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A review on the vortex and coherent structures in dusty plasma medium

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An ionized gas medium (plasma state) turns to a complex state of plasma or dusty plasma if micrometre- to submicrometre-sized solid dust particles are introduced in it. The dusty plasma medium exhibits fluid- as well as solid-like characteristics at different background plasma conditions. It supports various linear and nonlinear dynamical structures because of external perturbation and internal instabilities. The vortical or coherent structure in the dusty plasma medium is a kind of self-sustained dynamical structure that is formed either by instabilities or by external forcing. In this review article, the author discusses the past theoretical, experimental and computational investigations on vortical and coherent structures in unmagnetized and magnetized dusty plasmas. The possible mechanisms of the formation of vortices in a dust-grain medium are discussed in detail. The studies on the evolution of vortices and their correlation with turbulence are also reviewed.

Keywords: dusty plasmas, strongly coupled plasmas, plasma dynamics

1. Introduction

Adding submicrometre- to micrometre-sized solid dust particles to the plasma state of matter makes it more complex to study. In the plasma state having a neutral gas background, these dust particles (nanometre to micrometre radius) undergo various charging processes (Shukla & Mamun 2002*a*) and acquire negative or positive charges. In a laboratory plasma, dust particles are normally negatively charged (Barkan, D'Angelo & Merlino 1994; Goree 1994; Barkan, Merlino & D'Angelo 1995). But, in afterglow conditions, they acquire positive charges (Couëdel *et al.* 2006; van Minderhout *et al.* 2020; Chaubey *et al.* 2021; Chaubey & Goree 2023). To understand the dust-charging mechanism in an ionized gas, various theoretical models have been developed. The orbital motion limited theory (Kennedy & Allen 2003), modified orbital motion limited theory (Tang & Luca Delzanno 2014), radial motion theory (Kennedy & Allen 2002), etc., are the theories most used to understand the charging mechanism of dust grains in an unmagnetized plasma environment. However, there is still a lack of a comprehensive theoretical model that explains the charging processes of dust particles in a plasma with moderate ($B > 0.1$ T) to high ($B > 1$ T) magnetic field (Choudhary *et al.* 2020*a*).

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These charged dust particles experience a finite gravitational force that leads them to settle down on the wall of the experimental device. A strong electric field using various discharge configurations (Chu & Lin 1994; Thomas *et al.* 1994; Bandyopadhyay *et al.* 2008; Choudhary, Mukherjee & Bandyopadhyay 2016*a*,*b*) opposite to gravity can hold dust grains for a longer time in the plasma medium. The confined dust grains in the electrostatic potential well created by using different discharge configurations exhibit a collective response under the action of internal or external electromagnetic perturbations. In the last 30 years, a broad spectrum of theoretical, experimental and computational research has been performed to explore the physics of dusty plasma medium, which is an admixture of electrons, ions and charged solid particles. The collective response of dusty plasma under electromagnetic perturbation is observed in the form of dust acoustic waves (Schwabe *et al.* 2007; Bandyopadhyay *et al.* 2008; Flanagan & Goree 2010; Sarkar *et al.* 2013; Merlino 2014; Choudhary *et al.* 2016*a*, 2020*b*), dust lattice waves (Homann *et al.* 1998; Farokhi *et al.* 2000), dust voids (Morfill *et al.* 1999; Thomas, Avinash & Merlino 2004), dusty plasma crystals (Chu & Lin 1994; Jaiswal *et al.* 2017; Chaubey & Goree 2022), rotational and vortex motion (Sato *et al.* 2001; Agarwal & Prasad 2003; Vaulina *et al.* 2004; Chai & Bellan 2016; Bailung *et al.* 2020; Choudhary 2023), ring structures (Dharodi & Kostadinova 2023), Mach cones (Samsonov *et al.* 1999; Bandyopadhyay, Dey & Sen 2017), etc.

A large amount of charge on massive solid particles makes a dust-grain medium unique compared with a conventional two-component plasma. The dynamics of charged dust grains can be tracked easily because of their low-frequency ($\sim$1 to 100 Hz) response (Merlino 2014; Choudhary 2023). Moreover, the dust-grain medium exhibits liquid- or solid-like characteristics depending on the average potential energy of the dust component compared with the kinetic energy (Smith *et al.* 2008; Hariprasad *et al.* 2020). The fluid or viscoelastic nature of the dust plasma system strongly depends on the Coulomb coupling strength among charged dust grains. Therefore, the study of vortex and coherent structures similar to hydrodynamic fluid has been an active research topic in dusty plasmas for the last 30 years. The study of the small-scale or the large-scale vortex structures in unmagnetized or magnetized dusty plasmas helps to understand the heating of the dust-grain medium, heat transport mechanism, turbulence state of the medium, diffusion and transport processes, mixing of fluids of different densities, etc. The unique features of the dust plasma system may help in exploring the development and evolution of sheared flow, understanding boundary value problems, formation of vortex structures, etc., in colloidal systems (Fernández-Rico & Dullens 2021) and complex hydrodynamic fluids (Hunt 1987; Ohmura, Masuda & Wang 2021) at the molecular level. The analytical/computational/experimental study of localized potential structures or vortices in the liquid-like state of a dusty plasma due to driven instabilities/turbulence may also play a significant role in understanding the development and evolution of the vortices in astrophysical fluids or planetary systems or the solar system, such as Venus vortices (Garate-Lopez *et al.* 2013), Jupiter vortices (Marcus 1993), Saturn's hexagon (Fletcher *et al.* 2018), stratospheric vortices (Waugh & Polvani 2010), polar vortices (Mitchell *et al.* 2021), tropical cyclones (Ciottone & Gebhart 2024), solar convection cells (Miesch *et al.* 2008), accretion discs (Pringle 1981), spiral galaxies (Bertin *et al.* 1989), etc., by considering it as a model system.

In the last 30 years, various global research groups have performed extensive research (theoretical, computational and experimental) on the vortical and coherent structures in dusty plasmas. It has been claimed that the dust-grain medium (a model system) has great potential for exploring the dynamics of vortices observed in other physical systems (e.g. hydrodynamic fluids, astrophysical conducting fluids, colloidal media, biological

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media, etc.) at the kinetic level. However, there is a lack of a review article that compiles most of the research results on the vortices and coherent structures in dusty plasmas. Therefore, preparing a systematic review of the vortical and coherent structures in dusty plasmas is necessary to benefit the research community. Given this objective, a review that explores the basic physics of vortex formation and past research on the vortical structures in various dusty plasma systems is prepared.

The review article is organized asfollows. Section 2 deals with the mechanism for vortex formation and the role of boundary conditions in the formation and stability of vortices in a dust-grain medium. The results of vortex and coherent structures in unmagnetized dusty plasmas are presented in § 3. Section 4 discusses the vortices in magnetized dusty plasmas. The evolution and stability of dust vortices are discussed in § 5. The connection between vortices and turbulence is reviewed in § 6. Concluding remarks along with future perspectives on the study of vortex motion in dusty plasmas are given in § 7.

2. Formation of dust vortices

This section deals with the formation of vortices due to the rotational motion of dust grains about a common centreline and the coherent structures, which are organized patterns that emerge due to the collective response of the dust-grain medium and persist in the background flow for an extended period. It should be noted that the rotational motion of dust particles can be either an orbital motion about a common axis or a spin motion about their own axis. Since the spin motion of particles does not form a vortex structure, the term rotational motion is used in this article for the orbital motion of particles. The dust dynamics (rotation/transport) is understood by exploring the forces acting upon charged dust grains in the plasma medium, possible free energy sources to drive the rotational/vortex motion in an unmagnetized (magnetized) dusty plasma and the role of the boundary conditions in the flow characteristics of the dust-grain medium in the following subsections.

2.1. *Forces acting upon dust particles*

The dynamics of charged dust particles is governed by the various forces acting on them in the plasma medium. A brief overview of these dust forces is given.

(i) **Gravitation force.** The dust grains have finite mass; therefore, they will experience the force due to the Earth's gravity. For a spherical dust grain of mass M_d, the gravitation force F_g is (Nitter 1996; Shukla & Mamun 2002*a*)

$$\boldsymbol{F}_g = M_d\boldsymbol{g} = \frac{4}{3}\pi r_d^3\rho_d\boldsymbol{g}, \tag{2.1}$$

where g is the acceleration due to gravity, r_d is the radius of the dust grain and ρ_d is the mass density of the dust grain.

(ii) **Electrostatic force.** The dust grains undergo various charging mechanisms in the plasma background and acquire a large amount of charge ($Q_d \sim 10^2$–$10^5 e^-$) on their surface. The amount of charge on the dust-grain surface is decided by the surface potential of particles (V_s) with respect to the plasma potential and the size of dust particles (Goree 1994) ($Q_d = 4\pi\epsilon_0 r_d V_s$). This shows that the net charge on the dust-grain surface scales linearly with the radius of the dust particle for a given discharge. In laboratory discharges, the charged dust particles experience an electrostatic force F_E due to the electric field E. This force is (Nitter 1996; Shukla &

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Mamun 2002*a*)

$$\boldsymbol{F_E} = Q_d \boldsymbol{E} = \pm e Z_d \boldsymbol{E}, \tag{2.2}$$

where $Q_d = \pm e Z_d$ is the dust charge.

(iii) **Ion drag force.** The dust grains are confined in an electrostatic potential well. The streaming ions in the electric field exert a force on the dust grains in two ways. The ions transfer momentum to dust particles through direct impacts (F_{ic}). Secondly, the ions transfer momentum through Coulomb collisions with the charged dust particles (F_{io}). The formulations of both forces (Barnes *et al.* 1992; Nitter 1996; Shukla & Mamun 2002*b*) under the approximation $\lambda_D / l_i \ll 1$, where λ_D is the dust Debye (screening) length and l_i is the ion mean free path, are given as

$$F_{ic} = n_i v_s m_i v_i \pi b_c^2, \tag{2.3}$$

where n_i is the plasma number density, m_i is the ion mass, v_s is the mean speed and b_c is the collection impact parameter, and

$$F_{io} = n_i v_s m_i v_i 4\pi b_{\pi/2}^2 \Gamma, \tag{2.4}$$

where $b_{\pi/2}^2$ is the impact parameter whose asymptotic angle is $\pi/2$ and Γ is the Coulomb logarithm integrated over the interval from b_c to λ_D. So the net ion drag force acting on a charged grain is $F_i = F_{ic} + F_{io}$. Since $\boldsymbol{F_I}$ is acting in the direction of the electric field, it can be written in terms of local electric field vector $\boldsymbol{F_I} = F_i \hat{E}$. For a collisional dusty plasma, an updated formulation to estimate the ion drag force is required (Khrapak *et al.* 2002; Patacchini & Hutchinson 2008).

(iv) **Neutral drag force.** The neutral drag force is a kind of resistance experienced by the dust grains if they have relative velocity or motion with respect to the background neutral gas. For dust particles of size (r_d) smaller than the collision mean free path (λ_{mpf}), i.e. $r_d \ll \lambda_{mpf}$, and velocities much smaller than the thermal velocity of the gas, i.e. $v_d \ll v_{tn}$, the neutral drag force experienced by the dust particles is estimated using the Epstein expression (Epstein 1924):

$$\boldsymbol{F_n} = -M_d \nu_{dn} \boldsymbol{v_d}, \tag{2.5}$$

where ν_{dn} is the dust–neutral collision frequency and $\boldsymbol{v_d}$ is the relative velocity of dust particles to that of the neutral gas atoms. An expression for ν_{dn} is

$$\nu_{dn} = \delta \frac{4\pi}{3} r_d^2 n_g \frac{m_n}{M_d} v_n, \tag{2.6}$$

where n_g is the neutral number density, m_n is the mass of the neutral atoms and v_n is the average thermal speed of the gas atoms. The estimated value of δ is 1.44 ± 0.19 (Liu *et al.* 2003).

(v) **Thermophoretic force.** The thermophoretic force arises due to a temperature gradient in the background neutral gas. The gas atoms present in the high-temperature zone exert more momentum on the confined dust particles than those present in the lower-temperature zone. Consequently, a thermophoretic force is established opposite to the temperature gradient. The magnitude of this force (Shukla & Mamun 2002*a*) is written as

$$\boldsymbol{F_{th}} = -\frac{32}{15} \frac{r_d^2}{v_{th,n}} \left(1 + \frac{5\pi}{32}(1-\alpha)\right) \kappa_T \nabla T_n, \tag{2.7}$$

where κ_T is the translation thermal conductivity of the gas and T_n is the neutral gas temperature. The spatial scale of the temperature gradient is greater than the size

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(diameter) of the dust grains (Zheng 2002). The value of α is $\approx$1 for dust particles and neutral gas atoms having temperatures below 500 K.

2.2. *Physics of the driven vortices*

The observed vortices/coherent structures in a dusty plasma can be categorized as externally driven and instability-driven vortices. In the externally driven vortices, dust grains behave as trace particles in the plasma background. Since the dynamics of the dust-grain medium is associated with the background plasma species (electrons, ions and neutrals), any internal and/or external electromagnetic or non-electromagnetic perturbation alters the dynamics of ambient plasma species and sets the dust cloud into rotational motion.

In the fluid description of a dusty plasma, the transport/motion of charged dust particles in the background of ambient plasma is understood by solving the equation of motion of dust particles under the action of driving and friction forces. The fluid equation of motion for the dust-grain medium, which is assumed to be incompressible in nature, is (Akdim & Goedheer 2003; Bockwoldt *et al.* 2014)

$$M_d n_d \left(\frac{\mathrm{d}\boldsymbol{v}_d}{\mathrm{d}t}\right) = n_d(\boldsymbol{F}_g + \boldsymbol{F}_E + \boldsymbol{F}_i + \boldsymbol{F}_n + \boldsymbol{F}_{th}) - \nabla P_E + \eta \nabla^2 \boldsymbol{v}_d, \tag{2.8}$$

where $\boldsymbol{F}_g, \boldsymbol{F}_E, \boldsymbol{F}_i, \boldsymbol{F}_n$ and $\boldsymbol{F}_{th}$ are the gravitational force, electric force, ion drag force, neutral drag force and thermophoretic force acting on a single dust grain; n_d is the dust number density; $\boldsymbol{v}_d$ is the dust fluid element velocity; ∇P_E is the pressure force arising due to the dust–dust interactions and confinement of dust particles in an electrostatic potential well; η is the kinetic viscosity of the dust-grain medium; and the whole term $(\eta \nabla^2 \boldsymbol{v}_d)$ represents a viscous force acting between layers of flowing dust grains. If dusty plasma experiments are performed at higher pressure ($P > 15$ Pa), then the contribution of viscous friction can be ignored compared with the friction due to background neutral gas. In normal radio-frequency (RF) discharges and low-power direct-current (DC) discharges, the magnitude of the thermophoretic force acting on dust grains is a few orders lower than that of other dominant forces. Therefore, the contribution of thermophoresis force can also be dropped in the equation of motion (2.8). Equation (2.8) takes the form

$$\left(\frac{\mathrm{d}\boldsymbol{v}_d}{\mathrm{d}t}\right) = \frac{1}{M_d}(\boldsymbol{F}_g + \boldsymbol{F}_E + \boldsymbol{F}_i + \boldsymbol{F}_n) - \frac{n_d}{M_d n_d^2} \nabla P_E. \tag{2.9}$$

The vortex motion of dust grains in a two-dimensional (2-D) plane can be described by the vorticity equation. After taking the curl of (2.9), we get the vorticity equation for the dust-grain medium:

$$\begin{aligned} \frac{\mathrm{d}\boldsymbol{\omega}}{\mathrm{d}t} = \frac{1}{M_d} & \left(\nabla \times \boldsymbol{F}_g + \nabla \times \boldsymbol{F}_E + \nabla \times \boldsymbol{F}_i + \nabla \times \boldsymbol{F}_n\right) \\ & - \frac{1}{M_d n_d^2} \nabla n_d \times \nabla P_E, \end{aligned} \tag{2.10}$$

where $\boldsymbol{\omega} = \nabla \times \boldsymbol{v}_d$ is the angular frequency or vorticity vector. Since the gravitational field is curl-free, $\nabla \times \boldsymbol{F}_g = 0$. It is also observed in many experiments that a dusty plasma is nearly homogeneous in a 2-D plane. In the case of a large-aspect-ratio dusty plasma (Choudhary, Mukherjee & Bandyopadhyay 2018) the dusty plasma is expected to be inhomogeneous. However, the dust-grain medium is normally homogeneous to the length

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scale of the size of the vortex structure. Therefore, $\nabla n_d \approx 0$ for such a nearly homogeneous dusty plasma. With all these approximations, the vorticity equation (2.10) takes the form

$$\frac{\mathrm{d}\boldsymbol{\omega}}{\mathrm{d}t} = \frac{1}{M_d}\left(\nabla \times \boldsymbol{F_E} + \nabla \times \boldsymbol{F_i} + \nabla \times \boldsymbol{F_n}\right). \tag{2.11}$$

It is clear from (2.11) that vortex generation in a dusty plasma is possible if electrostatic or ion drag force is non-conservative in the background of neutral atoms having random motion. In such a dusty plasma system, the neutral drag force has only a dissipative effect on dust-grain motion. Coherent or vortex structures in dusty plasmas indeed have a finite lifetime; therefore, steady-state solutions of the vorticity equation (2.11) would describe the onset of such dynamic structures. For the steady-state condition, (2.11) transforms to

$$0 = \left(\nabla \times \boldsymbol{F_E} + \nabla \times \boldsymbol{F_i} + \nabla \times \boldsymbol{F_n}\right). \tag{2.12}$$

For a given discharge configuration, we can write the electric field force in terms of the plasma potential ($\varPhi$) and charge (Q_d): $\boldsymbol{F_E} = -Q_d \nabla \varPhi$. The ion drag force is directed along the electric field and flow of ions. Therefore, the ion drag force vector can be written as $\boldsymbol{F_i} = F_i \hat{E}$, where F_i is an ion drag force function (magnitude) and $\hat{E}$ represents the direction of ion drag force. The neutral drag force is $\boldsymbol{F_n} = -M_d \nu_{dn} \boldsymbol{v_d}$.

Once substituting the value of forces in (2.12), we have

$$M_d \nu_{dn} \nabla \times \boldsymbol{v_d} = \nabla Q_d \times \boldsymbol{E} + \nabla F_i \times \hat{E}, \tag{2.13}$$

$$\nabla \times \boldsymbol{v_d} = \frac{1}{M_d \nu_{dn}}\left(\nabla Q_d \times \boldsymbol{E} + \nabla F_i \times \hat{E}\right). \tag{2.14}$$

There are two possible driving forces or free energy sources, $\nabla Q_d \times \boldsymbol{E}$ and $\nabla F_i \times \hat{E}$, to sustain the vortex motion of a homogeneous and incompressible dust cloud against frictional losses. In other words, the stable vortex motion of charged microparticles in the dusty plasma medium can only occur in the presence of free energy sources, compensating for the energy losses.

The first term, $\nabla Q_d \times \boldsymbol{E}$, will be non-zero if $\nabla Q_d \neq 0$. This is the case when there is a finite dust charge gradient. Similarly, the second term, $\nabla F_i \times \hat{E}$, will be non-zero if $\nabla F_i \neq 0$. This means that the gradient in ion drag force, which is not parallel to the electric field, can also excite the vortex motion of the dust cloud. The values of these vortex driving terms strongly depend on the discharge configuration used to produce the dusty plasma.

In most experimental dusty plasmas (finite systems), there are two electric field ($\boldsymbol{E}$) components. One is required to hold dust grains against gravity and the other helps compensate for the repulsive forces of dust grains. The ion drag force can have a gradient vertically (along gravity) as well as horizontally (in plane) or along an arbitrary direction near the power electrode/wall of the chamber. Whenever the value of the driving force term $\nabla F_i \times \hat{E}$ is non-zero, dust grains experience a force that rotates them in the given plane. These dust grains rotating about a common axis passing through an origin (centre of the vortex structure) form the stationary vortex structures in that plane. A schematic representation of the rotational motion in the presence of an ion drag gradient orthogonal to the electric field is depicted in figure 1(*a*).

In RF capacitively coupled discharge dusty plasmas, it is possible to estimate the curl of ion drag force ($\nabla \times \boldsymbol{F_i}$) in terms of ion density gradient (∇n_i) and velocity gradient (∇v_i)

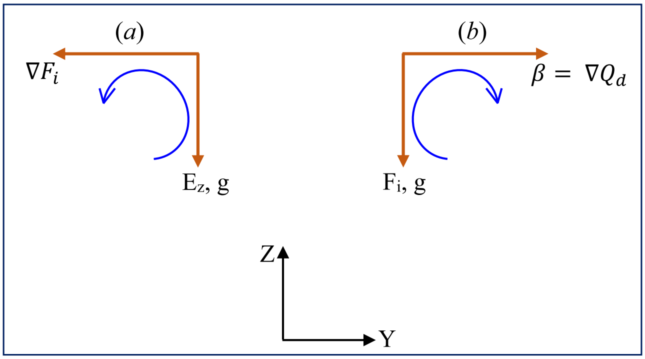

FIGURE 1. A schematic representation of the rotational motion in a 2-D plane due to (*a*) ion drag gradient along with orthogonal electric field and (*b*) dust charge gradient (β) along with orthogonal non-electrostatic force (gravity). The blue curved line with an arrow presents the direction of rotating particles in this Y–Z plane.

(Chai & Bellan 2016):

$$\nabla \times \boldsymbol{F}_i = G\nabla v_i \times \nabla n_i, \tag{2.15}$$

where v_i and n_i are the ion drift velocity and density, respectively. Parameter G depends on the grain potential, the radius of the dust particles, the ion density and the ambipolar diffusion coefficient (Chai & Bellan 2016). The finite curl of ion drag force on dust grains ($\nabla \times \boldsymbol{F}_i \neq 0$) is possible if the gradient of v_i is not parallel to the gradient of n_i. It should be noted that the formulation (expression) of $\nabla \times \boldsymbol{F}_i$ could be slightly different for different dusty plasma systems, but a finite value of $\nabla \times \boldsymbol{F}_i$ can set the dust grains into rotational motion, resulting in the formation of vortices or coherent structures in the dust cloud.

We consider a free energy source, $\nabla Q_d \times \boldsymbol{E}$, that can excite the vortex motion of dust particles. The spatial dependence of dust-grain charge in a dusty plasma system can convert the potential energy of the electric field into the kinetic energy of dust particles (Vaulina *et al.* 2000, 2004). The presence of a dust charge gradient (∇Q_d) in the dust–plasma system could be due to non-uniform charging mechanisms because of the inhomogeneity in plasma density and temperature, dispersion of the shape and size of dust grains, etc.

Apart from the fluid description, the onset of vortex motion due to spatial dependence of dust charge in the presence of non-electrostatic force $\boldsymbol{F}_{\text{non}}$ such as gravitational force ($\boldsymbol{F}_g$) or ion drag force ($\boldsymbol{F}_i$) can be explained by considering a dust system of finite particles having spatial charge dependence (Vaulina *et al.* 2000, 2003). In the presence of a free energy source, the dust particles in a dust cloud start to move in the direction of F_{non} where the dust particles have their maximum charge value and form a stable vortex structure. In figure 1(*b*), a schematic representation of dust rotation in a 2-D plane in the presence of a dust charge gradient and orthogonal non-electrostatic forces is displayed. The frequency (ω) of the steady-state rotation of particles in a vortex structure can be estimated by the formula (Vaulina *et al.* 2000, 2001*a*, 2004)

$$\omega = \left| \frac{F_{\text{non}}}{M_d} \frac{\beta}{eZ_0 \nu_{dn}} \right|, \tag{2.16}$$

where $\boldsymbol{\beta} = \nabla Q_d = e\nabla Z_d$, $Z_0 = Q_{d0}/e$ is the charge on the dust particle at an equilibrium position in the rotating plane and ν_{dn} is the dust–neutral collision frequency.

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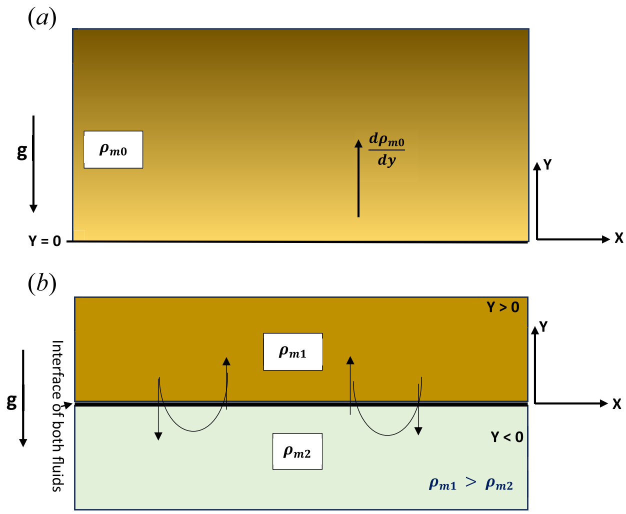

FIGURE 2. A schematic diagram of 2-D fluid (dusty plasma) having (*a*) inhomogeneous density variation opposite to the gravitational force and (*b*) sharp density variation at the separating boundary of two fluids of different densities/mass densities. The arrows indicate the direction of the flow of fluids during the evolution of RT instability.

It should be noted that the discussed theoretical models (§ 2) help to explore the driving mechanism for vortex formation in finite dusty plasma systems where the boundary and continuity are dominant effects. Therefore, such a theoretical description may not be of help in understanding the driving mechanism of vortex formation in extended dusty plasma systems.

The vortices in dusty plasmas can also arise due to instabilities such as Kelvin–Helmholtz (KH) instability, Rayleigh–Taylor (RT) instability, dust acoustic wave instability, etc. The RT instability is a buoyancy-driven fluid instability that occurs in the presence of gravitational acceleration (g). Whenever a light fluid or dusty plasma supports a heavy fluid or dusty plasma (high mass density) in the presence of gravity and a perturbation occurs at the boundary separating both fluids (Sen, Fukuyama & Honary 2010; Das & Kaw 2014; Avinash & Sen 2015), the perturbation grows with time and long-lived mushroom-like vortex structures are formed (Banerjee 2020; Wani *et al.* 2022). A single-fluid description of a dusty plasma helps in formulating the growth rate of RT instability. The stability of a dust–plasma system, in either a strongly coupled or weakly coupled state, can be understood by the dispersion relation. We consider a strongly coupled inhomogeneous 2-D dusty plasma (in the X–Y plane), as shown in figure 2(*a*), where dust density increases with height (along the y direction, which is opposite to $\boldsymbol{g}$) in comparison with the perturbation scale length. The dispersion relation for such a dusty plasma system is (Das & Kaw 2014; Avinash & Sen 2015)

$$\omega^2 = \frac{\eta}{\tau_m}k^2 - \frac{g}{\rho_{mo}}\frac{\mathrm{d}\rho_{m0}}{\mathrm{d}y}\frac{k_x^2}{k^2}, \tag{2.17}$$

where k_x is a perturbation length scale along the x axis, ρ_{m0} is the mass density of the fluid (dusty plasma) and η and τ_m characterize the nature of the dusty plasma. If $\eta \rightarrow 0$ and $\tau_m \rightarrow 0$ then the dusty plasma is considered as a simple hydrodynamic fluid (weakly coupled state). For the RT unstable dusty plasma system, the gradient in

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mass density or dust density gradient should be opposite to gravity, i.e. $\mathrm{d}\rho_{m0}/\mathrm{d}y > 0$ (as per figure 2). The growth rate strongly depends on the strength of the density gradient opposite to the gravitational force acting on the fluid/dust-grain medium. The value of the ratio $\eta/\tau_m = p_d\Gamma/\rho_{mo}$ demonstrates that the growth rate of RT instability reduces with increasing coupling strength (Γ) amongst dust grains.

If there is a sharp boundary separating two fluids of different densities (ρ_{m1} and ρ_{m2}) as shown in figure 2(*b*), then the dispersion relation is (Avinash & Sen 2015)

$$\omega^2 = \frac{\eta}{\tau_m}k^2 - gk\left(\frac{\rho_{m2}-\rho_{m1}}{\rho_{m1}+\rho_{m2}}\right). \tag{2.18}$$

In this case, the growth rate of RT instability depends on the wavelength of the initial perturbation (k^{-1}) as well as the coupling effects. The perturbation grows rapidly for shorter wavelength. It should be noted that the occurrence of RT instability in either case of dust–plasma system is possible above a critical wavenumber or initial perturbation wavelength (Avinash & Sen 2015).

The KH instability occurs at the interface of two fluids flowing with different velocities (Banerjee, Janaki & Chakrabarti 2012; Johnson, Wing & Delamere 2014). Such shear flow can lead to the generation of vortices, which is a result of the nonlinear stage of the KH instability. As per the schematic diagram in figure 3, two dust-grain mediums (fluids) of different mass densities (ρ_{01} and ρ_{02}) have a continuous velocity shear in the Y direction at the boundary of medium (fluid), while flowing in either horizontal direction ($\pm X$). A set of singly charged fluid equations are solved using the linear stability analysis technique along with some boundary conditions and initial values (incompressible perturbation, variation of perturbed quantities along the y axis) (Krall & Trivelpiece 1986; Dolai & Prajapati 2022). The dispersion relation is

$$\omega = k_x(\alpha_1U_1 + \alpha_2U_2) \pm \sqrt{-k_x^2\alpha_1\alpha_2(U_1-U_2)^2}, \tag{2.19}$$

where $\alpha_1 = \rho_{01}/(\rho_{01}+\rho_{02})$, $\alpha_2 = \rho_{02}/(\rho_{01}+\rho_{02})$ and k_x is the length scale of the perturbation. Velocities U_1 and U_2 are the equilibrium flow velocities of the charged fluid (dusty plasma) in $Y > 0$ and $Y < 0$ regions, respectively, as per the schematic representation in figure 3.

In most dusty plasma experiments, $\rho_{01} = \rho_{02}$; therefore, the dispersion relation will be

$$\omega = \frac{k_x}{2}(U_1+U_2) \pm \mathrm{i}\,\frac{k_x}{2}(U_1-U_2). \tag{2.20}$$

If ω is real, then the linear perturbation at the interface (see figure 3) will not grow with time, as it makes the dusty plasma a stable system. This is the case when there is no shear in the transverse direction at the separating boundary, i.e. $U_1 = U_2$. The dusty plasma system is KH unstable if ω is an imaginary or complex quantity. This is only possible when there is a finite velocity difference or shear in the velocity ($U_1 - U_2 \neq 0$) at the boundary. Once shear velocity ($U_1 - U_2$) crosses a critical velocity, either the thermal speed or phase velocity of a dusty acoustic wave, instability starts to grow at the interface. Since the vorticity is non-zero ($\nabla \times \boldsymbol{v}_d$) due to the discontinuity in velocity at the interface, it induces rotational velocity that can amplify the instability growth. As a result of this instability, vortex rolls or vortices are formed at the interface of the flowing dust-grain mediums (hydrodynamic fluids).

It should be noted that the growth rate of KH instability strongly depends on the compressibility in the dusty plasma (compressible dust perturbation). Therefore,

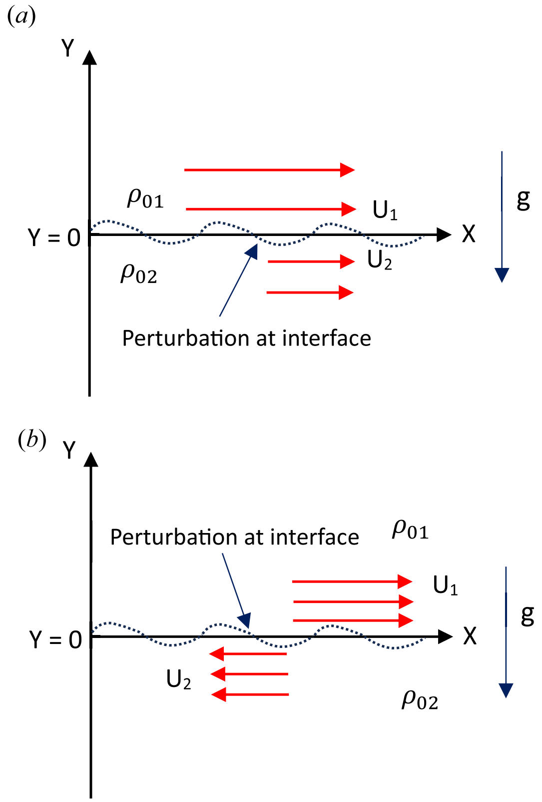

FIGURE 3. A schematic diagram of 2-D fluid flow geometry for KH instability. (*a*) Fluids flowing in the same direction but a finite shear in the velocity at the boundary separating both flowing fluids. (*b*) Fluids flowing in opposite directions with a finite shear in the velocity at the boundary separating both flowing fluids. The length and direction of the arrows indicate the magnitude of equilibrium flow velocity and direction of flow, respectively. The dotted curve represents a small linear perturbation at the interface of either flowing fluid.

the characteristics of vortex structures (shape and size) may become changed while incorporating the compressibility effect of the medium (Tiwari *et al.* 2012*d*). When the dusty plasma is in the strongly coupled state, its elastic nature also alters the characteristics of coherent or vortical structures (Tiwari *et al.* 2012*a*).

In a dusty plasma, dust-acoustic instability also plays a role in exciting the acoustic wave modes and vortex modes. Such instability arises due to the streaming of plasma ions and neutrals relative to the charged dust particles. The streaming plasma ions/neutrals are assumed to be the free energy sources for the charged dust component against the frictional losses due to the ion–neutral and dust–neutral collisions. The growth of the dust-acoustic instability in dusty plasma experiments (moderate collisional dusty plasma) is possible above a threshold electric field and increases with the electric field in the dusty plasma. However, the ion–neutral and dust–neutral collisions reduce the growth rate of the instability (Rosenberg 1993; Merlino 1997; Winske & Rosenberg 1998; Salimullah & Morfill 1999). Such low-frequency dust-acoustic instabilities (Rosenberg 1993; Salimullah & Morfill 1999) can lead to the formation of vortices (Tsai & Lin 2014) as the dust plasma system seeks to attain a more stable equilibrium state.

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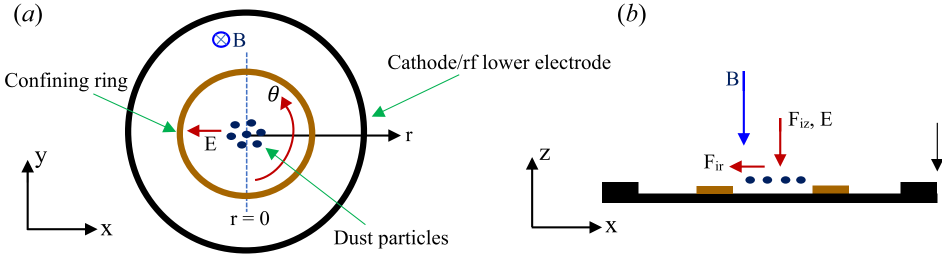

FIGURE 4. A schematic diagram of 2-D dusty plasma in (*a*) horizontal plane (*X–Y* plane) and (*b*) vertical plane (*X–Z* plane) in the presence of anexternal magnetic field (***B***). The arrows indicate the direction of the dust forces/motion in the given plane.

In the presence of an external magnetic field, the dust rotation can be induced by two mechanisms. In the first case, the magnetic field either modifies the existing ion drag gradient and/or dust charge gradient value or induces them by altering the dust-charging processes or confining potential distribution. Section 3 discusses the role of ion drag gradient and dust charge gradient along with electric field in establishing the vortex motion of the dust-grain medium (Choudhary *et al.* 2020*c*).

In the second case, the $\boldsymbol{E} \times \boldsymbol{B}$ drift of plasma particles (mostly ions) in the presence of an external magnetic field sets the dust particles into rotational motion. The schematic diagram in figure 4 represents the direction of ion drag or electric field in a cylindrical geometry where an additional ring against the dust–dust repulsive forces confines dust grains. The ions have radial as well z component of velocities in the cylindrical geometry (see figure 4*b*). In the presence of magnetic field, the path of the motion of ions (electrons) is changed from radial to azimuthal direction or in the $\boldsymbol{E} \times \boldsymbol{B}$ direction. These $\boldsymbol{E} \times \boldsymbol{B}$ drifted ions (electrons) or neutrals transfer the momentum to dust grains and set them into rotational motion in the plane perpendicular to the magnetic field (Konopka *et al.* 2000; Kaw, Nishikawa & Sato 2002). The dust grains rotating about a particular axis form the vortical structures/vortices.

2.3. *Boundary conditions and vortices*

The presence (absence) of boundary layers and the nature of boundary conditions (no slip, partial slip and perfect slip) play a crucial role in determining the dynamics of vortex formation in hydrodynamic fluid flows. A schematic representation of boundary conditions (no slip, partial slip and perfect slip) is depicted in figure 5. These boundary conditions affect the distribution of vorticity, the development of shear layers and, ultimately, the formation and evolution of vortices in the flow field (Sano 2015; Vasconcelos & Moura 2017). The velocity gradient or shear in flowing fluid around the boundary/surface of an object, which arises due to the non-slip or partial-slip boundary (see figure 5), determines the strength of shear stress in the tangential direction of flow. The boundary layer thickness (see figure 5) depends on various factors such as the medium's viscosity, compressibility, velocity of flowing fluid, mass density of fluid, pressure force, etc. If pressure decreases in the direction of fluid flow, the flow is accelerated. This results in a decrease in the boundary layer's thickness in the flow direction. However, the thickness of the boundary layer increases in the flow direction if pressure increases in the direction of fluid flow. In this case, the boundary layer gets separated from the surface of the body, and counter-rotating vortices are formed in the downstream flow or wake region of the object. The thickness of the boundary layer is predicted by the Reynolds

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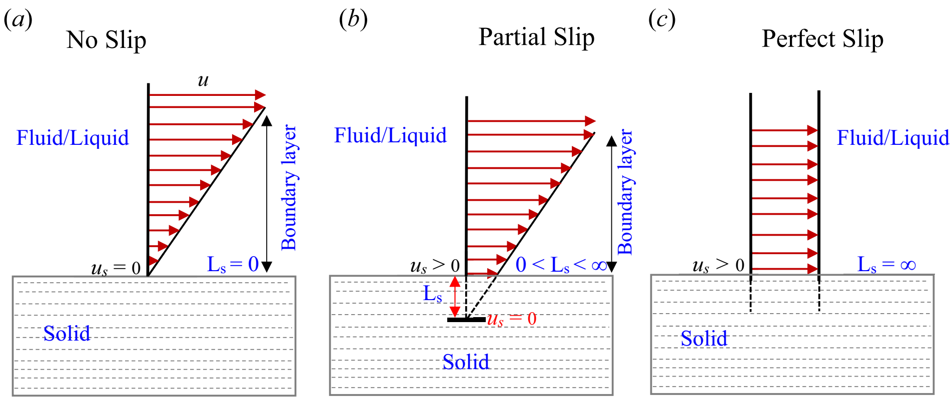

FIGURE 5. A schematic diagram representing boundary conditions for hydrodynamic fluid (liquid or gas) flowing over a solid surface. Length L_s is the slip length, u_s is the velocity at the surface and u is a constant flow velocity. The boundary layer is very thin or negligible in the perfect slip case.

number (Fornberg 1980; Sano 2015), which is a ratio of the inertial forces to viscous forces in the boundary layer. No flow separation occurs at a low value of the Reynolds number, formation of steady vortices or a vortex street is possible at an intermediate range of Reynolds number and flow becomes turbulent at a higher value of the Reynolds number (Fornberg 1980; Thom & Taylor 1933; Sato & Kobayashi 2012).

In the flowing dusty plasma, the boundary layer or Reynolds number has an effective role in the flow characteristics around the virtual boundary (potential barrier) of an object or void or confining electrode (Morfill *et al.* 2004). A typical schematic diagram to understand the physical and potential boundary (or virtual boundary) is shown in figure 6. The magnitude of dust-flow velocity or value of Reynolds number around the potential boundary (in the boundary layer) of the object/void determines the flow characteristics (laminar or turbulent) and vortex formation in the wake region of the obstacle. The existence of velocity gradient in the tangential direction (shear stress) of dust flow (as per the schematic diagram in figure 6) due to the no-slip or partial-slip boundary conditions is responsible for the formation of stable vortices and vortex street in the wake region (Morfill *et al.* 2004; Charan & Ganesh 2016). However, there is a velocity or Reynolds number range that favours vortex formation in the wake region of the object (Feng, Goree & Liu 2012; Bailung *et al.* 2020; Bandyopadhyay & Sen 2022).

In a bounded dusty plasma, dust grains are confined in an electrostatic potential well created by the biased and floating electrodes/surfaces. The rotating charged dust grains (as per figure 4) do not experience any drag/friction force due to the physical boundaries (surfaces/electrodes). However, the potential boundary could have a finite role in the flow characteristics of the dust-grain medium. In such bounded systems, studying the boundary conditions on the vortex motion/flow is challenging because of the potential boundaries rather than physical boundaries (see figure 6). The potential boundaries are expected to shift or modify on tuning the plasma parameters. If one changes the potential boundaries, the dynamics becomes altered in response. This is possible because of the change in dust parameters (charge, forces) associated with the ambient plasma parameters. Therefore, an explicit role of boundaries in the dynamical dust structures in most dusty plasma experiments (bounded systems) has not been explored.

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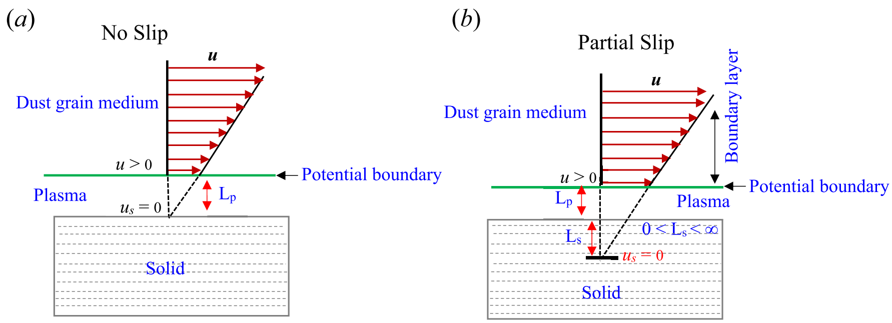

FIGURE 6. A schematic diagram of dusty plasma flow around a solid surface. (*a*) No slip and (*b*) partial slip. The potential boundary is separating the plasma and dust-grain medium. Length L_p is the length of the plasma column or sheath dimension or void dimension over the solid surface.

3. Vortices in unmagnetized dusty plasma

A dusty plasma without any external magnetic field is called an unmagnetized dusty plasma. This section discusses externally driven and instability-driven vortices in an unmagnetized dust-grain medium. The section is structured based on the driving mechanisms (external or instability) to form vortices and coherent structures against dissipation losses in an unmagnetized dusty plasma.

3.1. *External object and force-induced vortices*

Past study suggests that the vortex motion of charged particles can be excited by introducing external perturbation with the help of a floating or charged object (rod/probe) in a dusty plasma. The origin of counter-rotating vortices due to a non-uniform field around a biased probe (metal wire), which is shown in figure 7, is reported by Law *et al.* (1998). The dust vortex motion in vertical and horizontal planes was also observed in the presence of an external metal electrode in a planar RF discharge (Samarian *et al.* 2002). The dissipative instability induced by the dust charge gradient and orthogonal non-electrostatic force was considered as the primary source of vortex formation. Uchida *et al.* (2009) observed 2-D dust vortex flow in a DC discharge near the edge of a negatively biased metal plate introduced externally above the dust-levitating electrode. The numerical calculations conclude that asymmetric ion drag force due to the alteration of the potential distribution of confined dust grains in the presence of the biased metal plate plays a dominant role in forming these symmetric dust vortices. The experimental study by Yan *et al.* (2017) suggests that the vortex motion of dust grains can be set up with a modification in confinement electrostatic potential using an insulator saw structure above the conducting lower RF-powered electrode. The asymmetry of the saw-teeth gives rise to a non-zero curl of the total forces ($\nabla \times \boldsymbol{F} \neq 0$) acting on dust particles, which is required for vortex formation. Dai *et al.* (2020) reported vortex formation in an unmagnetized dusty plasma using a metal saw electrode instead of a disc-shaped planar-powered electrode. The asymmetry in the azimuthal direction, along with the sheath electric field and ion drag, was assumed to be the leading cause of vortex motion in such a configuration. There is also the possibility of generating rotational vortices in co-generated dusty plasma without a saw-like electrode (Mondal *et al.* 2018). The recent experimental work of Bailung *et al.* (2020) suggests that a pair of counter-rotating vortices can be formed in the wake region behind a stationary obstacle (a metal object) in a flowing dusty plasma medium. Images of vortices past an obstacle in a strongly coupled dust-flowing medium are shown in figure 8.

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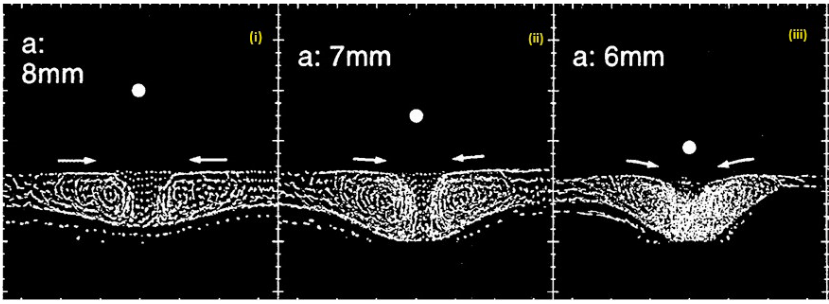

FIGURE 7. Eighteen overlapping video frames, side views, major ticks 2 mm. During experiments, an RF voltage of 90 V (peak-to-peak) at a pressure of 0.5 Torr was fixed. The probe (wire) was biased at 30 V. Three images (i)–(iii) were taken at different heights (8, 7 and 6 mm) of the probe (white circle in image) from the lower electrode. The biased-probe-induced vortex structures are clearly visible in these images. Reproduced with permission from *Phys. Rev. Lett.*, vol. 80, 1998, pp. 4189–4192. Copyright 1998 American Physical Society.

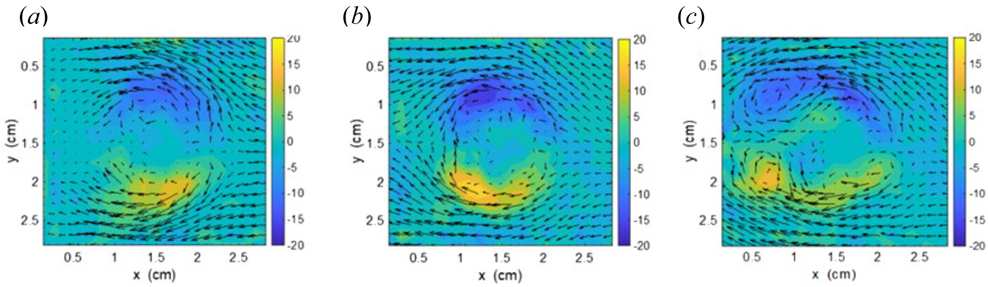

FIGURE 8. Particle image velocimetry images of dust-grain medium at different times: (*a*) 0.63–0.72 s, (*b*) 0.73–0.82 s and (*c*) 1.13–1.22 s. The dusty plasma was produced in a low-power ($P = 5$ W) RF (13.56 MHz) discharge at an argon pressure of 10^{-2} mbar. Monodispersed silica particles of size 5 ± 0.1 µm were used in these experiments. The colour bar shows the value of vorticity in S^{-1}. The vector-less region in images is the location of an obstacle (probe). The dust vortices past the obstacle in the wake region can be identified in the displayed images. Reproduced from *Phys. Plasmas*, vol. 27, 2020, 123702, with the permission of AIP Publishing.

They verified the role of the Reynolds number in the formation of vortices behind the obstacle in the wake region.

It is possible to modify the dynamical properties of a 2-D equilibrium dust-grain medium by exerting an external radiation pressure force on the dust grains with the help of laser manipulation (Feng *et al.* 2012; Melzer *et al.* 2012). The dynamical stability of a 2-D dust cluster with a finite number of dust particles under the action of external torque was investigated in the laboratory by Klindworth *et al.* (2000). Two opposing laser beams were used to create a torque between dust layers by using the concept of radiation pressure. They observed that the whole dust cluster rotates as a solid at low laser torque, but intershell rotation is possible at higher laser torque. A Monte Carlo simulation includes the non-ideal effects to understand the intershell rotation by external laser torque. A recent experimental investigation demonstrates that an energetic electron beam (8–10 keV) can exert a torque on charged particles. The dust particles in a cluster experience torque which is a result of electron drag (Ticoş *et al.* 2021). In a large dust cluster (2-D dust crystal), a pair of vortices on either side of the electron beam direction are formed with the passing of it

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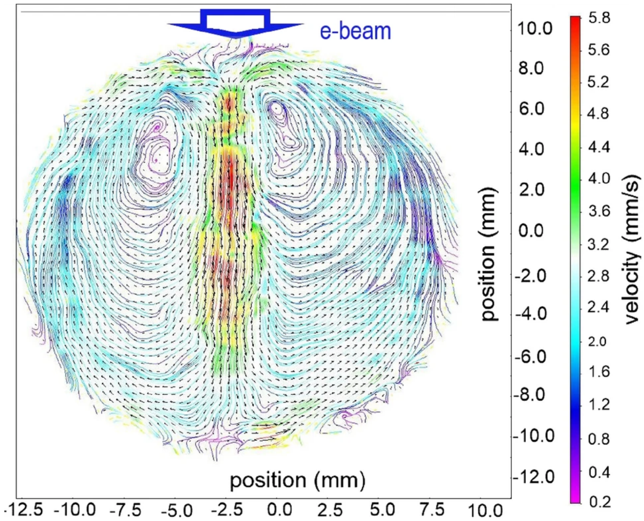

FIGURE 9. Particle image velocimetry image of electron-beam-induced dust flow forming two symmetric vortices relative to the irradiation direction. The streamlines show the geometry of the flow, while the flow speed is inferred from the colour bar. The electron beam of variable acceleration voltage or energy (10–14 keV) is produced in high vacuum (10^{-4} Torr), while the dusty plasma crystal is produced at high pressure (10^{-1} Torr) in a capacitively coupled RF (13.56 MHz) discharge. From Ticoş *et al.*, *Sci. Rep.*, vol. 13, 2023, 940; licensed under a Creative Commons Attribution (CC BY) licence.

through the dust-grain medium (Ticoş *et al.* 2023). A particle image velocimetry image of the electron-beam-induced vortices is depicted in figure 9.

3.2. *Ion-drag-induced vortex structures*

It has been experimentally demonstrated that a dust-grain medium exhibits vortex flow, as depicted in figure 10, in RF discharge under microgravity conditions (Morfill *et al.* 1999). The origin of vortex structures observed in microgravity dusty plasma experiments was explained by considering the combined role of ion drag force, electric force and screened Coulomb force acting on the dust particles (Akdim & Goedheer 2003; Goedheer & Akdim 2003; Bockwoldt *et al.* 2014) as discussed in § 2.2. In a novel ice dusty plasma experiment, Chai & Bellan (2016) observed the vortex motion of charged ice particles created in a device by cooling down water vapour in a controlled manner. The non-conservative nature of ion drag force due to the non-parallel ion density gradient and ion drift velocity gradient (see figure 11) acting on charged ice particles set them into vortex motion. Kaur *et al.* (2015*a*,*b*) have observed dust vortices (in a 2-D plane) in the poloidal plane of a toroidal geometry in a DC discharge configuration. The experimental estimation of forces acting on dust grains in the plasma background confirms the role of the non-conservative nature of the ion drag force in driving vortex motion. The experimental study of Mulsow, Himpel & Melzer (2017) explored the motion of dust grains in a cluster having 50–1000 particles using three-dimensional (3-D) diagnostic techniques (stereoscopy). It was observed that dust grains exhibit vortex motion in a poloidal plane when more particles are added to the cluster. The quantitative analysis confirmed the role of the radial gradient of ion drag force in exciting the vortex flow in the dust-grain medium. Vladimirov *et al.* (2001) reported vortex structures with a large number of dust particles in a nuclear-induced dusty

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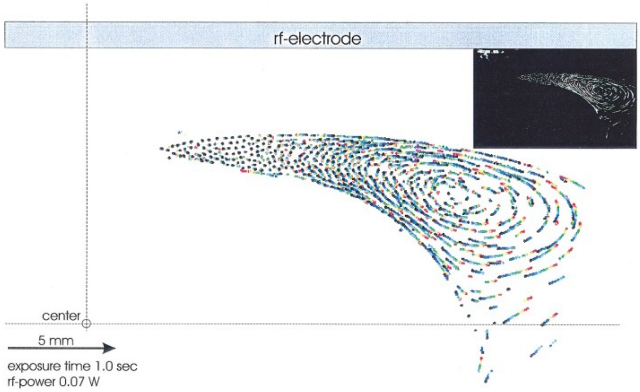

FIGURE 10. Cross-sectional view through the colloidal plasma condensation in microgravity (TEXUS 35 rocket flight). The RF power was 0.075 W, and 150 video images with a total exposure of 1.0 s were combined and colour-coded, thus tracing the particle trajectories (beginning with 'red'). In the inset, the original video image is shown. Reproduced with permission from *Phys. Rev. Lett.*, vol. 83, 1999, pp. 1598–1601. Copyright 1999 American Physical Society.

plasma system. It was suggested that the motion of ions in the external electric field set dust particles into vortex rotation through an ion–dust momentum transfer mechanism. A ground-based laboratory experiment with the concept of thermophoretic force against gravity on dust particles by Morfill *et al.* (2004) confirmed the vortex flow in the wake region of an obstacle (here void) in the flowing dusty plasma. To understand the onset and characteristics of vortices around a void in the dust-grain system under microgravity conditions, Schwabe *et al.* (2014) conducted a detailed numerical simulation of the 2-D dusty plasma system. The addition of extra dust particles to the equilibrium 2-D dusty plasma medium makes it unstable, and vortices are formed around the void due to the non-zero curl of the combined ion drag and electric forces acting on particles. A vast analytical and numerical study on the origin of vortex structures in dusty plasma fluid was done by Laishram, Sharma & Kaw (2014), Laishram & Zhu (2018), Laishram, Sharma & Kaw (2015), Laishram *et al.* (2017, 2018) and Laishram, Sharma & Zhu (2020) using 2-D hydrodynamics modelling. The authors explored the role of ion shear flow, nonlinearity, boundary conditions and viscosity of the medium in generating a self-organized vortex or coherent structures in the 2-D dusty plasma medium. Their study also predicts the formation of multiple co-rotating vortices in the extended 2-D dusty plasma medium. In a recent experimental study, Scurtu *et al.* (2023) have observed the stretching and compression of vortices in a CO_2 RF discharge dusty plasma and discussed the results based on ion drag force as discussed in § 2.2.

3.3. *Dust-charge-gradient-induced vortices*

The self-excited dynamical structures (vortices) in a dusty plasma system having an inhomogeneous plasma background were explored by Vaulina *et al.* (2000, 2001*a*,*b*, 2003, 2004). The role of dust charge gradient along with orthogonal non-electrostatic force such as gravitational or ion drag force in such a dissipative dusty plasma medium in the formation of vortices was discussed in § 2.2. A typical dust vortex flow pattern in the presence of dust charge gradient (β_r) along with gravitational force (mg) is presented in figure 12. The mathematical model provided in § 2.2 had helped to explain the

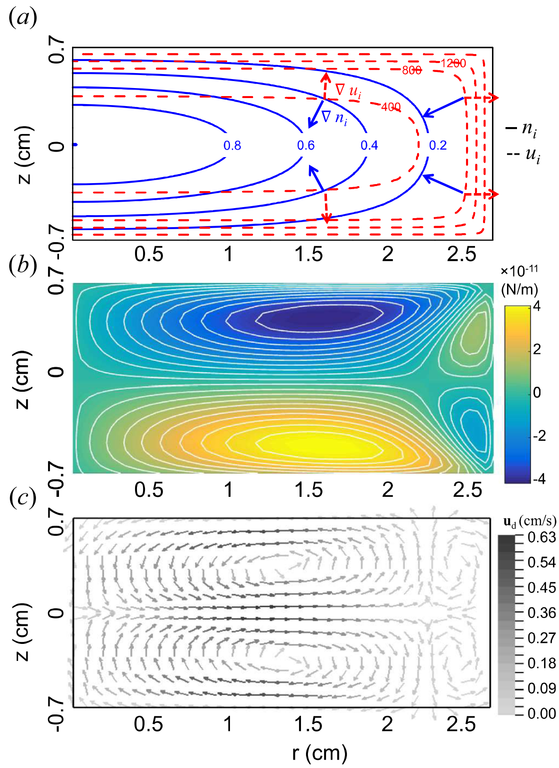

FIGURE 11. (*a*) Contour plots of u_i (dashed lines) and n_i/n_{i0} (solid lines). (*b*) Contour plot of $(\nabla \times F)$. (*c*) Flow velocity u_d obtained from a numerical partial differential equation solver. Reproduced from *Phys. Plasmas*, vol. 23, 2016, 023701, with the permission of AIP Publishing.

experimentally observed dust vortices in a planar RF discharge dusty plasma (Vaulina *et al.* 2001*b*; Samarian *et al.* 2002). Agarwal & Prasad (2003) observed the rotating structures (vortices) in a DC discharge strongly coupled dusty plasma without any external metal electrode. The vortex flow in such a dissipative dusty medium was understood with the help of the theoretical model provided in § 2.2. Ratynskaia *et al.* (2006) performed an experimental study of dust grains in a 2-D monolayer complex plasma and reported a wide range of vortical flows or structures. One of the causes for the formation of large-scale vortices in the 2-D complex plasma was assumed to be charge inhomogeneity across the dust layer. A recent experimental study by Choudhary, Mukherjee & Bandyopadhyay (2017) and Choudhary *et al.* (2018) has confirmed the dust charge gradient along with ion drag force or gravity as a driving force to excite the vortex motion against dissipative losses in a dusty plasma medium. In this work, a novel experimental configuration using an inductively coupled discharge was proposed to create a large-aspect-ratio dusty plasma with an inhomogeneous plasma background that can accommodate multiple self-sustained vortex structures (Choudhary *et al.* 2017, 2018) as shown in figure 13.

3.4. *Neutral-drag-driven vortex structures*

Mitic *et al.* (2008) observed for the first time vortex structures (see figure 14) in a dust-grain medium confined in a vertical glass tube due to the thermal creep of background atoms/molecules. In their study, the gas flow driven by thermal creep was anti-parallel to gravity. The background gas atoms driven by thermal creep exert a drag force on dust

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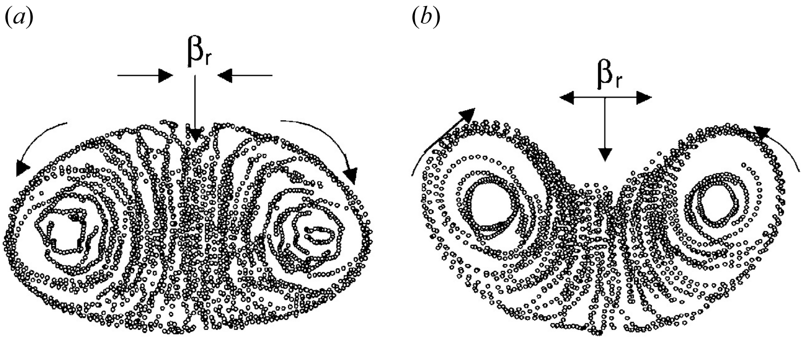

FIGURE 12. Examples of dust vortex motion (trajectories of particles) obtained from numerical simulations for different parameters (given in the original article). Here β_r represents the dust charge gradient direction from the centre of the dust cloud, and *mg* is the gravitationalforce acting on particles. The direction of β_r decides the direction of vortex flow. Reproduced with permission from *New J. Phys.*, vol. 5, 2003, pp. 82.1–82.20. Copyright 2003 Institute of Physics (IOP). CC BY-NC-SA.

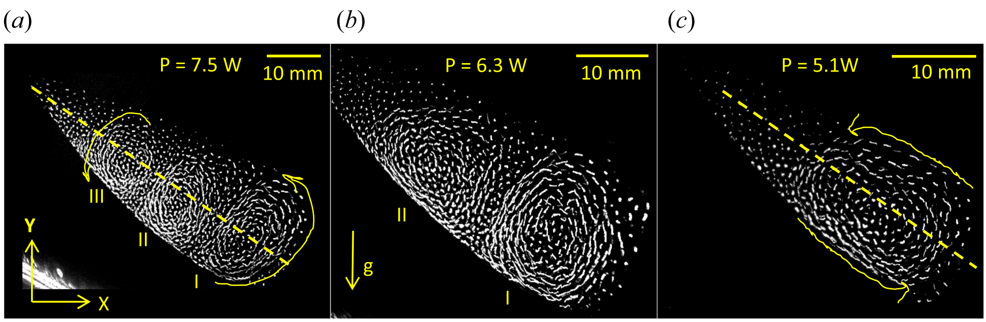

FIGURE 13. Video images of a dust cloud in the X–Y plane. All images are obtained by superposing five consecutive images at a time interval of 66 ms. The vortex structures were observed at (*a*–*c*) different input RF powers. Yellow solid lines with arrows indicate the direction of the vortex motion of dust grains, and the dashed line corresponds to the axis of the dust cloud. Reproduced from *Phys. Plasmas*, vol. 24, 2017, 033703, with the permission of AIP Publishing.

grains, forming vortices in the dust-grain medium (Schwabe *et al.* 2010). The experimental study by Flanagan & Goree (2009) also demonstrated the role of thermal creep flow in setting dust grains into rotational motion. The temperature gradient along a surface in contact with a low-pressure gas creates thermal creep flow, resulting in the formation of 2-D vortex flow due to the easy response of dust particles with ambient gas flow. A recent experimental study under microgravity conditions (Schmitz *et al.* 2023) also confirms the role of thermal creep in driving the dust grains into rotational motion, resulting in counter-rotating vortices. It has been reported (Kählert *et al.* 2012) that frictional coupling between dust particles and background neutral gas can be used to realize the magnetization of massive charged dust particles. The dust grains behave in a way that is equivalent to being magnetized in the absence of an external magnetic field. The directed flow (rotational flow) of background gas sets dust grains into rotational motion through momentum transfer mechanisms (Kählert *et al.* 2012). If sufficient dust grains are used in the experiment, dust vortices are expected to form in a strongly coupled dusty plasma

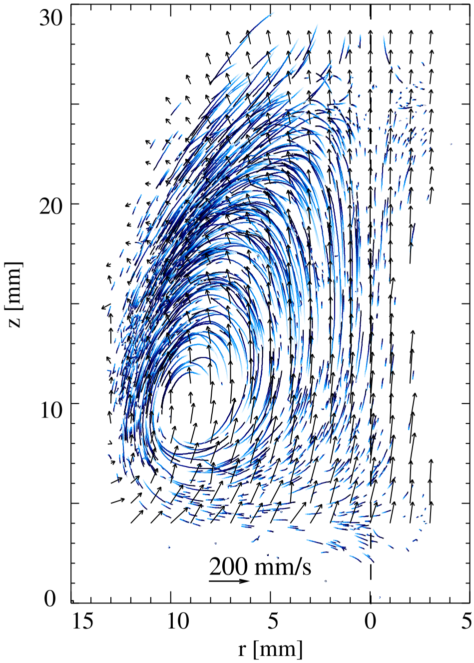

FIGURE 14. Averaged gas flow velocity field (vectors) superimposed with particle trajectories. The vertical dashed line indicates the centre of the tube. Reproduced with permission from *Phys. Rev. Lett.*, vol. 101, 2008, 235001. Copyright 2008 American Physical Society.

medium by rotating neutral gas. The role of frictional coupling of dust particles with background neutrals in exciting the large-scale shear modes such as vortices or intershell rotations in Yukawa balls (dusty plasma balls) was explored experimentally by Ivanov & Melzer (2009). They used singular value decomposition and normal mode analysis to explore the dynamical features of Yukawa balls. Their analysis predicted various modes, but large-scale vortices and intershell rotations were the dominant ones. In computer experiments, it is possible to create a temperature difference between charged dust layers and study the effect of temperature gradient on dust dynamics. With this objective, Charan & Ganesh (2015) performed a molecular dynamics (MD) simulations of a strongly coupled dusty plasma with a temperature difference between charged dust layers and observed the vortex flow.

3.5. *Instability-induced vortices*

The role of various instabilities in exciting vortices in finite or extended dusty plasma systems has been discussed in § 2.2. Veeresha, Das & Sen (2005) demonstrated the RT-instability-driven flow patterns or vortices in a dusty plasma. These vortex structures or modes were observed in the saturation state of the RT instability. The numerical work of Chakrabarti & Kaw (1996) also confirmed that the nonlinear evolution of RT instabilities can form coherent vortex structures in dusty plasmas. The stability of such coherent vortex structures depends on the strength of short-range secondary instability, which is excited in the core of the vortex (Jun *et al.* 2006). Recent numerical simulations by Dharodi & Das (2021) also observed the vortex-like structure as shown in figure 15 during the time evolution of RT instability in viscoelastic dusty plasma fluid. However, no experimental

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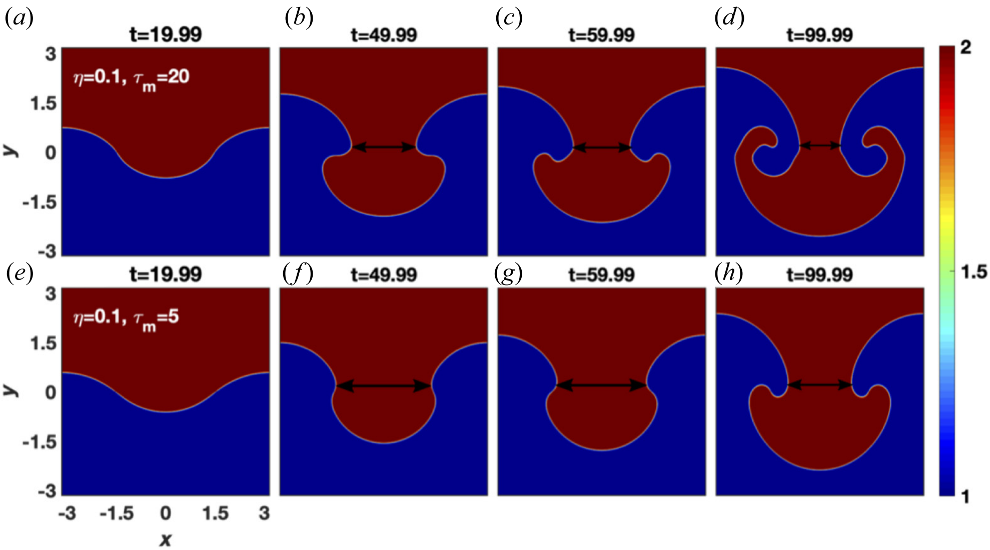

FIGURE 15. The growth of RT instability at the sharp interface of two viscoelastic fluids (dusty plasma) of different densities: (*a–d*) $\eta = 0.1$, $\tau_m = 20$; (*e–h*) $\eta = 0.1$, $\tau_m = 5$. Reproduced with permission from *J. Plasma Phys.*, vol. 87, 2021, 905870216. Copyright 2021 Cambridge University Press.

work has been reported to confirm the RT instabilities that drive coherent vortex structures in dusty plasmas.

Another kind of instability that has been studied for a long time in dusty plasmas is KH instability (Banerjee *et al.* 2012). Ashwin & Ganesh (2010) performed MD simulations to explore the KH instability in a strongly coupled dusty plasma. Time evolution of KH instability produces vortex roll in the nonlinear regime depicted in figure 16. Numerical and analytical studies of KH instability-driven flow patterns (vortex structures) in the nonlinear regime in weakly as well as strongly coupled dusty plasmas have been conducted by various research groups (Tiwari *et al.* 2012*c*,*b*, 2014; Das, Dharodi & Tiwari 2014; Dharodi, Patel & Das 2022). The analytical study by Janaki & Chakrabarti (2010) claimed the existence of dipolar vortex structures in a 2-D dusty plasma medium in the presence of sheared dust-grain flow. Gupta & Ganesh (2018) and Gupta, Ganesh & Joy (2018) performed computational fluid dynamics and MD simulations of a dusty plasma medium with Kolmogorov shear flows and observed the coherent vortex structures along with other flow patterns as a result of the sheared-flow-induced instabilities. A recent experimental study by Krishan *et al.* (2023) confirmed the KH instability-driven vortex structures in a DC discharge flowing dusty plasma. They generated shear at the interface of the moving and stationary layers of the dust-grain medium that excites the KH instability, and evolution of it gives vortex structures, as is shown in figure 17.

4. Vortices in magnetized dusty plasma

The previous section deals with vortex and coherent structures in unmagnetized dusty plasmas where different free energy sources to drive vortex motion against dissipation losses were elaborated in detail. As a magnetic field is introduced to a dusty plasma, then either electrons or both electrons and ions or all charged species (electrons, ions and charged dust grains) may get magnetized depending on the strength of the external

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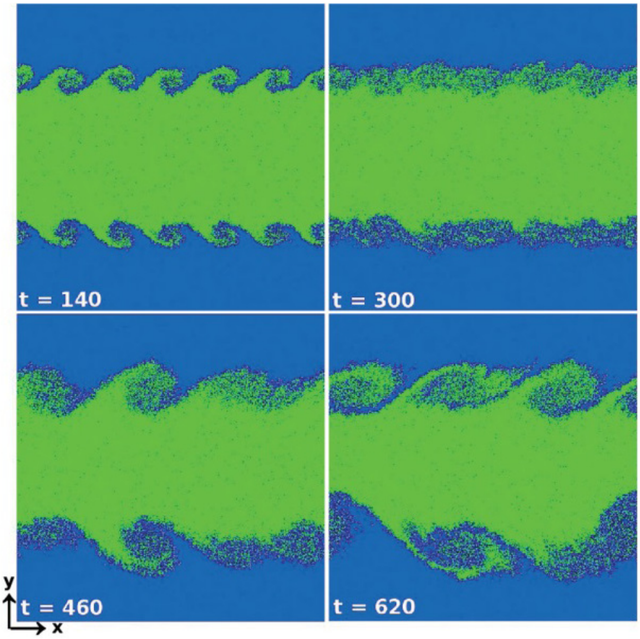

FIGURE 16. Blue-coloured fluid moves in the $+x$ direction and green-coloured fluid moves in the $-x$ direction. Inverse cascading of mode $m_n = 6$ starting from an initial state with a coupling constant of 50. The formation of vortices and their evolution due to KH instability can be seen in the images. Reproduced with permission from *Phys. Rev. Lett.*, vol. 104, 2010, 215003. Copyright 2010 American Physical Society.

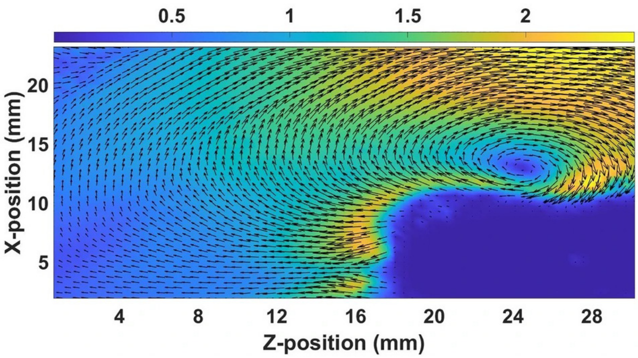

FIGURE 17. The velocity vector field with the magnitude of the velocity ($\mathrm{cm\,s^{-1}}$) for double-layer flow with the input pressure of the pulse valve being 300 Pa. The vortex pattern in the displayed image arises due to the KH instability. From Kumar *et al.*, *Sci. Rep.*, vol. 13, 2023, 3979; licensed under a Creative Commons Attribution (CC BY) licence.

magnetic field. If only electrons are magnetized at a weak magnetic field, then usually, the term weakly magnetized is used to define the dusty plasma. At an intermediate strength of magnetic field where both electrons and ions are magnetized, we call it a strongly magnetized dusty plasma. If massive charged dust grains are magnetized at a higher strength of magnetic field, then the plasma is termed a fully magnetized dusty plasma. Therefore, the term magnetized is used even if only one of the charged species of the

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dusty plasma is magnetized. As we know, the external magnetic field strongly affects the dynamics of charged species through magnetic or Lorentz force [$F_m = q(\boldsymbol{v} \times \boldsymbol{B})$]. The strength of Lorentz force strongly depends on the velocity (or energy and mass) of the charged particle; therefore, lighter charged particles (electron/ions) having higher velocity experience a strong magnetic force as compared with the massive slow-moving charged particles (dust grains) at a given strength of the magnetic field. Hence, the dynamics of electrons and ions get modified at a weak magnetic field, but a strong magnetic field is required to make Lorentz force effective for charged dust particles (Thomas, Merlino & Rosenberg 2012; Melzer *et al.* 2021). There are many challenges to achieving magnetization conditions for charged dust grains (Thomas *et al.* 2012; Choudhary 2023) in the laboratory; therefore, most past studies were conducted on magnetized dusty plasmas where only ambient plasma species (electrons and ions) were magnetized. The role of the external magnetic field in establishing the vortex structures through the dynamics of plasma species in the dust plasma system is discussed in this section.

4.1. *The* $\boldsymbol{E} \times \boldsymbol{B}$ *drift-induced vortex motion*

In the presence of an external magnetic field, $\boldsymbol{E} \times \boldsymbol{B}$ drifted ions (electrons) exert force on dust grains and set them into rotational motion (Konopka *et al.* 2000; Sato *et al.* 2001; Kaw *et al.* 2002; Dzlieva *et al.* 2016; Abdirakhmanov *et al.* 2019) or background neutral atoms are set into rotation by azimuthal ion flow, and then dust particles start to rotate via this neutral gas flow (Shukla 2002; Carstensen *et al.* 2009). The trajectories of the rotating dust grains can be rigid rotation (Reichstein, Pilch & Piel 2010; Wilms, Reichstein & Piel 2015) or shear rotation (Konopka *et al.* 2000; Choudhary *et al.* 2021) or vortex rotation (Vasiliev *et al.* 2011; Choudhary *et al.* 2020*c*). Huang *et al.* (2007) observed the various vortex patterns of dust grains in magnetized dusty plasma experiments (see figure 18) where the external magnetic field was 0.2 T. They observed the gathering and dispersive vortex structures in a 2-D plane after tuning the input RF power. The MD simulation and analysis of forces acting on dust grains confirmed the role of confining electric potential and strong magnetic field in the transition of circular rotating dust particles to vortex structures. To understand dust vortex patterns, Nebbat & Annou (2010, 2023) did calculations using a time-dependent nonlinear model for such a dusty plasma system and highlighted the role of magnetized ions having azimuthal velocity component in driving vortex motion. Vasiliev *et al.* (2011) presented experimental results on rotating dust structure (vortex) in a horizontal plane of a cylindrical device with DC discharge configuration under the action of a strong magnetic field up to 0.25 T. The rotation of dust grains in the structure was explained by calculating the ion drag force acting on particles against friction force arising due to the background neutrals. In a strong magnetic field ($B > 0.5$ T), dust clusters in the 2-D horizontal plane also exhibit vortex-like motion that was confirmed in an MDPE dusty plasma device (Jaiswal *et al.* 2017). Saitou & Ishihara (2013) studied the dynamics of a dust-grain medium in a strong magnetic field. They observed the transition from horizontal rotational motion to vortex motion in the vertical plane of a cylindrical system once the strength of the external magnetic field is increased. The disturbance of the magnetohydrodynamic equilibrium of the dust-grain medium at a higher value of magnetic field was considered the leading cause of the vortex motion of dust grains in the vertical plane. It should be noted that dust clouds that rotate as a whole at low to moderate magnetic fields in a horizontal plane break up into smaller vortices at high magnetic fields ($B > 1$ T). Schwabe *et al.* (2011) performed experiments in a low-pressure dusty plasma and observed small-scale rotating or vortex structures in a 2-D dusty plasma at strong magnetic field ($B > 1$ T). The breaking up of the rotating 2-D dust medium into

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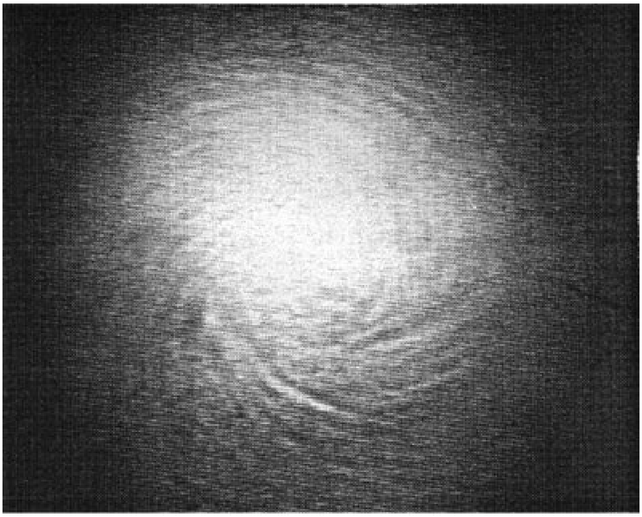

FIGURE 18. Experimental spiral vortex pattern (power = 40–50 W, $p = 120$ Pa). Reproduced with permission from *Plasma Sci. Technol.*, vol. 9, 2007, pp. 11–14. Copyright 2007 IOP Sciences.

multiple rotating structures is a result of the plasma filamentation at a strong magnetic field (Schwabe *et al.* 2011; Thomas *et al.* 2019).

4.2. *Sheared-flow- and dust-charge-gradient-driven vortices*

The analytical study using a fluids model conducted by Bharuthram & Shukla (1992) of a non-uniform dusty plasma in the presence of a magnetic field predicted dipolar vortices as a result of the stationary solution of nonlinear equations. Their study demonstrates that shear in ion flow excites low-frequency electrostatic modes, which interact with and give rise to vortex structures in dusty plasma systems. In an external magnetic field, the equilibrium sheared plasma flow or non-uniform plasma is considered a free energy source (as discussed in § 2.2) to excite various linear and nonlinear modes in the medium. The saturation state of nonlinear coupling of excited modes gives various vortex structures such as vortex chain, tripolar vortices (see figure 19) and global vortices in a magnetized dusty plasma system (Vranješ, Petrović & Shukla 2001). It is also possible to excite dipolar vortices in a magnetized dusty plasma because of the nonlinear saturation of KH instability (Rawat & Rao 1993; Shukla & Rao 1993; Ijaz, Mirza & Azeem 2007). The role of the sheared magnetic field that can produce sheared plasma flow perpendicular to the magnetic field in a dusty plasma was examined by Jovanović & Shukla (2001). The authors observed the formation of dipolar and tripolar vortices depending on the initial plasma density profiles in the non-uniform magnetized dusty plasma.

Dasgupta & Maitra (2021) investigated the dust dynamics numerically in the presence of an external magnetic field and predicted vortices in the dust plasma system by considering the role of dust–dust interactions, dust diffusion and ion drag force in the formation of vortex structures. A recent numerical simulation by Kumar & Sharma (2020) examined the dynamics of a dusty plasma medium in a weakly non-uniform magnetic field. The non-uniformity in the external magnetic field induces $\boldsymbol{E} \times \boldsymbol{B}$ drift flow of plasma particles. The sheared $\boldsymbol{E} \times \boldsymbol{B}$ drift ions play a major role in driving the vortex motion as discussed in § 2.2 in a magnetized dusty plasma system. Laishram (2021) further extended the study of

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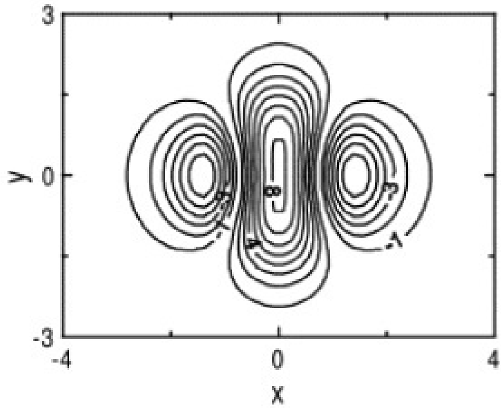

FIGURE 19. The tripolar vortex for given perturbed potential and other parameters (see the original paper (Vranješ *et al.* 2001)). Two lateral vortices have opposite direction of rotation with respect to the central vortex. Reproduced with permission from *Phys. Lett.* A, vol. 278, 2001, pp. 231–238. Copyright 2001 Elsevier.

a dusty plasma in a non-uniform external magnetic field and observed the shear between electrons and ions due to $\boldsymbol{E} \times \boldsymbol{B}$ and $\nabla B \times \boldsymbol{B}$ drifts in the presence of magnetic field. The sheared nature of these drifts was considered as the vorticity source to establish the vortex structures in the dusty plasma. It was also found from numerical investigation that temperature gradient in background ions plays a dominant role in forming vortices in a magnetized dusty plasma (Haque & Saleem 2006). In recent experimental work, Choudhary *et al.* (2020*c*) reported the existence of a pair of counter-rotating vortices, as shown in figure 20, in the vertical plane of a 3-D dusty plasma in the presence of a strong magnetic field ($B > 0.05$ T). The vortex structures originating in the dust-grain medium were explained by the combined effect of dust charge gradient and iron drag force gradient along with gravitational force/electric force in the cylindrical system. An analytical work by Shukla & Mamun (2003) reported the electrostatic and electromagnetic vortices in a non-uniform magnetoplasma containing immobile dust grains. The evolution of nonlinear dispersive solitary modes (electrostatic and electromagnetic) explains the origin of dipolar vortices in such dusty plasma systems.

5. Evolution of vortex patterns

The vortex development and evolution in a normal fluid are entirely different from that observed in a dusty plasma medium considered a viscoelastic fluid. The stability of vortices or coherent structures in an inviscid fluid is perfectly stable over time, but the destabilization of vortices is expected in a dusty plasma medium. It should be noted that the concept of inviscid flow is a simplification in the case of conventional fluids. Several factors can affect the stability of vortices. For example, the viscosity of the medium, interaction strength between charged grains, external perturbation, changes in the flow regime (laminar to turbulence flow), the interaction of vortices and instabilities develop in the system. In recent years, numerous authors have performed analytical and computational works to explore the evolution, interaction and stability of dust vortices. Dharodi, Kumar Tiwari & Das (2014) performed a numerical simulation to explore the evolution and interaction of coherent vortices in a strongly coupled dusty plasma by considering its viscoelastic nature. They observed the originating transverse shear waves

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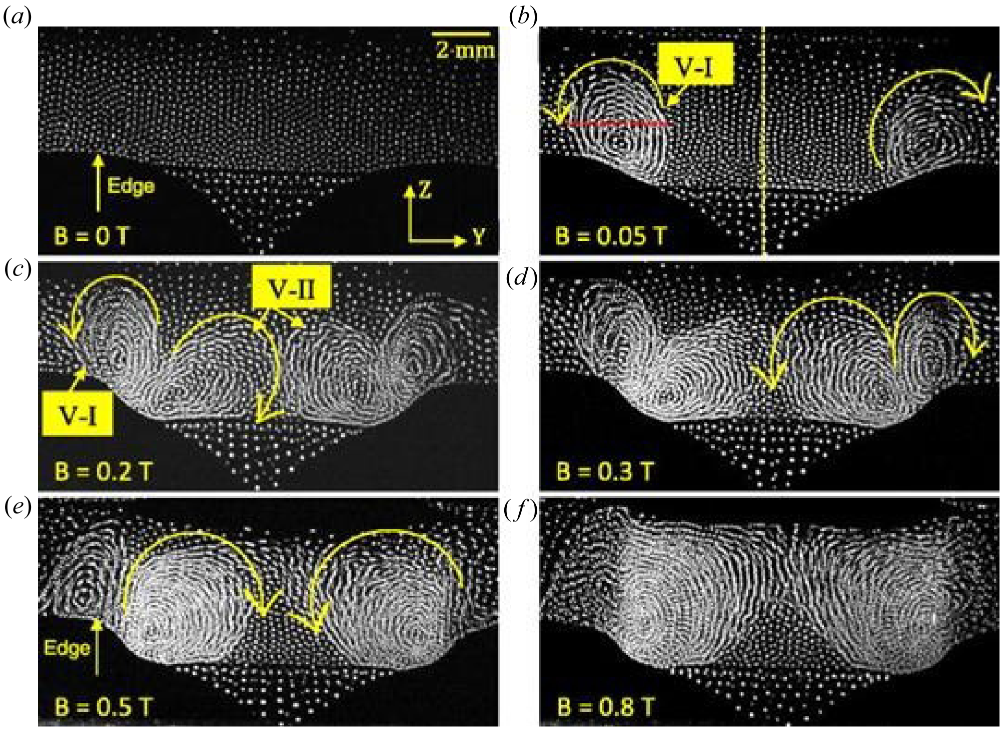

FIGURE 20. Video images of a dust cloud (aluminium ring) in the vertical (Y–Z) plane. Images at different magnetic fields are obtained by a superposition of five consecutive images at a time interval of 65 ms. The edge vortex and central region vortex are represented by V-I and V-II, respectively. The vortex structures at different strengths of the magnetic field are observed at a fixed input RF power, $P = 3.5$ W, and argon pressure, $p = 35$ Pa. The dotted yellow line represents the axis of symmetry. The yellow solid line with an arrow indicates the direction of the vortex flow in the vertical plane of the 3-D dusty plasma. Reproduced from *Phys. Plasmas*, vol. 27, 2020, 063701, with the permission of AIP Publishing.

during the evolution of vortex patterns as is depicted in figure 21. The role of collision in the interaction and evolution of counter-rotating and co-rotating vortices in such a dusty medium was examined by numerical simulation (Jana, Banerjee & Chakrabarti 2016). The effect of viscoelasticity and compressibility on the vortex patterns and originating inertial waves due to vortex motion (see figure 22) were explored using computer experiments by Gupta, Mukherjee & Ganesh (2019), Gupta & Ganesh (2020) and Gupta (2022) in the strongly coupled state of a dust-grain medium. The interaction of coherent vortex structures at the interface of two inhomogeneous dusty plasma mediums gives birth to transverse shear as well as spiral density waves (Dharodi 2020). The large-scale MD simulation of a strongly coupled dusty plasma system predicted the emergence of isolated coherent tripolar vortices during the evolution of unstable axisymmetric flows (Ashwin & Ganesh 2011). A classical MD simulation study to explore the formation and collisions of dipolar vortices in a 2-D strongly coupled dusty liquid was carried out by Ashwin & Ganesh (2012). In their set-up, the dipolar vortices emerged from a subsonic jet profile in a less dissipative dust-grain medium. During a centred head-on collision between dipolar vortices, the vortex patterns are exchanged, not mass. The circular vortices are stable due to energy balance. However, elliptical vortices can be formed in a dusty plasma

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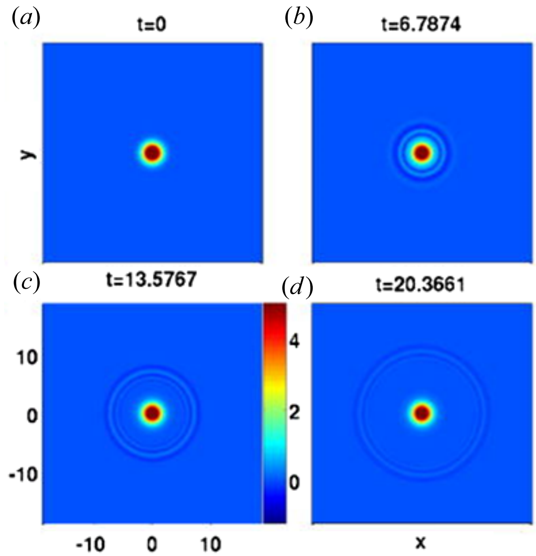

FIGURE 21. Evolution of smooth circular vorticity profile in time for a viscoelastic fluid (dusty plasma). Reproduced from *Phys. Plasmas*, vol. 21, 2014, 073705, with the permission of AIP Publishing.

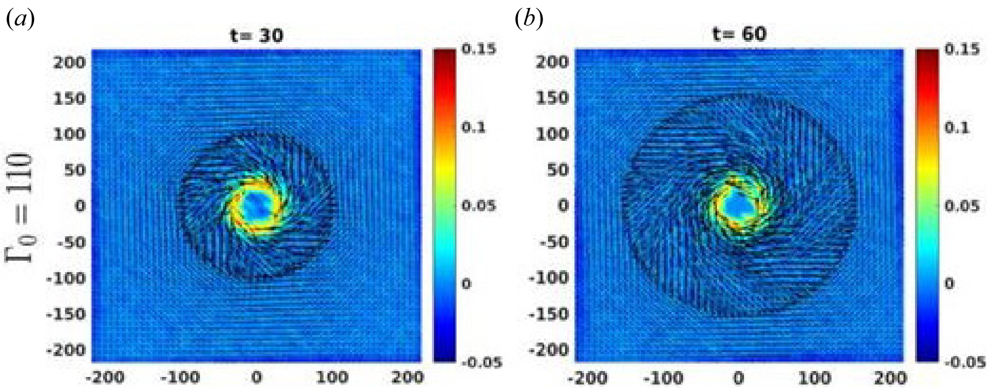

FIGURE 22. Contour plot of fluid vorticity obtained from MD simulation. Black-coloured arrows show the velocity field. The grain velocities in the bins are fluidized through a 55×55 grid to construct vorticity. Reproduced from *Phys. Plasmas*, vol. 27, 2020, 050701, with the permission of AIP Publishing.

medium if circular vortices deviate from their shape. The deformed dust vortices take an elliptical shape, which is unstable. The stability of elliptical vortices and the formation of new small-scale vortices in dusty plasmas were studied by Jana, Banerjee & Chakrabarti (2015). It should be noted that this section does not discuss the evolution and stability of vortices, which were mentioned in §§ 3 and 4. This section has highlighted some independent research works with exciting results (as discussed) during vortex evolution.

6. Turbulence and vortices

In fluids, turbulence is accompanied by vortices or vortex flow under certain flow conditions. Small-scale vortices can also be formed in a turbulent flow of a plasma or dusty plasma medium. The study of the development of turbulence in a dusty plasma at low Reynolds number was performed by Schwabe, Zhdanov & Räth (2017). The authors discussed the role of heartbeat instability and auto-oscillation in developing turbulence in the dust-grain system. To understand the turbulence in the wake region of an obstacle at the kinetic level, Joshi, Thoma & Schwabe (2024) performed a 3-D molecular simulation of complex plasma flowing past an obstacle. The obstacle was not a physical object but stationary negative charges that could repel the dust grains, forming a void around it. They observed the vortices along with shock structures in the fore-wake and wake of the obstacle. Charan & Ganesh (2016) carried out MD simulations to study the flow (at low Reynolds number) past an obstacle in a viscoelastic complex medium. The emergence of vortex street structures behind the obstacle was observed when the flow became laminar to turbulent. Such vortex street structures behind obstacles in the flowing dusty plasmas are even possible at low Reynolds numbers. Another many-body simulation study (Kostadinova *et al.* 2021) and numerical simulation (Schwabe *et al.* 2014) in a 2-D dusty plasma confirm the occurrence of turbulence in a dusty plasma at low-to-medium Reynolds numbers ($R < 100$). Various studies have also explored that dust-acoustic waves in a dusty plasma can trigger turbulence (Zhdanov *et al.* 2015). Pramanik *et al.* (2003) studied the nonlinear or self-excited dust-acoustic wave turbulent state of a dusty plasma at low dissipation losses. The experimental work by Tsai, Chang & Lin (2012), Hu, Wang & Lin (2019) and Zhdanov *et al.* (2015) also confirmed the self-excited dust-acoustic wave turbulence in dusty plasmas with decreasing dissipation losses. An experimental study by Tsai & Lin (2014) reported the self-excited fluctuating acoustic vortex pair in defect-mediated dust-acoustic wave turbulence. This acoustic vortex pair has helical waveforms oppositely winding around the hole filaments in a given plane (Tsai & Lin 2014). Lin & Lin (2018) extended this work to explore the dust-acoustic turbulence experimentally. Those authors used a multidimensional empirical mode decomposition technique to decompose the dust-acoustic wave turbulence and observed multiscale interacting dust acoustic vortices around the wormlike cores (Lin & Lin 2018). Thus, it can be stated that vortices in dusty plasmas are intricately connected to turbulence.

7. Summary and future perspective of vortex flow studies

In summary, extensive studies on the dynamical vortex and coherent structures in dusty plasmas have been performed either by individual researchers or research groups in the last 30 years. The observed dust vortices are divided into externally driven and instability-driven depending on the free energy source to drive the vortex flow. An external electromagnetic perturbation can modify the dynamics of background species (electrons, ions and neutrals), forming dust vortices through a momentum transfer mechanism between the plasma species/neutrals and charged dust grains. Those previous studies show that inhomogeneity in background plasma parameters (in the plasma volume or near the surfaces) can give rise to a dust charge gradient and ion drag gradient along a particular direction. The dust charge gradient and ion drag gradient along with non-parallel electric field component/gravity are assumed to be the free energy sources to drive the vortex motion against the dissipation losses of dust components. It has also been demonstrated that RT instability, KH instability and dust-acoustic instability can provide free energy to the dust plasma system. As a result of these instabilities, various kinds of vortex/coherent structures are observed in the dust-grain medium. The stabilizing rate of such dusty plasma instabilities is decided by various factors such as viscosity of the medium, compressibility of the dust-grain medium, Coulomb coupling strength amongst charged dust grains, background electric field, frictional coupling between dust and neutral atoms, etc. Some interesting results, such as the emergence of shear waves and inertial waves, the origin of tripolar vortices, etc., during the evolution of vortices in a dusty plasma medium were also discussed. In the presence of an external magnetic field, $\boldsymbol{E} \times \boldsymbol{B}$ drifted motion of background species (electrons, ions, neutrals) or gradient-driven forces (ion drag and dust charge gradient) are responsible for the vortex formation. The role of boundary conditions in the flowing dusty plasma around an object or void (virtual object) in dusty plasmas is highlighted. The value of the Reynolds number in such a flowing dust-grain medium determines the flow characteristics (laminar or turbulent) in the boundary layer and the vortex formation in the wake region of the object. The past studies have also demonstrated that there is a connection between the turbulent state of a dust-grain medium and vortices.

It has been discussed that the study of vortices/coherent structures in dusty plasmas with or without a magnetic field is an active research topic. A wide spectrum of work has been performed, but still, there are a lot of open problems. The author highlights some future research problems in this review article.

(i) An enormous amount of analytical and computer simulation research work on the KH-instability-driven vortices in dusty plasmas has been performed in the last few years. However, more attention is required to experimentally explore the uni-directional shear-induced vortices, the role of an external magnetic field in the growth and evolution of KH-instability-driven vortices, etc.

(ii) The experimental realization (verification) of analytical and simulation results of RT instability in an unstable equilibrium of two different dust-grain mediums in the presence of gravity is still challenging. How do we create a dusty plasma system with a density variation opposite gravity? The role of external perturbation induced by magnetic field, electric field, neutral flow, etc., in the RT instability and its long-time evolution needs to be investigated.

(iii) The experimental realization of the tripolar vortices in unmagnetized or magnetized dusty plasmas needs a lot of attention.

(iv) An external magnetic field changes the dust charge as well as potential distribution around a floating/biased object in a dusty plasma. Therefore, a detailed study of vortices behind the biased/floating object (in the wake region) in flowing dusty plasmas is needed.

(v) The role of boundary conditions (potential boundary) in the flow characteristics of bounded and flowing dusty plasmas in the absence or presence of a magnetic field needs to be studied.

(vi) The hexagonal vortices in simulation and experiments need to be explored.

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Declaration of interests

The author reports no conflict of interest.

Data availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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