scientific reports

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Rayleigh–Taylor instability in strongly coupled plasma

Rauoof Wani[1,2], Ajaz Mir[1,2], Farida Batool[1] & Sanat Tiwari[1]✉

Rayleigh–Taylor instability (RTI) is the prominent energy mixing mechanism when heavy fluid lies on top of light fluid under the gravity. In this work, the RTI is studied in strongly coupled plasmas using two-dimensional molecular dynamics simulations. The motivation is to understand the evolution of the instability with the increasing correlation (Coulomb coupling) that happens when the average Coulombic potential energy becomes comparable to the average thermal energy. We report the suppression of the RTI due to a decrease in growth rate with increasing coupling strength. The caging effect is expected a physical mechanism for the growth suppression observed in both the exponential and the quadratic growth regimes. We also report that the increase in shielding due to background charges increases the growth rate of the instability. Moreover, the increase in the Atwood number, an entity to quantify the density gradient, shows the enhancement of the growth of the instability. The dispersion relation obtained from the molecular dynamics simulation of strongly coupled plasma shows a slight growth enhancement compared to the hydrodynamic viscous fluid. The RTI and its eventual impact on turbulent mixing can be significant in energy dumping mechanisms in inertial confinement fusion where, during the compressed phases, the coupling strength approaches unity.

Rayleigh–Taylor instability (RTI)[1,2] occurs in a fluid system in which a heavier fluid (density, ρ_h) lies on top of a lighter fluid (density, ρ_l) under the effect of the gravity[3,4]. As it evolves, the modes at the fluid interface grow in amplitude, forming bubbles that rise due to buoyancy and spikes, which fall due to the gravity, eventually leading to turbulent mixing[5]. The instability is a primary mixing mechanism in supernovae explosions[6,7], solar corona[8], volcanic eruptions[9], tokamaks[10], Bose–Einstein condensate (BEC)[11,12], paramagnetic fluids[13,14], laser generated high-energy-density (HED) plasmas[15,16], and inertial confinement fusion (ICF)[17,18] covering multiple orders of length scales. Usually, hydrodynamic models explain the RTI for fluids, whether neutral or charged, using the Navier–Stokes (NS) model without or with Maxwell's set of equations. This paper focuses on RTI growth and its nonlinear evolution in strongly coupled plasmas (SCP). Under strong inter-particle correlations, these plasmas reflect visco-elastic nature that can not appropriately be represented using the standard hydrodynamic model. Also, kinetic effects become significant enough to influence the continuum effects in such scenarios. We employ a classical two-dimensional (2D) molecular dynamics (MD) model to study the growth and mixing properties of RTI. The work highlights the impact of strong inter-particle correlations and includes contributions from all scales, including thermal fluctuations.

In the recent past, MD simulations have been carried out at a microscopic level to study several hydrodynamic instabilities such as Kelvin–Helmholtz instability (KHI)[19,20], RTI[21–23], Rayleigh–Bénard instability[24], and bump-on-tail (BOT) instability[25]. Kadau et al.[21] first carried out a three-dimensional (3D) MD simulation for RTI in Lennard–Jones (LJ) fluids. Their results, in general, matched with linear stability analysis of the Navier–Stokes model and paved the way to explore mixing at microscopic scales. Further, Ding et al.[23] carried out RTI studies for Ar/He interfaces through LJ pairwise interactions. The work suggested the considerable difference in the formation and evolution of spikes at the microscopic level to the macroscopic scale. It also showed the detached droplet formation due to the thermal fluctuations. In both the works mentioned above, the focus was primarily on the role of microscopic fluctuations. Our focus is towards systems comprising a large number of charged particles, where dynamics is governed by the Coulomb force. As surrounding charges shield each charged particle, the effective pairwise potential takes the form of Yukawa/Debye–Hückel interaction potential given by[26]

$$\phi_{ij} = \frac{1}{4\pi\epsilon_0}\frac{q^2}{r_{ij}}\exp\left(-r_{ij}/\lambda_D\right). \tag{1}$$

[1]Department of Physics, Indian Institute of Technology Jammu, Jammu 181221, India. [2]These authors contributed equally: Rauoof Wani and Ajaz Mir. ✉email: sanat.tiwari@iitjammu.ac.in