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Chaotic mixing induced by a magnetic chain in a rotating magnetic field

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Introduction
We investigate the possibility of using self-assembling chains of magnetic particles, which act as active micro stirrers under the influence of a rotating magnetic field [1, 2], to actively induce chaotic mixing. Our focus is on the dynamics of the chain and the route to induce chaotic mixing, with an emphasis on the effect of the Mason number (Ma), the ratio of viscous force to magnetic force.

Figure 1. Schematic representation of a magnetic chain, formed by $N$ particles with the radius $a$, suspended in a liquid-filled 2D circular cavity under the influence of a rotating magnetic field.

Modeling
We employed a direct simulation method [3], taking into account the magnetic and hydrodynamic interactions in a coupled manner using a fictitious domain and the Maxwell stress tensor formulation.

Results

Dynamics of the chain
Three regimes of the Mason number:

- **Lower Mason number (Ma ≤ 0.001):** Rotating single chain with a phase lag.
- **Intermediate Mason number (0.001 < Ma < 0.01):** Break-up with the increasing number of chains with Ma.
- **Higher Mason number (Ma ≥ 0.01):** Rotating single chain in overall sense, but with an oscillatory motion.

Flow characteristics
Typical flow characteristics at the moment of break-up and reformation of the chain at Ma=0.002.

Figure 2. (a) Streamlines at the moment of break-up and reformation of the chain, (b) alternating two flow portraits: one rotating flow and two co-rotating flows.

Lyapunov exponent
An optimal Mason number is found around 0.002 at which a flow system is the most chaotic.

Figure 3. Spatial distribution of the maximum Lyapunov exponent. Blue areas indicate regular regions, where mixing is poor.

Mixing analysis
According to the spacial distribution of the interface (Figure 4) and the intensity of segregation (Figure 5 (right)), mixing at Ma=0.002 is the best.

Figure 4. Deformation of the interface with time at the three Mason numbers, (a) Ma=0.001, (b) Ma=0.002, and (c) Ma=0.005.

Figure 5. Evolution of the length stretch $\lambda$ of the interface, defined by $\lambda = l(t^*)/l_0$ (left) and the intensity of segregation (right).

Conclusions
Within a limited range of the Mason number, a magnetic chain rotates and breaks into smaller chains, and the detached chains connect again. The alternating topological changes lead to chaotic mixing by stretching at break-up and folding due to the rotational flows.

References: