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# Filling the RICH Radiator Vessel: Mixing of the Gases

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**Abstract**

An attempt was made to collect some data relevant for the understanding of the radiator gas system, in particular the mixing of the gases in the process of filling the vessel.

## 1 Introduction

In this report we shall try to see whether there are any constraints on the design of the gas system from the filling (and emptying) of the radiator gas vessel. The starting point of our discussion is the requirement that the filling of the vessel should be performed in such a way that the initial gas (nitrogen) gets mixed with the final gas ($C_4F_{10}$) as little as possible. We note, that such a requirement is not a must, as one could always build a good separation system for the two gases. Inevitably, however, the loses of freon are going to be larger in the cleaning procedure, which considering the cost of the gas should be avoided.

In the case the heavier gas is let into the radiator volume in the lowest part of the vessel, the mixing of the two gases is determined by two mechanisms, the initial mixing due to turbulence, and the diffusion. We shall first discuss the latter in some detail, and then briefly review the former.

## 2 Time development of concentrations of the two gases

To investigate the blurring of the boundary between the two gases we shall, for the sake of simplicity, assume that the radiator vessel is a rectangular box of $2a = 8$ m height, and that the boundary between the two gases is in the middle of the vessel (at $z = 0$). We further assume that the system is closed. In this case the boundary condition is given by the requirement that the flux at the top and bottom of the vessel ($z = \pm a = \pm 4$ m) equals to zero. The initial condition is that there is no light gas in the lower half, and in the upper part the concentration of it is equal to one. The solution of the diffusion equation for the concentration $c_1$ of the lighter gas,

$$\frac{dc_1}{dt} = D\frac{d^2c_1}{dz^2},$$

has for the given set of initial and boundary conditions the following form,

$$c_1 = \frac{1}{2} + \sum \frac{\sin\left((n-\frac{1}{2})\pi/a\right)}{(n-\frac{1}{2})\pi} \quad e^{-((n-\frac{1}{2})\pi)^2 t/\tau}.$$

The characteristic time $\tau$ is given by the diffusion constant D and the size of the vessel $\tau = a^2/D$. In Fig. 1 the concentration variation versus vertical coordinate is shown for three times.

It is also instructive to observe the progression in time of a layer with a given concentration value, as shown in Fig. 2. After an initial fast progression ($t < 0.01\tau$), the 1% and 10% nitrogen concentration surfaces move fairly uniformly.

What remains is the determination of the numeric value for the characteristic time $\tau = a^2/D$. In the literature I could not find any data on the particular combination of gases, and have therefore attempted to estimate its value. The diffusion constant for the diffusion of nitrogen into $C_4F_{10}$ can be estimated by taking into account its dependence on the mean free path in the gas and on the mean molecular velocity, $D = \frac{1}{3}\bar{l}\bar{v}$, which for the case of diffusion of a light gas into a much heavier one reads:

$$D = \frac{1}{3}\frac{1}{\pi(r_1+r_2)^2 n}\sqrt{\frac{8RT}{\pi M_1}},$$

where $n$ stands for the molecular density ($2.7 \cdot 10^{25}$ m$^{-3}$ at normal conditions), and $r_1$, $r_2$ are diameters of the lighter and heavier molecule, respectively. The usual factor $\sqrt{2}$ in the denominator due to the relative movement of the molecules drops out since one of the molecules is much heavier than the other, and is in this approximation assumed to be practically at rest. The diffusion constant is therefore related to the diffusion constant of pure nitrogen $D_1$ in the following way:

$$D = D_1\frac{\sqrt{2}(2r_1)^2}{(r_1+r_2)^2}.$$

To get the ratio of diameters, I have compared the diffusion constants of pure propane $C_3F_8$ (closest gas I could get), $D_2 = 0.4 \cdot 10^{-5}\mathrm{m^2s^{-1}}$, with the diffusion constant of nitrogen $D_2 = 1.4 \cdot 10^{-5}\mathrm{m^2s^{-1}}$. The resulting ratio of diameters (1.4) was then corrected by assuming that the butane $C_4H_{10}$ molecule is by another 30% larger than the propane. In addition, I

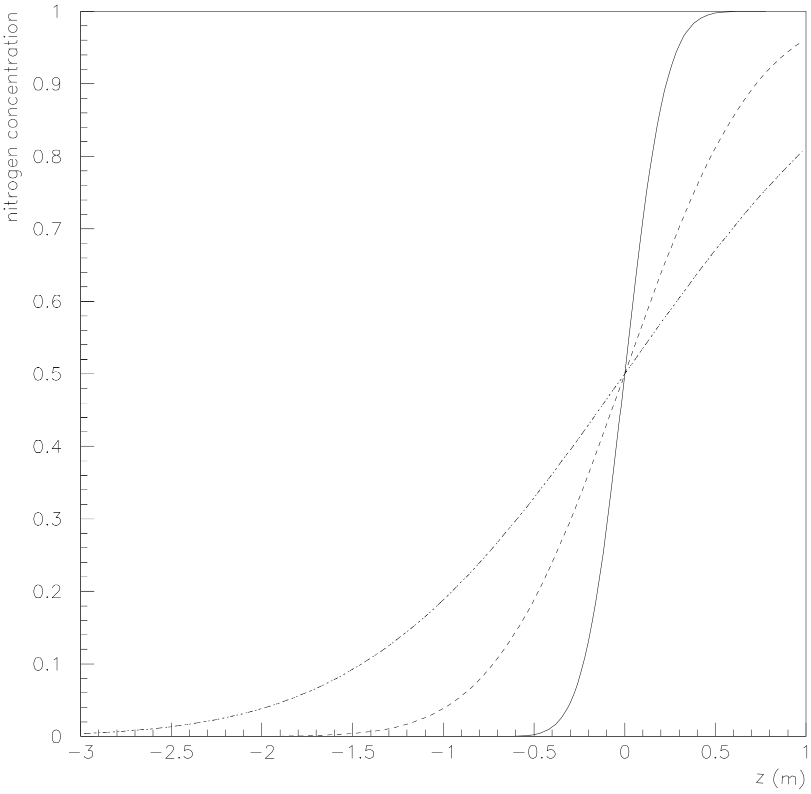


Figure 1: *Nitrogen concentration as a function of the vertical coordinate at $t/\tau$ equal to 0.001 (full line), 0.01 (dashed), 0.04 (dash-dotted).*

have assumed that the $C_4F_{10}$ molecule is of the same size as $C_4H_{10}$. It is worth noting that diffusion constants for both gases were extracted from the data on viscosity [1] by using the relation $\eta = \rho D$.

Finally, I arrived at a value of $D = 0.8 \cdot 10^{-5} \mathrm{m}^2\mathrm{s}^{-1}$. For a vessel of 8 m height, the characteristic time thus equals to $\tau = 2 \cdot 10^6 \mathrm{s} = 23$ days. The typical time scale on the plotted figures, $\tau = 0.01$, would thus correspond to about 5.5 hours. Needless to say that this is, because of the unknown value of $D_2$, only an estimate at a 20% level [1].

Note that the molecular drift due to buoyancy of the light gas in the heavier one could be neglected in the above description of the system, since the ratio of the buoyancy driven mass flux to the diffusion driven mass flux term is roughly equal to

$$\frac{\rho_2 g \bar{t}}{\rho_1 D (dc_1/dz)} = \frac{\rho_2 g \bar{l}/\bar{v}}{\rho_1 \frac{1}{3} \bar{l} \bar{v} (dc_1/dz)} = \frac{3\rho_2 g}{\rho_1 \bar{v}^2 (dc_1/dz)} \approx 0.001,$$

where the average time between two collisions is the mean free time, $\bar{t} = \bar{l}/\bar{v}$.

[1] As a cross-check, I have calculated the diffusion constant directly from the data on molecular diameters, where I could get data for $C_4H_{10}$ as well [1]. The result, $D = 0.7 \cdot 10^{-5} \mathrm{m}^2\mathrm{s}^{-1}$, is in good agreement with the estimated value.

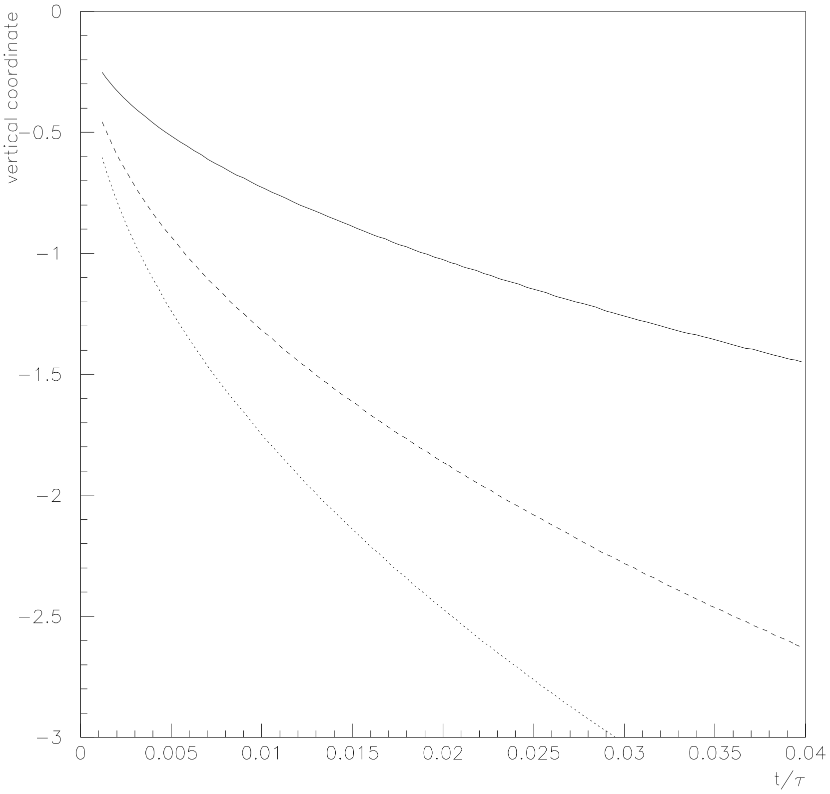


Figure 2: *Progression in time of a layer with a given concentration value:* $c_1 = 0.1$ *(full line),* $c_1 = 0.01$ *(dashed),* $c_1 = 0.001$ *(dotted).*

# 3 Gas flow into the vessel

Let us assume that the gas will be supplied to the vessel by a set of $N$ pipes of radius $R$. To determine the Reynolds number, $Re = 2\rho u R/\eta = uR/D_2$ for the case in question, we need the diffusion constant for the pure $C_4F_{10}$ gas, which we determine in a similar manner as was done above. We start from the diffusion constant for propane, correct for the difference in average molecular velocity ($\sqrt{44/238}$), and for the different size of the molecules, to arrive at $D_2 = 0.1 \cdot 10^{-5}\mathrm{m}^2\mathrm{s}^{-1}$.

The gas velocity $u$ is, of course, related to the volume flux, $\Phi_V = N\pi R^2 u$, so that we can rewrite the Reynolds number as

$$Re = \frac{2\Phi_V}{N\pi R D}.$$

Assuming a filling time of 10 h, a radius of gas pipes of 1 cm, we get $Re = 2 \cdot 10^5/N$. It is therefore clear that the we are far from a laminar flow.

Upon entering the vessel, the flux tube with such a high value of Reynolds number sets the neighbouring gas in movement (free turbulence), so that the diameter of the flux tube increases linearly with the distance $s$ from the entry point [2]. The average velocity is in this case inversely proportional to $s$, and turns out to vary as $u(s)/u(0) = 13R/s$ for $s >> R$. If we have 10 pipes of $R = 1$ cm, we get $u(0) = 0.9$ m/s, and this would be reduced to

$u(s) = 0.13$ m/s a meter away, if the flux were entering in the horizontal direction. If the gas is let in vertically, this reduction is helped by the gravity, and the gas will essentially stop in a few cm, without causing a blurring of the boundary.

# 4 Conclusions

From the considerations discussed in this report I conclude:

- If the vessel is filled in 10 hours ($t/\tau \approx 0.02$), about 0.15 of the gas volume gets contaminated with nitrogen by more than 1%, and about 0.25 is contaminated by more then 10%.

- The gas flow in supply pipes is turbulent, but does not cause a blurring of the boundary between the two gases, if the number of supply pipes is about ten.

Clearly, more data are needed to fully understand the gas system, and this report is only a contribution to the subject. The optimal filling time will most likely depend on the allowed level of nitrogen contamination, and capacity of the cleaning plant, in particular its loss/performance characteristics as a function of contamination level.

# References

[1] Handbook of Chemistry and Physics, CRC Press, Cleveland (1975).

[2] L. Prandtl, K. Oswatitsch, K. Wieghardt, Führer durch die Strömungslehre, Vieweg, Braunschweig (1990).