Magnetic vortex fluids offer new routes for non-contact mixing and heat transfer

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Background: There are many industries and technologies that require effective control of heat and mass transfer operations, and oftentimes these processes employ some means to move a fluid. Some conventional methods of moving fluids include:

- ***Forced convection–*** typically requires some combination of pumps, impellers, valves and pipes. These components require maintenance and are usually in direct contact with the working fluid (which can be at substantial pressures), making these systems prone to failure.
- ***Natural convection–*** a buoyancy-driven process that requires both gravity and a *parallel*, *destabilizing* thermal gradient, which limits its applicability. For example, natural convection cannot be used to cool the underside of a hot surface.
- ***Thermomagnetic convection–*** exploits the temperature-dependent magnetization of ferrofluids to induce flow, by applying a strong magnetic field gradient parallel to an existent thermal gradient. The requirement of a strong magnetic field gradient makes scaling up this technique difficult.
- ***Magnetohydrodynamics–*** requires the injection of large currents into a conducting liquid to which strong magnetic fields are applied to generate the Lorentz force which drives fluid motion.

Our approach: We have discovered several classes of spatially uniform, triaxial magnetic fields of modest strength that create ***vortex fluids*** in dilute magnetic particle suspensions *without requiring gravity, a thermal gradient, or a magnetic field gradient.* The triaxial magnetic fields we employ fall into one of two types:

- ***Symmetry-breaking Rational Fields–*** comprised of two orthogonal AC components whose frequencies form a rational number (*e.g.*, 1:2) and an orthogonal DC field that breaks the symmetry of the biaxial AC field to create the parity required to induce deterministic vorticity.
- ***Rational Triads–*** comprised of three orthogonal AC components whose frequency ratios are rational (*e.g.,* 1:2:3). Continuous 3D control of the direction and magnitude of the vorticity vector is possible by progressively transitioning the field symmetry of a rational triad by applying a DC bias along one of the principal axes. When one or more of the field frequencies are phase modulated the result is elaborate vorticity vector orbits, which provide the basis for highly effective mixing strategies wherein the vorticity axis periodically explores a range of orientations and magnitudes.

The defining characteristic of vortex fluids is that they possess a ***spatially-uniform torque density***. This unique aspect imparts vigorous vorticity to the suspension, enabling a variety of peculiar behaviors such as: active wetting, negative viscosity, and striking biomimetic dynamics. Additionally, the ability to control the strength and direction of the vorticity—by appropriate selection of the applied multiaxial rational magnetic fields—makes vortex fluids attractive for applications involving non-contact mixing and/or heat transfer. A few examples are highlighted below.

Advantages of Vortex Fluids

- ***Dilute particle suspensions*** (only ~1–2 vol.% of magnetic particles required).
- Spatially uniform torque density results in ***unique dynamics***.
- Mixing torque is ***independent of field frequency and fluid viscosity*** (within limits).
- Mixing torque is ***independent of particle size*** (adaptive from micro to industrial scale).
- ***Elimination of stagnation regions*** encountered with conventional single-axis stirring.
- ***Elimination of instabilities*** that traditional magnetic stir bars are vulnerable to.
- Modest uniform magnetic fields (~150 Oe) are ***simple to produce*** via Helmholtz coils.
- Magnetic fields ***easily penetrate most common enclosure materials***.

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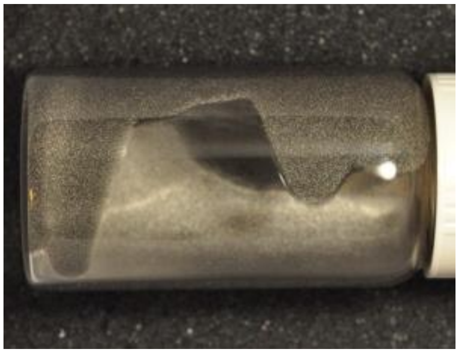
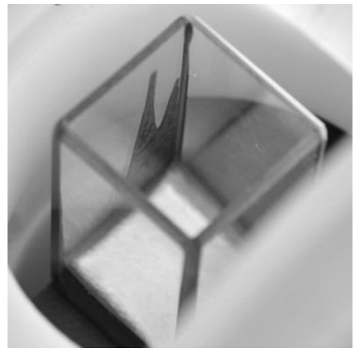
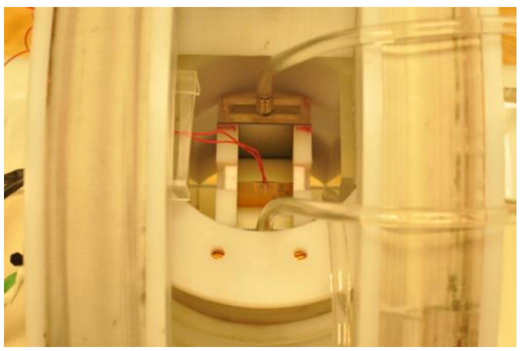
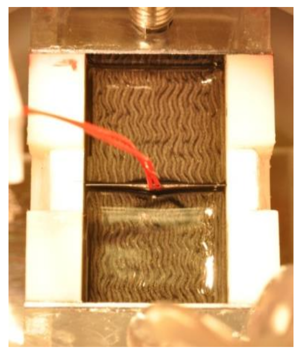
Active wetting

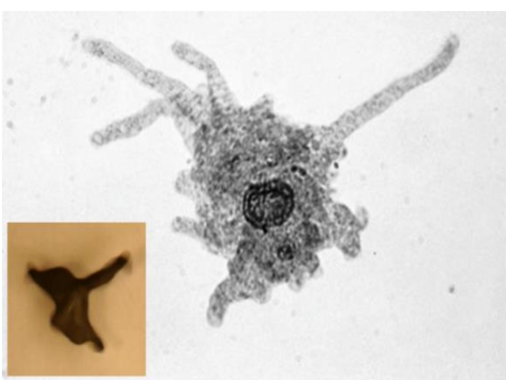
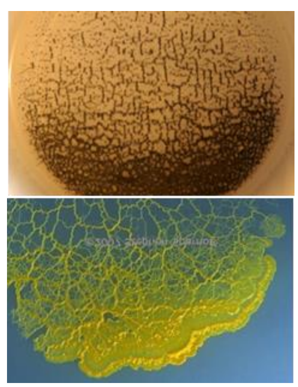
In the left figure a vortex fluid is driven around the inner surface of a cylindrical vial (gravity is into the page). In the right figure a fluid is seen climbing the wall of the 2-inch tall glass container. By creating the appropriate sense of vorticity in a vortex fluid subject to an applied shear strain rate, the observed shear stress could be made to vanish or even become negative (*i.e.*, zero or negative viscosities). Such "smart fluids" would possess unprecedented control ranges for magnetorheological clutches and dampers.

Tunable heat transfer

A "heat valve" with a control range of 100:1 was demonstrated that can switch from a thermally-insulating state to a highly-conductive state by simply changing the type of magnetic field applied to the suspension, which alters the structure and dynamics of the fluid. The highest apparent thermal conductivity achieved was 18.3 W/m·K, which is comparable to the metal antimony. Because gravity is not required to stimulate these flows, this method could be used for effective cooling in microgravity environments (*e.g.*, within satellites).

Biomimetic dynamics and droplet control


Magnetic fluid droplets suspended in an immiscible liquid display a wide variety of complex structures and dynamics that mimic those of living organisms such as amoebae (left), slime molds (middle), bees and parasites (right) etc. These are highly non-equilibrium phenomena that are driven by energy injection from the magnetic field in combination with interfacial tension and demagnetizing field effects. Practical applications include the ability to control and direct the movements of and mixing within droplets, which could be useful in microfluidic bioassays; and the scavenging of chemicals or microorganisms from contaminated liquids or alternatively the controlled dispersal of a chemical agent.