

Evaporation Rates for Microorganisms Captured by Research International's Electret Filters

There is concern that dry filter collection methods are harmful to delicate microorganisms. This stems in part from experience with paper filters where very high-pressure differences, up to a fraction of an atmosphere, are often used to improve sampling rates. The attendant high filter face velocities and the increased impaction and shear forces suffered by the organisms may indeed have some effect on organism viability. However, the Research International electret filters do not operate on impaction principles and face velocities are relatively low. Airflow velocities within the filter structure differ little from face velocities because of the low fill factor of about 4%. Paper filters, as a counter-example, have much higher volumetric densities and accordingly higher interior air velocities within the filter's free volume.

A third criticism of dry filter collection methods is that dehydration-sensitive microorganisms will become desiccated after being attached to the filter for a period of time. The argument is that free-floating aerosols will not dry out as rapidly as aerosol particles attached to a filter substrate because they are not subject to a large differential air velocity. We will show for air flow velocities characteristic of the SASS electret filters, that this is not a significant factor.

Measuring water evaporation rates from micron-sized aerosol particles would not be an easy task. However, there is a large body of literature on the heat transfer rate of spheres and rods in forced flows, and it is well accepted that through the use of dimensionless correlations, these results can be transferred to objects of any size until length scales become comparable to the mean free path of the gas or liquid the object is immersed in. Aerosol particles on the order of 1 micron in size are far above this limit.



It is also well accepted that the mass transfer of trace species in a fluid through diffusion and convection are analogous to the transfer of heat in the fluid and can be estimated using identical empirical correlations. This similarity principle is the basis of the Chilton-Colburn analogies⁽¹⁾. That is, at low concentration the movement of trace vapors in air is much like the flow of heat, with thermal conductivity being replaced by an ambipolar diffusion coefficient, and the heat transfer coefficient by a molar mass transfer coefficient. The transfer of heat from a sphere can be expressed as a function of the dimensionless velocity, Reynolds number, Re, and the Prandtl number, Pr, as follows⁽²⁾,

$$Nu = 2.0 + 0.60Re^{0.5}Pr^{(1/3)} \quad (1)$$

Where:

Nu = Nusselt number = hD/k

Re = Reynold's number = $(DV)/\nu$

Pr = Prandtl number = $(C_p u)/k$

This expression is valid over a wide range of flow, from stagnant conditions to a value of $RePr^{(2/3)}$ of about 100,000. In these expressions the particle diameter is "D", the local velocity is "V", the fluid's viscosity is "u", its kinematic viscosity (u/ρ) is "v", and its thermal conductivity is "k." The factor "h" is the heat transfer coefficient, which in the MKS system has units of watts/m²/K. The corresponding formula for molecular transfer is:

$$Nu_{AB} = 2.0 + 0.60 \times Re^{0.5} Sc^{(1/3)} \quad (2)$$

Where:

$Nu_{AB} = (k_x D)/(cD_{ab})$

Sc = Schmidt number = ν / D_{ab}

In this expression, D_{ab} is the diffusion coefficient, "c" is the trace species' concentration in suitable units, and " k_x " is the mass transfer coefficient, which in MKS units could be expressed as Moles/m²/mole fraction.

If an aerosolized microorganism is modeled as a sphere with an infinitely permeable negligibly thin outer membrane and a uniform interior with an average volumetric water content “ η ”, then the expression (2) for Nu_{AB} above can be used to develop an expression for the amount of time, t_e , required to fully evaporate the microorganism’s water content. This expression is:

$$t_e = (\eta\rho_l D^2)/[6D_{ab} Nu_{ab} C_{100}(RH_0 - RH_{\infty})] \quad (3)$$

Where:

ρ_l = Density of liquid water;

C_{100} = Saturation concentration of water vapor in air at the ambient temperature given as mass per unit volume of air;

RH_0 = Relative humidity immediately adjacent to microorganism’s outer cell wall;

RH_{∞} = Relative humidity of ambient air

This expression is computed for 1, 5, and 10 micron diameter microorganisms in Figure 1 as a function of air velocity. These calculations were performed assuming an ambient relative humidity of 50%, a relative humidity immediately adjacent to the cell wall of 90%, and a temperature of 20°C. The diffusion coefficient for the combination of water vapor and atmospheric pressure air was estimated to be 0.246 cm²/sec.

From these calculations we see that under either stagnant conditions or at an air velocity of 3.3 m/sec (the air velocity at the face of a Research International electret filter), a 1 micron particle will lose its water content in 440 and 400 microseconds, respectively; a 5 micron diameter particle will lose its water content in 11 and 8.6 milliseconds, respectively; and a 10 micron particle will lose its water content in 44 and 32 milliseconds, respectively. If a similar calculation is done for a rod-shaped aerosol particle that has an axis perpendicular to the air flow, then at a rod diameter of 5 microns and an air velocity of 3.3 m/sec the evaporation time is 35 milliseconds- very similar to the spherical particle.

All of these time periods are less than a second, and it would be difficult to adjust the boundary conditions so that the time to complete evaporation was greater than a few seconds for this velocity range. This modeling shows that diffusive and convective transport of water vapor from a micron-sized particle occurs very rapidly, and that the effect of air velocity on the rate in this range of velocities is not large. Vapor loss external to the particle will not dominate dehydration dynamics. If particles suffer reduced viability over time in air, it is because of processes occurring on the organism’s surface or internally, and increased air velocities after capture by an electret fiber are not relevant.

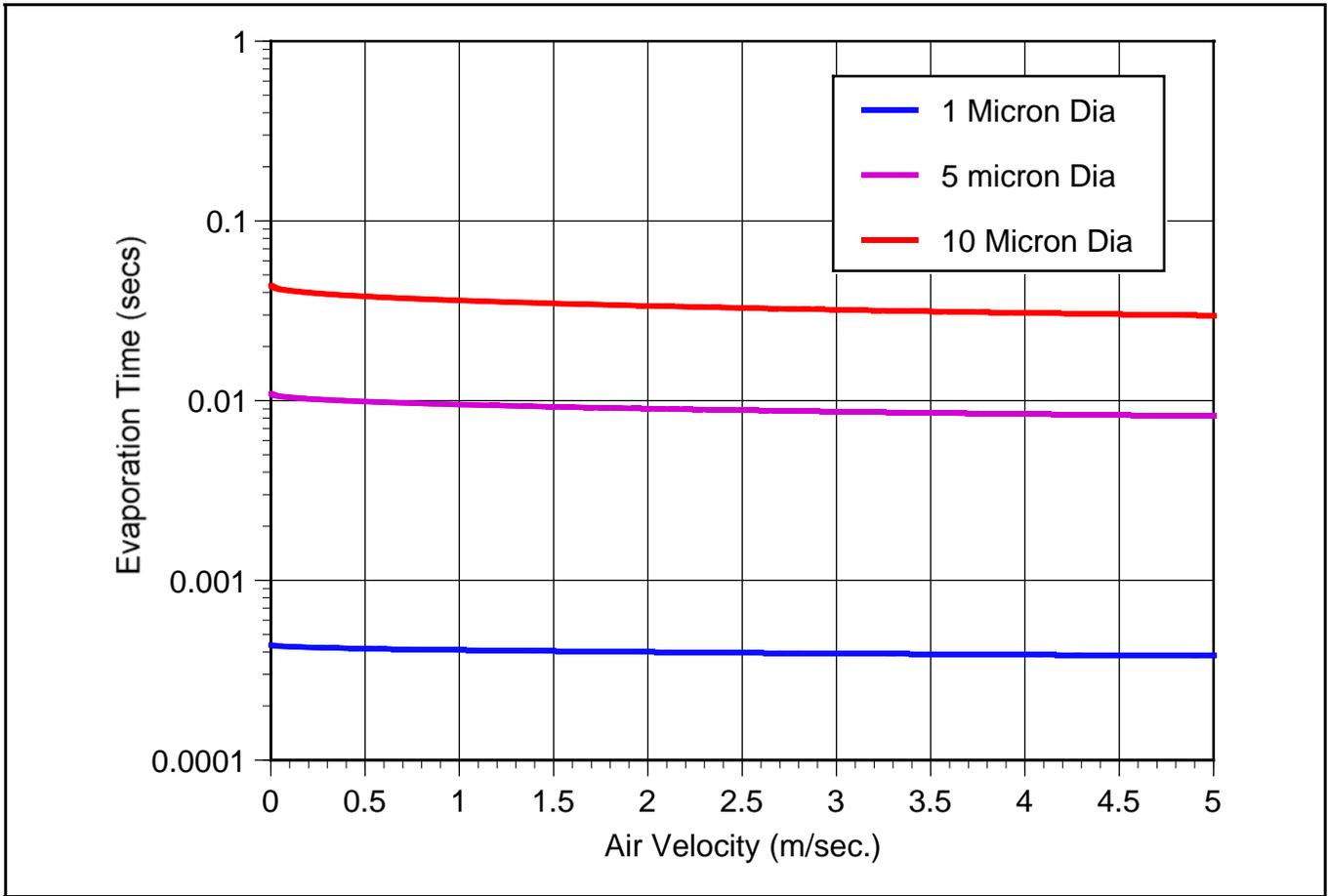


Figure 1: The time-to-evaporation of the water inside a stationary spherical aerosol particle as a function of the local air velocity and the particle size. The particle is initially assumed to be 90% water. Isothermal conditions at 20C.

References:

1. T. H. Chilton and A.P. Colburn, Ind. Eng. Chem., 26,1183 (1934).
2. Transport Phenomena, R. Bird, W. Stewart, and E Lightfoot, John Wiley & Sons, New York, N.Y., 1966.