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# Magnetic fluids—part 2

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In part 1 (*Phys. Educ.* 1985 **20** 61–5) we discussed what might be termed the internal features of magnetic fluids, but what of their bulk response to magnetic fields? At the simplest level magnetic fluids are attracted to a magnet—you can move a magnet near the fluid surface and see it follow the magnet around. Alternatively if a magnetic fluid is placed in a petri dish with a vertical current-carrying wire passing through it, the fluid will rise up the wire in response to the cylindrically symmetric field $H$; the rise however is small, typically only 10 mm for a 400 A current passing through a 5 mm diameter wire! The rise in the fluid level $h$ is given approximately by the equation

$$\Delta h \sim \mu_0 I^2 / 8\pi^2 \rho g r^2 \qquad (1)$$

where $I$ is the current, $\rho$ the fluid density, $g$ the acceleration due to gravity and $r$ the wire radius.

A simpler and more elegant experiment is shown in figure 1 where some magnetic fluid has been placed in the Quinke's tube apparatus, originally used to determine the paramagnetic susceptibility of certain salt solutions. As the magnetic field in the electromagnet increases, the fluid is attracted into the high uniform field region between the poles of the magnet, rising until the magnetic potential energy due to the fluid's magnetisation is balanced by its own hydrostatic potential energy $h\rho g$. The change in height $h$ which depends upon the difference in the magnetic field between the two arms is given for small fields by

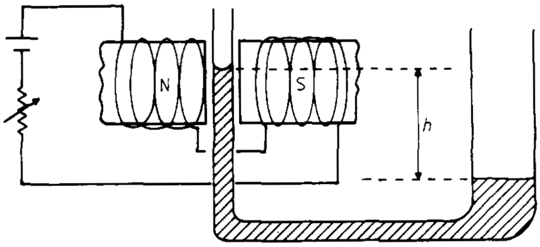
$$h = (\mu - \mu_0) H_0^2 / 2\rho g \qquad (2)$$

where $\mu$ is the initial permeability of the magnetic fluid. In practice (using, for example, a commercially available magnetic fluid) the fluid rise can easily be as large as 100 or 200 mm for a field of 400 kA m$^{-1}$ and thus may readily be demonstrated in the lecture theatre or laboratory.

In the Quinke's tube experiment we assume that the magnetic field is uniform in the gap of the magnet. However, another interesting property can be observed if the fluid is intentionally made non-uniform and a non-magnetic object dropped into the magnetic fluid as shown in figure 2. Energetically the magnetic fluid would like to be in the highest field region; thus the fluid tends to expel any non-magnetic objects into the low field region. This effectively enhances the Archimedean buoyancy of the non-magnetic object. This effect can be quite dramatic; it is relatively easy in the laboratory using tapered or wedge magnet pole pieces to make field gradients sufficient (i.e. ~10 T m$^{-1}$) to float aluminium and brass of specific gravities 2.7 and 8.5 g cm$^{-3}$ respectively in a typical magnetic fluid of specific gravity close to 1.0.

In the lecture demonstration buoyancy was demonstrated using a brass cylinder suspended by a fine wire from an electrobalance, the cylinder being immersed in a magnetic fluid which was itself placed between the poles of an electromagnet capable of producing ~0.1 T in the central region of the pole gap. As the magnetic

**Figure 1** Quinke's tube apparatus

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field was increased the apparent weight of the cylinder recorded by the balance decreased. Such apparatus can be used quantitatively to determine magnetic fluid properties.

Analytically all these special magnetic fluid properties can be explained by adding an extra term to the Bernoulli equation, so that now

$$P+\rho g h+\tfrac{1}{2}\rho v^2-\mu_0\int_{H_1}^{H_2} M(H)\,\mathrm{d}H=\text{constant} \quad (3)$$

where $P$ is the pressure, $v$ is the velocity and $M(H)$ the magnetisation of the fluid. $H_1$ and $H_2$ are the minimum and maximum fields bounding the volume of interest. Physically this modified Bernoulli equation also permits thermal instabilities, such as simple convection, for example, to be prevented by an appropriate choice of magnetic field gradient; the complexities and subtleties become almost endless!

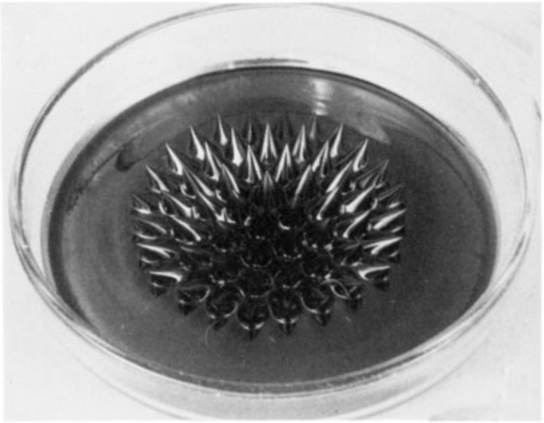
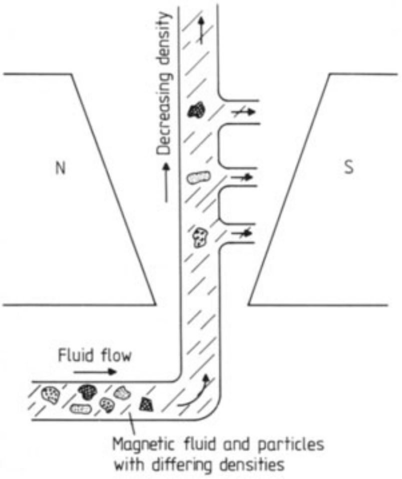


**Figure 3** The surface instability observed for a $Fe_3O_4$ water-based magnetic fluid in a magnetic field approximately normal to the fluid surface

**Surface instability**

Perhaps the *pièce de résistance* of bulk properties, however, is the surface instability. Here a magnetic field is arranged to be normal to the fluid surface. If the magnetic fluid is sufficiently concentrated then as the magnetic field is increased in strength a critical field is observed at which small peaks form in the fluid's surface; both their height and number then progressively increase as the field increases further until the fluid is magnetically saturated. This effect is shown in figure 3 where the field departs slightly from normality causing the peaks to tilt outwards. This complex undulating surface structure is the minimum energy surface for a magnetic fluid in the presence of a normal field and is a consequence of the competition between surface tension, magnetic and gravitational forces.

**Figure 2** Magnetic separation of large non-magnetic particles entrained in a magnetic fluid utilising the magnetic buoyancy effect




The peaks form on the surface when the fluid magnetisation $M$ exceeds the critical magnetisation $M_c$ where

$$M_c^2 \simeq \frac{2}{\mu_0}(g\rho\gamma)^{1/2} \quad (4)$$

where $\rho$ and $\gamma$ are the density and surface tension of the fluid respectively, whilst the initial peak separation is given by

$$L \simeq \frac{2\pi}{g}\left(\frac{\gamma}{\rho}\right)^{1/2} \quad (5)$$

Equation (4) implies that to observe the surface instability in a commercial magnetite–water-based fluid where $\rho \sim 10^3\,\mathrm{kg\,m^{-3}}$ and $\gamma \sim 80\,\mathrm{mN\,m^{-1}}$ then $M$ must exceed $\sim 6.7\,\mathrm{kA\,m^{-3}}$. Thus the surface instability will be observable in commercially available fluids whose saturation magnetisation is $\sim 8\,\mathrm{kA\,m^{-3}}$ ($\sim 100\,\mathrm{G}$), remembering that the magnetic field required to produce this magnetisation will be determined by the Langevin function (see part 1), in practice about 0.3 T for an $8\,\mathrm{kA\,m^{-3}}$ saturation magnetisation magnetite–water fluid. Thus the often used *lower school* phrase that a liquid *finds its own level* does not have quite the same physical consequences for a (liquid) magnetic fluid.

One further special fluid property, although not strictly a bulk property in the sense we have just been using, is birefringence. In a high magnetic field the constituent particles of a magnetic fluid tend to align and form chain-like aggregates along the magnetic field direction. In addition the particles are never perfect spheres but slightly

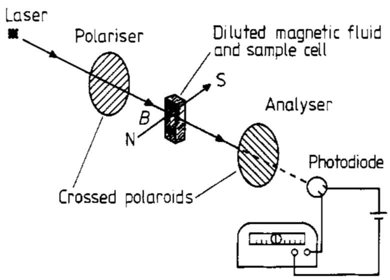



**Figure 4** Apparatus used to observe optical anisotropy in diluted magnetic fluids that show significant particle chaining in a magnetic field

elongated. The net effect is that in a high field the fluid becomes optically anisotropic, and this anisotropy can be detected using a transmitted light beam and crossed polaroids. Consider the apparatus of figure 4; in zero field with the polaroids crossed no light passes through to the simple photoresistive detector, but as the field is increased the fluid begins to behave rather like a polaroid itself, passing or scattering light preferentially in that direction parallel to the magnetic field, and so 'uncrossing' the polariser and analyser. As the field increases so the particle alignment and aggregation increase and more light reaches the photodetector. If the chains are many thousands of particles long the optical anisotropy is relatively large: magnetic fluids diluted even a thousand to one so as to appear almost clear to the naked eye show marked anisotropy even in the simple apparatus of figure 4.

There are many other interesting magnetic fluid properties such as their rotation and reverse rotation in rotating magnetic fields, enhanced and non-Newtonian viscosity in static magnetic fields and anomalous osmotic pressure to name but a few. Space precludes their discussion, however, if we are to mention a few of the practical applications of magnetic fluids.

## Applications

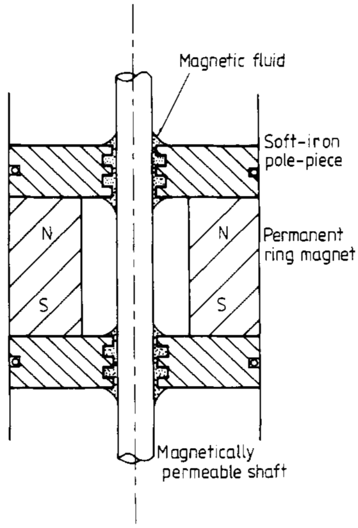
Despite the existence of a host of patents worldwide covering a multiplicity of applications, magnetic fluids have seen only limited technical acceptance. This, in part, is due to our present inability to tailor fluid properties to meet many of the design specifications required.

Magnetic inks, containing micrometre sized particles, are used in large quantities for magnetic inspection but little development has been made in their magnetic properties for forty years. Recent work has been in the incorporation of fluorescent dyes and pigments for easy visual detection. Ferrofluids, as the fine particle fluids are known, have been on the market for over 15 years. Their most successful application has been in rotary seals (figure 5). The fluid is retained between the pole pieces of a permanent magnet and forms a seal around the rotating shaft. A typical ferrofluid utilising an oil carrier liquid will form an excellent high vacuum seal against atmosphere pressure.

The viscosity of a ferrofluid is also a function of the external flux density and this effect finds application as dampers for stepping motors. Stepping motors are devices which rotate a shaft by a discrete angular step in response to an electrical pulse and are thus directly compatible with the pulse trains generated by a digital computer. Using them, computers can control mechanical motions in, for example, robots. In precision applications it is important to avoid overshoot and this is the function of the elegant ferrofluid damper (figure 6). A large inertial mass containing a permanent magnet self-levitates by the buoyancy effect in the ferrofluid surrounding it, keeping it off the container walls! For very rapid changes, the ferrofluid appears extremely viscous and thus only slowly attains the final equilibrium position. The damping is due to a mixture of viscous, inertial and eddy current losses.

An application in consumer electronics is the liquid-cooled hi-fi loudspeaker (figure 7). A small quantity of ferrofluid is introduced to the region surrounding the voice coil. It is retained, conveniently, within the region of maximum field where the voice coil is also situated. As the power

**Figure 5** Schematic diagram of a rotary vacuum seal



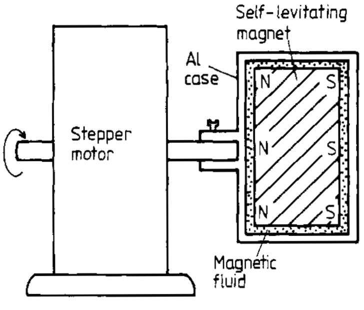
output from a loudspeaker is limited by the rate at which heat can be conducted away from the voice coil, such a good conducting medium surrounding the coil enables the power output to be increased by a factor of about three for the same operating temperature of the voice coil.

On a bulk scale, in Japan, scrap metal is being separated using ferrofluid. In a magnetic field gradient, the density of the ferrofluid can be varied and arranged so that, for example, aluminium cans will float while zinc scrap will sink. Several tons of scrap can be processed per hour using the pilot plant now in operation. On a microscopic scale, magnetic fluids with surfactant molecules consisting of enzymes which attach themselves specifically to certain types of bone marrow cancer cell have been used to separate healthy and malignant cells in a magnetic field gradient. Very substantial clinical success has been achieved with this technique. As suggested earlier, the main limitation to the application of fine particle fluids has been the absence of techniques for tailoring fluids to suit specific requirements. We believe we are on the threshold of being able to achieve this and expect to see the applications diversify very rapidly over the remainder of the decade.

**Notes for physical sciences teachers**

At the request of the editor we have included along with the discussion of each demonstration practical information which is intended to be sufficiently detailed to assist those readers who wish to reproduce the demonstrations in their own teaching laboratories. In general, with a little patience and ingenuity, only modest magnetic fields and about 20 ml of low viscosity ('100 gauss' or greater) commercial magnetite–water-based magnetic fluid are required. Commercial fluid may be obtained from Ferrox Ltd, Black Horse House, 11 West Way, Botley, Oxford OX2 0JB. The truly adventurous and chemically adept who wish to produce their own water-based fluids are referred to Khalafalla and Reimers (1980).

Figure 6 Cross-sectional diagram of a magnetic fluid stepper motor damper



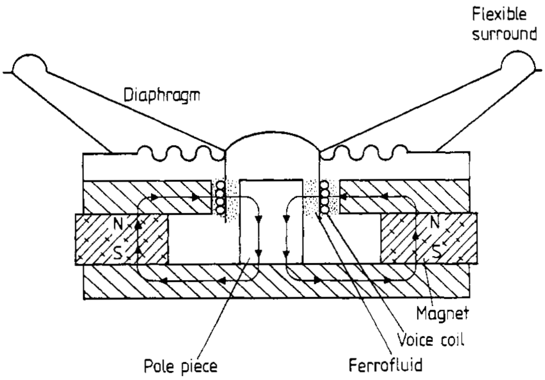




**Figure 7** Cross-sectional diagram of a liquid-cooled hi-fi loudspeaker

**Reference**

Khalafalla S E and Reimers G W 1980 *IEEE Trans. Magn.* **MAG-16** 178–83

# Physics at Work

The IoP helps to organise a number of Physics at Work exhibitions each year aimed students in the 14–15 age range. At each exhibition up to a thousand local children tour a number of displays in small groups, and exhibitors spend roughly 15–20 minutes with each group. This year exhibitions will be held in Farnborough (8–10 July), Kent (16–18 July), Cambridge (17–19 September) and Bodmin (15–17 October). There are also provisional plans for exhibitions in Northampton (July), Humberside (September), Enfield (Autumn), Edinburgh (Autumn), Newcastle, Manchester, Cardiff, Coventry and Dublin.

Further details can be obtained from Brian Davies, The Institute of Physics, 47 Belgrave Square, London SW1X 8QX (tel. 01 235 6111).