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Experimental Study on Scaling Law of Outgassing Rate with A Pumping Parameter

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Abstract

The outgassing rate of a small test chamber made of 304 type stainless steel has been measured as a function of pumping speed in a range from 0.3 to 200 *l*/s. In the experiment the chamber has been first exposed to the air and then pumped with different pumping speeds for 3 days at room temperature of 20 ℃ without baking. The typical outgassing rates of the chamber are determined from the measurement of steady pressures at the pumping time of 72 h. As a result of experiment, it is found that measured outgassing rates q obey a set of power laws of $q_1=c_1(S/A)^{m}1$ and $q_2=c_2(S/A)^{m}2$ where S/A is the ratio of pumping speed S to surface area A of the chamber, c_1 and c_2 are constants , exponents of m_1 and m_2 are 0.8282 for $S/A \geq 10^{-3}$ *l*/scm^2 and 0.4655 for $S/A \leq 10^{-3}$ *l*/scm^2 , respectively. Technical application of the obtained scaling law is discussed in connection with the design of pumping system for a large vacuum device.

Key words: outgassing rate, ultimate pressure, pumping parameter, LHD.

1. Introduction

This study is relating to vacuum pumping of a plasma vacuum vessel in the large helical device (LHD) which is under construction at National Institute for Fusion Science. A main objective of this study is to estimate the ultimate pressure of unbaked plasma vacuum vessel in the initial pumping down at the startup phase of LHD.

The ultimate pressure of a vacuum system attainable with a given pump is determined with the rate of gas influx into the system divided by the pumping speed, and when there is no gas admission, the rate of gas influx is replaced with the total outgassing rate from walls of the system. Thus, a conventional way to estimate the ultimate pressure is to quote the appropriate outgassing data to the vacuum system under consideration from literatures. We, however, must take into account the dependence of ougassing rate on pumping speed, because the dependence is very different between baked and unbaked vacuum systems. Figure 1 illustrates two types of models for the pumping speed dependence of outgassing. In the vacuum system after baking at a higher temperature than 250℃ , predominant residual gases are normally hydrogen and carbon monoxide ,and the gas desorption rate is governed by diffusion processes in a solid. Fig.1(a) shows the outgassing characteristic for such a baked vacuum system, in which the outgassing rate is independent of the pumping speed and the system pressure decreases linearly with the pumping speed. In the pumping down process of unbaked vacuum system after exposure to the air, a main desorption gas from the wall is usually water vapor. The gas desorption mechanism in such the unbaked vacuum system has been theoretically considered by Horikoshi and Kanazawa [1,2], and they have suggested that the true source of gas desorption is the excess portion of the adsorbed molecules, while the majority of the adsorbed molecules is in equilibrium with the ambient pressure of gas and the total outgassing rate from the surface is, as a result, equal to the pumping rate of gas phase molecules out of the system. If we accept this suggestion

although this has not been demonstrated yet, we can consider an extremely simplified outgassing model as shown in Fig.1(b) for the unbaked vacuum system. Where it is assumed that the outgassing rate increases linearly with the pumping speed, and the system pressure is consequently independent of the pumping speed. From this model, we can say that pumping the system with large pumping speed does not yield special benefit to attain as low ultimate pressure as possible. Thus, in order to estimate correctly the ultimate pressure of the plasma vacuum vessel, it is necessary to evaluate the relationship between outgassing rate and pumping speed.

In general the pumping speed of large-scale chamber, such as the plasma vacuum vessel of LHD, has a tendency to take inevitably a smaller value than that of small-sized or laboratory-scale chamber, because it is usually difficult to increase the pumping speed with the increase of surface area of the chamber. In this situation, if we introduce a pumping parameter which is defined as the ratio of pumping speed to surface area, as seen from Fig.1(b) the outgassing rate of large-scale chamber having a small pumping parameter may become smaller than that of small-sized chamber having a large pumping parameter. In addition, if we attempt to estimate the ultimate pressure of the plasma vacuum vessel using a typical outgassing rate which is ordinarily produced in the laboratory-scale chamber, we will probably overestimate for the pressure at least by the ratio between pumping parameters of the plasma vacuum vessel and the laboratory-scale chamber. This study, from such reason , is devoted to measure the outgassing rate of a test chamber in a wide range of corresponding pumping parameter by changing the pumping speed and to get ,as a result, a scaling law of outgassing rate as a function of pumping parameter. In the following sections experimental methods, results and discussion are described.

2. Experimental

A. Experimental apparatus

We have constructed an experimental apparatus for outgassing test. Figure 2 shows the schematic diagram of the vacuum system. A test chamber consists of a manifold and a cylindrical tube (1m long by 15 cm inside diameter) fabricated from 304 type stainless steel and has the total volume of 26 *l* and surface area of 7200 cm^2. The surface treatment for the cylindrical tube is only electropolished. But the manifold has been first electropolished and subsequently heated in the air at 420 ℃ for 6 h with an electric furnace by expecting formation of passivated oxide-layers on the surface[3]. A pumping system consists of a turbomolecular pump (nominal pumping speed of 300 *l*/s for N_2) and an oil rotary pump (350 *l*/min). For restricting pumping speed to the test chamber five kinds of orifices are prepared and set between a bottom port of the manifold and the gate valve as seen in Fig.2, and as a result the net pumping speed for N_2 can be changed in the range from 0.36 to 182 *l*/s with and without orifices which is equivalent to that of pumping parameter from 4.2 $x10^{-5}$ to 2.5 $x10^{-2}$ *l*/scm^2. A nude Bayard-Alpert ionization gauge is used for pressure measurement in the test chamber. The monitored pressure is recorded as a function of pumping time in a note-type personal computer.

B. Experimental method

Prior to starting experiments, the test chamber has been routinely exposed to the air (relative humidity of 60-80%) for 1 h and then pumped at 20 ℃ for 3 days under different pumping speeds. The starting time of pumping is reset as t=0 at when the chamber pressure reaches 20 Torr which is a typical vapor pressure of water at room temperature. The pressure measurement with the ionization gauge is started from the time of t=1 h. We have defined the measured pressure at the fixed pumping time of t =72 h as the final pressure of the test chamber and all of typical outgassing rate of the test chamber has been calculated with the final pressure in this study.

3. Experimental results

Figure 3 shows typical final pressures P of the test chamber measured at the pumping time of t=72 h as a function of pumping parameter S/A. By applying a power law to the plot of log(P) versus log(S/A), the pressure [Torr] is expressed in the form of

$$P = C(S/A)^{-n},$$

where C and n are constants. As a result, it is shown in Fig.3 that curve 1 and curve 2 are obtained in accordance with separate ranges of pumping parameter. When we write curve 1 and curve 2 as $P_1=C_1(S/A)^{-n1}$ and $P_2=C_2(S/A)^{-n2}$, constants and valid range of pumping parameter are determined as follows:

$C_1=1.3292 \times 10^{-8}$, $n_1=0.1718$, $S/A \geq 1.32 \times 10^{-3}$ l/scm^2

and

$C_2=1.2024 \times 10^{-9}$, $n_2=0.5345$, $S/A \leq 1.32 \times 10^{-3}$ l/scm^2

, where the dimension of constant C_i is [Torr · $(l/s \cdot cm^2)^{ni}$]. At the same time, the outgassing rate q of test chamber at t= 72 h can be also estimated as a product of final pressure and pumping parameter, $q=(S/A)P = C(S/A)^{1-n}$, as shown in Figure 4. In this figure, similarly to the dependence of pressure, the outgassing rate is also fitted by two curves. Two curves of q_1 and q_2 [Torr · $(l/s \cdot cm^2)$] are expressed with the same constants as in the pressures P_1 and P_2:

$q_1 = C_1(S/A)^{1-n1}$, $(1-n_1)=0.8282$, $S/A \geq 1.32 \times 10^{-3}$ l/scm^2

and

$q_2 = C_2(S/A)^{1-n2}$, $(1-n_2)=0.4655$, $S/A \leq 1.32 \times 10^{-3} l/scm^2$.

4. Discussion

It has been suggested theoretically by Horikoshi and Kanazawa [1,2] that outgassing rate depends on pumping speed in unbaked vacuum chamber. we have attempted to demonstrated experimentally their suggestion using a small test chamber. We have first measured the final pressure after the test chamber is pumped for 3 days without baking and then calculated the typical

outgassing rate of the test chamber as the product of the final pressure and the pumping parameter. The reason why a pressure at shorter pumping time than 50 h has not been used for the calculation is that the initial pressure depends rather predominantly on the difference of initial adsorption amount of water on the wall under influence of humidity in the air exposure than the magnitude of pumping speed [4]. The obtained data of final pressure and outgassing rate in this experiment are arranged as a function of the pumping parameter. From experimental results of Fig.3 and Fig.4, it is clearly shown that the final pressure monotonically decreases with the increase of pumping parameter and the outgassing rate shows the reverse characteristic. The outgassing rate obeys power laws in the form of $q=C(S/A)^{1-n}$. Thus, we can say that the dependence of outgassing rate on pumping speed evidently exists.

The observed outgassing characteristic in this study corresponds to the model of type of Fig.1(b) but different points from the model are that the outgassing rate is not directly proportional to the pumping parameter, because the value of exponents is smaller than 1 and there is observed the transition from curve 1 to curve 2 at the parameter value of $S/A=1.32 \times 10^{-3}$ l/scm^2 as shown in Fig.4. This pumping speed dependence can be qualitatively explained from the surface kinetics of adsorption and desorption and the evacuation of gas phase molecules in the test chamber. According to ref.1 and 2, we consider the number of adsorbed gas molecules per unit area of surface as $\sigma+\Delta\sigma$, where σ is an equilibrium value and $\Delta\sigma$ is the excess portion of adsorbed gas molecules. If the thermal desorption rate for σ is equal to the adsorption rate of gas phase molecules on the surface and that for $\Delta\sigma$ is equal to the pumping rate of gas phase molecules out of the system, each rate equation can be expressed as follows:

$$\sigma/\tau=cnv/4, \quad \sigma(S,t)=[\sigma(t_1)-(1/\alpha)(S/A)\int P(t)dt\ ],$$

$$\Delta\sigma/\tau=anv/4A, \quad av/4=S,$$

where $1/\tau$ is the thermal desorption rate of a gas molecule, c is the sticking coefficient, n is the number density of gas phase molecules, $\sigma(t_1)$ is the initial value of the number of adsorbed gas molecules at the starting time of pumping $t=t_1$, v is the arithmetic average velocity of a gas molecule, α is the conversion factor [Torr*l*/molecules] and a is the aperture of the pumping orifice. By neglecting n from the two equations, we obtain the following expression for outgassing rate q,

$$q = \alpha(\Delta\sigma/\tau) = (4\alpha/vc)(\sigma/\tau)(S/A).$$

Since the second term of the right hand side of $\sigma(S,t)$ can be replaced as $(1/\alpha)\int q(t)dt$, the equation of q is reduced to the following differential equation,

$$dq/dt = -(4/vc\,\tau)(A/S)q.$$

When a solution of this equation is expressed with a power law of $q = q_0 t^{-m}$, $(0 < m)$ where q_0 is a constant determined by initial condition, we can have the following expression as a function of pumping parameter in the form of

$$q = q_0(4/vc\tau m)^m(S/A)^m.$$

Thus, it is pointed out that the empirical law of q found out in this experiment just corresponds to the solution when the exponent m is equal to $m=1-n$, $(0 < n < 1)$. Another important parameter in the derivation of q is the sticking coefficient c. In a usual thermal adsorption, c is in the order of $0.1 \sim 1$, and c approaches unity for large value of σ but decreases to 0.1 for small value of σ. A reason that the slow decrease of outgassing rate or the transition is observed at the small value of S/A may be due to the change of c value, accordingly. Thus we can conclude that the empirical law of q measured in this study is consistent with the theoretical model of gas desorption [1,2]. In addition, it is usually very difficult to measure such parameter values as σ and c in practical vacuum systems but rather easy to measure empirical law of q like in this study, and the very important point is that it becomes possible using the empirical law of q to evaluate the pressure

conditions of many vacuum systems with different pumping parameters.

Now we use the obtained empirical law on the outgassing rate as a scaling law, and postulate that this scaling law can be used for estimating the pressure condition of a large-scale vacuum chamber. Our main subject is to estimate the ultimate pressure of the plasma vacuum vessel of LHD with this scaling law. In the present design of pumping system for LHD, the surface area of the vessel (made of 316 type stainless steel) A and the possible pumping speed provided for the vessel S are 7.3 x10 ^{6} cm^{2} and around 3000 *l*/s. So the pumping parameter for LHD S/A=4.1 x10^{-4} *l*/scm^{2}. If we ignore the difference of outgassing rates between kinds of stainless steel using in LHD and the small test chamber, the ultimate pressure of the vessel after pumping for 3 days without baking can be estimated from curve 2 of Fig.3 and is expected to be P_{LHD}=7.8 x10^{-8} Torr at 20 ℃ .

5. Conclusion

In order to investigate the dependence of outgassing rate on pumping speed, the pumping test of a small vacuum chamber has been made at room temperature without baking after initializing the wall surface by the air exposure. It is observed that the measured final pressure and outgassing rate at the pumping time of 72 h are expressed by power laws of pumping parameter in the range from 10^{-5} to 10^{-2} *l*/scm^{2}. These power laws is applied to estimate the ultimate pressure of LHD which is a typical large-scale vacuum chamber with the pumping parameter of around 4x10^{-4} *l*/scm^{2} .

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Figure captions

Figure 1: Simplified models of outgassing rates q and equilibrium pressures p as a function of pumping parameter S/A for (a) baked and (b) unbaked vacuum systems, where S is the pumping speed, A is the surface area of wall, c and q_0 are constants.

Figure 2: The schematic drawing of small test chamber.

Figure 3: The measured final pressure of the test chamber as a function of pumping parameter at the pumping time of 72 h.

Figure 4: The calculated outgassing rate of the test chamber with the final pressure of Fig.3 as a function of pumping parameter.

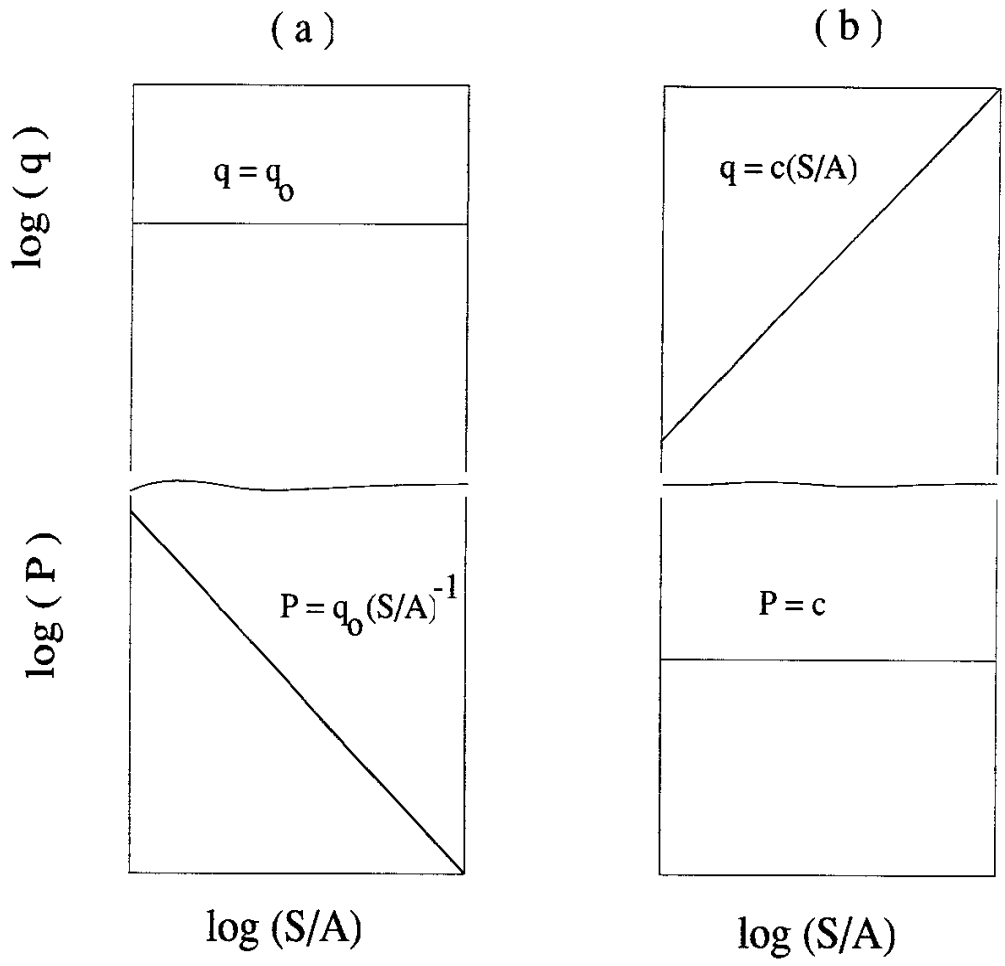
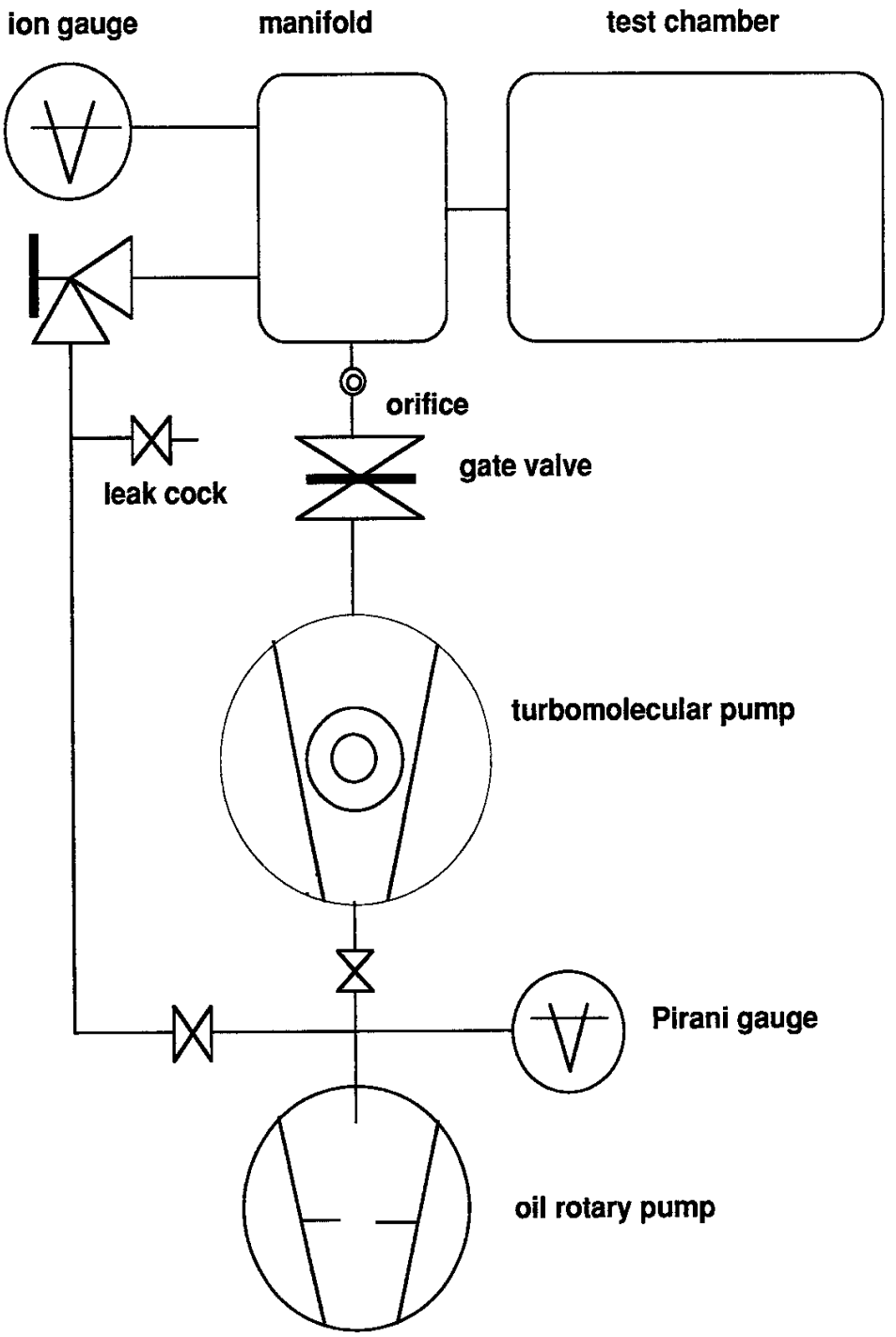


Fig.1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manifold
test chamber
orifice
gate valve
leak cock
turbomolecular pump
Pirani gauge
oil rotary pump

Fig.2

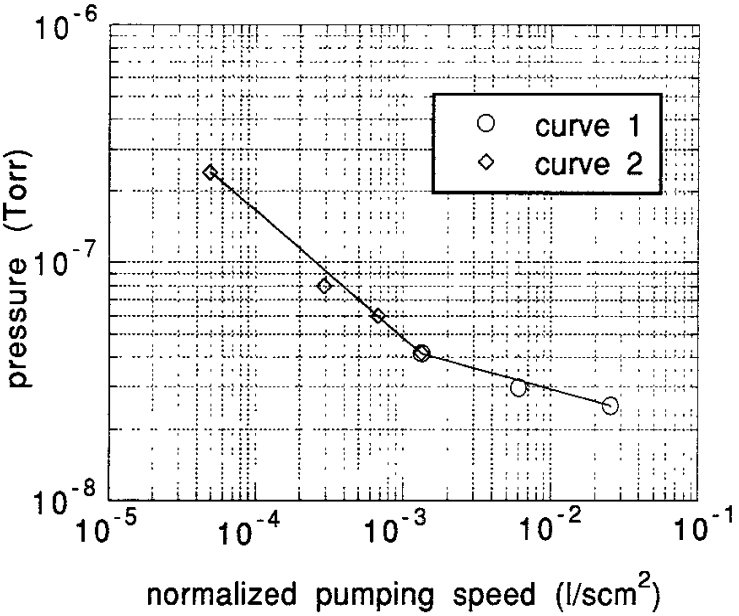
10^{-6}
10^{-7}
10^{-8}
pressure (Torr)
curve 1
curve 2
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
normalized pumping speed (l/scm^2)

Fig.3

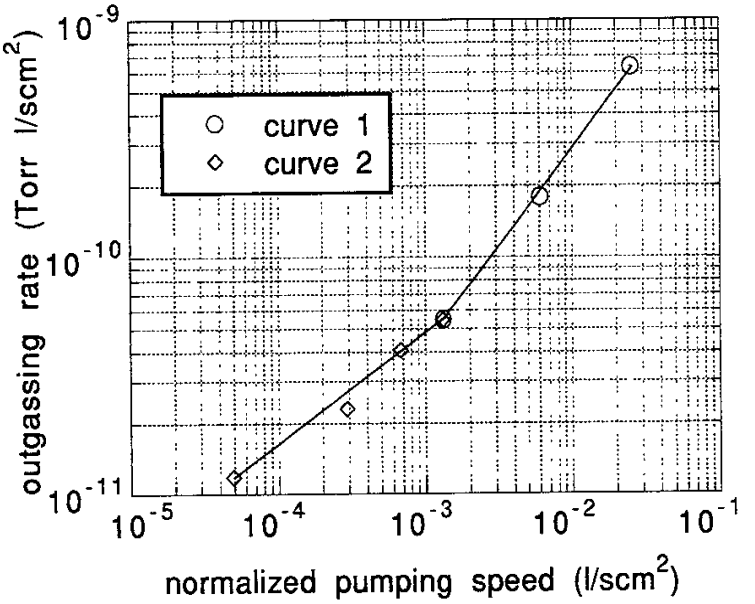
curve 1
curve 2
outgassing rate (Torr l/scm^2)
normalized pumping speed (l/scm^2)
10^{-9}
10^{-10}
10^{-11}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

Fig.4

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