FIBER DIELECTROPHORESIS

PRINCIPAL INVESTIGATORS
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Abstract — Dielectrophoresis is the motion of uncharged particles in nonuniform electric fields. We find that the theoretical dielectrophoretic velocity of a conducting fiber in an insulating medium is proportional to the square of the fiber length, and is virtually independent of fiber diameter. This prediction has been verified experimentally. The results point to the development of a fiber length classifier based on dielectrophoresis.

Fiber length is important in the assessment of fiber carcinogenicity;[1] hence, it is desirable to classify fibers by their length. This is difficult because most of the dynamic properties of fibers are more sensitive to diameter than length. The purpose of this work is to develop a classifier that is sensitive to length, but not to diameter. We have selected the seldom-used phenomenon called dielectrophoresis for our classifier.

A fiber placed in a nonuniform electric field becomes an electric dipole, with an excess of positive charge on one end and an excess of negative charge on the other. Because the two ends of the fiber are in slightly different electric fields, the electrical forces do not balance and the fiber moves in the direction of increasing field strength. The velocity of this motion is called the dielectrophoretic velocity. The specific purpose of this work was to quantify, both theoretically and experimentally, the dielectrophoretic velocity of a fiber.

THEORY

Fibers may be considered as prolate spheroids, with the minor axis equal to the fiber diameter D and the major axis equal to the fiber length L. An electrically conductive fiber is placed in a medium of dielectric constant K_m and viscosity η. An electric field E is applied to the medium. The problem is to determine the force on the fiber and the resulting velocity. Placzek[2] originally derived the force. The velocity is derived by matching the force with the drag force.[3] For fibers of aspect ratio β ($\beta = L/D$) the velocity is:

$$v = \frac{K_m \varepsilon_0}{24\eta} L^2 \frac{\ln 2\beta - 0.5}{\ln 2\beta - 1} \nabla E^2, \tag{1}$$

where ε_0 is the permitivity of vacuum (8.85×10^{-12} F/m). Ignoring the very weak aspect ratio dependence, the dielectrophoretic velocity is proportional to the square of the length, and is independent of the diameter.

A strong electric field is required to make dielectrophoresis an observable phenomenon; the presence of a strong field also means that electrophoresis will take place. To eliminate electrophoresis effectively, it is necessary to use alternating current (AC) voltage, rather than the DC voltage typically used for particle classification.

METHODS

A single fiber was observed moving in a well-defined electric field, and the time required to move between two positions was measured. This measured time was compared to the time predicted from Equation 1. The experiment proceeded as follows. A fiber settled in a liquid in the gap between two concentric cylindrical electrodes. A tele-microscope was used to observe the fiber, to measure its length, and to determine its position relative to the center electrode. When the fiber was at the desired starting position, the voltage was turned on and a stopwatch was started. The stopwatch was stopped when the fiber contacted the inner electrode.

The fibers were cut from aluminum wire supplied in three diameters: 25, 50, and 75 μm. The fibers were cut into lengths ranging from about 0.5 to 5 mm. A liquid medium of heavy mineral oil was used to obtain reasonably slow settling velocities. The inner electrode consisted of an aluminum rod 150 mm long and 15.7 mm in diameter. The rod was insulated with polyvinyl chloride tubing 2.8 mm thick. The outer electrode consisted of a 75 μm diameter, grounded aluminum wire spirally wound (3 winds per cm) around a cylindrical glass container with an outside diameter of 60 mm and a wall thickness of 2.5 mm. The fiber was observed with a zoom microscope. The distortion from the curved glass was eliminated by immersing the outer electrode in a flat-walled container filled with mineral oil. The AC power supply used was custom made. Its maximum voltage was 5 kV RMS at 60 Hz.

RESULTS

The parametric dependence of Equation 1 on the electric field E was confirmed. For the purpose of fiber classification, the dependence of velocity on fiber length is most important. The square dependence predicted by Equation 1 was verified over a 10-fold variation in fiber length, and a 3-fold variation in fiber diameter. The logarithm of the time required to move between two fixed positions is plotted against the logarithm of the fiber length in Figure 1.

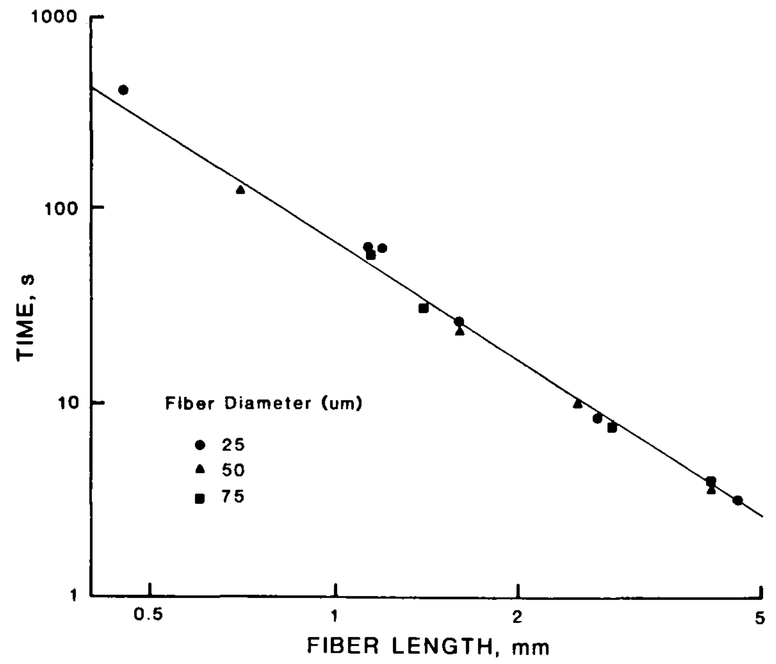

Figure 1. Effect of fiber length and diameter on time (or average velocity).

Although the velocity is not expressed explicitly, the average velocity of the fiber during its traverse is inversely proportional to the time. The line through the data is the best fit line, constrained to have a slope of exactly -2 as predicted by Equation 1. The line is a good fit to all the data ($r^2 = 0.9980$). The smallest aspect ratio of any of the fibers used was 16 and the largest was 400. Over this range, the value of $(\ln 2\beta - 1)/(\ln 2\beta - 0.5)$ varies from 0.831 to 0.919. Aside from this small effect of aspect ratio, Equation 1 predicts that the time is a function of length only, and not of diameter. This prediction is verified as shown in Figure 1 because the data from fibers of 25, 50, and 75 μm diameters all fall on the same line.

Although Equation 1 is parametrically correct, it predicts a velocity which is 40% of the actual velocity. The difference is due most likely to the assumed prolate spheroid shape for the fibers.

DISCUSSION

The fiber lengths of greatest interest to inhalation toxicologists are roughly between 5 and 200 μm. With the exception of carbon fibers, they are not electrically conductive. Equation 1 is valid only for conducting fibers. The problem is to make insulating fibers conductive and to generate sufficient force to move the fibers at a reasonable speed. It may be possible to make a fiber sufficiently conductive by adsorbing a conductive material, such as water or sulfuric acid, on its surface. Design calculations based on Equation 1 show that the shortest practical length that can be classified is about 10 μm. This is well within the range of interest to toxicologists.

REFERENCES

1. Stanton, M. F., M. Layard, A. Tegeris, E. Miller, M. May, and E. Kent. Carcinogenicity of Fibrous Glass: Pleural Response in the Rat in Relation to Fiber Dimension, J. Natl. Cancer Inst. 58: 587-603, 1977.

2. Placzek, G. Zur Dichten und Gestaltbestimmung Submikroskopischer Probekorper, Zeitschrift fur Physik 81: 81-119, 1929.

3. Happel, J., and H. Brenner. Low Reynolds Number Hydrodynamics, Prentice-Hall, New York, 1965.