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Implementation of multi-opening orifices in the primary metrology of vacuums and small gas throughputs

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ABSTRACT

A multi-opening orifice is a device for the primary measurement of gas flows and related vacuum quantities. This device maintains a constant molecular flow regime and thus the possibility to very accurately calculate the conductance from the geometrical dimensions for relatively high pressures, and the value of the conductance is sufficiently high to achieve reasonable parameters of the vacuum system in use. Suitable shapes of a multi-opening orifice duct and the principles of multi-opening orifice design are discussed. An example of the multi-opening orifice manufactured with grinding is given. The limits and requirements for further development are drafted.

1. Introduction

A basic quantity in vacuum metrology is the gas pressure p [Pa]. In practice, however, other quantities are also of great importance e.g. the gas throughput Q [Pa·m^3/s]. The measurement of this quantity is related to the pressure measurement:

$$Q = C\cdot(p_1 - p_2), \tag{1}$$

where the proportionality coefficient between the gas throughput Q [Pa·m^3/s] and the pressure difference (p_1–p_2) is the vacuum conductance C [m^3/s] of the duct.

Unfortunately, this conductance is generally pressure dependent which complicates using of equation (1) in primary metrology.

To determine the vacuum conductance for a given gas species and temperature accurately only from the geometrical shape and dimensions of the duct is only possible for gas flow in the case of a molecular flow regime. The gas flows through the duct as individual molecules that are only scattered at the walls, where the molecules can continuously equalise the temperature of the gas with the ambient temperature. Thus, the process of gas flow is very accurately determined from a thermodynamic point of view – the process is isothermal.

Then, if the dimensions of the duct are measured well, the conductance is most directly determined from primary principles, and a pressure measurement can be transformed into a gas throughput measurement, and vice versa, by means of equation (1).

Molecular flow occurs in the ducts with common transverse dimensions (10^{-3}–10^{-1} m) in rarefied gas cases only, which explains why the conductance concept is typical for vacuum sciences and techniques but is generally not introduced in other fields.

The ratio of the gas throughput to the difference of the pressures at the ends of a duct is formally introduced and denoted as the conductance in the fields related to the vacuum technique for comparison even if the gas does not flow in the molecular regime (viscous laminar flow, turbulent flow). However, the conductance can be determined from primary principles with the necessary accuracy for metrological purposes only in the case of molecular gas flow. As shown in Ref. [1], the pressure range for an orifice can be slightly extended towards higher pressures where the flow is not entirely collisionless by means of a correction, but the applicability of this procedure is naturally limited.

Because the mean free path of molecules is indirectly proportional to the gas pressure, the requirement of an entirely molecular gas flow either strongly restricts the maximum input pressure or forces the use of ducts that are as narrow as possible. Narrow ducts/small openings can now be not only manufactured but also very accurately measured. Of course, the absolute value of the conductance of such a duct is very small and substantially deteriorates the parameters of the measuring system.

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A solution to this problem is to use a large amount of the ducts in parallel. To accurately measure the dimensions of the individual ducts and calculate the conductance of each duct from these dimensions, the most advantageous shape of the duct is an opening in a thin slab – an orifice. The structure with multiple openings is hereafter denoted as a multi-opening orifice (MOO). This solution has some important advantages, but the implementation of this solution also creates both theoretical and practical challenges.

2. Theoretical considerations

2.1. Optimal shape of a single duct in the MOO

The ability to determine the orifice conductance from the dimensions is very important. As analysed below, the total aperture (the sum of the apertures of all the ducts) is limited by physical reasons in practical metrological applications. Moreover, even this limit may not necessarily be achieved because the manufacturing of a large amount of small and accurate ducts is difficult, time consuming and expensive. However, it is desirable to make the total MOO conductance as large as possible to achieve short time constants for the vacuum system. Thus, a duct that is as short as possible is desirable at a given aperture. For this reason, the best shape of the duct would be a circular opening in an infinitely thin wall. Moreover, only one dimension – the aperture diameter – must be measured. Unfortunately, it cannot be manufactured; in reality, the opening is always short tube. Two dimensions must be measured – the diameter and the length of the duct. It is usually more difficult to accurately measure the length than the diameter. It is also difficult to guarantee the uniformity of the cross section.

For this reason, a conical or spherical duct (see Fig. 1) could be the most advantageous shape. Three dimensions must be measured to determine the duct conductance [2,3] (for example, the aperture diameter, the cone angle and the wall thickness in the case of a conical duct or the aperture diameter, the diameter of the sphere and the wall thickness in the case of a spherical duct), but the measurement accuracy of only one of these dimensions can be of crucial importance for a suitable choice of dimension ratios. An analytical formula (2) is available to compute the conductance for a spherical duct; e.g., see Ref. [4].

$$C_{\mathrm{MOL}} = \sqrt{\frac{2\pi \cdot kT}{m}} \cdot R_N \cdot \frac{R_O^2 + b \cdot \sqrt{R_N^2 - R_O^2} - b \cdot R_N}{2R_N - b} \qquad (2)$$

k is the Boltzmann constant, T the thermodynamic temperature and m the mass of the gas molecule. The other variables can be related to those in Fig. 1 as follows: $D_O = 2R_O$, $D_N = 2R_N$.

The aperture diameter D_O is the best measurable quantity, whereas the "tool" diameter D_N is the worst measurable quantity. The sensitivity coefficients $\partial C_{MOL}/\partial R_O$, $\partial C_{MOL}/\partial R_N$ and $\partial C_{MOL}/\partial b$ determine the role of the uncertainties in the measurements of R_O, R_N and b in the total uncertainty. The ratios of the dimensions R_O : R_N and b : R_N can be readily chosen so that both $\partial C_{\mathrm{MOL}}/\partial R_N < 0.1 \times \partial C_{\mathrm{MOL}}/\partial R_O$ and $\partial C_{\mathrm{MOL}}/\partial b < 0.1 \times \partial C_{\mathrm{MOL}}/\partial R_O$ are simultaneously true. Thus, only one dimension must be measured with a high accuracy, and measurement uncertainties that are more than one order of magnitude higher for the other dimensions are sufficient.

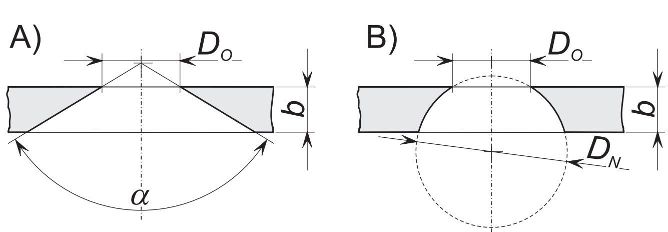

Fig. 1. The conical A) and spherical B) duct. D_O – the diameter of the aperture ($D_O = 2R_O$), b – the wall thickness, α – the cone angle, D_N – the diameter of the sphere ($D_N = 2R_N$).

It can be difficult to manufacture exactly spherical or conical ducts and to keep the optimum ratios; however, if the duct shape retains the important property that the narrowest part of the duct is an edge in one plane, and if the duct broadens rapidly outside this plane, the influence of the uncertainties of all dimensions except for the diameter of the opening is small.

2.2. Minimum desired conductance of the MOO

An important parameter of each dynamic vacuum system is the ratio of the chamber's volume to the effective pumping speed in the chamber. This time constant τ determines how quickly the equilibrium state is achieved after an adjustment of the parameters. The effective pumping speed is given practically only by the MOO conductance. The time constant τ less than 10 s is usually required; $\tau = 100$ s could still be considered acceptable in the extreme (the equilibrium is established within several minutes);

If a reasonable volume of a chamber for metrological purposes is 10 ℓ, the total conductance of the MOO should be at least 1 ℓ/s. The total area A of the MOO aperture must then be approximately 10 mm^2 (according to the gas species and thickness of the wall in which are the openings made).

MOOs with hundreds of openings must be used to extend the pressure range at which they can be used for metrological purposes up to an order of magnitude of pascals. Even when the chamber volume is reduced to 1 ℓ, many tens of openings should be used. It is necessary to adapt the technology of manufacturing the MOO to these circumstances. The manufacturing of one opening must not be too time consuming and/or expensive.

2.3. Necessary relative uncertainty in the determination of one duct's conductance

The relative uncertainty in the determination of the conductance from the geometrical dimensions is higher for small openings than for larger ones. Irregularities, edge damages and possible burrs (if mechanically manufactured) play greater roles at small openings. However, if these conductance uncertainties of individual openings are not correlated, the total uncertainty may be acceptable.

Consider a MOO consisting of N openings, where the conductance of the i-th opening is C_i, the average conductance of one opening is C_{AVER}, the absolute conductance uncertainties of the individual openings $u(C_i)$ are not too different and the maximum uncertainty is u_{MAX}. The total relative uncertainty of MOO conductance is then

$$u_{\mathrm{RMOO}} = \frac{\sqrt{\sum [u(C_i)]^2}}{\sum C_i} \le \frac{u_{\mathrm{MAX}} \cdot \sqrt{N}}{N \cdot C_{\mathrm{AVER}}} = \frac{1}{\sqrt{N}} \cdot \frac{u_{\mathrm{MAX}}}{C_{\mathrm{AVER}}} \qquad (3)$$

If $N = 1000$, for example, the total relative uncertainty of the MOO conductance is approximately 30–times less than the relative uncertainty of the single openings.

2.4. Mutual distance of the individual openings in a MOO

The aim of a MOO application is to keep the molecular flow regime up to the same pressure as is found in a single opening.