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EFFECTS OF BAFFLE SIZE ON PRESSURE DISTRIBUTION IN VACUUM CHAMBER DURING DYNAMIC GAS FLOW

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Abstract - Vacuum technology is one of the established advanced technologies, of present age, in the field of research and industry. Having numerous applications, in the areas of human activities, one is concerned with a relatively large vacuum chamber where pressure distribution is, usually, not uniform during dynamic gas flow. To minimize the pressure non-uniformities in such chambers, baffles are generally used. In the present work, rectangular-shaped baffles of different sizes are used in a cylindrical-shaped chamber of a flow-control system, developed by Korea Research Institute of Standards and Science (KRISS). The chamber is large enough and has been experimented for pressure distribution at four different points in the pressure range from 0.1 Pa to 133 Pa by using five identical Capacitance Diaphragm Gauges (CDGs). One of these gauges serves as a reference gauge and is fixed at one point while the readings of the other four gauges were recorded by using baffles of various sizes and, at the same time, producing the pressure dynamically in the chamber. It is worth mentioning that before installation, all of these gauges were calibrated on Ultrasonic Interferometer Manometer (UIM). The data, thus obtained, along with relative deviations of the gauges' readings are plotted for all the three baffles which represent the behavior of gas pressure in this particular chamber.

Keywords: vacuum chamber, baffle plate, flow control system.

1. INTRODUCTION

Vacuum chambers have wide applications for a variety of purposes such as vacuum gauge calibration, material processing, electron simulated desorption, etc. In many industrial vacuum processes, pressure is generated dynamically in vacuum chambers. For example, the calibration of vacuum gauges according to secondary standards is usually performed in calibration chambers where the pressure is generated dynamically [1]. The throughput Q of the calibration gas – argon or nitrogen – is introduced through a fine control variable leak valve and pumped continuously by a pumping system. 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 non-uniform distribution of pressure occurs over the whole chamber [2]. The term "non-uniformity of gas distribution" refers to the change of the flow, density and pressure values depending on the position in a vacuum system [3]. There are two (main) sources of non-equilibrium and the pressure non-uniformity in a vacuum chamber where pressure is generated dynamically [4]; inlet of the gas and its sink in the pump. Repa [2] has calculated pressure differences of a few percent between various positions for gauges on a vacuum chamber in the range 10^{-3} Pa – 10^{-1} Pa. Similarly, G. Horikoshi [5] has shown, by obtaining some functional relations, that even in a one-dimensional model the pressure is not constant in a vacuum chamber (in the range 10^{-1} Pa – 1 Pa) during dynamic gas flow.

In order to suppress the influence of the gas sources and sinks, 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 [4]. Chambers of spherical or cylindrical shapes are used for this purpose [2]. The stream of the calibration gas is scattered in order to achieve a uniform pressure distribution [1] within the chamber. The scattering of calibration gas is usually done by using a baffle on the path of the gas molecules. As has been shown by experiments, when a simple baffle is placed on the path of the gas molecules, the "beaming effects" will be reduced [6]. An appropriate position of the baffle is also essential, since it scatters the molecules by itself, thereby changing the spatial distribution of the gas [6].

One such system having facility of gas flow control & baffle installation is developed at Vacuum Technology Center, Korea Research Institute of Standards & Science (KRISS), for the purpose of vacuum gauge calibration & related experiments. The chamber of the system has been experimented for pressure uniformity by using baffles of three different sizes. From the data obtained, it is concluded that for fixed volume of chamber, proper size of baffle, depending on chamber's geometry, can be used for minimizing the pressure non-uniformities.

2. THEORY

Analysis of vacuum system characteristics is based on

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the assumption that molecular velocity distribution is Maxwellian and their flux intensities are isotropic. The assumptions have been confirmed in many experiences [7]. The kinetic theory of gases provides a straightforward relationship between the number density of molecules and pressure in such cases [8]. However, 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 non-uniform 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 [8]. Such systems are termed as "nonisotropic" systems. The system under consideration is a nonisotropic system working in the medium vacuum range (0.1 Pa – 133 Pa).

Depending on pressure and the cross dimensions of a tube, three types of flow can be differentiated [9]: continuum or viscous flow, molecular flow, and transitional flow. Knudsen in 1910 found experimentally that the number $K_n = \lambda/d$ (Knudsen number) which is the ratio of mean free path (λ) of the gas particles to the cross dimension (d) of the vacuum component, can supply information concerning the gas flow regime [10]. Similarly, to describe the type of gas flow, it is convenient to use the Knudsen number [11]. The value of λ for gas consisting of molecules of same diameter is given by [10]:

$$\lambda = \frac{3.107\times10^{-24}T}{p\ \delta_m^{\ 2}} \quad \text{(m)} \qquad (1)$$

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.

On the basis of Knudsen number gas flows can be classified as [8]:

$K_n < 0.01$ Viscous flow
$K_n > 3.0$ Molecular flow
$0.01 < K_n < 3.0$ Transitional flow

These defining values are not as sharp as is implied, but their general correctness is founded in experimental results [12].

In the viscous (continuum) 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, mean free path becomes greater than the container's characteristic dimension. Molecule-surface collisions dominate the gas behavior, molecule-molecule collisions become quite rare, and 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 [9]. The gas flow in this regime, also called the "Knudsen flow", is composed of viscous (laminar) and molecular flow. On further decreasing the pressure, the flow becomes molecular while increasing the pressure, the flow shifts towards the continuum state.

3. EXPERIMENTAL SETUP AND PROCEDURE

The flow control system is shown in Fig. 1. The 36.65 l chamber 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/m). The chamber is equipped with different types of vacuum gauges, ranging from low to high vacuum range & mass flow controllers. Of these gauges, five capacitance diaphragm gauges (CDGs) are used for recording the experimental data as the capacitance sensing technique results in a high degree of pressure sensitivity. It is one of the most important gauges in low and middle vacuum range [13] 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 [14]. It is worth mentioning that before installation, all the CDGs were calibrated on ultrasonic interferometer manometer (UIM). The positions of all five CDGs on the vacuum chamber are shown in Fig.1.

Initially the system was evacuated to base pressure < 6×10^{-6} Pa through gate valve (GV). During experiment, the GV remained closed and the system is pumped through bypass line. The test gas was leaked into the system through mass flow controllers MFC1 & 2 with respective gas flow ranges of 1 slm & 3 sccm (1slm = 1.69 $Pa.m^3s^{-1}$ and 1sccm = 1.69×10^{-3} $Pa.m^3s^{-1}$).

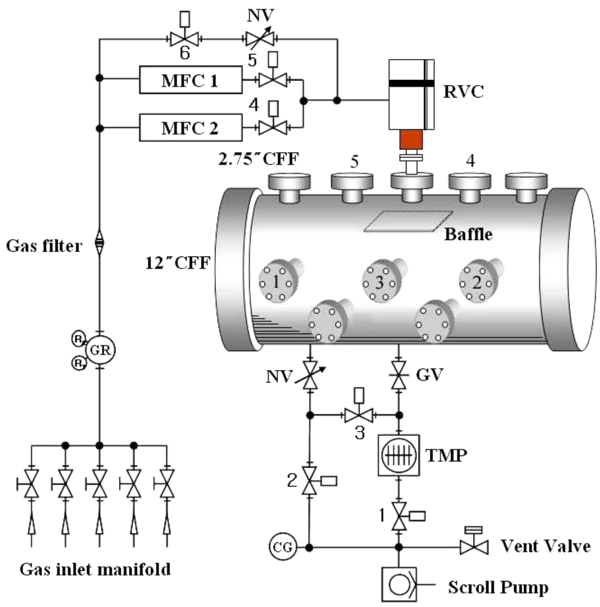


Fig. 1. The dynamic flow control system.

It was observed that the gas molecules become in equilibrium within the chamber in about 25 - 30 minutes after gas injection. The gas flow versus generated pressure (CDG3) without baffle is shown in Fig. 2.

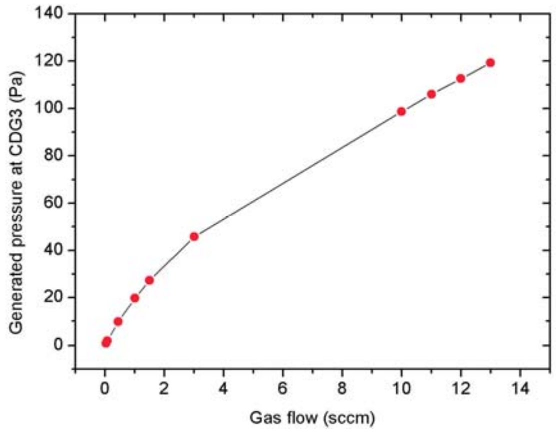


Fig. 2. Gas flow versus generated pressure (CDG3) in the chamber without baffle.

Ten data points (one set) in the desired range of pressure were recorded. Each set of data points was repeated four times. The system is fully operated through Labview computer software program. The test gas used was nitrogen of 99.99 % purity.

Three baffle plates of respective cross sectional areas 132 cm^2, 289 cm^2, and 405 cm^2 at a distance of 30 mm from the top of the chamber were used one by one and the distribution of pressure was checked. For convenience, on the basis of their sizes, these baffles are called small, medium, and large size baffles respectively.

4. RESULTS AND DISCUSSIONS

The graph of gas flow versus generated pressure (CDG3) in the chamber without baffle is shown in Fig. 2. It is clear from the graph that its slope ($\frac{\Delta p}{\Delta q}$) 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.

Fig. 3 shows the relation between mean free path *(λ)* of the gas molecules versus gas flow in the chamber without baffle. The value of λ is calculated from (1) with p as "average generated pressure" which is the mean of all the CDGs readings.

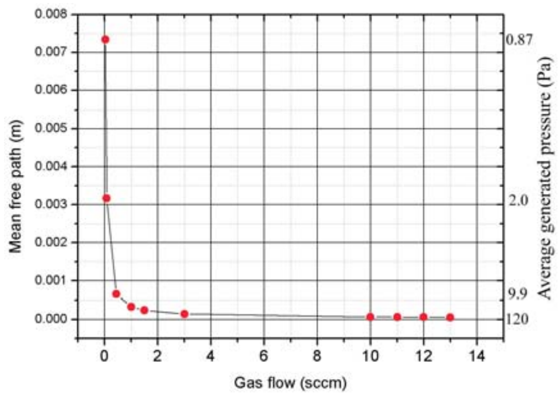


Fig. 3. Gas flow versus mean free path of the gas molecules in the chamber.

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

Pressure (Pa)	Mean Free Path λ (m)	Knudsen number K_n
0.87	0.00734	0.02867
2.0	0.00316	0.01236
2.5	0.00257	0.01000
9.9	0.00065	0.00253
19.7	0.00033	0.00127
27.4	0.00024	0.00091
45.9	0.00014	0.00054
99.3	0.000064	0.00025
106.7	0.000060	0.00023
113.2	0.000056	0.00022
120.0	0.000053	0.00020

From Table 1, it is clear that, for pressure $p < 2.5$ Pa, the value of K_n remains in the limits 0.0286 – 0.01 confirming that the gas flow in the chamber in this pressure range is transitional. Above 2.5 Pa pressure, $K_n < 0.01$ showing that as pressure increases above 2.5 Pa, the flow in the chamber 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. 4.

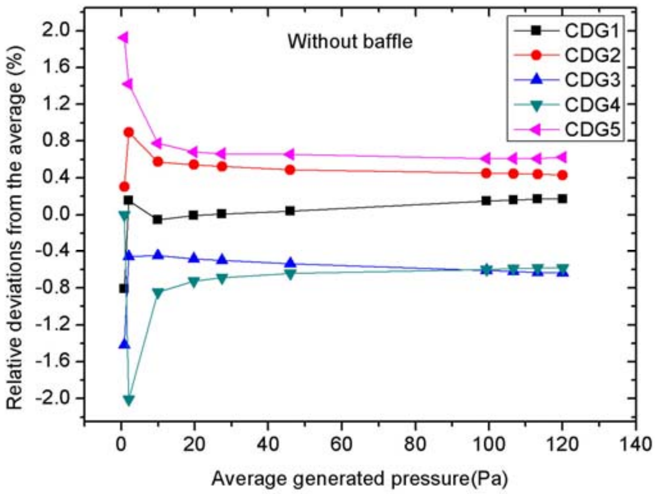
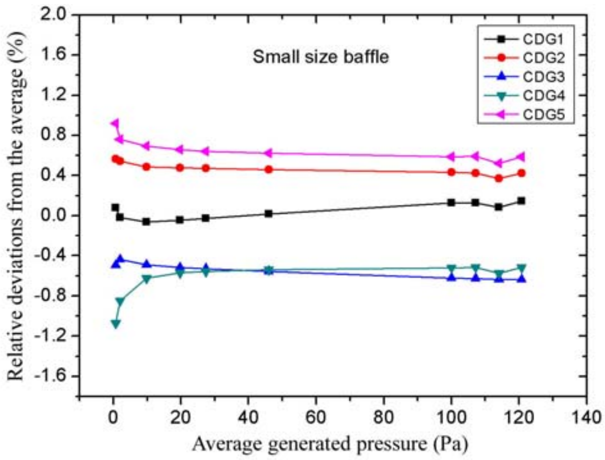


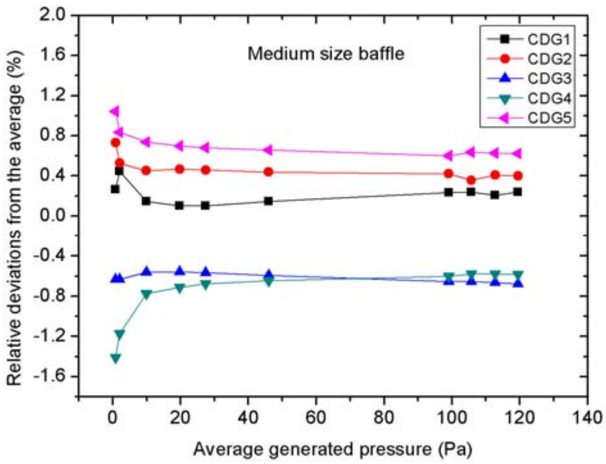
Fig. 4. Relative deviations from the average (%) versus average generated pressure in the chamber without baffle.

A simple explanation to these graphs is that as CDG5 is close to the inlet port and pumping line, it shows high pressure and, hence, maximum deviations than CDG3 & 4. CDG1 & 2 are at extreme ends of the chamber and as the chamber is pumped through bypass line, where CDG1 is near the pumping port, it shows comparatively less pressure than CDG2 which is far away from the pumping port.

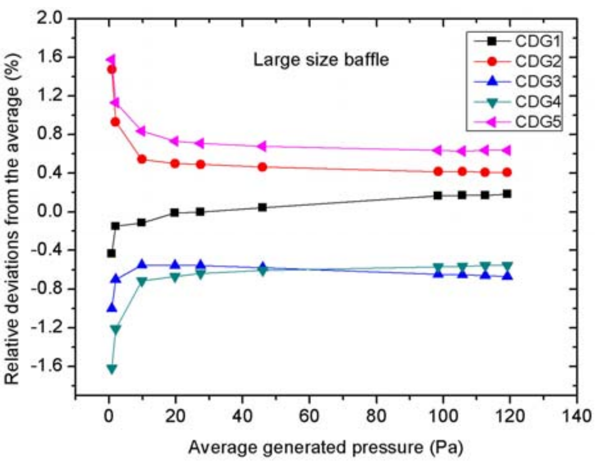
When baffle plate is placed on the path of the gas molecules, the distribution of gas molecules is changed as shown by their relative deviations in Fig. 5.



(a). Small size baffle



(b). Medium size baffle



(c). Large size baffle

Fig. 5. Relative deviations from the average (%) versus average generated pressure; (a). Small size baffle (b). Medium size baffle (c). Large size baffle

A common characteristic observed in all the graphs (with and without baffle) is that; below 2.5 Pa the deviations are maximum while above 2.5 Pa (up to 20 Pa) these deviations are reducing / becoming almost constant. As discussed above, at 2.5 Pa the value of K_n is 0.01 transitional flow exists after which as pressure increases, the flow becomes viscous laminar which is more regular flow and hence less deviations. Since in viscous state, the fluid behaves like a continuous fluid, the deviations are minimizing. This behavior of the gas is clear from all the graphs (Figs. 5 & 4) with and without baffle plates.

A comparison of the two cases, with and without baffle (Fig 5 & 4), shows that in the presence of baffle plate, the deviations in the pressure range 0.8 Pa to 10 Pa are less than without baffle case. Furthermore, the data for all the baffles show that these deviations are minimum for the smaller baffle. This means that if we use baffle plate in order to vary pressure distribution in the chamber, the small size baffle (area 132 cm^2) will be more suitable in this case.

5. CONCLUSIONS

A cylindrical-shaped vacuum chamber of 36.65 l capacity was experimented for pressure uniformity in the range 0.1 Pa to 133 Pa during dynamic gas flow by using three baffle plates of different sizes. It was observed that the small size baffle plate was giving fewer deviations than other two sizes (medium & large). These deviations are specific for this system depending on various factors like gas inlet and outlet ports, gauge position on the chamber, baffle plate size, its position from the gas inlet port etc. From this we conclude that in order to vary pressure distribution in the vacuum chamber during dynamic gas flow, proper size of the baffle plate should be used.

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