Thermal ratchet effect in ferrofluids with mean-field interaction

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Non-equilibrium fluctuations can be rectified with the help of so-called ratchets. In such a device a periodic potential, i.e., a force field with zero spatial average, and undirected random noise conspire to produce directed transport [1].

In [2] a thermal ratchet system for ferrofluids was introduced. The ferrofluid was subjected to a magnetic field of the form

$$H = (H_x, H_y(t), 0) \qquad (1)$$

with a constant x-component and a time periodic y-component. The magnetic grains where modelled as *non-interacting* overdamped particles with frozen-in magnetic moments. The field (1) contains no net rotating component and without thermal fluctuations no full rotation of the particles take place. This impkies that no averaged angular momentum can be transferred to the fluid [3]. However, under the influence of fluctuations full rotations may occur. With a suitable time dependence of $H_y(t)$ an averaged torque shows up which acts on the fluid due to the rectification of thermal fluctuations. Necessary conditions for the occurrence of this effect are a non-vanishing constant field

$$H_x \neq 0, \qquad (2)$$

and a dynamical symmetry breaking induced by a time-dependence of $H_y(t)$ satisfying

$$H_y(t + \Delta t) \neq H_y(-t) \quad \text{for all} \quad \Delta\text{t}. \qquad (3)$$

Mean field interactions

To go beyond the one-particle approach we propose a simple model taking into account the interactions between the orientations of the magnetic grains. To keep things simple, we restrict the orientation of the particles to the x-y plane. In addition we do not model the direct magnetic dipole-dipole interaction and the indirect hydrodynamic interaction between the grains in full detail but consider a mean-field like attractive coupling between the orientations $\phi_i(t)$.

The system may then be described by the following set of N coupled Langevin equations.

$$\begin{aligned}\partial_t \phi_i = -H_x \sin\phi_i + H_y(t)\cos\phi_i - \\ -\frac{K}{N}\sum_{j=1}^{N} \sin(\phi_i - \phi_j) \qquad (4)\end{aligned}$$

In the limit $N \to \infty$ it is possible to derive a mean-field Fokker-Planck equation for the orientation density

$$P(\phi, t) := \frac{1}{N}\sum_{i=1}^{N} \delta(\phi - \phi_i(t)). \qquad (5)$$

This equation has a similar form as the one in the single-particle approach, however,with an *effective* magnetic field of the form [4]

$$H_x(t) = H_x + S(t), \quad H_y(t) = Hy(t) + C(t). \qquad (6)$$

The functions $S(t)$ and $C(t)$ are suitable averages with the distribution $P(\phi, t)$ and respresent the influence of the interactions on the particle dynamics. As characteristic for a mean-field model they have to be determined self-consistently.

We study the influence of the particle interactions on the magnetic torque and in particular investigate whether the ratchet effect in the many-particle system may operate even if the conditions (2) and (3) are not met.

References

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