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Rapid communication

A standard to test the dynamics of vacuum gauges in the millisecond range

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ABSTRACT

Vacuum gauges that control fast processes in industrial applications, e.g. load locks, should immediately react to pressure changes. To study the response time of vacuum gauges to rapid pressure changes, a dynamic vacuum standard was developed where the pressure may change from 100 kPa to 100 Pa within 20 ms in a step-wise manner or within longer times up to 1 s in a predictable manner. This is accomplished by a very fast opening gate valve DN40 and exchangeable orifices and ducts through which the mass flow rate can be calculated by gas flow simulation software. A simple physical model can be used to approximate the calculations. Experiments have been performed with capacitance diaphragm gauges with improved electronics to give a read-out every 0.7 ms. Preliminary results indicate that their response time is at most 1.7 ms, but may be significantly less.

In industry there are many fast processes that require rapid changes of pressures in the vacuum regime, e.g. leak testing, CD metallization and coating processes. Typically, vacuum load locks are used for such processes, where the pressure changes from atmospheric to medium vacuum within 1 s or less. The control of such systems is triggered by vacuum gauge readings. Vacuum gauge manufacturers are interested to know how fast their gauges can follow such rapid changes of pressure.

To investigate the response time of vacuum gauges for rapid pressure changes, in the framework of the European project EMRP IND12 [1] the Physikalisch-Technische Bundesanstalt (PTB) has developed a dynamic pressure standard, where the pressure changes in a predictable manner from 100 kPa to 100 Pa within one second or less. This is accomplished by expansion of gas via a calculable conductance and a very fast opening DN40 gate valve. Also, a pressure step with a time constant of less than 2 ms (pressure reduction to 37% of the initial value) can be generated when the full opening is used.

Fig. 1 shows the schematic of the system. The pressure reduction is realized by gas expansion from a very small volume V_1 (0.09472 L) into a much larger volume V_2 (185.4 L). During this expansion the valve to the pump system is closed. Either volume may be evacuated or filled independently with gas up to a desired pressure of less than 100 kPa. The expansion is released by a fast opening DN40 gate valve which opens the full diameter within 4.6 ms [2]. The gas within V_1 is depleted via an exchangeable orifice, duct or nozzle with conductance C. The dead volume V_1' (0.03309 L) between this duct and the valve plate contributes to an offset p_{offs} in pressure in V_2 after the valve opening, which can be calculated by

$$p_{offs} = p_{01}\frac{V_1'}{V_1' + V_2} = 1,785\cdot 10^{-4} p_{01}, \quad (1)$$

where V_2 was evacuated to a negligible pressure before and p_{01} is the initial pressure in both V_1 and V_1'. When the expansion is completed and the gas recovers room temperature, the final pressure is determined by the expansion ratio

$$f_2 = \frac{V_1 + V_1'}{V_1 + V_1' + V_2} \quad (2)$$

and the final pressure in both chambers will be

$$p_f = f_2 p_{01} = 6.889\cdot 10^{-4} p_{01}. \quad (3)$$

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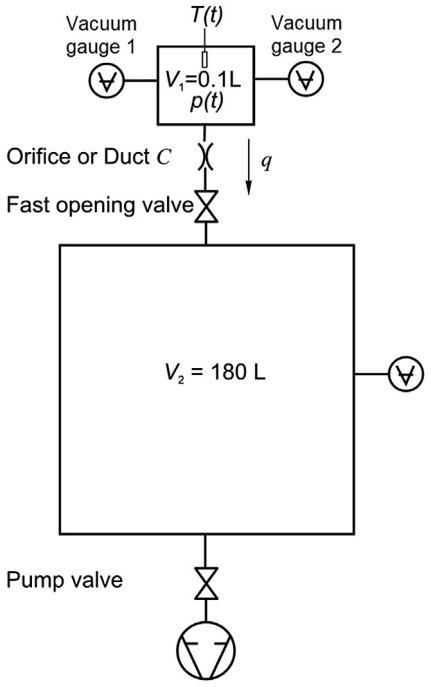

Fig. 1. Diagram of the dynamic vacuum standard. Gas inlets are not shown.

When no orifice or duct is mounted and the full opening is used, the expansion is the fastest possible with this system. The final pressure is again given by Eq. (3). The vacuum gauges to be investigated are mounted on the upper chamber V_1. They will slightly change the value of the upper volume which has to be corrected.

To calculate the pressure $p_1(t)$ in the small volume V_1 after the valve has being opened, the mass flow rate q_m through the conductance C is needed. In the viscous flow regime q_m depends on $p_1(t)$ and the ratio $p_2(t)/p_1(t)$, while in the molecular flow regime q_m will depend on $(p_1(t) - p_2(t))$ and the conductance C, which will be pressure independent. To decide which regime of flow is valid, the shape and the dimensions of the conductance element need to be known. One of the ducts used in our apparatus is shown in Fig. 2. At around 100 Pa and 293 K the Knudsen number in the small volume is $Kn < 0.06$ for all gases. This means that the molecular flow regime will not be reached in the area in front of the duct of Fig. 2; rarefaction effects, however, will play some role in the later stage of the expansion, while the viscous flow regime will dominate the first part of the expansion starting at 100 kPa.

The critical pressure ratio p_2/p_1 for choked flow for all gases and for short conductance elements (length to radius of about 1) may be estimated to be around 0.3 [3] so that choked flow can be expected for the first phase of the expansion as long as $p_2(t)/p_1(t) < 0.3$. Since, for $p_{01} = 100$ kPa, $p_f = 65$ Pa (Eq. (3)) choked flow may prevail until $p_1(t) = 220$ Pa. At this low pressure, however, $Kn > 0.01$ and the flow may exhibit a different characteristic than viscous. As a rough

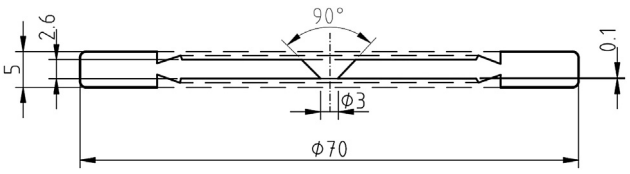

Fig. 2. Orifice between upper chamber and lower one.

estimate, choked flow can be expected in the period where 100 kPa $> p_1(t) >$ 500 Pa. In this period, the flow rate through the duct, expressed as throughput q^*_{pV}, can be estimated by [4]

$$q^*_{pV} = K\bar{c}_1 p_1, \tag{4}$$

where $\bar{c}_1$ is the mean thermal speed of the gas in V_1 and K is a constant

$$K = \sqrt{\frac{\pi}{4}} A \Psi\left(\frac{p^*_2}{p_1}\right), \tag{5}$$

with A as the smallest effective cross sectional area of the duct and Ψ the dimensionless flow function at choked flow condition p^*_2.

In a first approach we will assume isothermal conditions and set

$$K' = K\bar{c}_1, \tag{6}$$

which has the physical unit of conductance. The change of pressure in the upstream chamber V_1 is then determined by the following differential equation

$$V_1 \frac{dp_1}{dt} = -K' p_1, \tag{7}$$

We denote the time constant

$$\tau_1 = \frac{V_1}{K'}, \tag{8}$$

and solve Eq. (7) with the initial boundary condition $p_1(t = 0) = p_{01}$ by

$$p_1(t) = p_{01}\exp[-t/\tau_1]. \tag{9}$$

The isothermal condition is no reasonable assumption, as it is well known for fast gas expansions [5] that the gas in the upstream chamber will cool down to quite low temperatures. This has the consequence that $\bar{c}_1$ and K' will decrease and τ_1 will increase with time. The exponential pressure decrease described by Eq. (9) will therefore be slowed down. To consider this, we assume $\bar{c}_1(t)$ to be time dependent replacing Eq. (6) with

$$K' = K\bar{c}_1(t). \tag{10}$$

Inserting this into Eq. (8), we obtain with Eq. (9) an implicit function to characterize the pressure decay in the upstream chamber until p_1 reaches 500 Pa. We will see later that this function gives a good fitting function for the condition of choked flow of both experimental results and results obtained by numerical simulations.

K' for the case of the duct shown in Fig. 2 and nitrogen at 20 °C has the value of 1.43 L/s which gives $\tau_1 = 69$ ms. For comparison, the conductance at molecular flow conditions is 0.78 L/s, calculated from the minimum open area (diameter 3.006 mm) of the duct and a transmission probability of 0.938 obtained by Direct Simulation Monte Carlo (DSMC) method.

Numerical simulations are needed to more accurately predict $p_1(t)$ and K' for the conductance element of Fig. 2 which will be called orifice in the following. As a first approach, a commercially available computational fluid dynamic module, ANSYS CFX®, was used. Since the package available for us did not include boundary conditions appropriate for the slip regime as well as due to numerical difficulties for low downstream pressures <1 kPa, it was used to calculate flows into V_2 with initial pressures that ensured that viscous flow prevails throughout the expansion. It could be expected that the results for $p_1(t)$ of these simulations do not