

EXAMPLE 9.4-1: Diffusion Tubes

Perhaps the easiest and least costly way to measure the concentration of an air pollutant is with a diffusion tube. A standard diffusion tube, shown in Figure 1, has a length $L = 71$ mm and internal diameter $D = 11$ mm. A chemical trap that either absorbs or reacts with the pollutant is placed at one end of the tube while the other end of the tube is open to the atmosphere. The tubes are usually mounted with the open end facing down (as shown) so that rain and dirt are not collected in the tube. After exposure to the atmosphere for a known period of time, the tubes are sealed and sent to a laboratory where the amount of pollutant in the trap is measured. Based on this information, the average level of pollutant in the atmosphere can be determined.

In a particular case, a diffusion tube that has been exposed to the environment for $t_{exp} = 30$ days has accumulated a total of $M_{NO_2} = 2$ μg of nitrogen dioxide. The average ambient temperature during the month was $T = 18^\circ\text{C}$. The mass fraction of nitrogen dioxide at the surface of the trap can be assumed to be zero.

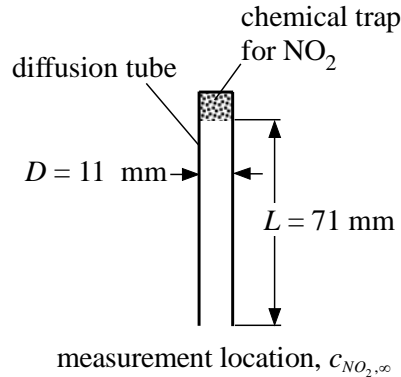


Figure 1: Diffusion tube

- a.) Estimate the average concentration of nitrogen dioxide in the environment during the measurement period ($c_{NO_2,\infty}$ in $\mu\text{g}/\text{m}^3$).

The inputs are entered in EES:

```
"EXAMPLE 9.4-1: Diffusion Tubes"
$UnitSystem SI MASS RAD PA K J
$Tabstops 0.2 0.4 0.6 3.5 in
```

```
L=71 [mm]*convert(mm,m)
D=11 [mm]*convert(mm,m)
M_NO2=2 [microgram]*convert(microgram,kg)
t_exp=30 [day]*convert(day,s)
T=converttemp(C,K,18)
p=1 [atm]*convert(atm,Pa)
```

```
"length of the diffusion tube"
"diameter of the diffusion tube"
"mass of nitrogen dioxide"
"time of exposure"
"average temperature"
"pressure"
```

The average mass flow rate of nitrogen dioxide from the atmosphere to the sample trap during the measurement period is:

$$\dot{m}_{NO_2} = \frac{M_{NO_2}}{t_{exp}}$$

The associated average mass flux is:

$$\dot{m}''_{NO_2} = \frac{4\dot{m}_{NO_2}}{\pi D^2}$$

`m_dot_NO2=M_NO2/t_exp`

"average mass flow rate of NO2"

`m``_dot_NO2=m_dot_NO2/(pi*D^2/4)`

"average mass flux of NO2"

The diffusion coefficient for nitrogen dioxide in air ($D_{NO_2,air}$) is estimated using the `D_12_gas` function in EES, discussed in Section 9.2.2. The density of the mixture (ρ) is assumed to be the density of air at atmospheric pressure and the average temperature. (This assumption is valid provided that the mass fraction of nitrogen dioxide is small).

`D_NO2_air=D_12_gas('NO2','Air',T,p)`

"diffusion coefficient"

`rho=density(Air,p=p,T=T)`

"density"

Stefan's law for this problem, Eq. (9-68) is:

$$\dot{m}''_{NO_2} = \frac{\rho D_{NO_2,air}}{L} \ln \left[1 - mf_{NO_2,\infty} \right] \quad (1)$$

Equation (1) is solved for the mass fraction of nitrogen dioxide in the atmosphere:

$$mf_{NO_2,\infty} = 1 - \exp \left(\frac{L \dot{m}''_{NO_2}}{\rho D_{NO_2,air}} \right)$$

The concentration of nitrogen dioxide in the atmosphere is therefore:

$$c_{NO_2,\infty} = \rho mf_{NO_2,\infty}$$

`mf_NO2_infinity=1-exp(-L*m``_dot_NO2/(rho*D_NO2_air))` "mass fraction of NO2 in the environment"

`c_NO2_infinity=mf_NO2_infinity*rho`

"concentration of NO2 in the environment"

`c_NO2_infinity_ugm3=c_NO2_infinity*convert(kg/m^3,microgram/m^3)`

"in microgram/m^3"

which leads to $c_{NO_2} = 39.5 \mu\text{g}/\text{m}^3$. This value can be compared to target values of $20 \mu\text{g}/\text{m}^3$ for ecosystem protection and an upper daily average regulatory limit of $100 \mu\text{g}/\text{m}^3$ for human health; these standards have been proposed in many European countries.