Non-equilibrium (thermo)dynamics of colloids under mobile piston compression

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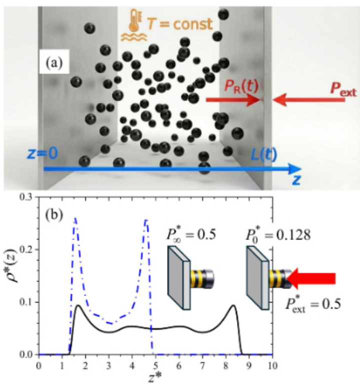
We investigate the non-equilibrium compression of a confined colloidal fluid driven by a mobile boundary within dynamical density functional theory [1]. The system consist of a hard-sphere fluid confined between two parallel walls, one of which acts as an overdamped piston subjected to a sudden increase in external pressure. The piston motion is characterized by a mobility parameter K . By varying K over several orders of magnitude, we identify a crossover from quasi-static compression to a diffusion-limited strongly driven regime. For small K , the system evolves through near-equilibrium states and the total injected work attains its minimal value, equal to the equilibrium free-energy difference. In contrast, for large K , the piston rapidly adjusts and the dynamics becomes controlled by the intrinsic diffusive relaxation of the confined colloidal fluid, leading to universal saturation behavior of the piston trajectory, pressure--position relation, particle currents, and center-of-mass velocity. In this regime, the total injected work and entropy production are bounded, reflecting fundamental constraints imposed by diffusive transport. We find that the maximum injected power scales linearly with K , while the entropy-production peak exhibits a crossover from quadratic growth to saturation. The corresponding peak times display distinct $1/K$ asymptotic regimes separated by an intermediate crossover. The entropy change of the thermal bath is computed explicitly and shown to interpolate between the reversible limit, where it exactly compensates the configurational entropy loss of the fluid, and a strongly driven regime dominated by irreversible dissipation. Finally, the time evolution of the configurational entropy and the external potential energy reveals a dynamical decoupling between geometric confinement and structural relaxation, including transient non-monotonic behavior in the high-mobility regime. These results provide a quantitative thermodynamic characterization of boundary-driven compression and uncover generic non-equilibrium features governed by a single mobility parameter.

Keywords:
non-equilibrium thermodynamics, hard spheres, entropy production, dynamical density functional theory, overdamped piston



Schematic illustration of a hard-sphere fluid confined between two parallel walls. The right boundary is an overdamped mobile piston subjected to an externally imposed pressure

References:

[1] https://arxiv.org/abs/2603.18618