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Backstreaming of Impurity Gas through a Leak in a pressurized Vessel

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Abstract

The presence of a leak in a vessel containing pure gas can induce the contamination by atmospheric gas diffusing into the vessel. In order to avoid this, a gas which has to be kept pure also in presence of a leak is usually pressurized, to reduce the flow of contaminating gas through the leak owing to the molecular drag by the outstreaming pure gas.

In this paper, a simple model calculation of backstreaming based on the solution of the diffusion + drag equation in cylindrical coordinates is presented. It is shown that both the pressure difference and the dimension of the leak are critical in determining the contaminating flow, a maximum in the backstreaming flow appearing when the drag velocity of the outstreaming gas equals the diffusion velocity.

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The presence of a leak in a vessel containing pure gas can induce the contamination by atmospheric gas diffusing into the vessel. In order to avoid this, a gas which has to be kept pure also in presence of a leak is usually pressurized, to reduce the flow of contaminating gas through the leak owing to the molecular drag by the outstreaming pure gas.
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1 INTRODUCTION

A problem commonly encountered in cryogenics is the one of a leak in a gas circuit or a vessel containing a pure gas. In order to prevent contamination of the pure gas by air from the surrounding athmosphere, an overpressure is usually applied inside the vessel, so that the outstreaming gas hinders the air to flow in. The scope of this paper is to describe the relation between the leak rate of the pure gas and the contamination rate (or the backstreaming flow) of air.

This work has been initiated to define the maximal acceptable leak rate of a separating element between adjacent cold masses of the LHC accelerator (sectorization plug). The most restraining working condition for such a plug occurs during a short intervention on the machine at room temperature, when one sector is kept under helium atmosphere while the adjacent one is opened to air, the helium having to be kept free of gaseous impurity; for this reason, the calculations refrain to helium and air.

2 FLOW REGIMES

The leak is represented for simplicity as a tiny cylindrical duct of length l and diameter d, or radius R, connecting a volume filled with helium at pressure p with air at NTP, hence at pressure p_0. The outstreaming helium mass flux is q_{He}, the backstreaming air flux is q. The whole system is at room temperature.

Depending on the dimensions of the orifice, we distinguish two different flow regimes [1]. The leak can be considered as *molecular*, if the Knudsen number $Kn>1$, i.e. if the mean free path of the molecules, λ, is comparable to the linear dimension of the leak, d. If on the contrary $d>>\lambda$, or $Kn<<1$, then the flow through the leak is *viscous*. In the first case, the outstreaming helium flux and the instreaming air flux are independent, since intermolecular collisions occur with a small probability, hence an overpressure in the vessel will not affect the air leak. In the second case, the collisions between the outstreaming molecules drag the air molecules out of the duct, and the impurity flux depends on the overpressure inside the vessel.

For helium at 1.3 bar ($\lambda = 1.75 \cdot 10^{-20} T / (\xi^2 p)$ [cm], with $\xi = 2.2 \cdot 10^{-8}$ cm molecular diameter, and p in mbar), the dimension of the orifice for which molecular flow characterizes the leak is d 0.08 µm.

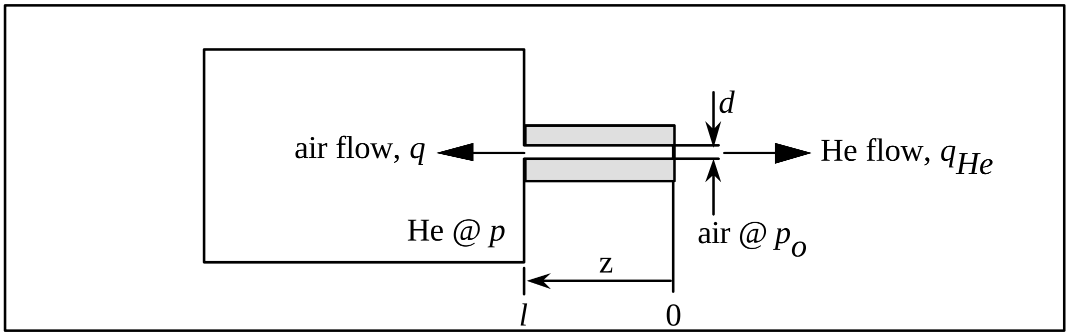

Figure 1: Model of a leak as a tiny duct of dimensions d x l, connecting a vessel filled with helium at pressure p with the atmosphere.

2.1 Molecular flow

The backstreaming air flux equals the diffusion of air in molecular conduction, i.e.,

$$q = C(p_{air} - p_{o,air}) \tag{1}$$

C being the molecular conductance of the leak. In the model of a cylindrical tube, C is given by:

$$\frac{1}{C} = \frac{1}{C_{orifice}} + \frac{1}{C_{tube}} \tag{2}$$

with $C_{orifice} = \frac{v}{4} A$ and $Ctube = \frac{\pi}{12} v \frac{d^3}{l}$, A being the orifice surface and $v = 1.45 \cdot 10^4 \sqrt{T/M}$ [cm/s] being the mean velocity of ideal gas, with M=29 molecular mass of the air. Hence:

$$C = Gv = \left[\frac{4}{A} + \frac{12l}{\pi d^3}\right]^{-1} v = \frac{\pi d^3}{16d + 12l} v = \frac{3.66 \cdot 10^4}{4d + 3l} \quad [\mathrm{cm^3/s}] \tag{3}$$

where d and l are given in [cm] in the last expression of equation (3). For d =0.08 mm, l =4 cm, and p_o =1 bar, the air flux equals 1.56 · 10^{-12} mbar l/s. In comparison, the helium leak for p =1.3 bar, would be equal to 5.5 · 10^{-12} mbar l/s. In reality, a molecular leak appears through porous media, and the overall impurity flux in that case can be much larger than the one calculated for a single duct. Summarizing, if a leak is due to a porous separating element between the vessel and the atmosphere, the overpressure in the vessel does not affect the impurity flux, which can be estimated by comparison with the helium leak.

2.2 Viscous flow

Assuming the outward flow to be laminar (it is easy to verify that a large leak, typically of the order of ~10^{-2} mbar l/s, would be characterized by turbulent flow only for very small diameters, actually such that the regime is not viscous anymore, but rather molecular), the velocity u of the helium gas is given by Poiseuille's law [2]:

$$u = u_m \left[1 - \left(\frac{r}{R}\right)^2\right] \tag{4}$$

u_m being the velocity at the center of the duct, and r the radial coordinate.

The axial flux from the volume element $2\pi r\, dr\, dz$ is given by Fick's first law of diffusion, plus a drag term:

$$\dot{M}_z = -D 2\pi r\, dr \frac{\partial \eta}{\partial z} + 2\pi r\, dr\, u(r) \eta \tag{5}$$

with η local impurity concentration. The second term on the right hand side represents the air molecules crossing the surface $2\pi\, r\, dr$ in unit time under the effect of drag by the helium molecules.

The radial flux from the same volume element is due only to diffusion, yielding:

$$\dot{M}_r = -D 2\pi r\, dz \frac{\partial \eta}{\partial r} \qquad (6)$$

The rate of change of η in the elementary volume due to the radial flow is then obtained as

$$\left.\frac{\partial \eta}{\partial t}\right]_z = \dot{M}_{z+dz} - \dot{M}_z = \frac{\partial \dot{M}_z}{\partial z} dz \qquad (7)$$

In the same way, differentiating (5) with respect to z, we obtain the rate of change of η due to axial flow. Finally, we divide by the volume element $2\pi\, r\, dr\, dz$ in order to make the equation homogeneous in the two variables, obtaining:

$$\frac{\partial \eta}{\partial t} = -D\left[\frac{1}{r}\frac{\partial \eta}{\partial r} + \frac{\partial^2 \eta}{\partial r^2} + \frac{\partial^2 \eta}{\partial z^2}\right] + u_m\left(1 - \frac{r^2}{R^2}\right)\frac{\partial \eta}{\partial z} \qquad (8)$$

Equation (8) gives the time evolution of the impurity concentration along the tube.

The problem is solved numerically by searching the steady state along the tube, and then calculating the impurity flux inside the vessel from the last cell of the discretization of the tube. We assume as boundary conditions for the calculation that at $z = 0$ the air concentration is equal to 1, whereas at $z = l$, it is vanishing. The impurity leak is then given by the diffusion flow from the very last unit volume of the tube, or

$$\varphi = -D\int_0^a 2\pi r \frac{\partial \eta(r,z)}{\partial z} dr \qquad (9)$$

The most useful form to display the results of the simulation is to compare the helium leak with the backstreaming air leak. The helium leak is itself driven by the pressure gradient, causing drift along the tube, and by the concentration gradient, causing diffusion along the tube. Instead of integrating the diffusive motion of the helium molecules into the model, we shall split the viscous leak range into two parts. At low helium leak, the molecular motion is completely determined by diffusion, at high helium leak, it is completely determined by drift, the diffusion velocity being negligible with respect to the drift velocity. In the second case, the above model applies to the description of the backstreaming impurity flux, whereas in the first, diffusion govern both fluxes.

In the latter case, the leak is equal to [1,3]:

$$q_{1,diff} = \eta \frac{p_1}{2\bar{p}L}\left[\frac{p_1}{p_2 m_2} + \frac{p_2}{p_1 m_1}\right] \cdot kT \cdot \pi a^2 \qquad (10)$$

$\bar{p}$ being the average pressure, and having assumed a constant concentration gradient along the tube for both gases. For simplification, we have also taken the same viscosity for both gases (true to within 10%). In (10), the subscript hold place for helium or air.

Figure 2a) displays the results of the calculation. We see that the maximal air leak occurs for small overpressures and small helium leaks. The worst case, in which the two fluxes are identical or comparable, occurs with overpressures of the order of some hundreds of mbar for leaks of the order of 10^{-4} mbar l/s. In figure 2b), we display the ratio between helium and air leak as a function of the leak diameter; for small leaks (inferior to 10 µm), this ratio approaches 1, or the ratio between the concentrations at the two extremities of the duct.

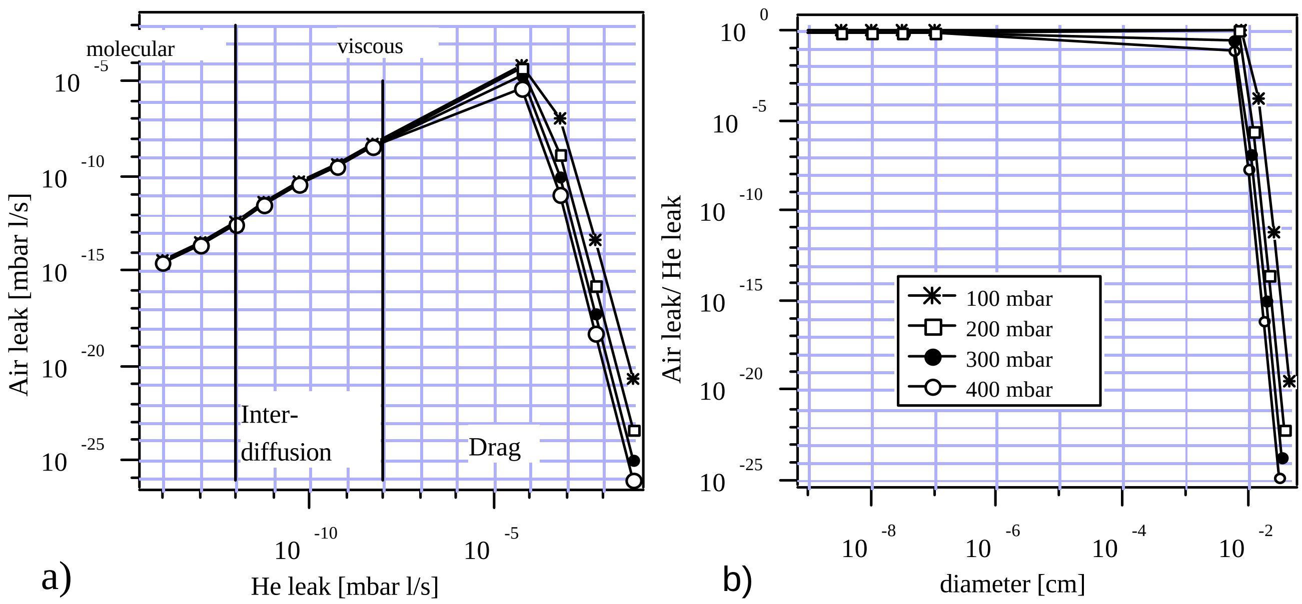

Figure 2: Backstreaming flow of air through a helium leak, calculated for different values of the helium overpressure, for a duct length of 1 cm. a) Air leak versus He leak. b) ratio air to helium leak as a function of leak diameter.

Summarizing, we distinguish between two flow regimes, a molecular one at very low leaks (or very small leak dimension), and a viscous one, at higher leaks. In molecular flow, the helium and the air flux are independent, and they differ by a factor $\sqrt{m_{air}/m_{He}}\cdot p/p_o$. In viscous flow, again we have to distinguish between two regimes. Below $5\cdot 10^{-9}$ mbar l/s (the exact value slightly depending on pressure difference), diffusion between the two gases dominates, the two opposite fluxes being identical to within a factor p/p_o. Above $5\cdot 10^{-9}$ mbar l/s, the helium flux is dominated by drift, and the outstreaming gas effectively hinders the backstreaming of impurities, with a maximal air flux appearing for helium leaks of the order of 10^{-4} mbar l/s. Therefore, this appears to be the dimension of the helium leak to which most care has to be devoted, in order to prevent contamination of the vessel by air.

4 CONCLUSIONS

Preventing contamination of a pure gas contained in a leaking vessel by the air streaming back through the leak is possible by applying an overpressure to the pure gas, only if the linear dimension of the leak exceeds ~10 µm. If this is not the case, than the overpressure has to be adapted to the maximal allowed contamination rate of the vessel. Typically, for some hundreds of mbar overpressure, the maximal rate of backstreaming occurs for helium leaks of the order of 10^{-4} mbar l/s, and it does not exceed the same order of magnitude.

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5 REFERENCES

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