Chapter 5

Tunable rheological behavior of magnetized complex plasma

In this chapter, the shear viscosity (η) of a 3D liquid dusty plasma has been estimated as a function of magnetic field (B) and normalized ion flow velocity (M) from the simulation data using Green–Kubo formalism with the help of Langevin dynamics simulation. It has been shown that in the strongly correlated liquid state, complex plasma may exhibit sharp changes in viscosity with magnetic field and ion drift velocity. In the presence of ion drift, an oscillatory and attractive wake potential develops among charged particles, as discussed in the earlier chapters. The amplitude of this wake potential can be modulated by applying an external magnetic field. In this work, we explore how an external magnetic field influences the rheological properties of complex plasma via anisotropic wake potential. It is observed that the rheological properties of such plasma depend on the dominant interaction operating among the particles and can be controlled by applying an external magnetic field. A novel regime of the magnetic field is observed in which strongly correlated complex plasma liquids exhibit a sharp response to an external magnetic field.

5.1 Introduction:

Viscosity is a measure of a fluid's internal friction or resistance to flow when there is relative motion between different layers of the fluid [190]. When a fluid flows, its layers move at different velocities due to the presence of internal friction. Liquids with high viscosity, such as honey or molasses, offer significant resistance to motion and flow more slowly compared to low-viscosity fluids, like water or alcohol. The viscous force between these layers resists this relative motion and tends to oppose the flow, generating a shearing effect. Viscosity plays a crucial role in various natural phenomena and engineering applications, affecting fluid dynamics, heat transfer, and the behavior of many complex systems [190; 191; 192]. In the context of fluid dynamics, when an object descends through a fluid, it drags the layer of the fluid in contact with it, creating a relative motion among the fluid's different layers. This action leads to the object experiencing a decelerating (retarding) force due to the fluid's internal resistance or viscosity. The viscous force exerted on the object is directly proportional to the object's velocity and acts in the opposite direction to its motion, thus slowing down the object's movement [193]. The viscous drag force (F) experienced by a sphere moving through a fluid depends on several factors, including the viscosity (η) of the fluid and the radius (a) of the sphere.

$$F = 6\pi\eta a v$$

where: F is the viscous drag force experienced by the sphere, η is the viscosity of the fluid, a is the radius of the sphere and v is the velocity of the sphere relative to the fluid. This expression is known as Stokes' Law and is widely used to describe the viscous drag force experienced by a small sphere moving at a low speed through a fluid. Stokes' Law is especially applicable to situations where the Reynolds number (a dimensionless parameter representing the ratio of inertial forces to viscous forces) is small, indicating that the flow is laminar and the viscous forces dominate the fluid dynamics [194].

Rheology, a branch of physics, explores the intricate study of how materials respond to applied forces or stresses, involving their flow and deformation behaviors. This discipline aims to clarify the complex interplay between materials and external forces, including shear, tension, compression, and elongation while illuminating various flow characteristics such as viscosity and elasticity [195; 196; 197].

5.1.1 Viscosity in complex plasma:

In complex plasmas, the viscous transport of momentum arises from the movement of dust particles relative to one another during shearing motion [198]. As these particles collide, they exchange momentum across the flow. This collision-induced momentum exchange is responsible for the unique viscoelastic behavior observed in complex plasmas [199].

In the past few decades, transport properties of strongly coupled plasmas have been investigated in detail through theoretical and simulation techniques [200; 201; 202; 203; 185; 204; 205; 187; 206; 183; 207; 208; 209; 210; 211]. Using equilibrium molecular dynamics simulation, Hamaguchi *et al.* calculated the shear viscosity of strongly coupled Yukawa system [200]. The shear thinning behavior of 2D Yukawa liquid has been shown by Donko *et al.* using non-equilibrium molecular dynamics (MD) simulation [212]. Finding a minimum value of viscosity with temperature (or coupling parameter) in many experimental and simulation works is a distinctive feature of complex plasma, which is not found in most simple liquids [207; 200; 205]. The minimum viscosity arises from the temperature dependence of kinetic and potential contributions to momentum transport [205; 200]. An experiment was performed by Hartmann *et al.* to calculate the static and dynamic shear viscosity of a single-layer complex plasma [201]. In 2011, the static viscosity and the wave-number-dependent viscosity were calculated from the microscopic shear in the random motion of particles [204]. Recently, Feng *et al.* have studied the shear viscosity of 2D liquid dusty plasmas under perpendicular magnetic fields using Langevin dynamics simulations [213]. It has been found that, when a magnetic field is applied, the shear viscosity of a 2D liquid dusty plasma is modified substantially. The different variational trends in the viscosity with the external magnetic fields can be explained on the basis of the kinetic and potential parts of the shear stress under external magnetic fields [213].

In the present work, shear viscosity is calculated using the Green Kubo relation by considering the fact that in the presence of ion flow and magnetic field, the effective inter-particle potential is the superposition of isotropic Yukawa and anisotropic attractive wake potential. Here, we explore the rheological property of complex plasma which shows a transition from an ordered to a disordered phase accompanied by a change in viscosity when an external magnetic field is applied. Due to the inclusion of wake potential, we observe several novel features of rheological properties of complex plasma which was not seen in previous studies.

5.2 Description of the model:

We consider a 3D dusty plasma consisting of electrons, ions, neutral particles, and micron-sized grains. The ions are streaming in the vertical Z - direction perpendicular to an external magnetic field applied along the X - direction. The effective interaction potential among the dust particles in such flowing magnetized plasma may be expressed as a superposition of spherically symmetric Debye H$\ddot{u}$ckel and anisotropic wake potential as described in the previous chapter [162].

$$\phi = \phi_Y + \phi_W \tag{5.1}$$

Where, ϕ_Y is the Yukawa potential and ϕ_W is the wake potential defined as [162],

$$\phi_W = \frac{-Q\rho}{\lambda_{De}\epsilon_0} \frac{sin(\sqrt{\alpha\rho}z)}{2(\rho+1)(\rho\alpha+1)} \tag{5.2}$$

Here, $\alpha = \frac{P}{2M^2}$, ρ = -1 + $\sqrt{1+\left(\frac{R}{P}\right)^2}$, $P = M^2 - f_i^2 - 1$ and $R = 2Mf_i$ are normalized parameters, $M = \frac{u_{io}}{\omega_{pi}\lambda_{De}}$ is the Mach number, $f_i = \frac{\omega_{ci}}{\omega_{pi}}$ is the normalized ion gyro frequency, u_{io} is the ion drift velocity, ω_{pi} is the ion plasma frequency and ω_{ci} is the ion cyclotron frequency. It is clearly seen that the external magnetic field B, can be adjusted to tune the amplitude of the wake potential. This property of tunable interaction potential of complex plasma is explored in this work as a possibility of using complex plasma as magnetorheological soft matter. It is well known that the transport properties like self-diffusion and shear viscosity depend on inter-particle forces. It is shown here how a magnetic field can be used to control the viscosity of complex plasma via tunable wake potential. The study may have applications in a variety of strongly coupled dusty plasma systems in astrophysical, laboratory, and industries.

5.3 Langevin dynamics simulation:

The spatial ordering and time evolution of many-particle systems can be studied with the help of Molecular Dynamics (MD) or Langevin Dynamics (LD) simulation. Here, simulation is performed using a 3-dimensional Langevin Dynamics code. The LD code has been thoroughly bench-marked against known past results. The diagnostics implemented in the LD code can explicitly reveal various properties like crystallization, phase behavior, and transport properties of strongly coupled dusty plasma. In the current study, we have performed the simulation for 1372 dust particles immersed in a plasma medium to mimic a 3D dusty plasma system. For the charged dust particles the Langevin differential equation is given by [125; 214],

$$m\ddot{r_i}(t) = Q_d\left(\dot{r_i}(t) \times B\right) - \nabla \sum_{i \neq j} \phi_{i,j} - \nu m \dot{r_i}(t) + \zeta(t) \tag{5.3}$$

Here, the first term on the right-hand side is the usual Lorentz force due to the external magnetic field. The second term gives the pair potential. In our simulation, we have modeled our system considering a binary Yukawa inter-particle interaction together with particle-wake interaction. The third term is the frictional drag force acting on moving dust particles. The expression for ν (dust-neutral collision frequency) used in our simulation is given by: $\nu = 1.4 \times \frac{8\sqrt{2\pi}}{3} m_n n_n a^2 \frac{v_n}{m_d}$ where m_n, n_n, a, v_n and m_d are mass of neutrals, neutral density, dust radius, thermal velocity of neutrals and mass of dust respectively. For the considered parameter regime $\nu \approx 1Hz$ corresponding to $n_n \sim 10^{21} m^{-3}$, $m_n \sim 10^{-27} kg$, $v_n \sim 10^2 m/s$ and dust mass $m_d \sim 10^{-18} kg$ for sub micron sized dust grain. $\zeta(t)$ is the random force due to thermal fluctuations of the plasma particles. The expression for $\zeta_i(t)$ is given by $\zeta_i(t) = \sqrt{\frac{\beta^2}{\delta t}} * N(0,1)$. β is an undetermined coefficient and in equilibrium, it is related to the drag coefficient through the fluctuation-dissipation theorem, δt is the simulation time step and N(0,1) represents the normal random variable with mean zero and variance 1. In order to have a clear idea of the transport of particles in a real experimental situation, the contribution of streaming ions and the magnetic field have been incorporated via the relevant interaction potential operative among dust grains. The physical quantities length, mass, time, velocity, and energy are normalized by λ_D, m_d, $\sqrt{\frac{m_d\lambda_D^2}{K_BT_d}}$, $\sqrt{\frac{m_d}{K_BT_d}}$ and K_BT_D respectively.

The system is taken to be a cubical box of size $L_x = L_y = L_z = 10^{-3}$ m (Volume, V = $L_xL_yL_Z$) consisting of 1372 (say N) particles. The code implements a velocity varlet algorithm to solve the Langevin equation of motion which in turn yields positions of particles at every time step [125]. Periodic boundary conditions are imposed along all directions to ensure the conservation of particles [125; 214]. In a particular run, the basic steps followed in the simulation are: (i) canonical ensemble (NVT) run: In this step, three parameters of the system are fixed throughout the simulation: number of particles (N), volume (V) and temperature (T). This step helps to take the system to thermal equilibrium at the required Γ. (ii) micro-canonical ensemble (NVE) run: The micro-canonical ensemble represents an isolated system. The second phase involves conducting an NVE run to attain the desired equilibrium state, and data collection commences thereafter.

The Green–Kubo relations give the exact mathematical expression for transport coefficients in terms of integrals of auto-correlation functions. In this formalism, first, the stress auto-correlation function (SACF) is calculated as

$$C_\eta(t) = \langle P_{xy}(t).P_{xy}(0)\rangle \tag{5.4}$$

The angular brackets represent the averaging over the entire ensemble of particles. $P_{xy}(t)$ is the off-diagonal element of the stress tensor defined by the formula

$$P_{xy}(t) = \sum_{i=1}^{N}\left[mv_{ix}v_{iy} + \frac{1}{2}\sum_{j\neq i}^{N}\frac{x_{ij}y_{ij}}{r_{ij}}\frac{\partial\phi(r_{ij})}{\partial r_{ij}}\right] \tag{5.5}$$

Where i and j are indices for different particles, N is the total number of particles, and $r_{ij} = |r_i - r_j|$. From this expression, it is evident that the stress auto-correlation function is connected with the interaction potential operating among the dust particles. In the absence of ion flow or magnetic field, $\phi(r_{ij})$ represents symmetric Yukawa potential. In the present model, it is assumed that the dielectric response function gets affected by the magnetic field applied perpendicular to the streaming of ions, which results in an asymmetric potential. Thus, the viscosity is affected by the external magnetic field and ion flow via the effective anisotropic inter-particle potential.

The first term in the equation is the kinetic contribution: $P_{xy}^{kin}(t) = \sum_{i=1}^{N}(mv_{ix}v_{iy})$ and the second term is the potential contribution: $P_{xy}^{pot}(t) = \left(\frac{1}{2}\sum_{i=i}^{N}\sum_{j\neq i}^{N}\frac{x_{ij}y_{ij}}{r_{ij}}\frac{\partial\Phi(r_{ij})}{\partial r_{ij}}\right)$. Therefore we can rewrite the equation as

$$C_\eta(t) = \langle P_{xy}^{kin}(t).P_{xy}^{kin}(0)\rangle + \langle P_{xy}^{pot}(t).P_{xy}^{pot}(0)\rangle + 2\langle P_{xy}^{kin}(t).P_{xy}^{pot}(0)\rangle$$

$$= C_\eta^{KK}(t) + C_\eta^{PP}(t) + 2C_\eta^{KP}(t) \tag{5.6}$$

Here, $C_\eta^{KK}(t)$ is the self-correlation of the kinetic part, $C_\eta^{PP}(t)$ is the self-correlation of the potential part and $C_\eta^{KP}(t)$ is the cross-correlation. Once the SACF is obtained, the static viscosity η is being calculated from the Green–Kubo relation as [213; 200],

$$\eta = \frac{1}{Vk_BT}\int_0^\infty C_\eta(t)\,dt \tag{5.7}$$

Here, V is the volume of the simulation box, k_B is the Boltzmann constant and T is the temperature. After splitting $C_\eta(t)$ into 3 parts, we get

$$\eta_{kin} = \frac{1}{Vk_BT}\int_0^\infty C_\eta^{KK}(t)\,dt \tag{5.8}$$

$$\eta_{pot} = \frac{1}{Vk_BT}\int_0^\infty C_\eta^{PP}(t)\,dt \tag{5.9}$$

$$\eta_{cross} = \frac{2}{Vk_BT}\int_0^\infty C_\eta^{KP}(t)\,dt \tag{5.10}$$

Here, η_{kin}, η_{pot}, and η_{cross} are the kinetic, potential, and cross parts of shear viscosity respectively. Therefore, $\eta = \eta_{kin} + \eta_{pot} + \eta_{cross}$. It is to be noted that in the present study, we have modeled our system considering a binary isotropic Yukawa inter-particle interaction together with an anisotropic particle-wake interaction. Since the isotropy of the system breaks in the presence of anisotropic wake potential and external magnetic field, therefore, in our simulation, each of the three components i.e., $C_\eta^{xy}(t)$, $C_\eta^{yz}(t)$, $C_\eta^{zx}(t)$ has been separately calculated [125].

the structural properties of the system can be computed using radial distribution function g(r) [125]. It is a measure of the structural correlations between particles that may organize in a solid or fluid-like state. For a 3D system, radial distribution function (RDF) is defined as [125; 214],

$$g(r) = \frac{V}{N}\frac{N(r,dr)}{4\pi r^2 dr} \tag{5.11}$$

To measure the existence of long-range order in the system, an important diagnostic tool is the Lattice correlation factor (LCF) [125; 214]. LCF can be computed from the position of the particles. It can be measured experimentally through the X-ray scattering technique [125]. The local density of particles $\rho(\mathbf{r})$, at a point $\mathbf{r}$, can be expressed as [125],

$$\rho(\mathbf{r}) = \sum_{j=1}^{N} \delta(\mathbf{r} - \mathbf{r}_j(t)) \tag{5.12}$$

where $\mathbf{r}_j(t)$ denotes the position of particle j at time t and N is the total number of particles. The density can be spatially Fourier transformed and its Fourier transform is simply the Lattice Correlation Factor (LCF) [125],

$$\rho(\mathbf{k}) = \frac{1}{N}\sum exp(-i\mathbf{k}.\mathbf{r}_j) \tag{5.13}$$

For a perfectly crystalline state (fully ordered), $|\rho(k)| \approx 1$. Mean-squared displacement (MSD) [125] is used as another diagnostic tool to determine the phase behavior, which is defined as

$$\mathrm{MSD(t)} = \langle|\mathbf{r}_\mathrm{i}(\mathrm{t}) - \mathbf{r}_\mathrm{i}(0)|^2\rangle \tag{5.14}$$

Where $\mathbf{r}_i(t)$ is the position of the i^{th} particle at time t and the angular bracket denotes an ensemble average. By calculating the particle positions at different time steps, the mean-squared displacement (MSD) can be measured from the simulation data.

5.4 Results and discussions:

We present the results of our simulation study of the shear viscosity of three-dimensional strongly coupled complex plasma. The dependence of shear viscosity on the magnetic field and ion flow velocity has been analyzed. The present work helps in realizing the explicit contribution of repulsive Debye−Hückel potential and attractive wake potential on the overall behavior of viscosity in complex plasma.

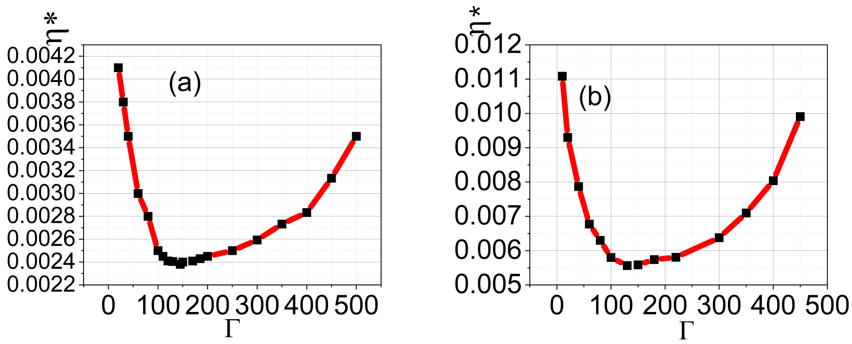

Figure 5.1: (a) Variation of normalized shear viscosity ($\eta^\star$) with Coulomb coupling parameter (Γ) when B = 0.001 T, κ = 2 and ν = 1 Hz ($n_n = 10^{21} m^{-3}$). The simulation was performed considering Yukawa potential only along with the Lorentz force term. (b) Normalized shear viscosity ($\eta^\star$) versus Coulomb coupling parameter (Γ) considering both Yukawa and magnetized wake potential. All other simulation parameters are the same as Fig. (a).

(A) Variation of viscosity with Γ:

The variation of shear viscosity (η) with Γ is shown in Fig. 5.1(a). The simulation was performed with Yukawa potential only and the Lorentz force term. A prominent feature of the η versus Γ curve is the minimum occurring at intermediate coupling $\Gamma \approx 150$. This minimum of η has been confirmed in many experimental and simulation works [207; 200; 205]. The minimum arises from the temperature dependence of kinetic and potential contributions to momentum transport. To understand this behaviour, we separate the stress tensor $P_{xy}(t)$ into two parts as : (i) the first term (kinetic part) $P_{xy}^{kin}(t) = \sum_{i=1}^{N} [m v_{ix} v_{iy}]$ and (ii) the second term (potential part) $P_{xy}^{pot}(t) = \left[\frac{1}{2}\sum_{i=i}^{N}\sum_{j\neq i}^{N} \frac{x_{ij} y_{ij}}{r_{ij}} \frac{\partial \Phi(r_{ij})}{\partial r_{ij}}\right]$. The kinetic part depends on particle velocities and represents the momentum transport by the displacement of particles. The potential part depends on the effective pair potential between the dust particles. Therefore, the kinetic part of η, decreases with Γ while the potential part of η increases with Γ. At high temperatures (low Γ), the system behaves more like a gas. On the other hand, when Γ is larger than 150, η increases with Γ because the system gradually goes to a fluid regime and brings in regularity to the system, and attains an ordered structure. Fig. 5.1(b) depicts the variation of shear viscosity (η) with Coulomb coupling parameter (Γ) considering both Yukawa and magnetized wake potential.

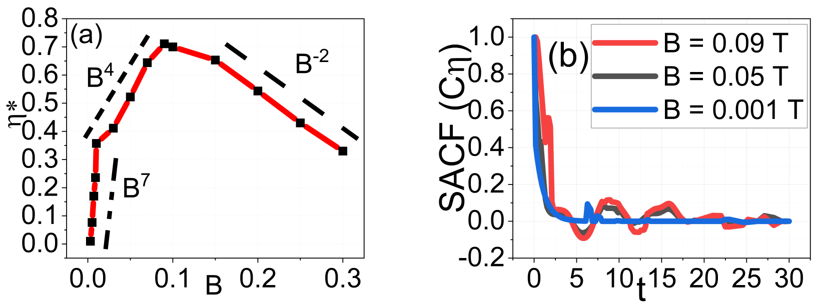

Figure 5.2: (a) Normalized shear viscosity ($\eta^{\star}$) versus magnetic field B (in Tesla) when $\Gamma = 450$, $\kappa = 2$, M $= 1.9$ and $\nu = 1$ Hz ($n_n = 10^{21} m^{-3}$). Fig. (b) - The stress auto-correlation function (SACF) for a range of B values.

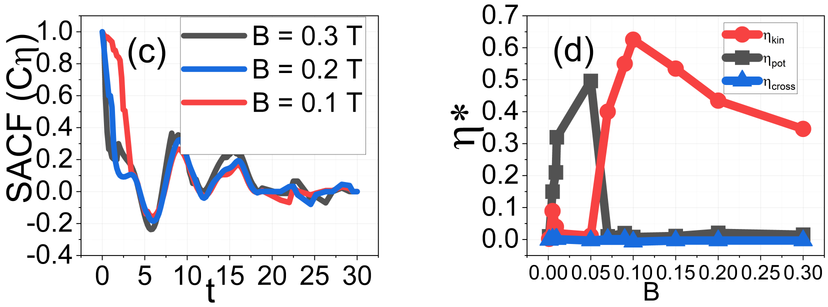

Figure 5.2: Fig. (c) - The stress auto-correlation function (SACF) for a range of B values. Fig. (d) - variation of kinetic, potential, and cross part of viscosity with the magnetic field.

(B) Variation of viscosity with magnetic field:

The primary objective of the present work is to explore the behaviour of shear viscosity in the presence of magnetized wake. The variation of shear viscosity (η)

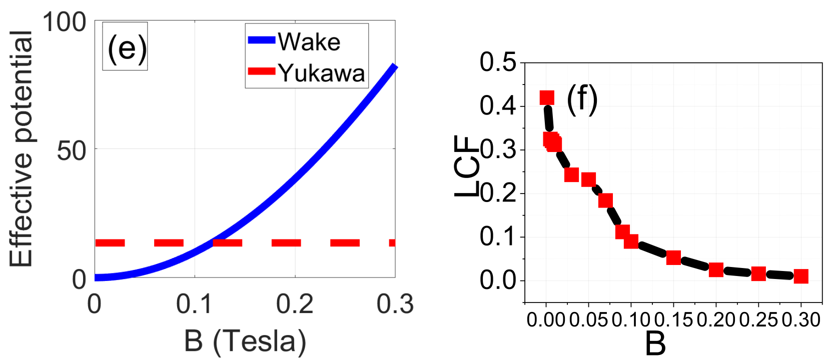

Figure 5.2: Fig. (e) - comparison of the amplitude of wake and Yukawa potential. Fig. (f) - Lattice Correlation Factor (LCF) for a range of B values.

with the magnetic field is studied for the range of B from 0.001 T to 0.3 T as shown in Fig. 5.2(a). For the entire study, we have focussed on the supersonic regime of ion flow. The values of neutral density n_n, coupling parameter Γ, screening parameter κ and ion Mach number M are kept fixed at $10^{21}m^{-3}$, 450, 2 and 1.9 respectively. The different variational trends of viscosity (η) with the external magnetic field can be explained on the basis of the behaviour of shear stress ($P_{xy}(t)$) under external magnetic fields. From Fig. 5.2(a), the entire range of observations can be classified into three regions.

Region I: This regime is characterized by an ultra-low magnetic field (B = 0.001 T to 0.05 T), where the dust ensemble exhibits a sharp increase in the values of viscosity with a magnetic field. The normalized value of viscosity shows a B^7 dependence in this regime. The plot of the stress auto-correlation function (SACF) in Fig. 5.2(b) reveals that this function decays relatively weakly with smaller ripples for the range of magnetic field considered here. This novel behaviour of sharp response of viscosity to small changes in the magnetic field may be explained on the basis of tunable inter-particle interaction of complex plasma. In this regime, the complex plasma behaves like a strongly correlated liquid with LCF lying between 0.42 - 0.232 as seen in Fig. 5.2(f). For the range of parameters chosen here, the Yukawa potential is dominant over the wake potential (Fig. 5.2(e)). However due to the field-dependent attractive wake potential, the effective potential increases with the magnetic field resulting in a sharp change of viscosity with the magnetic field. The potential part ($(C_\eta^{PP}(t))$) of SACF is found to dominate over the kinetic part such that $\eta_{pot} > \eta_{kin}$ in this regime which may be attributed to dominant Yukawa interaction among the particles.

It is to be noted that the effective inter-particle potential is controlled by the interplay between Yukawa and wake potential. Although Yukawa potential does not depend on the external magnetic field, the dependence of wake on the magnetic field gets reflected in the behaviour of effective potential. For the range of magnetic field where the wake potential is weak, the transport property of the medium is decided mainly by Yukawa potential. The overall dynamics of the system are governed by the effective inter-particle potential. Although the kinetic part of η has no direct relation with the magnetic field, it depends on particle velocity which is affected by the inter-particle interaction via Yukawa and magnetic field-dependent wake potential.

Region II (B = 0.05 T to 0.09 T): The second regime is characterized by a low magnetic field and continues to show a rise in viscosity with a magnetic field with a lesser slope ($\propto B^4$). The Yukawa dominance of the effective potential gradually decreases although the plasma maintains a strongly correlated fluid state, however with a decreasing value of LCF. This observation is supported by the rise of the kinetic contribution of viscosity as seen in Fig. 4(d).

The trend of viscosity in this low magnetic field regime is in agreement with the results found in the work by Feng *et al.* in the cold plasma limit [213]. The shear viscosity was found to increase with the external magnetic field. However, the sharp increase in η with B observed in our work in the presence of supersonic ion flow was not visible in their work with isotropic Yukawa potential. We emphasize that the response of viscosity to the external magnetic field can be made more efficient by suitably tuning the wake potential.

Region III (B = 0.09 T to 0.3 T): For a relatively high magnetic field the viscosity exhibits a complete reversal with the variation of the magnetic field. Fig. 5.2(c) shows that the SACF decays rapidly with ripples having higher amplitudes. Here, the kinetic part of viscosity dominates over the potential part. It is found that η_{pot} drops to a low value in this regime, resulting in a decreasing trend of viscosity with the magnetic field. Here, we see the agreement of our result with the Braginskii equations [215; 213], where the dependence of shear viscosity on the magnetic field is estimated as $\eta \propto \frac{1}{B^2}$. The decreasing trend of η_{pot} and η with B may be attributed to the strong anisotropic wake potential operating among the dust particles in this regime. This can be seen from Fig. 5.2(e), where the effective potential becomes wake dominant and the complex plasma transits to a gaseous state (LCF: 0.08 - 0.01).

In order to see the relationship with other transport properties, we have also observed the evolution of mean squared displacement (MSD). From Figs. 5.3(a) and 5.3(b), it is explicit that the MSD increases with B. But the values of MSD from 0.001 T to 0.005 T (Fig. 5.3(a)) are much lesser than that of Fig. 5.3(b) (B from 0.1 T to 0.3 T). In this regime (B from 0.1 T to 0.3 T), the Lorentz force $Q_d\,(\dot{r_i}(t) \times B)$, starts to become effective and shows its influence on transport properties of the system. The MSD of the dust particles is also very high as depicted by Fig. 5.3(b). It is the combined role of Lorentz force and magnetized wake that is responsible for the decrease in the values of shear viscosity in this regime.

From the above observations, we can infer that the phase state of the complex plasma is closely connected with the nature of the interaction among the particles. For the range of magnetic fields where repulsive and isotropic Yukawa potential is dominant, such that the system is in a strongly correlated fluid state, the potential part of viscosity increases with the magnetic field, resulting in a sharp rise in viscosity. This is identified as a novel regime because the response of viscosity is very sensitive, even to a small change in magnetic field. On the other hand, in the regime, where the wake potential is dominant, due to its anisotropic character, the particles lose their strong correlation and tend towards a gaseous state, thus exhibiting a decreasing trend of viscosity with a rise in magnetic field.

(C) Variation of viscosity with ion flow velocity:

In order to understand the role of ion Mach number on shear viscosity, we perform simulations by varying Mach number M in the supersonic regime from 1.1 to 1.9.

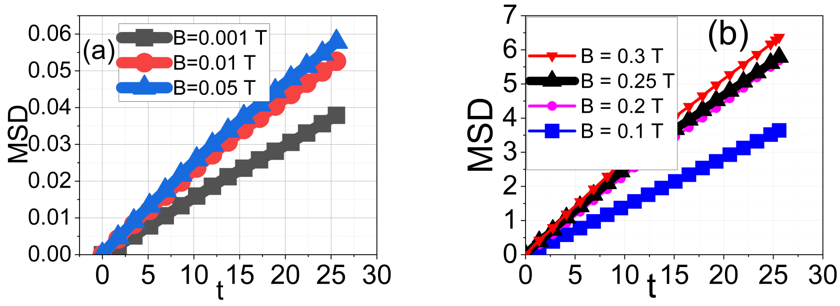

Figure 5.3: (a) and (b) - The evolution of mean-squared displacement (normalized value) for a range of B values when $\Gamma = 450$, $\kappa = 2$, M = 1.9 and $\nu = 1$ Hz ($n_n = 10^{21} m^{-3}$). In the simulation, MSD and time are normalized by λ_D^2 and $\sqrt{\frac{m_d \lambda_D^2}{K_B T_d}}$ respectively.

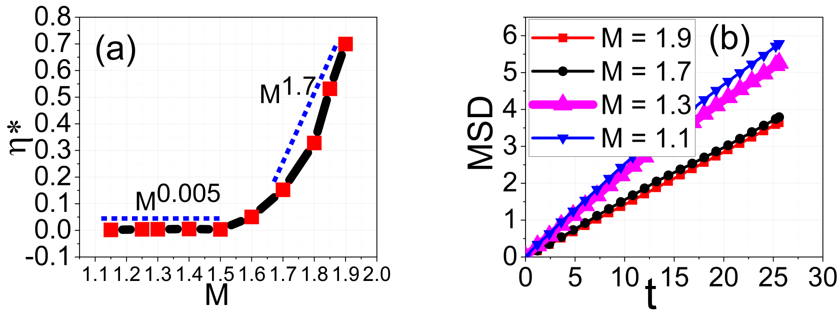

Figure 5.4: (a) Normalized shear viscosity ($\eta^\star$) versus Mach number when $B =$ 0.1 T, $\Gamma = 450$, $\kappa = 2$, and $n_n = 10^{21} m^{-3}$. (b) The evolution of MSD for a range of M values when B = 0.1 T, $\Gamma = 450$, $\kappa = 2$, and $n_n = 10^{21} m^{-3}$.

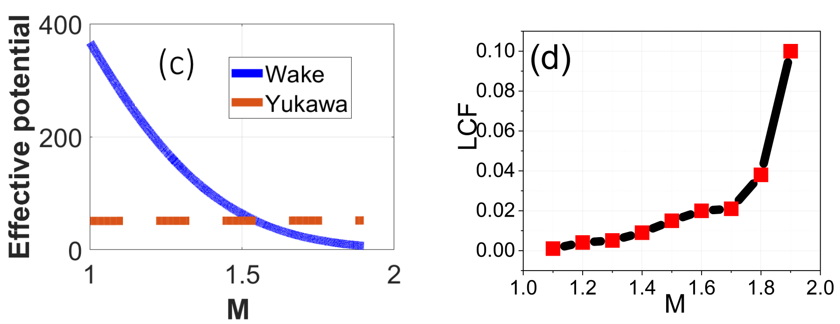

Figure 5.4: Fig. (c): Comparison of the amplitude of wake and Yukawa potential for a set of Mach numbers. Fig. (d): Lattice Correlation Factor (LCF) for a range of M values.

The results are shown in Fig. 5.4(a). In the range 1.1 < M <1.5, the shear viscosity does not show significant change. The plot of the amplitudes of Yukawa and wake potentials in Fig. 5.4(c) shows that this is the wake-dominant regime, where the dusty plasma behaves like a gas. The LCF values (Fig. 5.4(d)) in this regime are less than 0.02, indicating the gaseous state. The MSD plot of Fig. 5.4(b) supports this observation.

The regime of interest starts from M$\geq$ 1.5, when the wake potential becomes comparable to isotropic Yukawa potential. When the ions move faster, the accumulation of ions downstream of the dust particles gets reduced, resulting in a weakening of wake potential. The complex plasma attains a fluid-like state due to the balance between repulsive Yukawa and attractive wake potential. In this strongly correlated fluid state, the shear viscosity increases with Mach number, accompanied by a decrease in MSD values. It may be concluded that dusty plasma exhibits high viscosity for moderate values of the magnetic field in the supersonic regime of ion drift.

5.5 Conclusions:

The shear viscosity (η) of a 3D liquid dusty plasma has been estimated from the simulation data using the Green–Kubo formalism with the help of Langevin dynamics simulation. The dependence of shear viscosity on magnetic field and ion flow velocity has been analyzed. The novel feature of this work is that the viscosity of complex plasma is found to be sensitive even for small changes in magnetic field because of the role of tunable wake potential with magnetic field. The shear viscosity of dusty plasma has been extensively studied in recent years using analytical methods, simulation, and experiments [200; 212; 205; 207; 201; 204; 216]. The reason for the discrepancy between simulation results and experiments has been attributed to the interaction mechanism operating among the dust particles [216]. The effect of ion flow is not reflected when the simulation is performed with isotropic Yukawa potential.

The present study reveals that the correct treatment of interaction potential in the presence of magnetized wake opens avenues for new magnetic field-dependent shear viscosity. A new regime of parameters has been identified with $\Gamma = 450$, $\kappa = 2$, $\nu = 1$ Hz, $B = 0.001-0.09$ T in the supersonic ion flow regime, where shear viscosity shows sharp variation with a small change in the magnetic field. In the Yukawa-dominant, strongly coupled liquid state, the viscosity is found to vary as B^7 with magnetic field in the range 0.001 T - 0.05 T and B^4 in the range 0.05 T - 0.09 T. On the other hand, when the system moves towards a gaseous state, the viscosity is found to vary as $\frac{1}{B^2}$ with a magnetic field in the range 0.09 T - 0.3 T. In the absence of magnetized wake potential, such a response of shear viscosity to a low magnetic field is not manifested. Although the Yukawa potential does not depend on the magnetic field, the tunable wake potential controls the effective interaction among the dust grains and plays a crucial role in bringing out the unique nature of shear viscosity. We have also seen that for moderate values of Mach number, in the gas-like state, the viscosity does not change much, whereas, for a strongly correlated fluid state characterized by high Mach number ($M \geq 1.5$), the viscosity shows a significant rise with M. It is to be noted that the viscosity of such systems is closely connected with the phase state of dusty plasma.

Feng *et al.* [213], in their work observed that when a magnetic field is increased, the shear viscosity of a 2D liquid dusty plasma increases at low temperatures, while at high temperatures its viscosity diminishes. This behaviour may be explained on the basis of the phase state of the system. In low temperatures, our results are in agreement with that of Feng *et al.*, in the absence of wake potential. However, the behaviour of shear viscosity in a low magnetic field regime as discussed above does not manifest itself in the absence of magnetized wake.

The dust-neutral collision frequency may have an important role in the rheological property of the medium. In the absence of wake potential, we observe a rise in shear viscosity with dust neutral collision frequency of the medium and the results show a similar trend with the experimental results reported by Gavrikov *et al.* [216]. It would be interesting to see the effect of neutral pressure and dust-neutral collision on the rheological behaviour of the medium. It is found that the wake potential gets destroyed in the presence of strong ion-neutral collision frequency and therefore a completely different model may be required to see the dependence of shear viscosity on neutral pressure [166].

The generalized hydrodynamic model is widely used to study collective modes in strongly coupled liquid dusty plasma where the dust particles are treated as viscoelastic fluid. A correct estimate of the shear viscosity of such a medium may have important consequences on the behaviour of collective modes and nonlinear structures. Shear viscosity may have an important role to play in the onset of vortex in dusty plasma. In a recent experiment, Bailung *et al.*, [217] have reported that a pair of vortex are formed when Reynold number falls in the range 60-90, where they have ignored the dependence of shear viscosity on particle interaction completely. The present article shows the way to calculate shear viscosity in laboratory conditions where ion flow-induced wake may be dominant and hence predict a correct range of Reynold number for which vortex structures may appear in dusty plasma.

Due to the unique property of tunable viscosity, complex plasma may be used as a platform to study magneto-rheological characteristics of soft matter and there is a possibility of using dusty plasma as a magneto-rheological material in the near future.