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Induced Fibration of Suspensions

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This paper describes some of the phenomena found to have their origin in electrically induced fibration of small particles in fluid liquid suspension. Particular attention is given to induced shear resistances found in layers of the fluid (0.01 to 0.15 cm) when bounded by potentialized electrode surfaces. Ingredients and manner of compounding concentrated fluids capable of reversible shear resistance up to several hundred grams per cm^2 are described. Dynamic induced shear resistance or the corresponding induced bulk viscosity are shown to be a parabolic function of field strength wherein parameters dependent on surface conditions of the particles are involved. Various properties of these fluids are discussed with regard to the mechanism of induced fibration, its application in slip clutches and other hydraulic devices, and some of the factors for best results. Consideration is given to the analogous magnetically induced fibration of ferromagnetic particles in fluid suspension. It is found that the observed values of induced shear resistance approximate those predictable from the well-known formulas for tractive force in both the electric and magnetic cases. Mention is also made of fluid suspensions of ferrite powders which respond to both electric and magnetic fields.

A SERIES of experiments begun in 1939 has established that certain kinds of particles suspended in low viscosity oils tend to form an oil-occluding fibrous mass when acted upon by an electric field. The fibers form in the general direction of the field and in such a manner that the electrodes are mechanically linked together.[1] The effect has been found intrinsically reversible under action of shear or, in the case of very fluid suspensions, by action of kinetic agitation alone.

Particles found most suitable have been semiconductive solids of high dielectric constant. Particularly good results have been obtained with slightly moist hydrophile adsorbent materials of about one micron particle diameter, such as activated silica gel powders, which have been worked into a kerosene fraction to a concentration of about 50 percent by volume. This is accomplished with addition of suitable dispersing agents such as metallic soaps, sorbitol fatty acid esters, etc., and by prolonged circulation through a screw pump.

In general, concentrated suspensions with particle volume exceeding 38 percent, and with viscosity of the oil below 20 c.p. at 25°C, yield the best results as determined by rotational electro-viscometer tests using the instrument of Fig. 1. With such high concentration, migration due to cataphoresis is a neglible factor and the dynamic induced shear resistance of thin films reaches several hundred grams per sq. cm for over-all field strength of 30,000 volts per cm.

In all types of fluids, maximum ratio of induced viscosity to normal viscosity requires the use of a low viscosity vehicle in the range of 2 to 20 c.p. at 25°C in order to hold the normal viscosity to a minimum. Such vehicles for practical uses should have minimum vapor pressure times viscosity to avoid also difficulties caused by thickening as a result of volatilization. Diester liquids such as dibutyl sebacate may be used for the vehicle.

The observed increase in bulk viscosity of the fluid is apparently due to those components of force along the fluid film arising from tension of inclined fibers. At high concentrations an additional component is added, apparently caused by compression or jamming of closely packed particles.

The induced shear resistance, S, i.e., the increase above that for the de-energized fluid, is found to be nearly a parabolic function of applied potential, V,

$$S \pm S_0 = K(V \pm V_0)^2. \tag{1}$$

The supplemental potential, V_0, the supplemental shear resistance, S_0, and the factor, K, appear to be associated with the particle surfaces, depending upon the type and amount of dispersing agent used. The applied potential, V, may be either alternating or direct. With 60-cycle supply the viscometer produces a 120-cycle hum.

Typical curves obtained with the viscometer of Fig. 1 are illustrated in Fig. 2 and show Eq. (1) to be valid for a range of voltages up to over half of the breakdown value. The curves shown are from data taken at a slip speed of 65 cm per second with a spacing of 0.025 cm.

Although the described fibration is impeded by high viscosity of the oil phase, it is desirable that ingredients such as stearate soaps be added to impart gelcosity or thixotropy. Otherwise settling and phase separation in bulk may occur. A further requirement of practical importance is stability of the particle surface under the rubbing action occurring at high concentration. Stability can be achieved initially by the pumping operation mentioned.

The resistivity of the most effective fluids lies in the range of 10^8 to 10^{10} ohm cm, and depends, among other

[1] Willis M. Winslow, U. S. Patent 2,417,850 (March 25, 1947).

factors, on the amount of water or like substance of high dielectric constant imbibed by the particles. Tests on slipping clutches in which appreciable heat is generated have shown that resistivity decreases with temperature, being at 25°C several times that at 80°C.

The power factor depends upon the kind of ingredients, the field strength, and the temperature. In general the silica gel type mix gives, for 60-cycle supply, power factors down to about 0.5 by holding the water content to a minimum; for higher water content, temperature, and field strength the power factor increases to about 0.7. For frequencies of higher order such as used in tests on audiofrequency response, the power factor of silica gel mixes is low and compares favorably with electrolytic condensers. Power factor measurements were made by a comparison of currents flowing through the field responsive fluid, and a parallel resistor.

$$pf = 1-(I_1+I_2+I_3)(I_1+I_2-I_3)/2I_1I_2, \qquad (2)$$

where I_1 is the current drawn by the electric fluid sample under test, I_2 the current drawn by the parallel resistor, and I_3 the total current drawn by the paralleled sample and resistor. Such measurements are made with the electric fluid contained between the flat plates of Fig. 3 or the electro-viscometer of Fig. 1.

Efficiencies in terms of induced shear resistances and input have reached 25 kg shear per watt. The upper limit is still a matter of conjecture. Undoubtedly, it is determined by barriers at the surface of the particles which in turn determine the over-all breakdown strength of the fluid. The highest bulk breakdown value measured in the viscometer experiments was 40,000 volts per cm for a film 0.01 cm thick. It is apparent that the surface active agents used should be chosen relative to insulating qualities since most of the potential drop is between contacting particles.

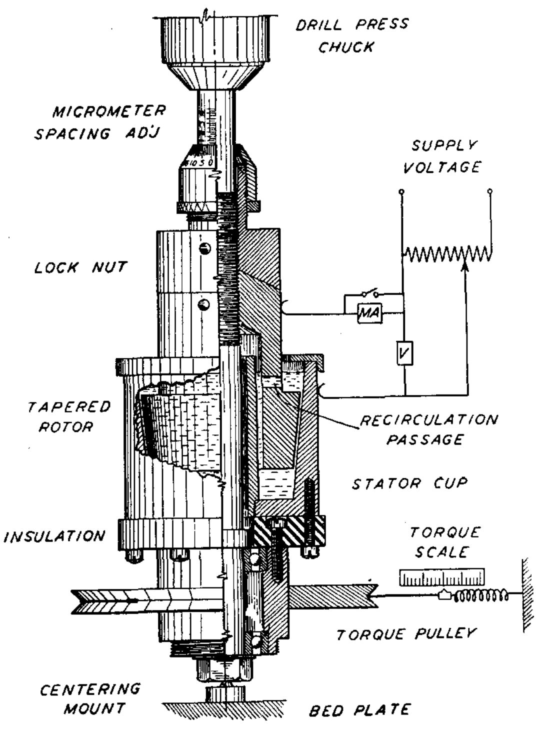


FIG. 1. Electro-viscometer.

A dilute film of zinc hydroxide suspension between microscope slides and potentialized by foil electrodes in the plane of the film enables one to see separate fibers. Formation of long and straight fibers is achieved by shearing at right angles to the field.

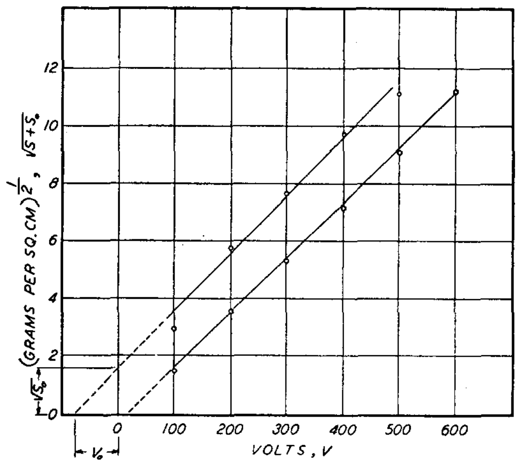


FIG. 2. Correlation of experimental shear-voltage data.

The fluids when confined have been found to exhibit some electro-striction. Also, it is found that on stopping the viscometer the dial returns rapidly to a minimum and then moves slowly upward a short distance indicative of a tightening or shortening of the inclined fibers.

The trailing edge of a plate potentialized with 60-cycle voltage and slid over a film of electro-viscous fluid will produce an oscillographic deposition of the film. Contour-like lines are obtained, caused by intermittent migration of particles at the edge region by reason of higher field intensity. This effect is shown in Fig. 3.

About ten grams of concentrated electro-viscous fluid can be lifted from a beaker between probes at 10,000 volts a.c., thus illustrating electrically induced fibration. Pictures of this experiment are shown in Fig. 4.

The response to audio frequencies can also be demonstrated with the plates of Fig. 3. With the modulated output of a small radio applied to the plates a reproduction of music and voice is had on sliding one plate relative to another.

The pumped flow of an electro-viscous fluid through a narrow passage can be regulated or blocked by an electric field normal to the direction of flow. In this manner a fluid pressure can be built up which has a parabolic dependence on the applied voltage. The valve used in experiments of this nature is shown in Fig. 5(A).

A screw-type viscosity pump containing electro-viscous fluid will develop a higher pressure and pump

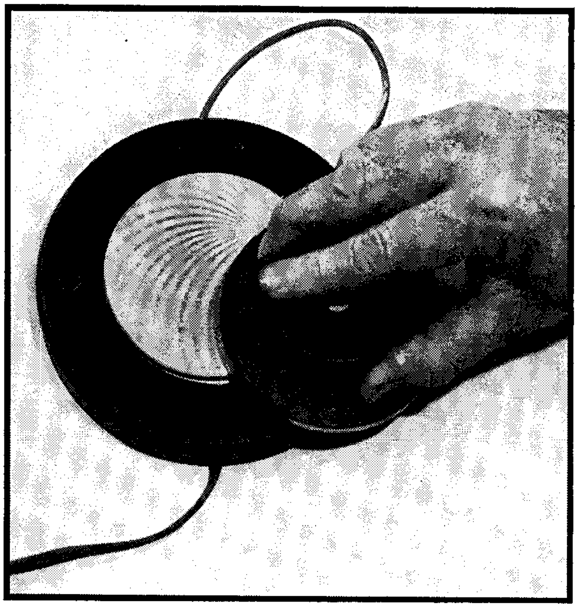


Photo by Ernest Galway.

FIG. 3. Flat metal plates showing trailing edge contours.

more efficiently when an electric field is impressed across the working space.

Induced fibration and the marked increase in bulk or averaged viscosity associated with it is to be distinguished from the induced viscosity of dilute colloids reported by Bjornstahl and Snellman.[2] In their work orientation occurs and the important factors are the nematic form and polar character of the elementary particles. In contrast, induced fibration will occur when the particles are spherical and depends basically on minute lateral migrations of particles to regions of high field intensity between gaps of incomplete chains followed by mutual attraction thereafter. By the present effect it is possible to produce a greater relative change in bulk viscosity and the induced resistance to shear is many times larger in absolute value.

A study of magnetically induced fibration of concentrated iron suspensions has recently been undertaken at the National Bureau of Standards.[3] The behavior of magnetic fluids is very similar to electric fluids, differing mainly in that magnetic saturation rather than dielectric strength is the limiting factor. The N. B. S. experiments have shown it possible to exceed the above efficiency of electric fluids by the use of an efficient magnetic circuit. On the other hand, the electric effect is favored by small over-all weight of the equipment and its limitations have not yet been reached.

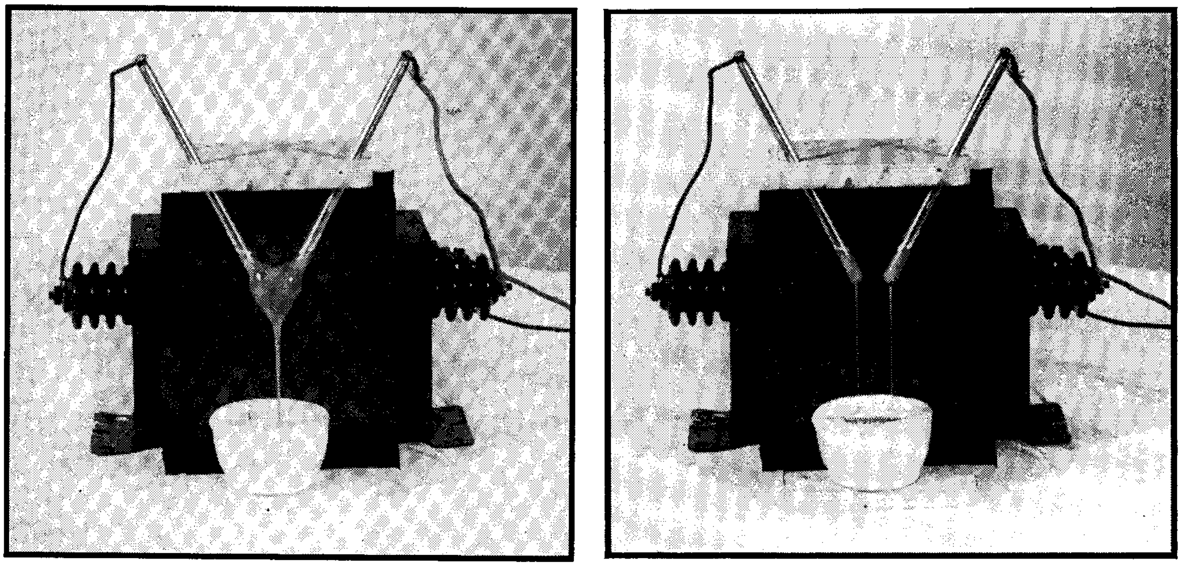
The shearing resistance, on theoretical grounds, is the tractive force normal to supposedly flat parallel particles multiplied by a factor A to account for the actualities of reduced particle contact area and the effective inclination of fibers. The tractive force in dynes per cm² between flat parallel particles is

$$F = kE^2/8\pi \tag{3}$$

for the electric effect, and

$$F = B^2/8\pi \tag{4}$$

for the magnetic effect, where E is the field intensity *between particles* in abvolts per cm, and B is the magnetic induction *between iron particles* in maxwells. A value for A of about 0.05 gives approximate agreement between calculated and observed shear resistance in the two cases. The factor k applicable in Eq. (3) to



Photos by Paul Saville.

(A) (B)

FIG. 4. Electrically induced fibration between probes. (A) voltage = 10,000; (B) voltage = 0.0.

[2] Von Y. Bjornstahl and K. O. Snellman, Kolloid Zeits. 79, 259 (1937).
[3] "Magnetic fluid clutch," News Bull. J. Research Bur. Stand. 32, 54–60 (May, 1948).

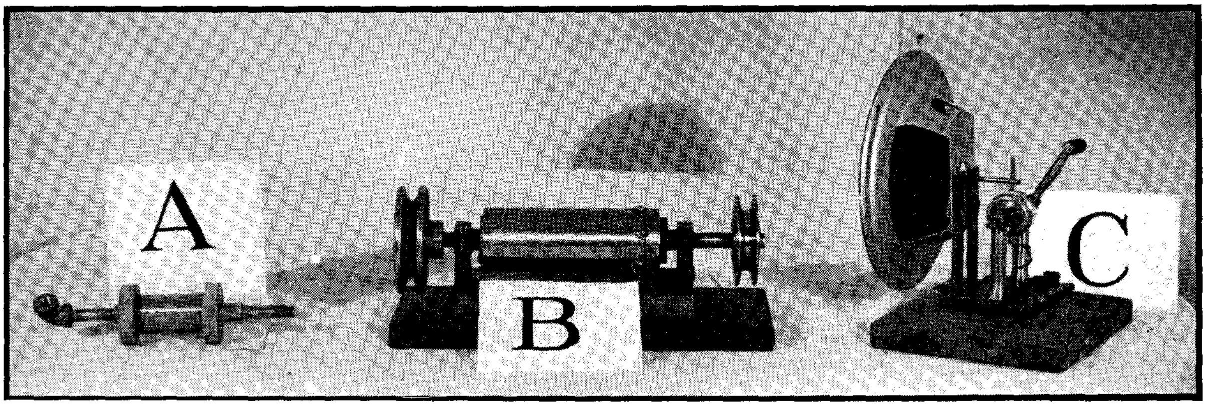


Photo by Paul Saville.

FIG. 5. Electrically controlled valve with no moving parts (A); clutch or brake (B); clutch-driven loudspeaker (C).

the electro-fibration effect is the dielectric constant of the boundary layers between adjoining particles.

It is also apparent that the bulk dielectric constant for the electric fluids in the direction of the field is about 0.05 of that for a pile of sheet conductors of individual thickness equal to the mean particle diameter and separated by films of thickness equal to the films between the particles in contact. Likewise, for magnetic fluids in the presence of a field, the bulk permeability in the direction of the field is about 0.05 what it would be if the fluid were replaced by a similar pile of ferromagnetic material of the same composition as the particles. The factor 0.05 is representative of those found for intense fields and varies to some extent with the shape of the particles. A lower factor is obtained for fluids having particle volume lower than 50 percent, and for low field strengths.

The rate of response and release for electric fluids is found to be higher than for magnetic fluids. This is an important advantage for certain applications of the effect. Moreover, the difficulties encountered in the use of magnetic fluids, caused by residual magnetization, have no counterpart in the use of electric fluids. On the other hand purity of the ingredients used is far more important for electric than magnetic fluids. Thus, while soaps or other surface agents are used to advantage in both types of fluids to render them thixotropic and non-settling, and to preclude agglomeration which causes unstable torque during operation at high shear stresses, such agents in the case of the electric fluids must be chosen for minimum conductivity.

Maintenance of proper clearance between clutch surfaces is inherently more important for the electric than the magnetic type but is found to present no difficulties. For example, the small clutch unit of Fig. 5(C) has a clearance of about 0.01 cm maintained by the fluid itself, being in this respect like the plates of Fig. 3. The unit of Fig. 5(C) operates on a modulated bias of about 100 volts which is about one-third of the breakdown value. A similar unit having fluid-maintained spacing and connected to drive a switch was operated in a recycling circuit for 18 days (200,000 cycles) without breakdown of the fluid film.

While oil-like vehicles are used for both electric and magnetic fluids, in the first of necessity to sustain the electric field and in the second to lubricate and reduce eddy current losses, it is possible to use conductive vehicles in case of magnetic fluids. For example, a magnetic fluid of iron powder and mercury similar to one patented by Lucas[4] shows high values of induced shear resistance in a viscometer when subject to magnetic fields produced by direct or low frequency current.

Finely ground precipitates of magnetic oxides, that is, Fe_3O_4 and composite oxides or so-called ferrites of the type described by Snoek,[5] when dispersed in a low viscosity oil, have been found responsive to both magnetic and electric fields, either separately or simultaneously applied, to produce induced shear resistances many times the normal shear resistance of the fluid. Apparently, for best results, the internal resistance of the particles of an electric fluid should be moderately high and possessed of electron trapping properties. The viscometer used in testing fluids responsive to both magnetic and electric fields is similar to that shown in Fig. 1 except that the rotor has five annular grooves containing alternately wound magnetizing coils.

Relative to ultimate possibilities of fibration effects, it is a curious fact that the tractive force for pure iron, when subject to maximum magnetic induction of about 22,000 maxwells, is substantially the same as the tractive force for thin dielectric, when subject to maximum electric field strength, the latter being of the order of 4 to 15×10^6 volts per cm.[6]

In general, both phenomena have been found quite forceful, depending, of course, on the area of the working film, thus pointing to practical applications in clutches and brakes, Fig. 5(B), and hydraulic equipment, Fig. 5(A), using concentrated suspensions for the working fluid, these devices lending themselves to smooth regulation through electrical control of the applied fields.

[4] Ralph Lucas, U. S. Patent 2,149,782 (March 7, 1939).
[5] J. L. Snoek, U. S. Patents 2,452,529 to 31 (October 26, 1948).
[6] A. E. Austin and S. Whitehead, Proc. Roy. Soc. 176, 33 (1940).