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Controlling the jamming transition of sheared hard spheres

THOMAS HAXTON, Lawrence Berkeley National Laboratory

Many applications require understanding how disordered materials flow under an external load such as a shear stress. Since external loads drive systems out of equilibrium, their behavior cannot be described solely in terms of equilibrium parameters like temperature and pressure. However, simulations and experiments show that sheared spherical particles possess an *effective* temperature that relates low-frequency fluctuations of various observable quantities to their associated response functions. Here, we show that the mobility of a mixture of sheared hard spheres is largely controlled by the dimensionless ratio of effective temperature to pressure, $T_{\mathrm{eff}}/p\sigma^3$, where σ is the sphere diameter. We define the effective temperature as the consistent value that relates the amplitudes of low-frequency shear stress and density fluctuations to their associated response functions. We find that the relaxation time τ characterizing the mobility depends on $T_{\mathrm{eff}}/p\sigma^3$ according to two distinct mechanisms in two distinct regimes. In the *solid response* regime, the behavior at fixed packing fraction ϕ satisfies $\tau\dot{\gamma} \propto \exp(-cp\sigma^3/T_{\mathrm{eff}})$, where $\dot{\gamma}$ is the strain rate and c depends weakly on ϕ, suggesting that the effective temperature controls the average local yield strain. In the *fluid response* regime, τ depends on $T_{\mathrm{eff}}/p\sigma^3$ as it depends on $T/p\sigma^3$ in equilibrium. This regime comprises a large part of the hard-sphere jamming phase diagram including both near-equilibrium conditions where T_{eff} is similar to the kinetic temperature T_{kin} and far-from-equilibrium conditions where $T_{\mathrm{eff}} \neq T_{\mathrm{kin}}$. In particular, the dynamic jamming transition is largely controlled by the fluid-response mechanism; like equilibrium hard spheres, sheared hard spheres can flow only if low-frequency fluctuations are large enough compared to the pressure. By presenting our results in terms of the dimensionless jamming phase diagram, we show how these mechanisms likely apply to systems with soft repulsive interactions.