. We can evaluate the ultimate pressure of the pump connected to the atmosphere, indirectly from a pumping speed curve, or directly from a final value of the maximum compression ratio. The ultimate pressures estimated from the pumping speed curves extrapolated to the zero line are around 100 Pa for hydrogen, 2 Pa for helium, and less than 1 Pa for nitrogen and argon. The ultimate pressure for hydrogen, helium and nitrogen obtained from the maximum compression ratio measurement are about 70 Pa, 1.6 Pa and 0.5 Pa, respectively.

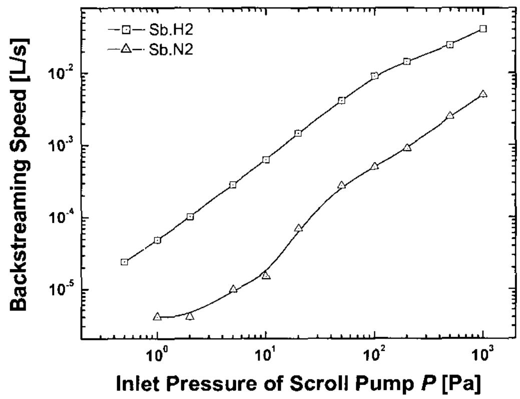


Fig. 8. Back-streaming speed curves of the scroll pump calculated from pumping speed curves.

## V. Applications

The scroll pump is now being used for backing up the TMP (1000 L/s) installed on the ion source chamber (~300 L) of the test stand for the KSTAR NBI system, which can be isolated from the main NBI tank of 60 $m^3$ by a ϕ630 large gate valve. Its function is to roughen the ion source chamber without a contamination of the hydrocarbons before opening the gate valve, and sometimes maintain the chamber pressure, when isolated from the main tank, at an optimum level for making a good arc plasma .

The question is, in the latter case, whether the scroll pump can function when the ion source is heavily gassed with hydrogen. For the optimum condition of the arc discharge in the ion source, the arc chamber pressure needs to be about 0.5 Pa and the required hydrogen throughput is about 500 sccm (~0.84 Pa·$m^3$/s). The allowable limit of the backing pressure of the TMP is about 100 Pa, thus the pumping speed of the backing pump should be larger than 5 L/s at this pressure. The inlet pressure of the TMP is permitted up to about 10 Pa.

Fig. 9 shows that the above condition can not be satisfied by using the scroll pump alone (line B), because the pumping curve does not cross the limit line (100 Pa) of the backing pressure of the TMP. If the scroll pump is exhausted through the diaphragm pump (line A), the backing pressure and the inlet pressure of the TMP can be simultaneously maintained below the allowable limits as long as the throughput is kept below 0.9 Pa·$m^3$/s (horizontal dash-dot line).

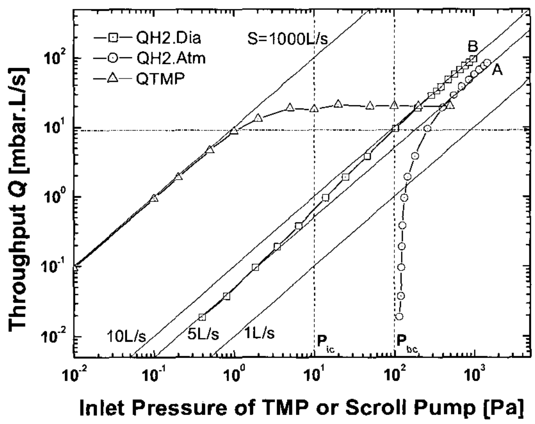


Fig. 9. Operational diagram of TMP and the scroll pump. Linear lines are from $Q=SP$ for constant $S$s. Two vertical lines are the limits of the inlet ($P_{ic}$) and outlet ($P_{bc}$) pressure.

## VI. Conclusions

The pumping speed for hydrogen of a scroll pump exhausted directly to the atmosphere not only has a considerably lower value than those for heavier gases at the same inlet pressure, but also diminishes drastically when the pressure decreases to 100 Pa. In this condition the scroll pump can not be used for backing the TMP operated with a large hydrogen throughput. However this severe deterioration in the hydrogen pumping characteristics of the scroll pump can be moderated by connecting a small diaphragm pump to the outlet of the scroll pump.

## References

[1] M. Toshioka *et al.*, J. Jpn. Vac. Soc. **33**, 9 (1990).

[2] E. Morishita *et al.*, J. Jpn. Mech. Soc. **54**, 410 (1988).

[3] Y. Su *et al.*, Vacuum **47**, 815 (1996).

[4] E. Bez and D. G. Guarnaccia, Vacuum **41**, 1819 (1990).

[5] L. Laurrenson and D. Turrell, Vacuum **38**, 665 (1988).

[6] U. Kirchhof *et al.*, Test of Dry Mechanical Forepumps for Use in the ITER Vacuum Pumping System, FZKA 5578 (1995).

[7] ISO 1607/1, Positive-displacement Vacuum Pumps – Measurement of Pumping Speed; 1607/2, Measurement of Ultimate Pressure.

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# 스크롤 펌프의 수소 배기특성

인상렬*

한국원자력연구소 핵물리공학팀, 대전 305-600

(2005년 12월 19일 받음)

스크롤 펌프는 초청정 진공 시스템에서 많이 사용되고 있지만 막상 수소 배기특성에 대해서 잘 알려져 있지 않다. 이런 정보부족은 수소를 다량 사용하는 핵융합 실험장치에서 스크롤 펌프가 사용 가능한지 판단하기 어렵게 만든다. 이 논문에서는 특히 수소에 대한 스크롤 펌프의 배기속도, 압축비 및 역류특성을 측정하기 위해 구성한 실험장치, 측정절차와 실험결과에 대해 기술하고 논의했다.

주제어 : 스크롤 펌프, 배기속도, 최대압축비, 수소

* [전자우편] srin@kaeri.re.kr