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A Study of Non-uniform Pressure Distribution in Vacuum Chamber during Dynamic Gas Flow

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Vacuum chambers have wide application for a variety of purposes such as material processing, vacuum gauge calibration, etc. As the dynamic pressure generated in such chamber is non-uniform, in many industrial as well as research processes, it is vital to know the non-uniform gas distribution with associated gas flow regimes and the ways of minimizing these pressure non-uniformities. In the present work, the behavior of gas flow in a vacuum chamber, during continuous gas flow, is described in the pressure range 0.1-133 Pa and the effect of baffle plate in minimizing the pressure non-uniformities is investigated. It was observed that maximum deviations in the pressure occur near the gas inlet point and that the effect of baffle plate in minimizing the pressure non-uniformities is more obvious in the transitional flow regime.

Keywords : Vacuum chamber, Dynamic gas flow, Baffle plate, CDGs

Ⅰ. INTRODUCTION

Vacuum is any air or gas pressure less than a prevailing pressure in an environmental or, specifically, any pressure lower than the atmospheric pressure and is used by a wide verity of scientists and engineering [1]. Increasing demand of vacuum science and technology in industry and research organizations has triggered its applications to wide areas of knowledge and has become an important tool in research and industrial environments. Improvements achieved in vacuum science and technology often contributed to advances in other areas of studies, such as surface physics, metallurgy, food industry, semiconductor technology and display fabrication etc.

In various industrial vacuum processes (like fabrication of semiconductor devices, calibration of vacuum gauges, etc) pressure in the process chamber is generated dynamically. The throughput of the calibration gas–argon or nitrogen–is introduced through a fine control variable leak valve and pumped continuously by a pumping system [2]. Under such circumstances, the pressure in the chamber is determined by the equilibrium between the gas flow in and the gas flow out. As regions of the chamber act as sources and sinks for the gas flow, a nonuniform distribution of pressure occurs over the whole chamber [3]. The term “non−uniformity of gas distribution” refers to the change of the flow, density and pressure values depending on the position in a

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vacuum system [4]. In [5], six reasons have been given for non–uniformity of gas distribution, which are:

(a) The presences of a pump
(b) The presence of a gas source
(c) Particle migration on the surface
(d) Adsorption–desorption processes
(e) Temperature differences inside the vacuum system
(f) The difference between the particle reflection law and the cosine law.

The effects of nonuniform gas distribution, likely to occur in practice, have been the subject of many recent detailed investigations [6]. P. Repa et al. [3] have measured pressure differences of a few percent between various positions for gauges on a vacuum chamber in the range of 10^{-3}–10^{-1} Pa. Similarly, G. Horikoshi et al. [7] have shown, by obtaining some functional relations, that even in a one–dimensional model of gas flow, the pressure is not constant in a vacuum chamber (in the range of 10^{-1}–1 Pa) during dynamic gas flow. The results of these studies have in turn influenced the techniques used in obtaining meaningful measurements [6].

In order to suppress the influence of sources of non–equilibrium and pressure nonuniformity, the chamber has to have a suitable shape, it has to be sufficiently large, the gas after admission should be scattered by impinging on the walls, etc [8]. The stream of gas is scattered in order to achieve a uniform pressure distribution [2]. Baffle plates are usually used for this purpose. An appropriate position of a baffle is also essential, since it scatters the molecules by itself, thereby changing the spatial distribution of the gas [9].

Korea Research Institute of Standards & Science (KRISS) has assembled a dynamic flow control system for vacuum gauge calibration and other related vacuum experiments. The chamber of this system has been experimented for pressure distribution during dynamic gas flow in the pressure range of 0.1–133 Pa. Maximum deviations were recorded near the gas source (gas inlet point) which is situated on the top of the chamber. In addition, it was observed that pressure deviations are larger in the intermediate flow regime than in viscous flow and that baffle plate mainly affects the former type of flow.

II. THEORY

Simplified analysis of vacuum systems considers the gas to be Maxwellian, with uniform characteristics [5]. In addition, for such systems, it is assumed that gas molecules neither interfere with each other nor interact with the surface at which they collide. After collision with the surface, molecules leave it in a diffuse way according to the cosine distribution of direction and reenter the gas phase with an average kinetic energy corresponding to the temperature of the surface. The incidence rate of molecules on a plane within the volume is independent of the normal orientation to the plane. The gas system under such conditions is termed as isotropic for which the kinetic theory of gases provides a straightforward relationship between the number density of molecules and pressure [10]. Unfortunately, a real vacuum system can seldom be considered to contain a Maxwellian gas [5]. The isotropic state is disturbed by the dynamic molecular flow of gas resulting from localized or distributed (usually both) sinks and/or sources. Depending on their contribution to the process, these sources and/or sinks cause nonuniform and non–isothermal gas flow in the pumped vessel. Industrial vacuum equipment subject to dynamic working conditions does not permit isotropic gas conditions at reduced degree of rarefaction. Such systems are termed as “nonisotropic” systems. The system under consideration is a nonisotropic system working in the medium vacuum range of 0.1–133 Pa.

With the active development of semiconductor fab–

rication technology, dilute gas flow phenomena are attracting attention recently. The gas flow through a vacuum component can be continuous, transitional, or molecular depending on the pressure range and geometries involved [11]. In the continuous (viscous) flow regime, gas behaves as a (continuous) fluid and molecule-molecule collisions with mean free path much less than the equipment size determines gas behavior. At low pressures, the mean free path of gas molecules becomes greater than the container's characteristic dimension. Molecule-surface collisions dominate the gas behavior; molecule-molecule collisions become quite rare. The gas flow under such conditions is termed as molecular flow.

The intermediate flow regime between viscous & molecular, known as transitional regime, occurs in the medium vacuum range. In this range, collisions of gas particles with the wall (surface) occur just about as often as mutual collisions amongst gas particles [12]. The gas flow in this regime, also called the "Knudsen flow", is composed of viscous (laminar) and molecular flow. When the pressure is further decreased, the flow gradually shifts towards molecular state while increasing the pressure, the flow converts to the continuum state.

To describe the type of gas flow, it is convenient to use the Knudsen number Kn $=\frac{\lambda}{d}$ [13] with λ as mean free path of the gas molecules and d as characteristic dimension of the vacuum component. On the basis of Knudsen number, gas flows can be classified as [12]:

$Kn < 0.01$	Viscous flow
$Kn > 0.5$	Molecular flow
$0.01 < Kn < 0.5$	Transitional flow

For gas consisting of molecules of same diameter, the mean free path can be calculated from [14]:

$$\lambda = \frac{3.107\times 10^{-24} T}{p\delta_m^2} \quad (\mathrm{m}) \qquad (1)$$

Where T (K), p (Pa), and δ_m(m) are temperature, pressure and diameter of the gas molecules respectively. For nitrogen gas the value of δ_m is 3.78×10^{-10} m. At room temperature (23℃), equation (1) reduces to:

$$\lambda = \frac{6.43\times 10^{-3}}{p} \quad (\mathrm{m}) \qquad (2)$$

By using this equation we can calculate the mean free path and, hence, the values of Knudsen number in a vacuum component which, in turn, can give us information on the type of gas flow in the chamber.

Ⅲ. EXPERIMENTAL SET-UP AND PROCEDURE

The dynamic flow control system is shown in Fig. 1. This system consists of a large vacuum chamber of 36.65 l capacity which is pumped by a high vacuum pumping unit consisting of a turbomolecular pump (pumping speed = 560 l/s for N_2) and a scroll pump (pumping speed 300 l/min). These two pumps can be used for the production of clean vacuum. As the industry requiring clean vacuum condition like semi-conductor and display manufacturing expands, im-

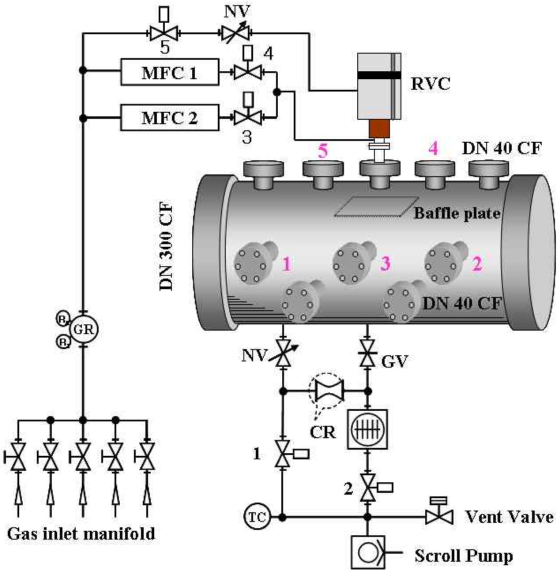

Figure 1. The dynamic flow control system.

portance of dry vacuum pumps has been increased [15]. Both the vacuum chamber and high vacuum pumping unit are separated by a pneumatically actuated DN 200 CF flange gate valve (GV). Various types of vacuum gauges, ranging from low to high vacuum range, residual gas analyzer and mass flow controllers are installed on the chamber. In addition, for accurate measurement of pressures in the chamber, five capacitance diaphragm gauges (CDGs) are used, as the capacitance sensing technique results in a high degree of pressure sensitivity [16]. Capacitance diaphragm gauge is one of the most important gauges in low and middle vacuum range [17] and is widely used in industries based on vacuum technology as measuring device because of the easy use, good accuracy and resolution as well as good compatibility with most of gases [18]. It is worth mentioning that before installation, all the CDGs were calibrated on ultrasonic interferometer manometer (UIM) whose working principle is somewhat different from the traditional mercury manometer. The difference in heights owing to difference in pressures between the mercury columns is measured using ultrasonic interferometry [19-22]. The positions of all five CDGs on the vacuum chamber are shown in Fig. 1 by points 1, 2, 3, 4,and 5 respectively.

Initially the system was evacuated to base pressure less than 6×10^{-6} Pa through GV. During experiment, the GV remained closed and the system was pumped through the bypass line in which a conductance reducer (CR) is installed. It is worth mentioning here that the permissible pressure at the inlet of a turbomolecular pump (TMP) is usually 0.1 Pa. However, with the help of this CR, a pressure of 133 Pa can be generated within the chamber of this system. And this range of pressure can be used for different purposes including the calibration of vacuum gauges by comparison method as well.

In addition, two mass flow controllers MFC1 & 2 with respective gas flow ranges of 20 and 3 sccm are attached to the chamber as shown below (1sccm = 1.69×10^{-3} Pa m^3 s^{-1}). The chamber also has the facility of installation of baffle plate. That is why, in order to know pressure distribution inside the chamber, the experiment was carried out in two different modes; first pressure distribution data was recorded without baffle plate and then a baffle plate of cross sectional area of 132 cm^2 was installed at a distance of 30 mm from the top of the chamber. For each case, ten data points were recorded in the desired pressure range of 0.1-133 Pa and the experiment was repeated four times under similar conditions. During experiment, nitrogen gas of 99.99% purity was used as the test gas. The system is fully operated through LabView computer software.

IV. RESULTS AND DISCUSSION

On closing the GV at pressure less than 6×10^{-6} Pa, a constant throughput of the test gas was delivered to the chamber through MFC 2. After some time, when the gas molecules become in dynamic equilibrium within the chamber, the gas throughput was gradually increased, step by step, until the whole pressure range was covered. It was observed that af-

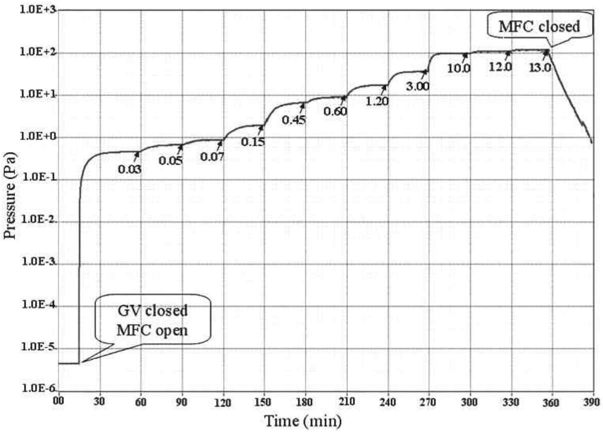

Figure 2. Generated pressure vs. time in response to changes in the test gas throughput. Arrows show different values of gas-flow in sccm.

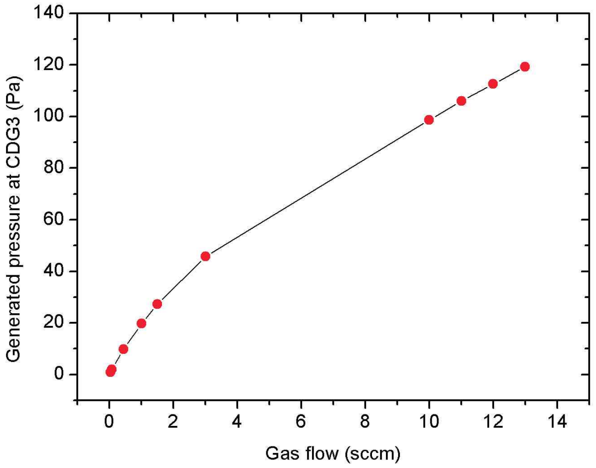

Figure 3. Gas flow versus generated pressure in the chamber for without baffle.

ter each throughput of the test gas, the gas molecules become in dynamic equilibrium within the chamber in about 25–30 minutes as shown in Fig. 2. This time of dynamic equilibrium is different for different systems depending on the system basic characteristics, like, volume, pumping speed, etc.

The graph of gas flow versus generated pressure (CDG3) in the chamber without baffle is shown in Fig. 3. It is clear from the graph that its slope ($\Delta p/\Delta q$) decreases as pressure rises. This means that more gas flow is required in order to raise pressure through same increment as we go up the graph.

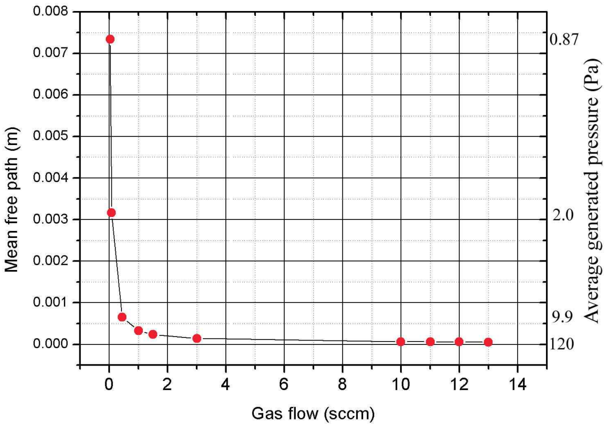

Figure 4. Gas flow versus mean free path of the gas molecules in the chamber.

Table 1. The values of mean free path λand Knudsen number Kn for different values of average generated pressure with chamber's dia 0.256 m.

Pressure (Pa)	Mean Free Path λ(m)	Knudsen number (Kn)
0.87	0.00734	0.02867
2.00	0.00316	0.01236
2.50	0.00257	0.01000
9.90	0.00065	0.00253
19.70	0.00033	0.00127
27.40	0.00024	0.00091
45.90	0.00014	0.00054
99.30	0.000064	0.00025
106.70	0.000060	0.00023
113.20	0.000056	0.00022
120.00	0.000053	0.00020

The relation between mean free path λ of the gas molecules versus gas flow in the chamber without baffle is shown in Fig. 4. The value of λ is calculated from equation (1) in which p is the average generated pressure i.e. the mean of all five CDGs readings.

In order to describe the type of gas flow in the chamber, the value of Knudsen number Kn is calculated at different values of the average generated pressure as given in Table 1. It is clear from the table that, for pressure $p \leq 2.5$ Pa, the value of Kn remains in the limits 0.0286–0.01 which shows that the gas in this pressure range is transitional ($0.01 < Kn < 0.5$). Above 2.5 Pa, the value of $Kn < 0.01$ and the flow is shifting toward viscous state with frequent collisions of gas molecules, reduced mean free paths, and rapid transfer of momentum.

The relative deviations versus average generated pressure in the chamber without baffle have been plotted in Fig. 5. However, when baffle plate is placed on the path of the gas molecules, the distribution of gas molecules is changed as shown by their relative deviations in Fig. 6.

A common characteristic observed in both the graphs (with and without baffle) is that; up to 2.5 Pa, the deviations are maximum while above 2.5 Pa (up to

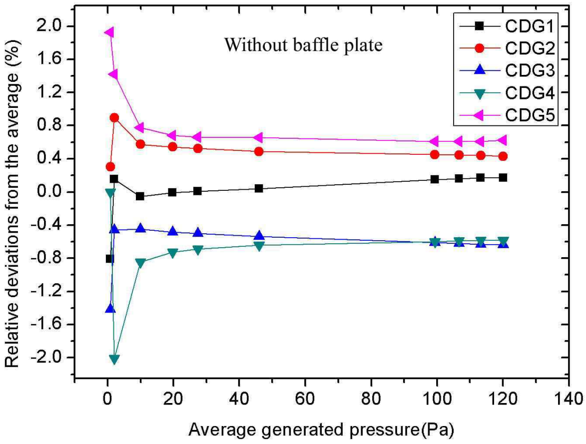

Figure 5. Relative deviations from the average (%) versus average generated pressure in the chamber without baffle plate.

20 Pa) these deviations are reducing / becoming almost constant. These variations can be attributed to the changes in flow regimes of the gas which in turn are caused by change in pressure of the chamber.

As discussed above that up to 2.5 Pa, transitional flow exists within the chamber. However, when pressure is raised above 2.5 Pa, the flow regime changes from intermediate to viscous laminar which is more regular than intermediate state where the fluid behaves like a continuous fluid and as a result, the deviations are minimizing. This behavior of the gas flow is clear from all the graphs (Fig. 6 and Fig. 5) with and without baffle plates.

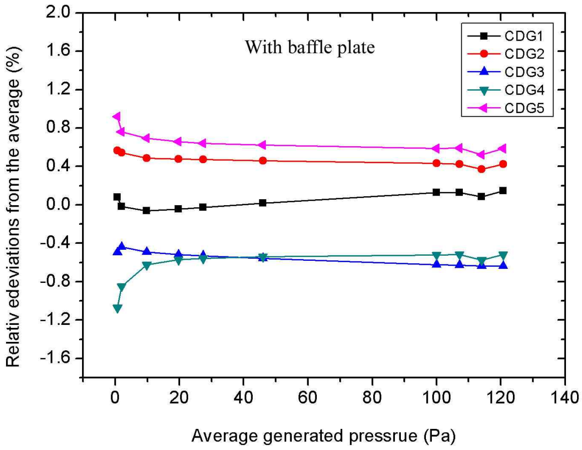

Figure 6. Relative deviations from the average (%) Vs. average generated pressure with baffle plate.

As regard the pressure uniformity in the presence and absence of a baffle plate, the comparison of two cases shows that the presence of baffle plate reduces deviations in the pressure range 0.8 Pa–10 Pa. Furthermore, it can be seen from the graphs that the employed baffle plate largely affects the intermediate flow $(0.01 < Kn < 0.5)$ than viscous flow regime. This is because the intermediate flow is more irregular in nature than viscous flow.

V. CONCLUSIONS

A cylindrical–shaped vacuum chamber of 36.65 l capacity was experimented for pressure uniformity in the range of 0.1–133 Pa during dynamic gas flow. It was observed that maximum pressure differences occur at points near to the gas source (gas inlet port). In addition, the effect of baffle plate on reducing the pressure non–uniformities in the chamber was also investigated. From the data obtained, it was concluded that the effect of baffle plate on pressure distribution was prominent in transitional flow regime as compared to the viscous flow regime. This type of study becomes more important in various fields like vacuum gauge calibration (by comparison method), semiconductor industry, etc, where pressures are generated dynamically.

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기체유입이 되는 진공챔버 안의 불균등한 압력분포 연구

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진공챔버는 진공게이지 교정, 산업에서의 재료처리 등 여러 가지 다양한 용도에 맞게 적용이 가능하다. 이 진공챔버 내부에서 가스가 유입되는 과정에서의 진공도는 일정하게 유지하기가 힘들다. 산업체 응용에서뿐만 아니라 연구과정에서도 진공챔버 내부에 가스가 유입되는 동안의 내부압력분포와 최대도달 평형압력을 아는 것이 매우 중요하다. 이러한 진공챔버 내부의 압력 불균형을 감소시키기 위해서 가스 주입구 부분에 baffle을 이용하는 방법이 있다. 현재 지속적인 기체흐름이 있는 진공챔버 내부의 기체흐름의 작용에 관해 0.1 Pa~133 Pa 영역에서 불규칙한 압력을 최소화하기 위한 baffle plate의 효과에 대해 연구하였다. 최대편차는 가스 주입구 부분에서 나타나는 압력으로 baffle plate가 전환흐름영역에서 큰 영향을 미치는 것으로 나타났다.

주제어 : 진공 용기, 동적 기체 흐름, 배플판, 용량형 진공게이지

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