A thermo-effusion pump for air sampling: Theoretical considerations.

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Introduction

The study of Volatile Organic Compounds (VOCs) can yield useful information on environmental processes, such as the formation of the mysterious "fairy circles" in the Pro-Namib desert[1].

Figure 1: A "fairy circle" in the Pro-Namib desert.

The VOCs in air are easily monitored by trapping them on silicone rubber multi-channel traps (MCTs)[2] followed by gas-chromatographic analysis.

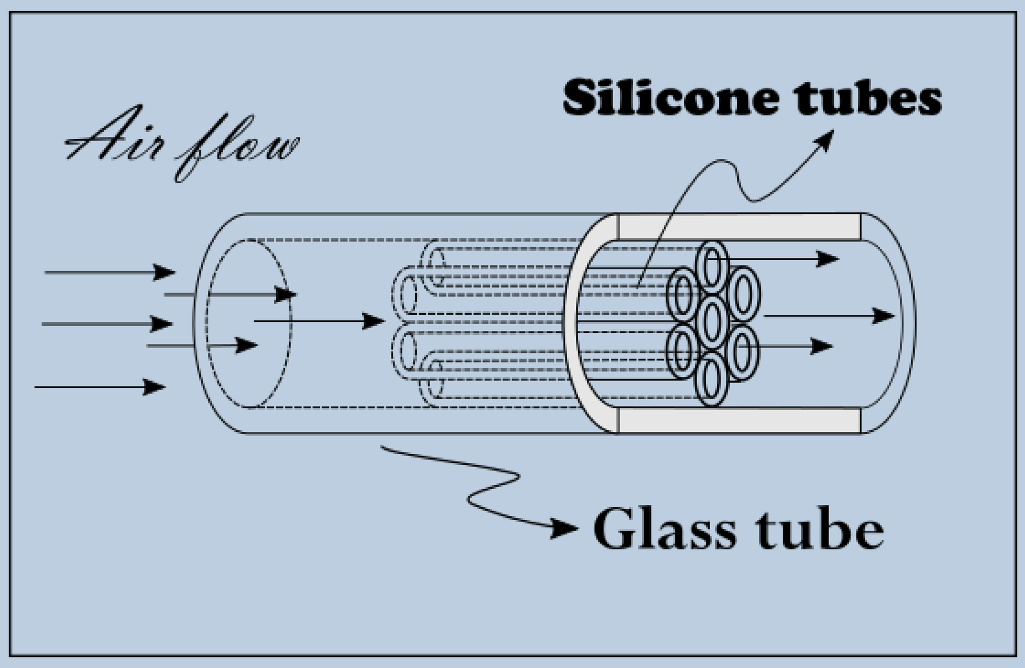

Figure 2: A multi-channel trap (MCT) consists of a bundle of silicone rubber tubes held in a glass tube. VOCs diffuse from the sampled air and is absorbed by the silicone rubber. The VOCs are freed from the silicone rubber and transferred to the gas chromatograph by heating the MCT.

Sampled air needs to be forced through the MCT, which requires a pump. An electric pump requires a power source and a trained operator. We propose to design a solar-powered air pump with no moving parts that can be easily deployed in the natural environment.
This poster discusses the theoretical underpinnings of such a pump.

Mechanism of operation

Knudsen flow regime The description of gas behaviour that applies to conditions where the mean free path of the molecules is much larger than the scale under discussion.

Effusion Transport of gas molecules through an aperture under the Knudsen regime.

Mesoporous membrane A membrane with pores between 2 and 50 nm diameter.

Under ambient conditions the scale of the pores of a mesoporous membrane is smaller than the mean free path of air, so that the transport of air is in the Knudsen regime. Effusion depends not only on the pressure, but also on the temperature. When a temperature difference exist across a mesoporous membrane in air, the air will be pumped from the cold side of the membrane to the hot side.

A concept device

Solar radiation passes through the **window** and is absorbed by the black **heater**. The heater heats the air above the mesoporous **membrane**. Below the membrane the air is kept at ambient temperature by the **diffuser** and the **cooler**. Thin air gaps are maintained on either side of the membrane by suitable seals. The stack is held together by screws through the **holder**. When the device is exposed to the sun, a temperature difference is established and thermo-effusion pumps air from the cold (bottom) side of the membrane to the hot (top) side of the membrane. This pumping action pulls air through the channels of the multi-channel trap.

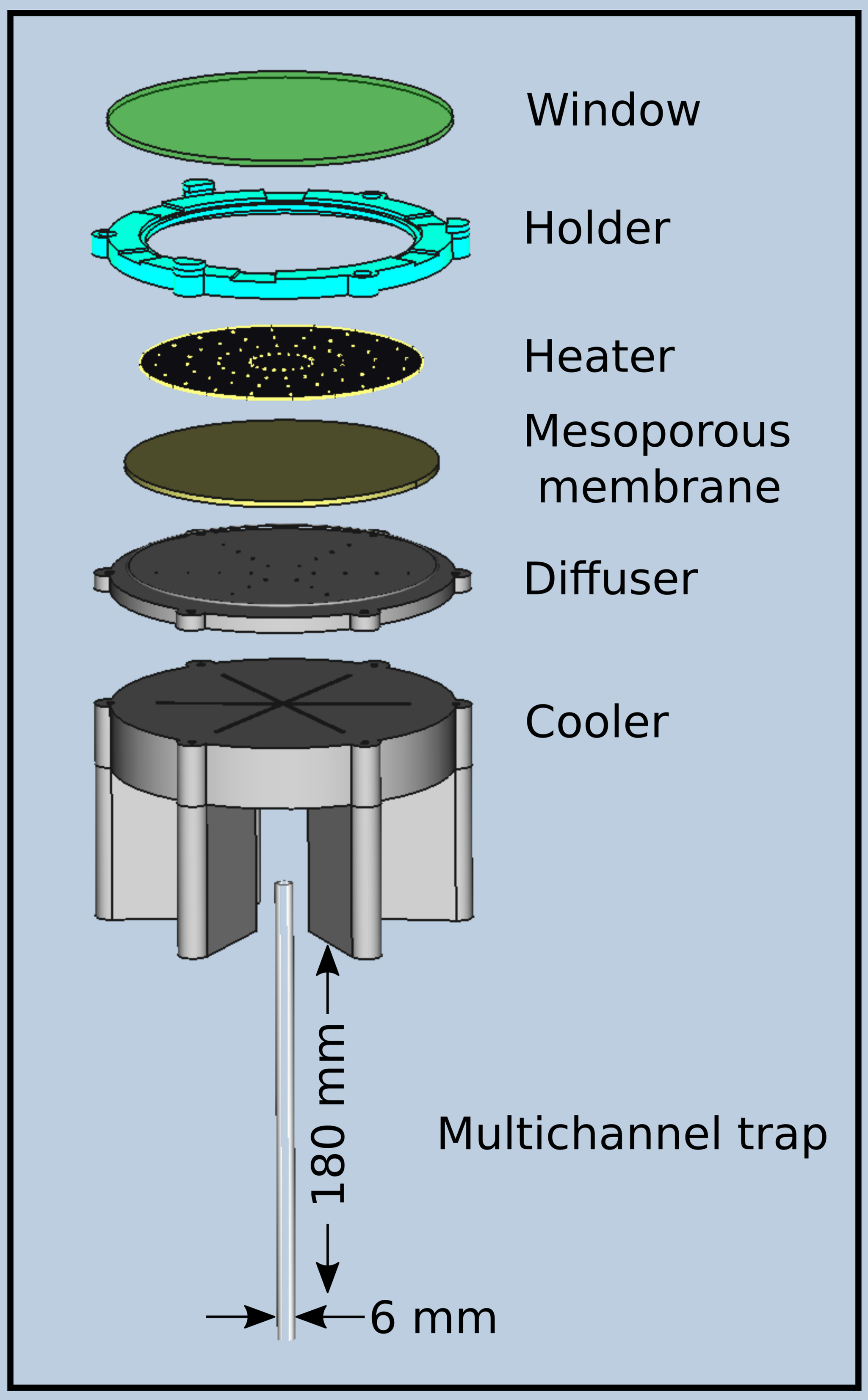

Figure 4: A concept device

Because of its open construction the pressure drop across an MCT is only 20 Pa, so that the necessary flow (up to 200 ml/min) is easily obtained a by low-power pump.

Theoretical performance

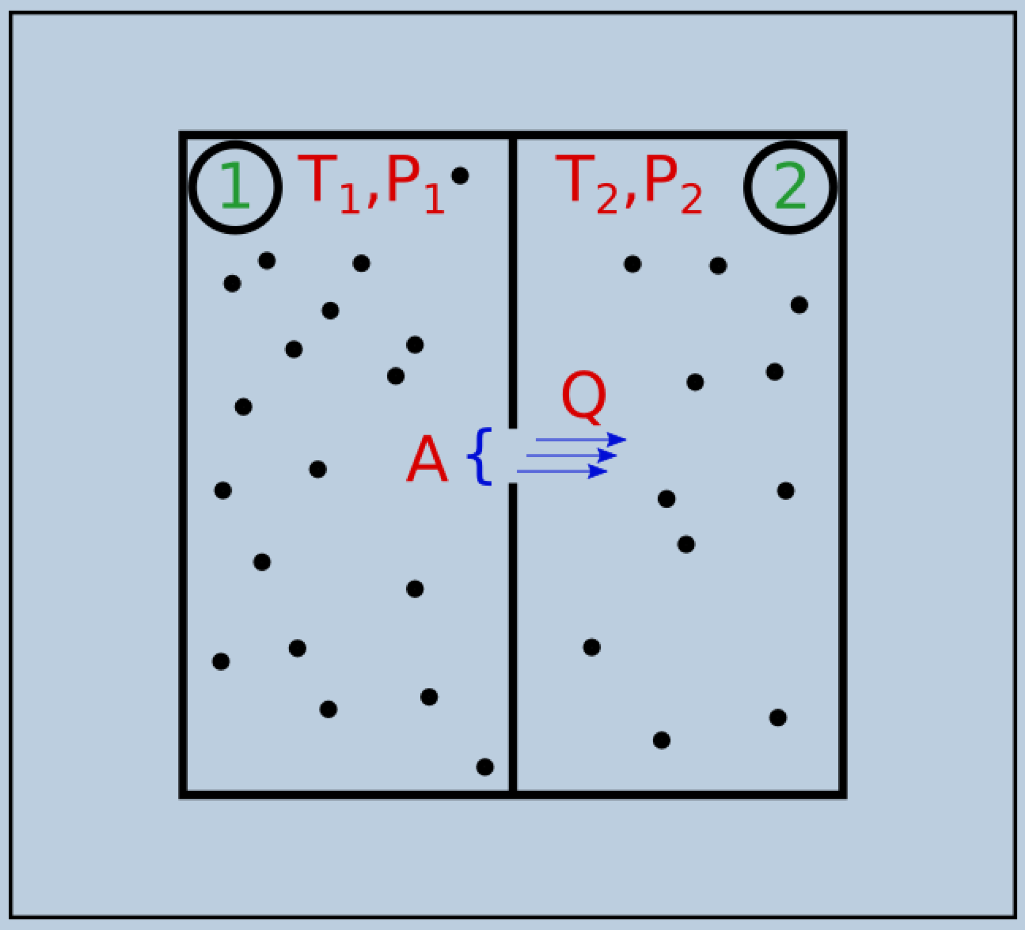

Figure 3: Effusion is the process in which a gas escapes from a container through a hole of diameter considerably smaller than the mean free path of the molecules. T_i and P_i are the temperature and pressure of the gas in compartment i, A is the area of the aperture, and Q is the flow rate.

The nett effusive flow rate Q_{total} through a mesoporous membrane can be calculated from

$$Q_{total} = \frac{A}{\sqrt{2\pi MR}}\left(\frac{P_2}{\sqrt{T_2}} - \frac{P_1}{\sqrt{T_1}}\right) \quad (1)$$

where M is the molar mass of the gas and R is the universal gas constant.

For a given volumetric flow rate Q_v at temperature T, and under isobaric conditions ($P_1 = P_2$) the required total aperture area can be calculated:

$$A = \frac{Q_V\sqrt{2\pi MR}}{RT}\left(\frac{\sqrt{T_1T_2}}{\sqrt{T_1}-\sqrt{T_2}}\right) \quad (2)$$

With $T_1 = 25$ °C and $T_2 = 30$ °C a flow of 200 ml/min can be obtained using a total pore area of 3.4 mm^2.

If we take the mean free path of ambient air to be 66 nm [3] a pore size of 6.6 nm will allow free molecular flow in the Knudsen regime.

If a membrane with pores of 6.6 nm diameter and a 20% porosity is used, a piece of only 4 mm × 4 mm will contain pores with a total area of 3.4 mm^2, which will yield the required flow.

The maximum pressure obtainable from thermo-effusion (at $Q_v = 0$) is given by $\frac{P_2}{P_1} = \frac{\sqrt{T_2}}{\sqrt{T_1}}$. For the given conditions the obtainable pressure difference is 835 Pa, which is well in excess of the 20 Pa required.

Conclusion

The calculation shows that there is no theoretical barrier to designing a solar-powered thermo-effusion air pump for sampling VOCs in air using MCTs.

While these theoretically-obtained values are certainly optimistic and a real system will not be nearly as efficient, they indicate that a useful flow can probably be obtained using practical membrane sizes and temperature differences. Membranes with suitable porosity and pore sizes are commercially available and could be used in future experimental investigations.

References

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