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Temperature Dependence of the Drift Velocity of Ferromagnetic Nanoparticles in Viscous Fluids

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In Refs. [1, 2], the deterministic theory of drift of single-domain ferromagnetic nanoparticles in viscous fluids, which occurs due to the Magnus effect, has recently been developed and numerically confirmed. Here, we present analytical and numerical results obtained within the stochastic theory on the influence of temperature on the drift velocity.

Assuming that the nanoparticle is subjected to a periodic external force acting in the direction of x axis and a magnetic field nonuniformly rotating in the xy plane, we have shown in the limit of small Reynolds numbers that the nanoparticle drifts along the axis y with the dimensionless drift velocity

$$\langle s_y \rangle = \gamma \int_0^1 \langle \sin\theta_{\mathrm{st}}(\xi) \sin\chi_{\mathrm{st}}(\xi) \rangle \sin(2\pi\xi - \phi)\, d\xi. \tag{1}$$

Here, the angular brackets denote averaging over thermal fluctuations, $\gamma = \rho a^2 M H_m / 36\eta^2$ is the dimensionless parameter, ρ is the fluid density, a is the particle radius, M is the particle magnetization, H_m is the magnetic field magnitude, η is the dynamic viscosity of the fluid, and ϕ is the initial phase of the external force. The azimuthal angle in the steady state, $\theta_{\mathrm{st}}(\tau)$ $[\tau = n + \xi, n = 0,1,2,\dots, \xi \in (0,1)]$, and the lag angle in the steady state, $\chi_{\mathrm{st}}(\tau)$, are the solutions of the set of stochastic equations

$$\begin{gathered}\dot{\theta}(\tau) = \alpha \cos\theta(\tau) \cos\chi(\tau) + \beta^2 \cot\theta(\tau) + \sqrt{2}\beta\zeta_1(\tau),\\ \dot{\chi}(\tau) = \dot{\psi}(\tau) - \alpha \frac{\sin\chi(\tau)}{\sin\theta(\tau)} - \sqrt{2}\beta \frac{1}{\sin\theta(\tau)} \zeta_2(\tau)\end{gathered} \tag{2}$$

at long times ($n \gg 1$). Here, the overdot denotes the derivative with respect to the dimensionless time τ, $\alpha = \pi M H_m / 3\eta\Omega$, Ω is the angular frequency of the external force, $\beta^2 = k_B T / 4\eta a^3 \Omega$, k_B is the Boltzmann constant, T is the absolute temperature, and $\zeta_1(\tau)$ and $\zeta_2(\tau)$ are independent Gaussian white noises of unit intensity. Using Eqs. (1) and (2), we studied in detail the temperature dependence of the particle drift velocity and observed an unexpected reversal of the drift direction with changing the temperature.

1. S.I. Denisov, B.O. Pedchenko, *J. Appl. Phys.* **121**, 043912 (2017).
2. S.I. Denisov et al., *J. Magn. Magn. Mater.* **443**, 89 (2017).