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Gas flow in a short micro-tube

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ABSTRACT

The flow of gases into high vacuum through a short micro-tube of 20.5 μm diameter and 15 μm length has been measured for inlet pressures up to 1 atm. At low pressures molecular flow is found to be augmented by an additional mode of gas transport, whose contribution increases linearly with both inlet pressure and the molecular weight of the gas. This additional mode of transport is ascribed to the sliding movement of gas adsorbed on the tube wall. At higher pressures the flow rate can be accurately represented by a power law, the exponent of which is independent of the nature of the gas, whilst the coefficient increases with the molecular weight.

1. Introduction

Experiments described in a previous publication [1] involved the introduction of short pulses of gas from a reservoir at near atmospheric pressure into an apparatus at high vacuum. In order to do this in a reproducible manner, the gas was passed through an opening of about 20 μm diameter, which merely served as a simple and stable pressure reduction device. Details of the mode of gas flow through the opening were at that stage of little interest. However with further development of the work it became desirable to have more information regarding the nature of the flow, thus giving rise to the present investigation.

2. Experimental arrangement and procedure

The opening in question was an aperture of the type used in the optical column of a scanning electron microscope. It was constructed from a platinum sheet of ~0.5 mm thickness, and consisted of two sections, the first of which, a circular bore of diameter $d = 20.5$ μm and of length $l = 15$ μm, constituted a short micro-tube of length to diameter ratio 0.73. This micro-tube ended into a funnel shaped section of much larger dimensions, with a diameter that increased from 645 μm at the micro-tube exit to a final value of 1180 μm at a further axial distance of ~500 μm. The conductance for molecular flow of this second section exceeded that of the micro-tube by 3 orders of magnitude. Therefore its influence on the gas flow will in the following be neglected.

A schematic diagram of the experimental arrangement is shown in Fig. 1. Gas was introduced through the micro-tube from a reservoir into a vacuum system of 28.2 L volume. This was equipped with a liquid nitrogen cooled cold finger, that protruded into the main volume, and served to minimize the effect of outgassing. The system was evacuated to a base pressure of about 1×10^{-6} mbar by a turbo-molecular pump, from which it could be isolated by a flap valve (not shown).

The reservoir pressure was variable from high vacuum to about atmospheric pressure, and as described in [1], the gas was admitted in single pulses of about 1 s duration, using two electronically controlled solenoid valves. One of these valves served to control gas flow from the reservoir. When this valve was open, the second valve was closed; it opened when the reservoir was cut off, allowing the residual gas in the space in front of the micro-tube to be rapidly removed by an auxiliary pump. Without this auxiliary pumping the gas would only slowly have drained from this space, and the pulse repetition rate would have been unacceptably slow.

During the time of gas admission the flap valve was manually closed, and the resulting pressure rise in the system was measured with an ionization gauge. In these experiments the gas introduced never caused the system pressure to rise above the 10^{-5} mbar range, so that at all times the pressure difference across the micro-tube could be taken as equal to the reservoir pressure P, which also represents the entrance pressure to the micro-tube.

The increase in the ion current I of the gauge was recorded on a storage oscilloscope. Steady conditions of the gas flow rate were reached in about 0.3 s, when the rate of current rise became very accurately constant (see Fig. 2). Its value dI/dt was then proportional to the steady rate of gas flow Q. The ion gauge having been calibrated (see below), this flow rate could then be obtained in

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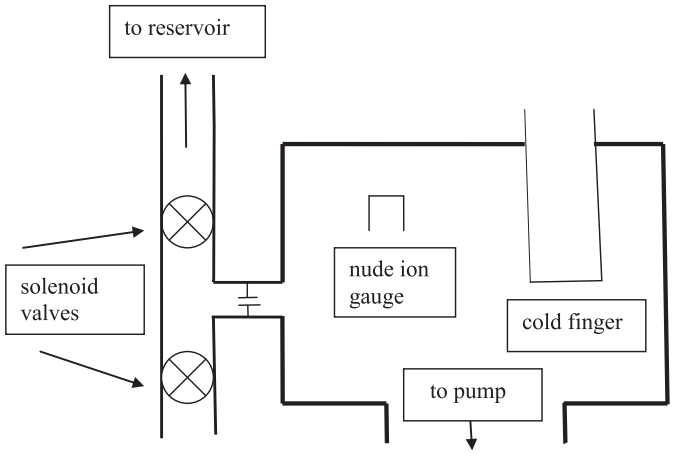

Fig. 1. Experimental arrangement (schematic).

mbar × L/s from dI/dt and the known volume of the system. However at low inlet pressure it was necessary to apply a correction to dI/dt in order to allow for the pressure rise due to outgassing from the walls. This was determined at the beginning of each measurement from the pressure rise in the time interval between closing the flap valve and the begin of gas admission. At high inlet pressure the effect of outgassing was negligible, and in Fig. 2 ($P = 930$ mbar) the slight pressure rise seen after $t \sim 1.5$ s, i.e. after the reservoir had been cut off, is not due to outgassing, but due to gas draining from the space in front of the micro-tube.

It is well known that ionization gauges of apparently identical construction are liable to differ significantly both in their sensitivity factor and in the gas factor g. Therefore the gauge was calibrated in terms of the measured Poiseuille flow of several gases through a precision glass capillary of diameter 207 ± 1 μm, and a length of 30.5 cm, which for this purpose replaced the micro-tube. From the flow rate through the capillary, calculated from the Poiseuille equation, using published gas viscosity data [5], the gauge sensitivity was found to be 8.87/mbar, and the gas factor g was determined for argon, oxygen and helium as 1.3, 0.83 and 0.24 respectively, relative to nitrogen for which g is by convention 1. From these data the rate of ion current increase dI/dt was found to correspond to a gas flow rate

$$Q = \frac{5.5 \times 10^{-3}}{g} \frac{\mathrm{d}I}{\mathrm{d}t} \text{mbar} \times \text{L/s} \tag{1}$$

where dI/dt is expressed in μA/s.

As will be shown below, in the pressure ranges of interest, the functional dependence of the flow rate Q on the inlet pressure P was either linear or could be represented by a power law. Having this knowledge, it became apparent that in order to obtain satisfactory results, it was necessary to "condition" the apparatus before each experimental run by injecting a number of gas pulses at high inlet pressure. If this was not done, the first few measurements of any run would tend to lie some distance off the trend line that was consistently followed very closely by all subsequent measurement points of the same run. We shall return again later to a discussion of the need for this preliminary conditioning.

3. Experimental results

Typical experimental results using nitrogen are shown in Figs. 3 and 4, where dI/dt is plotted against the entrance pressure P. In Fig. 3 results are given for the low pressure range, whilst Fig. 4 shows data for up to about atmospheric pressure. It is seen (Fig. 3) that up to $P \sim 49$ mbar the measured points lie on average within ±2% of a straight line passing through the origin and having slope α.

Therefore at low values of P

$$\frac{\mathrm{d}I}{\mathrm{d}P} = \alpha P \tag{2}$$

so that, using the calibration constant of equation (1), the measured gas flow rate

$$Q = \frac{5.5 \times 10^{-3}}{g} \alpha P \text{ mbar} \times \text{L/s} \tag{3}$$

This linear dependence of the gas flow on P is characteristic of molecular flow, which one expects at pressures low enough for the mean free path λ of the gas to be larger that the tube diameter d. But it should be noted that the upper pressure limit for linearity of about 49 mbar indicated by Fig. 3 implies that linearity persists in this case down to the unexpectedly low λ/d ratio of ~0.06 at the micro-tube entrance. This does of course not mean that molecular flow persists down to $\lambda/d = 0.06$, but merely shows that in this particular case the flow conditions are such that other factors come into play that compensate for the effects of intermolecular collisions in such a way that the data can be numerically represented to sufficient accuracy by an extension of the straight line from the Knudsen regime.

By definition the measured conductance of the micro-tube is from equation (3)

$$F_{\text{meas.}} = \frac{5.5 \times 10^{-3}}{g} \alpha \text{ L/sec} \tag{4}$$

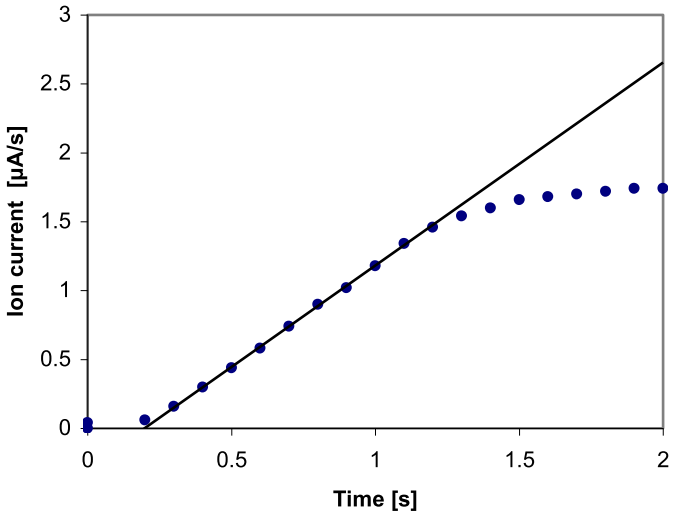

Fig. 2. Increase in ion current during gas admission. Gas: Argon $P = 930$ mbar.

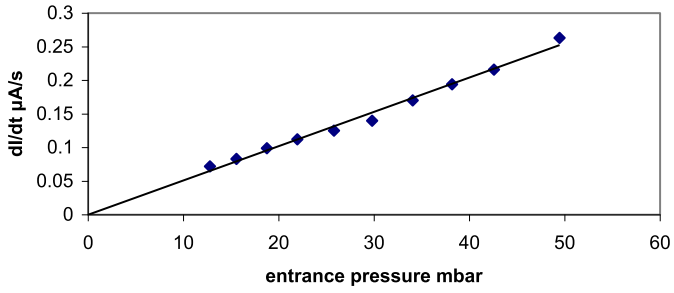

Fig. 3. dI/dt as function of entrance pressure P. Low pressure range. Gas:Nitrogen.