XX IMEKO World Congress
Metrology for Green Growth
September 9–14, 2012, Busan, Republic of Korea

MULTI-OPENING ORIFICE - A TOOL FOR PRIMARY METROLOGY OF VACUUM AND SMALL GAS THROUGHPUTS

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Abstract: Multi-opening orifice is a device for gas flow and related vacuum quantities primary measurement. It keeps molecular flow regime and thus possibility to calculate the conductance very accurately from geometrical dimensions up to relatively high pressure. Moreover, the value of the total conductance could be sufficiently high to achieve reasonable parameters of the used vacuum system. Suitable shape of a multi-opening orifice duct and principles of multi-opening orifice design are discussed. An example of the multi-opening orifice manufactured with grinding is given. Limits and requirements for further development are drafted.

Keywords: Orifice, multi-opening orifice, orifice flow standard, gas throughput.

1. INTRODUCTION

One of the most accurate methods of determining small gas throughputs based on primary quantities measuring is measurement of the pressure difference upstream and downstream an orifice the gas flows through. This method is often used also vice versa for determining the upstream pressure from a known gas throughput, downstream pressure and the conductance of the orifice. It is certain analogy of Ohm's law in electricity but the conductance of a duct at gas flow is of much more complex character than electric conductance in many cases.

The gas can flow through the duct in some different regimes according to the value of Knudsen number Kn i.e. ratio between mean free path and transverse dimension of the duct. Only under the conditions of molecular flow the conductance can be computed from geometrical dimensions only with high accuracy. For metrogical purposes the molecular flow regime should be considered from Kn>100 only. On the contrary the conductance of the duct depends not only on geometrical dimensions but also on the gas pressure in viscous flow regime (Kn<1). Moreover, because the gas flows as continuum, changes in temperature and viscosity cause increase of uncertainty at the conductance calculation. The conductance has to be measured which is less advantageous in the primary metrology.

Because the mean free path of molecules is indirectly proportional to the gas pressure, the requirement of entirely molecular gas flow either strongly restricts maximum pressure at which the gas can flow through the orifice or forces on using as narrow ducts as possible. Narrow ducts – small openings can be now not only manufactured but also very accurately measured with dimensional metrology. Of course absolute value of the conductance of such duct is very small. It deteriorates substantially the parameters of the measuring system.

Obvious solution of this problem is to use large amount of ducts in parallel. For enabling to measure accurately the dimensions of the single ducts and calculate the conductance from each of the dimensions, the most advantageous shape of the duct is an opening in a thin slab – an orifice. A multi-opening orifice (MOO) originates. This solution has some important advantages but its implementation brings also some troubles both theoretical and practical.

2. THEORETICAL CONSIDERATIONS

Minimum desired conductance of the MOO

Inevitable condition for correct calculating of the orifice conductance from geometrical dimensions is not only molecular gas flow but also the Maxwellian gas molecule velocity distribution at least in the chamber upstream the orifice. Thus, the total area of the orifice aperture must not exceed a negligible fraction (1/1000 e.g.) of the surface of the largest sphere inscribed in the chamber upstream the orifice.

From practical reason let us consider a chamber of approximately 3 ℓ volume minimum. To achieve a time constant no more than 30 s the total conductance of the MOO has to be at least 0.1 ℓ/s. Then the total area *A* of the MOO aperture must be approximately 10 mm^2 (according the gas species and thickness of the wall in which are the openings done – the wall is never infinitely thin).

Circular openings down to a diameter 0.1 mm can be manufactured and very accurately measured. (May be even smaller can be manufactured and measured, but, certain regularity and reproducibility is necessary to calculate conductance of each single opening from a large set.) In order to provide the total area of aperture 10 mm^2 it have to be manufactured ≈1300 openings of 0.1 mm diameter or ≈320 openings of 0.2 mm diameter or ≈142 openings of 0.3 mm diameter etc.

Suitable shape of one duct in MOO

Because an opening in infinitely thin wall cannot be manufactured the most advantageous shape of the duct is spherical duct - usually called NPL orifice. An analytical formula is available to compute the conductance of this duct, see e.g. [1]. If the ducts in MOO are sufficiently regular and mutually similar another shape of the duct can be used as well and the conductance can be computed by means of Monte Carlo method. Nevertheless it is advantageous to retain the important property of the NPL orifice – the narrowest part of the duct is an edge in one plane and the duct broadens rapidly outside this plane. Conical duct for example has this property [2]. As it is shown in [3] the pressure range in which the orifice is applicable can be slightly extended towards higher pressures where the flow is not entirely collisionless by means of a correction.

Necessary relative uncertainty in determination of one

Relative uncertainty in conductance determination from geometrical dimensions is higher at small mechanically manufactured openings than at larger ones. Irregularities, edge damages and possible burr play greater role at small openings. Thus, the conductance of one single small opening is most likely determined with higher uncertainty than that of large opening. But if these uncertainties are not correlated the total uncertainty may be quite acceptable. Let MOO consists of *N* openings, the conductance of *i*-th opening is C_i, the average conductance of one opening is C_{AVER}, uncertainties of conductance of single openings $\mathrm{u}(C_i)$ are not mutually too different, maximum of them is u_{MAX}. Then the total relative uncertainty of MOO conductance is

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

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

Mutual distance of single openings in MOO

The aim of MOO application is to keep the molecular flow regime up to the same pressure up to which it is kept with one single opening. Thus, the openings have to be mutually sufficiently distant in order the flow through one of them not to influence the flow through the neighbouring ones because it would cause the transition from molecular flow regime at lower pressure.

From the point of view of design it is suitable that the openings are arranged as closely as possible in order not to be the MOO too large with regard to the size of vacuum chamber. This question has not been solved in literature. Based on Liepmanns considerations [4] it can be estimated that a critical distance in case of circular openings of a diameter *D* is about 2*D* up to 3*D*. The problem was solved experimentally [5], the result also gives a value of about 3*D*.

3. PRACTICAL IMPLEMENTATION OF MOO

One possible way of MOO manufacturing satisfying above mentioned considerations with opening down to the diameter of about 0.5 mm is mechanical grinding. This technique was used for manufacturing of a MOO with 1027 openings of the diameter 1 mm serving to attain the range 10^{-6} Pa to 10^{-1} Pa in a new orifice flow standard (part of UHV primary standard) developed in Czech Institute of Metrology (CMI). Total conductance of this MOO is $(9{,}103 \pm 0{,}064)\cdot 10^{-2}$ m^3/s and $(7{,}624 \pm 0{,}054)\cdot 10^{-2}$ m^3/s respectively for nitrogen and argon gas respectively.

The openings are 1 mm of the diameter. The ducts are of spherical shape (NPL orifices) and are cut through a wall of thickness 0.3 mm. Openings are arranged in triangular grid, the distance between centres of two adjacent openings is 3 mm, thus 3*D*.

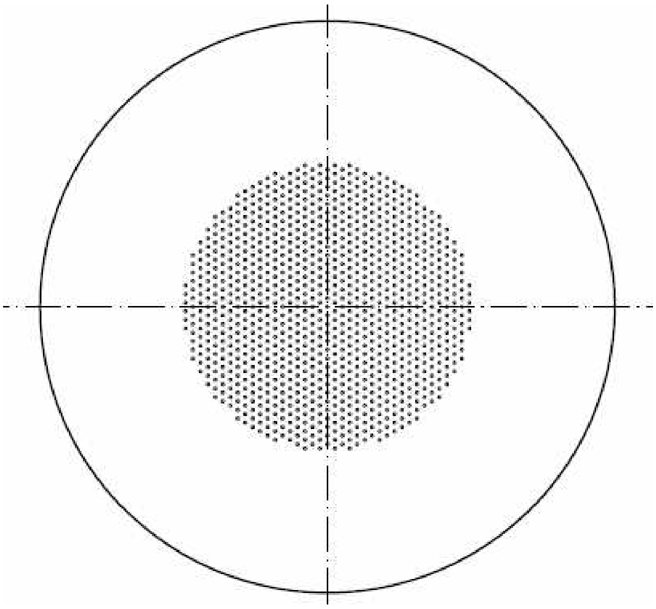


Fig. 1 Arrangement of the openings in MOO

Each duct was measured individually using optical method (see Fig. 5) and its conductance was computed. Statistical distribution of opening conductances is in figure 2.

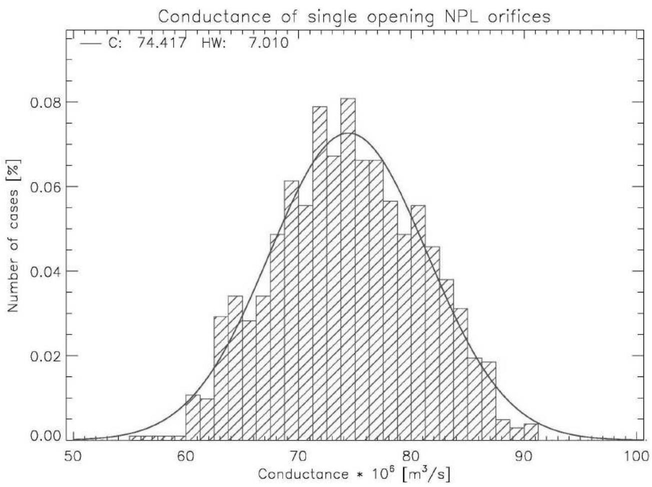


Fig. 2 Statistical distribution of opening conductances in a MOO manufactured with grinding.

Irregularities at the edge of an opening after grinding are shown in figures 3 and 4.

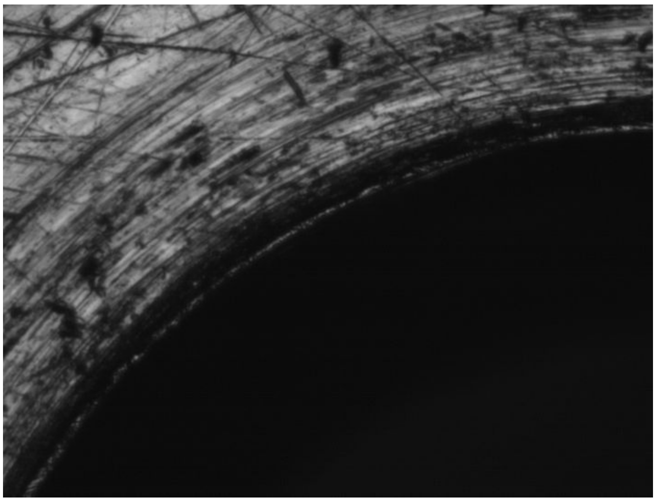


Fig. 3 Edge of an opening manufactured with grinding.

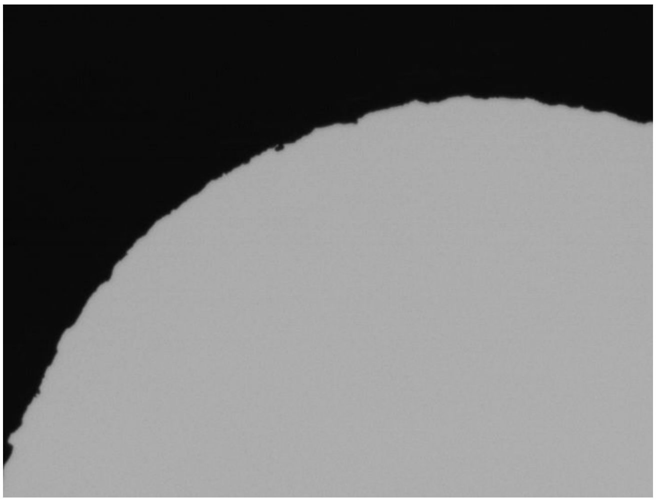
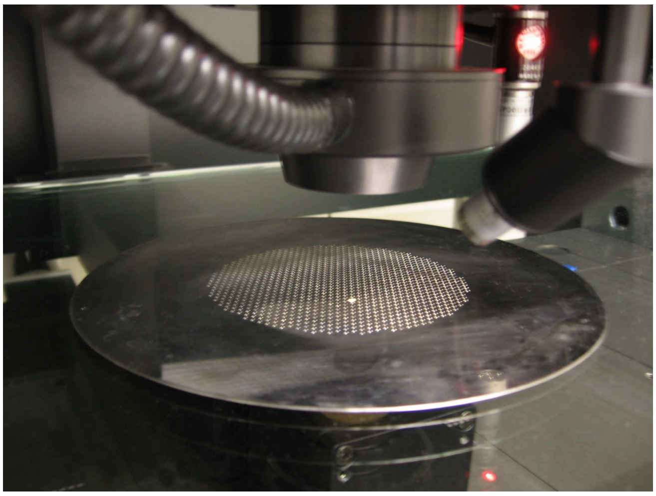


Fig. 4 Irregularities at the edge of an opening manufactured with grinding.



Obr. 5 Measuring of single opening dimension using optical way.

Manufacturing of this MOO showed that the practical limit of this technique are openings with approximately 0.5 mm of the diameter (hardly less than 0.3 mm) at total amount of some hundreds of openings. The dispersion of opening conductance values is relatively wide. It is related to attainable uncertainty of the total conductance.

More suitable technology of MOO manufacturing is needed to suppress more the uncertainty of the total MOO conductance and achieve the diameter of one opening approximately 0.1 mm. Because both high accuracy of the conductance determination from geometrical dimensions and stability of the total conductance value are demanded, to achieve the diameter of one opening substantially smaller is not necessary.

4. CONCLUSIONS

The pressure range where the gas flows through the orifice in the molecular flow regime and the conductance is for a given gas species constant, dependent on the duct dimension only can be extended with utilising multi-opening orifices

Suitable shape of one duct in MOO is spherical duct (NPL orifice), conical duct or another duct shape whose narrowest part is in one plane only.

A MOO with 1027 spherical ducts of 1 mm opening diameter was manufactured with grinding. The technique of grinding can be employed down to the opening diameter of about 0.5 – 0.3 mm.

Quality of the MOO is satisfactory, nevertheless it could be improved utilising more suitable technique for MOO manufacturing suppressing better the edge irregularities and enabling to achieve narrower distribution of opening conductance and thus lower uncertainty of the total conductance.

5. REFERENCES

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