

Drag modulation by finite-size particles in viscoelastic Taylor-Couette turbulence

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We experimentally investigate drag modulation by finite-size particles in viscoelastic Taylor-Couette turbulence. Three spheroidal particle shapes, namely oblate, spherical, and prolate particles, are considered. By combining global torque measurements with particle-distribution measurements, we identify two distinct particle-polymer-turbulence coupling regimes. At lower Reynolds number, the flow is particle dominated: polymer elasticity only weakly modifies the carrier turbulence, while finite-size particles introduce additional particle-related stresses and locally enhance the particle-polymer interaction. In this regime, the particle-induced drag penalty increases monotonically with polymer concentration. At higher Reynolds number, the flow becomes polymer dominated: stronger elasticity suppresses turbulent fluctuations and weakens the ability of particles to enhance angular momentum transport, leading to a nonmonotonic dependence of the particle-induced drag penalty on polymer concentration. Particle shape further modulates this particle-polymer-turbulence coupling. Spherical particles generate larger torque than oblate and prolate particles, and this shape dependence is amplified in the viscoelastic fluid, suggesting that polymer elasticity enhances the sensitivity of the global drag to shape-dependent local disturbances. Particle-distribution measurements provide the spatial signature of the two regimes: polymers have little influence at low Reynolds number, whereas at high Reynolds number they reduce the near-wall accumulation of spherical particles and make the axial distribution more strongly organized by Taylor vortices. These results reveal the regime-dependent coupling mechanisms in complex multiphase turbulence, where dispersed particles, polymer elasticity, turbulence, and secondary flows act as a coupled dynamical system to determine the particles and momentum transport.

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I. INTRODUCTION

Particle-laden turbulent flows are ubiquitous in natural environments, industrial processes, and everyday life. Examples range from atmospheric aerosols, rain, snow, and volcanic ash plumes to sediment transport in rivers and estuaries [1–3]. In engineering systems, suspended particles are encountered in combustion, pollutant transport, slurry pipelines, fluidized beds, chemical reactors, and mineral processing processes [4–11]. In such flows, particles are not simply passive tracers of

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the carrier turbulence. Depending on their inertia, size, and density, particles may preferentially concentrate, sample specific turbulent structures, and migrate under the combined effects of turbulence, coherent motions, and walls [1,4,6,12]. The particles, in turn, can feed back on the carrier phase by modifying the mean flow, turbulence intensity and interphase momentum exchange [5,13,14]. These two-way interactions become even richer for finite-size particles, for which particle-induced stresses, wakes, near-wall organization, and particle-wall interactions can directly affect the global transport properties of the flow [15,16]. Therefore, understanding particle-laden turbulence is important not only for predicting and controlling environmental particulate transport, but also for optimizing engineering systems involving suspensions and particulate flows. Despite substantial progress, the problem remains challenging because the dynamics depend on a broad range of parameters, including particle size, inertia, concentration, shape, density ratio, wall confinement, and multiscale structure of the carrier turbulence [4–6,17–19].

Adding minute amounts of long-chain flexible polymers to a turbulent flow is a classical and highly efficient strategy for reducing frictional drag, known as the Toms effect [20,21]. When stretched by local velocity gradients, polymer molecules store elastic energy and exert an additional stress on the carrier flow. This stress modifies the near-wall turbulence regeneration cycle, weakens vortical motions and reduces the correlation between streamwise and wall-normal velocity fluctuations, thereby suppressing turbulent momentum transport [22,23]. Beyond the global drag response, polymer additives also redistribute turbulent kinetic energy among scales. Previous studies have shown that polymers can inhibit the nonlinear transfer of energy from large to small scales, suppress small-scale random fluctuations, and alter the organization of coherent structures [24–28]. Thus, polymer additives provide not only a practical route for drag reduction, but also a powerful tool for probing how elasticity reshapes turbulence, momentum transport, and multiscale energy transfer.

Polymer additives also provide a means of controlling particle motion. In dilute viscoelastic solutions, gradients of elastic normal stresses can drive particles across streamlines, leading to lateral migration, focusing, and separation even in geometrically simple channels [29–31]. This mechanism has been exploited in microfluidic devices, where elastic lift can passively focus particles or cells without sheath flows, external fields, or complex channel geometries. The focusing strength can be tuned through the rheology of the suspending fluid, particle size, and flow rate, thereby enabling efficient particle manipulation and size-based separation [29,31]. For biological applications, DNA solutions have been shown to act as highly effective elasticity enhancers, producing robust particle focusing over a wide range of flow rates and offering potential routes for portable flow cytometry and cell sorting [32].

Polymer additives can also be used to control particle dynamics in turbulent flows. In homogeneous turbulence, polymer elasticity modifies the small-scale flow dynamics and can either enhance or reduce inertial-particle clustering, depending on the particle response time and the polymer relaxation time [33]. In wall-bounded turbulence, drag-reducing polymers attenuate turbophoresis by reducing the wall-normal variation of velocity fluctuations, thereby decreasing near-wall particle accumulation and enhancing particle transport in the streamwise direction [34]. For finite-size particles, the coupling becomes more intricate: experiments in turbulent duct flow showed that viscoelasticity promotes stronger migration toward the core and modifies the drag increase induced by particles [35]. Direct numerical simulations further revealed that particles can suppress turbulence while enhancing polymer stresses, so that polymer additives may lose part of their drag-reducing capability, or even increase drag in particle suspensions [36–38]. These studies suggest that polymers provide a route to manipulate particle clustering, transport, and drag, but also highlight the nonlinear nature of particle-polymer-turbulence coupling.

In these studies [35–38], spherical particles were used at a fixed flow Reynolds number. The present work examines how finite-size particles and polymer additives jointly modulate momentum transport in a turbulent flow where coherent secondary motions coexist with broadband turbulent fluctuations over a range of flow Reynolds number. Moreover, different particle geometries are considered. The remainder of this paper is organized as follows. In Sec. II, we describe

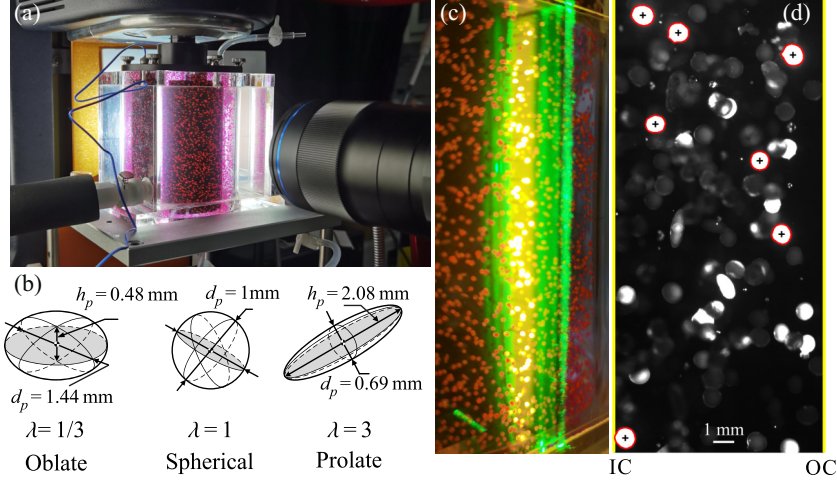


FIG. 1. (a) Picture of the two-phase viscoelastic Taylor-Couette turbulence setup. (b) Three kinds of particle shape used in this study. From left to right: oblate, spherical, and prolate particles. (c) Picture of the stained particles illuminated by a laser sheet with a thickness of about 2 mm. (d) Instantaneous snapshot of the captured spherical particle image. The red circles and black pluses mark the edges and centers of the spherical particles.

the experimental apparatus and methodology, including the Taylor-Couette (TC) facility, torque measurements, finite-size particles, working fluids, and control parameters. In Sec. III, we present the experimental results, focusing on the drag modulation induced by particles and polymers, the nonlinear particle-polymer coupling, the effect of particle shape, and the corresponding particle distributions. Finally, in Sec. IV, we summarize the main findings and discuss their implications for momentum transport in particle-laden viscoelastic turbulence.

II. EXPERIMENTAL SETUP AND METHODOLOGY

A. Experimental setup and torque measurement

The experiments were conducted in a turbulent TC facility consisting of an inner cylinder (IC) and an outer cylinder (OC), similar to the apparatus used in [19,39], and [40]. The setup was constructed based on a rheometer (Discovery Hybrid Rheometer, TA Instruments). The IC, made of anodized aluminium to minimize optical reflections, had a radius of $r_i = 25$ mm and a height of $L = 100$ mm. The OC was fabricated from transparent Plexiglas to enable optical access and had an inner radius of $r_o = 35$ mm and a height of 110 mm. The gap width between the cylinders was therefore $d = r_o - r_i = 10$ mm, corresponding to a radius ratio $\eta = r_i/r_o = 0.714$ and an aspect ratio $\Gamma = L/d = 10$. A picture of the setup is shown in Fig. 1(a).

In this study, only the IC was rotated while the OC remained stationary. The flow was driven by imposing a constant angular velocity ω_i on the IC. The OC was enclosed within a cubic water jacket connected to a refrigerated circulator to maintain a nearly constant temperature of the working fluids, which was monitored by a PT100 sensor during the experiments.

The global response of the system was quantified through direct torque measurements. The torque exerted by the fluid on the IC was measured by the rheometer with a resolution of 0.1 nNm. Similar to previous TC studies, the measured torque contains contributions from both the cylindrical TC flow and the end effects associated with the von Kármán flow generated near the top and bottom boundaries. The latter contribution was corrected following the procedure described in our previous studies [15,19,39,41,42]. The corrected torque associated with the TC flow is denoted by

τ throughout this study. To improve statistical convergence, each torque measurement was repeated three times independently.

B. Finite-size particles and particle distribution measurements

To investigate the influence of particle shape on turbulent drag modulation and particle transport, three types of particles were employed, namely oblate, spherical, and prolate particles. The particles were fabricated using a three-dimensional printer (Formlabs Inc.) and subsequently cured at 60 °C for 60 min following the procedure described by [15]. The density of the particle is $\rho_p = 1.06 \times 10^3 \text{ kg/m}^3$ [15]. The particle volume fraction C_p ranges from 0 to 7%.

To isolate the effect of particle shape, the particle volume was kept the same for all particle geometries. The particle aspect ratio was defined as $\lambda = h_p/d_p$, where h_p is the particle length along the symmetry axis and d_p is the length perpendicular to it. Three aspect ratios were investigated: $\lambda = 1/3$ (oblate particles), $\lambda = 1$ (spherical particles), and $\lambda = 3$ (prolate particles). The characteristic dimensions of the particles are summarized in Fig. 1(b). The equivalent spherical diameter for all particle types is $d_e = 1 \text{ mm}$.

Particle distributions in the gap were measured using planar imaging techniques. The particles were dyed by immersion in a Rhodamine-B solution for one hour and were subsequently rinsed several times with fresh water. A laser sheet with thickness of about 2 mm and wavelength 532 nm illuminated the particles in the $r - z$ plane, where r and z denote radial and axial directions, respectively; see Fig. 1(c). Particle images were recorded using a CCD camera (Photron Nova S12) positioned normal to the illuminated plane. The camera was equipped with a 100 mm macro lens and a filter to allow the induced fluorescence light to pass. In the particle distribution measurements, the particle volume fraction is fixed to be $C_p = 1\%$, since larger C_p results in severe optical obstruction. Previous experiments [15,35] and numerical simulation [43] had demonstrated that particle distribution is similar at different C_p .

The instantaneous particle positions were extracted using image-processing algorithms based on intensity thresholding and centroid detection; see Fig. 1(d). From the detected particle positions, the particle distribution function (PDF) of particle location across the gap width could be quantified. In addition to the radial distributions, axial particle distributions were also measured to characterize the interaction between particles and Taylor vortices. Since Taylor vortices generate organized large-scale radial transport, the axial concentration modulation provides direct information on the preferential accumulation of particles within vortex inflow and outflow regions.

C. Working fluids

The Newtonian working fluid used in the present study was a glycerol-water mixture with a glycerol mass fraction of 28%. The experiments were conducted at a constant temperature of $T = 28 \text{ }^\circ\text{C}$, controlled by a refrigerated circulating bath surrounding the outer cylinder. The temperature variation during the experiments remained within $\pm 0.1 \text{ }^\circ\text{C}$. The density of the fluid $\rho_f = 1.064 \times 10^3 \text{ kg/m}^3$, giving a 0.3% density mismatch from the particle density. To generate viscoelasticity, polyacrylamide (PAM) polymers with a molecular weight of $M_w = 5.5 \times 10^6$ were dissolved in the glycerol-water solution. The polymer solutions were prepared by slowly adding the polymer powder into the solvent under stirring. After mixing, the solutions were mildly stirred for about 16 hours to ensure complete dissolution and homogenization of the polymer molecules [25,26,39,40].

The polymer concentration ϕ ranged from 0 to 80 ppm (parts per million by weight), corresponding to the dilute regime of polymer solutions. The overlap concentration of PAM is about 940 ppm, which is substantially higher than the concentrations explored in the present study, ensuring that intermolecular interactions between polymer chains remained weak [39,44]. Consequently, the viscoelastic behavior primarily originated from the stretching and relaxation of isolated polymer molecules within the turbulent flow.

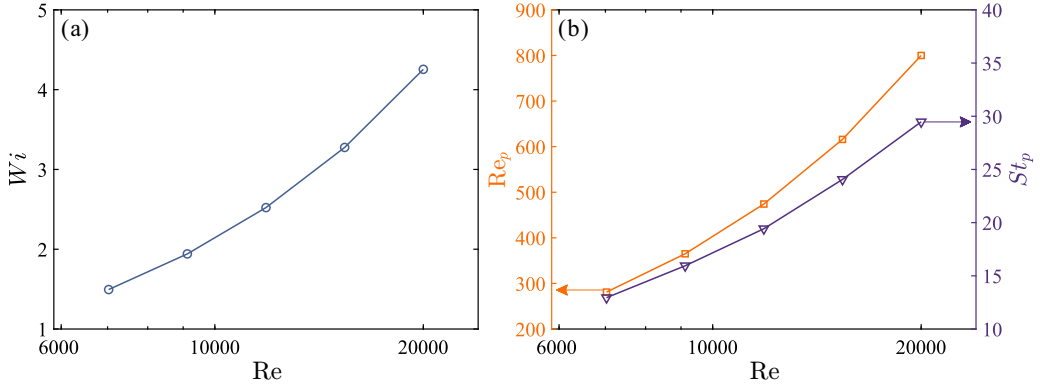


FIG. 2. (a) Weissenberg number Wi of the polymer solution as a function of the Reynolds number Re . (b) Particle Reynolds number Re_p (left axis) and Stokes number St_p (right axis) as a function of Re . Note that the horizontal axis is logarithmic, whereas the vertical axes are linear.

The rheological properties of the polymer solutions were measured using a rheometer (Discovery Hybrid Rheometer, TA Instruments) equipped with a cone-plate geometry of diameter 40 mm and cone angle 2° . The shear viscosity μ was measured as a function of shear rate for all polymer concentrations. It is found that the viscosity variation was less than 3% over the measured shear rate range, thus the shear-thinning effects were negligible for the polymer solutions used in this study (see Appendix A). The characteristic relaxation time of the polymer solution was estimated using the Zimm model for dilute polymer solutions [39], namely, $t_p = N^{9/5} a^3 \mu / (k_B T)$, where N is the number of monomers in a polymer chain, a is the monomer length, and k_B is the Boltzmann constant. The Zimm model is appropriate for dilute flexible polymer solutions where hydrodynamic interactions dominate polymer-chain dynamics [45,46]. Previous studies have shown that Zimm predictions provide relaxation times consistent with experimental measurements for dilute polymer solutions [47].

D. Control and response parameters

The primary control parameter is the Reynolds number,

$$Re = \frac{\omega_i r_i d}{\nu}, \quad (1)$$

where $\nu = \mu / \rho_f$ is the kinematic viscosity of the working fluid. For viscoelastic flows, an additional control parameter is required to quantify polymer elasticity. The Weissenberg number is defined as

$$Wi = \frac{t_p \omega_i r_i}{d}, \quad (2)$$

which represents the ratio between the polymer relaxation timescale and the characteristic shear timescale of the flow. Increasing Wi corresponds to enhanced elastic effects arising from polymer stretching within the turbulent flow. Figure 2(a) presents the explored parameters in this study. Wi ranges from 1.5 at the lowest Re to 4.3 at the highest Re . The explored Wi are relatively small. More importantly, no measurable degradation is observed over the duration of the experiments, the degradation of polymers can be neglected (see Appendix B). The Weissenberg number and the polymer concentration characterize different aspects of the viscoelastic effect. The former measures the degree of polymer stretch, whereas the latter controls the magnitude of the polymeric stress by the number of polymer chains. Since all solutions are well within the dilute regime, the relaxation time and Wi are assumed to vary only weakly with polymer concentration (see Table I).

TABLE I. Polymer concentrations and the corresponding dimensionless parameters used in the present experiments. Here, $\phi^* = 940$ ppm is the overlap concentration.

ϕ (ppm)	ϕ/ϕ^*	Wi range	Re range	C_p range
10	0.011	1.5–4.3	$7 \times 10^3 - 2 \times 10^4$	1–7%
20	0.021	1.5–4.3	$7 \times 10^3 - 2 \times 10^4$	1–7%
40	0.043	1.5–4.3	$7 \times 10^3 - 2 \times 10^4$	1–7%
80	0.085	1.5–4.3	$7 \times 10^3 - 2 \times 10^4$	1–7%

The global response of the system is quantified through the dimensionless torque

$$G = \frac{\tau}{2\pi L \rho_f v^2}. \quad (3)$$

The dimensionless torque G directly reflects the angular momentum transport across the gap and is widely used as the global drag measure in turbulent TC flow. In the present experiments, the drag modification induced by particles was evaluated by comparing G with its corresponding Newtonian or viscoelastic single-phase value at the same Reynolds number.

In addition to the flow-scale control parameters, the particle inertia is characterized by the particle Reynolds number Re_p and the particle Stokes number St_p . Since the slip velocity between the particles and the carrier fluid and the velocity field of the continuous phase is not directly accessible in the particle-laden experiments due to optical obstruction by the particles, the particle Reynolds number is estimated using the bulk velocity of the TC flow, and the Stokes number is based on a globally inferred dissipation time [15]. These quantities provide approximate orders of magnitude and do not account for local modifications of the velocity and dissipation fields induced by the particles. In the Reynolds-number regime considered here, the bulk velocity can be empirically estimated as $u_b \approx 0.4\omega_i r_i$ [15,48]; thus, using the flow Reynolds number defined above, the particle Reynolds number is written as

$$Re_p = \frac{d_e u_b}{\nu} \approx 0.4 \frac{d_e}{d} Re. \quad (4)$$

Since $d_e/d = 0.1$ in the present experiments, Re_p increases linearly with Re , as shown. Note that the horizontal axis in Fig. 2(b) is logarithmic, whereas the vertical axes are linear; therefore, this proportional relation does not appear as a straight line in the figure.

The particle Stokes number is defined as the ratio between the particle response time and the Kolmogorov time scale of the turbulent carrier flow. Using the same estimation as [15], it can be expressed in terms of the measured dimensionless torque G and the Reynolds number Re as

$$St_p = \frac{\rho_p d_e^2}{18 \rho_f [(r_o^2 - r_i^2) r_i d]^{1/2}} (GRe)^{1/2}. \quad (5)$$

This definition accounts for the global energy dissipation rate of the TC system through the measured torque. In contrast to Re_p , which is directly proportional to Re , the Stokes number depends on both the imposed driving and the global torque response of the flow.

Figure 2(b) shows the variations of Re_p and St_p with Re . In the explored parameter range, Re_p increases from approximately 2.8×10^2 to 8.0×10^2 , St_p increases from about 13 to 30, and normalized particle size d_e/η_k increases from about 9 to 18. These estimates indicate that finite-size and inertial effects are non-negligible over the explored parameter range [4,17]. Here, η_k is the Kolmogorov length scale estimated in the bulk region of TC flow.

III. RESULTS

A. Drag modulation

We first examine how finite-size particles and polymers separately and jointly modify the global drag of Newtonian TC turbulence. The reference case is the single-phase Newtonian flow without particles and polymers. Its dimensionless torque is denoted by $G_{\text{sp},n}$. When only particles are added to the Newtonian fluid, the corresponding dimensionless torque is denoted by $G_{\text{mp},n}$; when only polymers are added, it is denoted by $G_{\text{sp},v}$; and when particles and polymers are simultaneously added, it is denoted by $G_{\text{mp},v}$. Here, sp, n, mp, and v denote single-phase, Newtonian, multiphase, and viscoelastic, respectively.

To quantify the drag modulation relative to the Newtonian single-phase reference, we define the drag reduction rate

$$\text{DR}_1 = 1 - \frac{G}{G_{\text{sp},n}}. \quad (6)$$

Accordingly, the drag modulation induced by particles, polymers, and their combined effect can be written as $\text{DR}_1^{\text{mp}} = 1 - G_{\text{mp},n}/G_{\text{sp},n}$, $\text{DR}_1^v = 1 - G_{\text{sp},v}/G_{\text{sp},n}$, and $\text{DR}_1^{\text{mp},v} = 1 - G_{\text{mp},v}/G_{\text{sp},n}$. Here, a positive value of DR_1 indicates drag reduction relative to the Newtonian single-phase flow, whereas a negative value corresponds to drag enhancement.

For the particle-polymer-laden TC turbulence considered here, the measured dimensionless torque $G_{\text{mp},v}$ reflects the total radial transport of angular momentum from the IC to the OC. Following the angular-velocity-flux framework for TC flow [49], particle-laden flows [43,50], and particle-laden viscoelastic channel flows [36–38], this transport can be decomposed schematically as

$$J_{\text{mp},v}^\omega = J_{\text{vis}}^\omega + J_{\text{tv}}^\omega + J_{\text{rs}}^\omega + J_{\text{rs},\text{mp}}^\omega + J_{\text{ps}}^\omega + J_v^\omega, \quad (7)$$

with $G_{\text{mp},v} = J_{\text{mp},v}^\omega/\nu^2$. The right hand side of Eq. (7) represents in sequence the angular velocity flux contributed by viscous diffusion, Taylor vortices, turbulent Reynolds shear stress, particle Reynolds shear stress, particle-induced stress, and polymer stress. The latter three terms provide additional pathways for angular momentum transport and are responsible for the nonlinear coupling between particles, polymers, and turbulence observed in the drag modulation. The present measurements do not permit a direct quantitative separation of these fluxes. Equation (7) is therefore used as a schematic framework for interpreting the competing contributions of particles, polymers, turbulence, and Taylor vortices to the global torque.

Figure 3 shows DR_1 as a function of Re (Wi) in the lower (upper) horizontal axis for three different situations: particle-only, polymer-only, and particle–polymer-laden flows. The error bars, obtained from the standard deviation of repeated experiments, are smaller than the symbols, and hence will be omitted hereinafter. The spherical particles are used at a volume fraction of $C_p = 7\%$, and the polymer concentration is fixed at $\phi = 80$ ppm. The addition of particles alone leads to negative values of DR_1^{mp} over the entire range of Re , indicating that finite-size particles enhance the drag of Newtonian TC turbulence. This drag enhancement is expected because finite-size particles introduce additional particle-induced stress flux J_{ps}^ω and particle Reynolds stress flux $J_{\text{rs},\text{mp}}^\omega$ [43,51,52]. Interestingly, the magnitude of this negative drag reduction decreases slightly with increasing Re , suggesting that the relative contribution of particle-induced stress and particle Reynolds shear stress to the total angular momentum transport becomes weaker at higher Re , where J_{rs}^ω becomes dominant.

In contrast, the addition of polymers alone results in positive values of DR_1^v , which increase monotonically with Re . This behavior is consistent with the classical drag-reducing effect of dilute polymer additives in wall-bounded turbulence [53]. As Re increases, the characteristic shear rate and the Weissenberg number both increase, leading to stronger polymer stretching and a more pronounced suppression of turbulent Reynolds stress flux J_{rs}^ω [39]. Consequently, the torque of the viscoelastic single-phase flow becomes smaller than that of the Newtonian reference flow, and DR_1^v

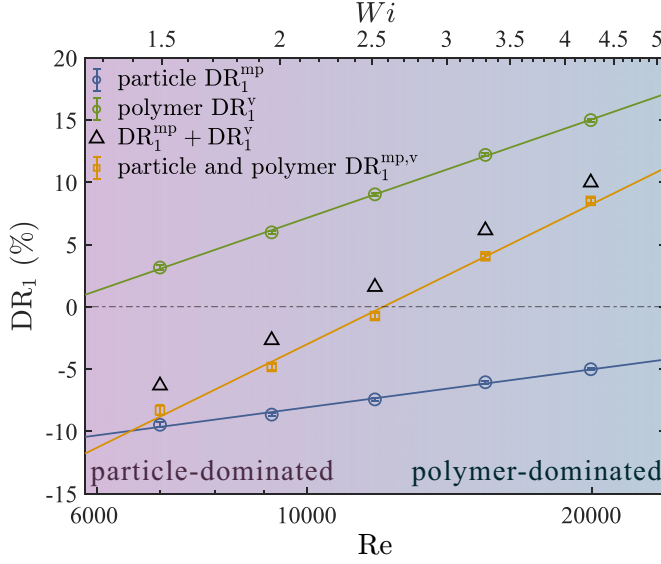


FIG. 3. Effect of particle, polymer, particle, and polymer on the drag of Newtonian turbulence, quantified by the drag reduction rate DR_1 . The particle used is a spherical particle at volume fraction of $C_p = 7\%$, and the polymer concentration is $\phi = 80$ ppm. The solid lines represent least square fits to the experimental data with the form of $DR_1 = A \log_{10} Re + B$, where A and B are fitting parameters. The upper horizontal axis shows the corresponding Wi .

increases from a few percent at low Re to more than 15% at the largest Re investigated. This low drag reduction efficiency of polymer in TC flow originates from the fact that polymers suppress turbulence but only has a slight influence on the Taylor vortices, leading to a reduction of J_{rs}^ω and almost unchanged J_{tv}^ω [39,54,55]. The Taylor vortices, however, contribute to about 50% of the total angular momentum transport in the present explored range of Reynolds number [56].

When particles and polymers are added simultaneously, the resulting drag modulation $DR_1^{mp,v}$ is not a simple repetition of either the particle-only or polymer-only case. At relatively low Re , $DR_1^{mp,v}$ remains negative, indicating that the particle-induced drag enhancement dominates over the polymer-induced drag reduction. As Re increases, however, $DR_1^{mp,v}$ gradually increases and eventually becomes positive. This crossover reveals a transition from a particle-dominated regime to a polymer-dominated regime. In the particle-dominated regime, the additional stresses and flow disturbances produced by the finite-size particles overwhelm the drag-reducing capability of polymer additives. In the polymer-dominated regime, the increasing elastic effect of the polymer solution becomes sufficiently strong to compensate for the particle-induced drag penalty, so that the combined particle-polymer system exhibits net drag reduction relative to the Newtonian single-phase flow.

To further assess the coupling between particles and polymers, we compare the measured $DR_1^{mp,v}$ with the value expected from a linear superposition of the two individual effects, i.e., $DR_1^{mp} + DR_1^v$. If particles and polymers acted independently on the flow, $DR_1^{mp,v}$ would collapse onto $DR_1^{mp} + DR_1^v$. The deviation between these two quantities therefore measures the nonlinear interaction between particle-induced and polymer-induced drag modulation. As shown in Fig. 3, the measured combined effect is lower than the simple additive prediction, implying that the particles and polymers interact dynamically rather than contributing independently to the torque. Physically, finite-size particles can locally enhance velocity gradients as demonstrated in [57] and [16], thus polymer stretching in their vicinity (thereby increasing polymeric stress flux J_v^ω). At the same time, polymers suppress turbulent fluctuations and weaken particle transport, which can

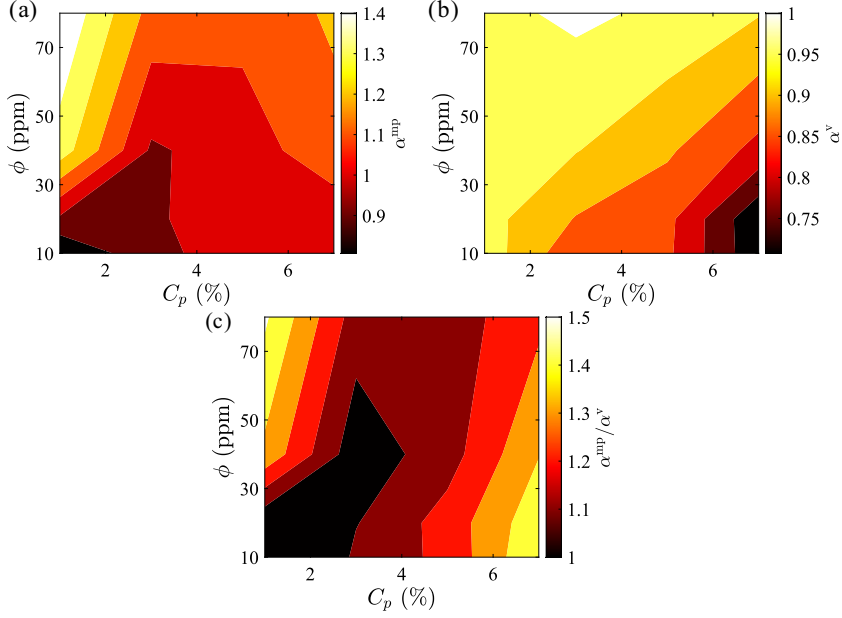


FIG. 4. (a), (b) Contour of weighting factor α in the plane of polymer concentration ϕ and particle volume fraction C_p for particle (a) and polymer (b), respectively. (c) Ratio of α^{mp} and α^{v} . Spherical particles are used here.

modify particle dispersion and particle-wall interactions. The observed $\text{DR}_1^{\text{mp,v}}$ therefore results from the competition between particle-induced drag enhancement and polymer-induced turbulence suppression. This behavior is consistent with particle-resolved simulations of viscoelastic channel flows [36–38], which showed that finite-size particles suppress turbulent momentum transport but enhance particle-related and polymeric stresses. The present experiments further show that the balance between these contributions changes with Reynolds number and polymer concentration, leading to particle-dominated and polymer-dominated regimes.

To quantify the nonlinear coupling among polymers, particles, and turbulence, we fit the experimental data in Fig. 3 using

$$\text{DR}_1^i = A^i \log_{10} \text{Re} + B^i, \quad (8)$$

where $i = \text{mp}, \text{v},$ and mp,v . The solid lines in Fig. 3 denote the corresponding least-square fits. Although empirical, this form captures the approximately logarithmic dependence over the explored range of Re . We further express the combined response as

$$\text{DR}_1^{\text{mp,v}} = \alpha^{\text{mp}} \text{DR}_1^{\text{mp}} + \alpha^{\text{v}} \text{DR}_1^{\text{v}}, \quad (9)$$

which, together with Eq. (8), gives

$$A^{\text{mp,v}} = \alpha^{\text{mp}} A^{\text{mp}} + \alpha^{\text{v}} A^{\text{v}}, \quad B^{\text{mp,v}} = \alpha^{\text{mp}} B^{\text{mp}} + \alpha^{\text{v}} B^{\text{v}}. \quad (10)$$

Here, $\alpha^{\text{mp}} = \alpha^{\text{v}} = 1$ corresponds to a purely additive response, whereas deviations from unity quantify the nonlinear modification of the particle and polymer contributions.

Figure 4 summarizes the resulting weighting factors. Over most of the explored parameter space, $\alpha^{\text{mp}} > 1$, whereas $\alpha^{\text{v}} < 1$, indicating that polymers amplify the effective particle-induced drag contribution while particles reduce the drag-reducing efficiency of polymers. This trend is consistent with particle-resolved simulations showing that finite-size particles can enhance particle-related and polymeric stresses in viscoelastic turbulence [36–38]. Correspondingly, $\alpha^{\text{mp}}/\alpha^{\text{v}}$ in Fig. 4(c) is larger

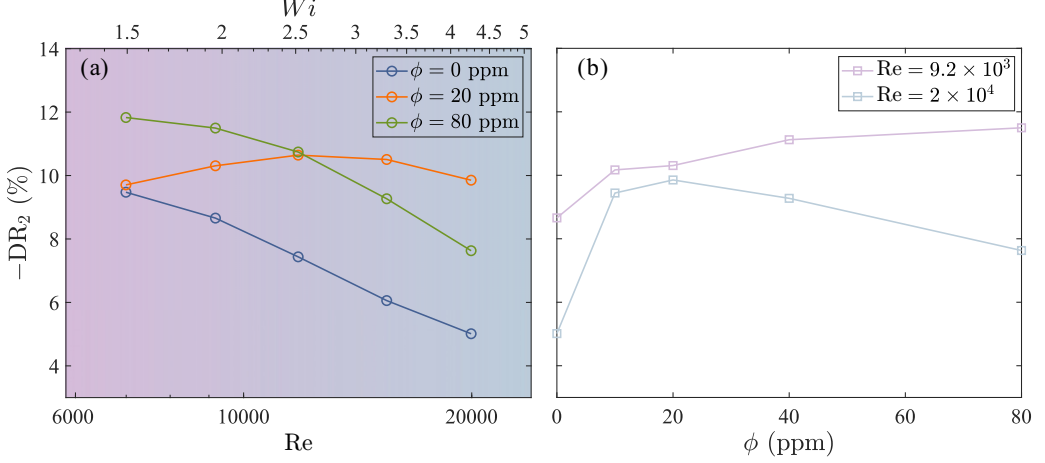


FIG. 5. (a) Effect of spherical particle on the drag of viscoelastic turbulence at different polymer concentration, which is quantified by the drag reduction rate DR_2 . The upper horizontal axis shows the corresponding Wi . (b) $-DR_2$ as a function of polymer concentration ϕ for two typical Reynolds numbers. Here, spherical particles at volume fraction of $C_p = 7\%$ are used.

than unity over most of the parameter space, demonstrating that the nonlinear coupling is generally biased toward an enhanced particle contribution.

To examine how this coupling changes between the particle-dominated and polymer-dominated regimes, we quantify the direct influence of particles on the corresponding viscoelastic flow by

$$DR_2 = 1 - \frac{G_{mp,v}}{G_{sp,v}}, \quad (11)$$

where $DR_2 < 0$ indicates particle-induced drag enhancement. Figure 5 therefore plots $-DR_2$ as the particle-induced drag penalty for spherical particles at $C_p = 7\%$. In the Newtonian case, $-DR_2$ decreases with Re , consistent with the decreasing relative contribution of particle-related stresses to the total torque [15]. With polymers, however, the trend depends strongly on polymer concentration: at $\phi = 20$ ppm the drag penalty varies only weakly with Re , whereas at $\phi = 80$ ppm it decreases markedly at high Re . This confirms that the particle-polymer coupling changes as the carrier flow becomes more strongly elastic [36–38].

Figure 5(b) makes this distinction clearer. At $Re = 9.2 \times 10^3$, $-DR_2$ increases monotonically with ϕ . At this relatively small Wi , polymers only weakly modify turbulent transport, while finite-size particles can enhance local velocity gradients [15,16] and thereby increase the polymeric contribution around the particles; the polymer stress also increases with polymer concentration [36]. At $Re = 2.0 \times 10^4$, by contrast, $-DR_2$ first increases and then decreases with ϕ . At low and moderate concentrations, the particle-induced enhancement of local polymer stress increases the drag penalty, whereas at sufficiently high ϕ the stronger polymer elasticity suppresses turbulent fluctuations [54], weakening particle-flow interactions and hence the particle-induced enhancement of angular momentum transport.

The different responses are supported by the Reynolds shear stress measurements in Fig. 6, obtained from our previous PIV measurements [39]. The measurements were performed in the r - θ plane at different axial positions, and the velocity fluctuations were averaged over time, azimuthal direction, and an axial range covering the Taylor-vortex structure. The normalized Reynolds shear stress is evaluated as $\langle u'_\theta u'_r \rangle_{t,\theta,z} / (\omega_i r_i)^2$. In the explored range of Re , one Taylor-vortex pair spans approximately $2.1d$ [39].

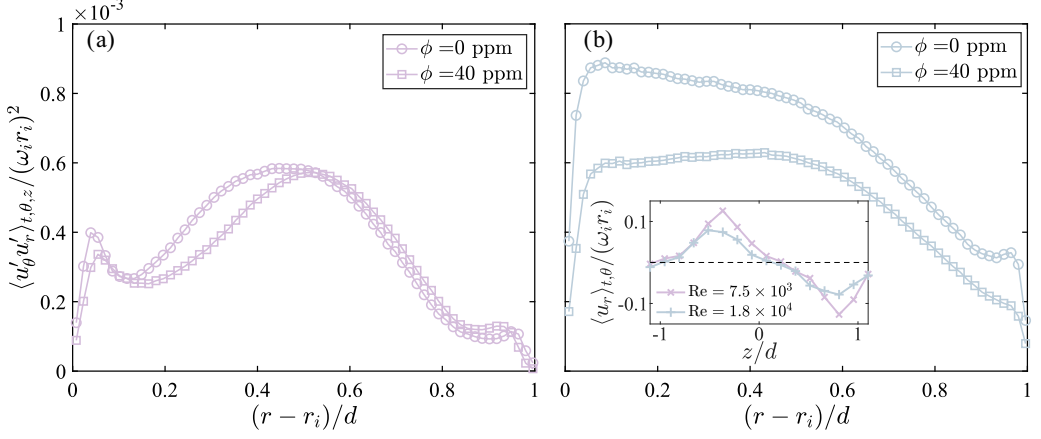


FIG. 6. Radial dependence of the normalized Reynolds shear stress at $\text{Re} = 7.5 \times 10^3$ (a) and $\text{Re} = 1.8 \times 10^4$ (b). Inset in (b): Axial dependence of the normalized mean radial velocity at the middle gap $(r - r_i)/d = 0.5$.

At $\text{Re} = 7.5 \times 10^3$, Fig. 6(a) shows that polymer addition only mildly suppresses the Reynolds shear stress, particularly away from the IC. This weak modification is consistent with the monotonic increase of $-\text{DR}_2$ with ϕ at low Re , where the particle-polymer interaction can increase while the background turbulence remains largely intact. At $\text{Re} = 1.8 \times 10^4$, however, Fig. 6(b) shows a substantial suppression of Reynolds shear stress across the gap. The resulting reduction of turbulent fluctuations weakens particle-flow interactions and explains the decrease of $-\text{DR}_2$ at high polymer concentration. Thus, Figs. 5 and 6 consistently show that the balance between particle-induced drag enhancement and polymer-induced turbulence suppression changes with Re and ϕ , providing the physical basis for the transition from the particle-dominated regime to the polymer-dominated regime identified in Fig. 3.

B. Particle shape effects

We next examine how particle shape modifies the global drag response of particle-laden TC turbulence. To isolate the shape effect, the particle volume is kept the same for the three particle geometries, and the torque induced by spherical particles is compared with that induced by oblate and prolate particles. Figure 7 shows the ratios $G_{\text{mp}}^{\text{o}}/G_{\text{mp}}^{\text{s}}$ and $G_{\text{mp}}^{\text{p}}/G_{\text{mp}}^{\text{s}}$ as functions of Re , where the open symbols denote the Newtonian cases and the closed symbols denote the viscoelastic cases at $\phi = 10$ ppm. The superscripts s, o, and p denote spherical, oblate, and prolate particles, respectively. Two particle volume fractions are considered: $C_p = 1\%$ in Fig. 7(a) and $C_p = 7\%$ in Fig. 7(b). At $C_p = 1\%$, the particle-induced modification of the global torque is relatively small, and the torque ratios remain close to unity. Consequently, small variations in the measured torque become more apparent in the ratios, and no systematic Re dependence can be identified. The deviations of the torque ratios from unity become more pronounced at $C_p = 7\%$, where particle-related stresses are stronger. At $C_p = 7\%$, the ratios are smaller than unity, indicating that spherical particles lead to a larger dimensionless torque than both oblate and prolate particles.

In Newtonian turbulence, the larger torque induced by spherical particles can be understood from the different rotational and orientational dynamics of the particles [51]. Although all three particle types have the same volume, nonspherical particles can preferentially align with the local shear and azimuthal mean flow. Such alignment reduces their effective projected area normal to the dominant flow direction and weakens the local disturbance imposed on the carrier flow. By contrast, spherical particles do not have a preferential orientation and continuously present the same effective geometry

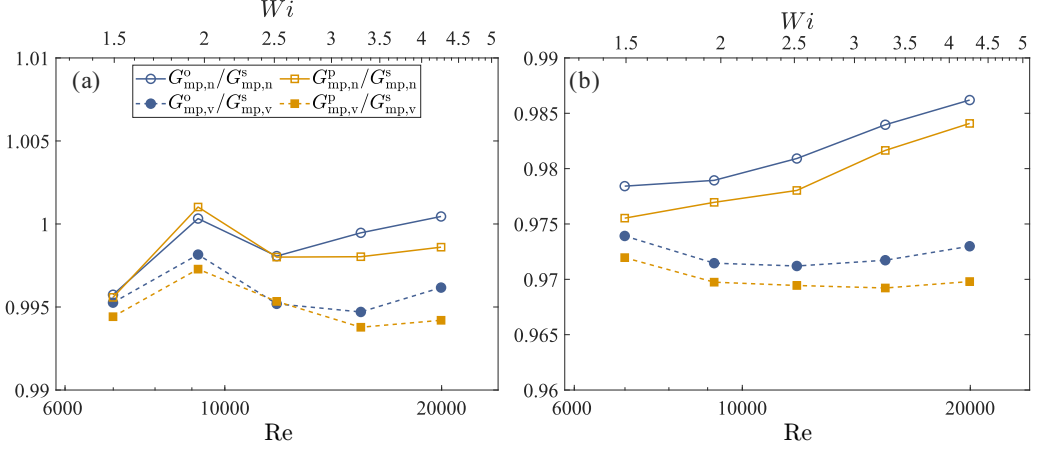


FIG. 7. (a) Torque ratio of oblate particle and spherical particle, prolate particle, and spherical particle in Newtonian fluid (open symbols) and viscoelastic fluid at polymer concentration $\phi = 10$ ppm (closed symbols). The particle volume fraction $C_p = 1\%$. (b) Same as (a) but at particle volume fraction $C_p = 7\%$. The upper horizontal axis shows the corresponding Wi .

to the surrounding flow. They may therefore generate stronger local velocity disturbances, stronger particle-induced stresses, and more efficient momentum exchange with the carrier flow. In addition, spherical particles are more likely to form a robust near-wall particle layer, which can enhance the angular momentum transport between the inner and outer cylinders [15,43,51,52]. These effects explain why $G_{mp,n}^s$ is systematically larger than $G_{mp,n}^o$ and $G_{mp,n}^p$ in the Newtonian cases. We further note that both G_{mp}^o/G_{mp}^s and G_{mp}^p/G_{mp}^s increase with increasing Re , suggesting that the sensitivity of the global torque to particle geometry becomes progressively weaker at higher Reynolds numbers.

Though the torque ratios are nonmonotonic at $C_p = 1\%$ in Fig. 7(a), a consistent trend is observed at both particle volume fractions: the torque ratios in the viscoelastic fluid are generally smaller than those in the Newtonian fluid. This effect becomes more clearly resolved at the higher particle volume fraction, where particle-related contributions to the global torque are stronger. This indicates that particle shape becomes more important once polymer elasticity is introduced. In a viscoelastic carrier fluid, the drag is not controlled only by particle-induced stress and Reynolds shear stress, but also by polymer stresses generated by local shear and extensional deformation around the particles [36,38]. Particle geometry affects the local disturbance flow, near-particle boundary layer, and orientational dynamics of finite-size anisotropic particles [16,51,52,58]. Therefore, different particle shapes are expected to interact differently with the local shear and extensional regions of the carrier flow. Spherical particles, which produce relatively strong and nearly orientation-independent disturbances, may generate larger local polymer deformation and hence larger polymeric stress contributions. In contrast, oblate and prolate particles can partially align with the mean shear, reducing the effective disturbance and weakening the local stretching of polymer molecules.

Therefore, the reduction of G_{mp}^o/G_{mp}^s and G_{mp}^p/G_{mp}^s in the viscoelastic cases suggests a coupling between particle shape and polymer elasticity. The reduction of the torque ratios in the viscoelastic cases suggests that polymer elasticity amplifies the sensitivity of the global drag to particle geometry. One possible mechanism is that particle shape modifies the local disturbance flow and, consequently, the polymer deformation around the particles. This additional coupling channel makes the global torque more sensitive to particle geometry in viscoelastic TC turbulence than in Newtonian TC turbulence.

Ardekani and Brandt [51] and Wang *et al.* [15] found that the drag modulation of particle is closely related to its spatial distribution. We thus further investigate how polymer additives modify the spatial organization of particles with different shapes. Figure 8 shows the radial particle

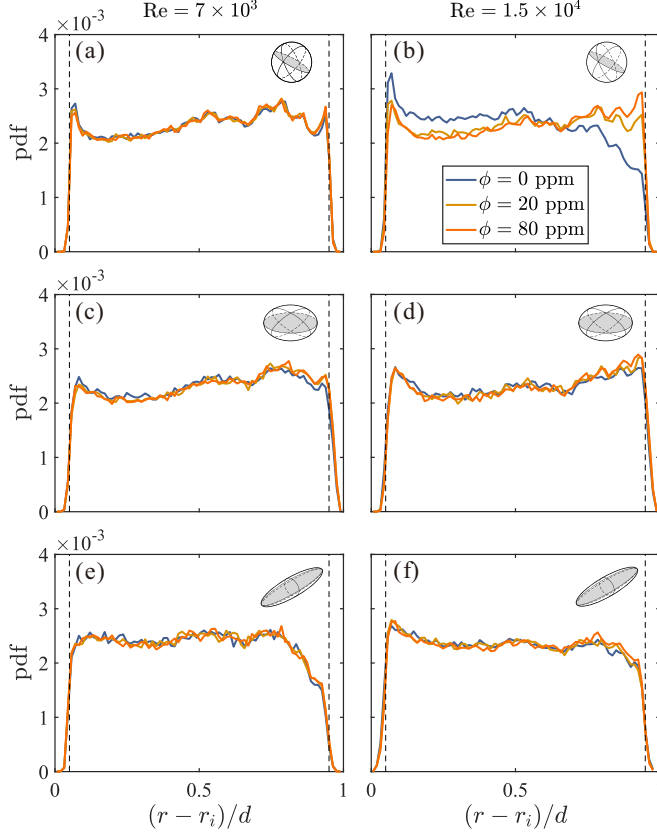


FIG. 8. Radial dependence of particle distribution for spherical particle (a), (b), oblate particle (c), (d), and prolate particle (e), (f). Left panels: $Re = 7 \times 10^3$; right panel: $Re = 1.5 \times 10^4$. The particle volume fraction $C_p = 1\%$. The two vertical dashed lines at $d_e/2d = 0.05$ and $1 - d_e/2d = 0.95$ denote the position of equivalent radius of the particle away from the walls.

distribution for spherical, oblate, and prolate particles at two representative Reynolds numbers. The particle volume fraction is fixed at $C_p = 1\%$ for the distribution measurements. The two vertical dashed lines indicate $(r - r_i)/d = d_e/(2d)$ and $(r - r_i)/d = 1 - d_e/(2d)$, corresponding to the closest possible positions of the particle center to the IC and OC, respectively. We first focus on the spherical particles shown in Figs. 8(a) and 8(b). Local enrichment of particles can be observed near both IC and OC. A direct comparison of the radial distributions for the three particle shapes can be found in Appendix C, where the local peak near the wall is much weaker or absent for the oblate and prolate particles. This observation is consistent with previous numerical studies of finite-size nonspherical particles [15,51,52], and suggests stronger near-wall organization of spherical particles. At the lower Reynolds number, $Re = 7 \times 10^3$, the radial distributions for different polymer concentrations almost collapse [see Fig. 8(a)]. This indicates that polymer additives have little influence on the radial migration of spherical particles in this weakly elastic state. This observation is consistent with the Reynolds-stress results in Fig. 6(a), where the polymer solution only mildly modifies the turbulent momentum transport at low Re .

At the higher Reynolds number, $Re = 1.5 \times 10^4$, the effect of polymers on spherical particle distribution becomes more visible [see Fig. 8(b)]. In the Newtonian case, spherical particles exhibit pronounced near-wall accumulation, especially close to the IC, consistent with previous studies [15]. With the addition of polymers, the near-wall particle concentration is reduced, and the radial

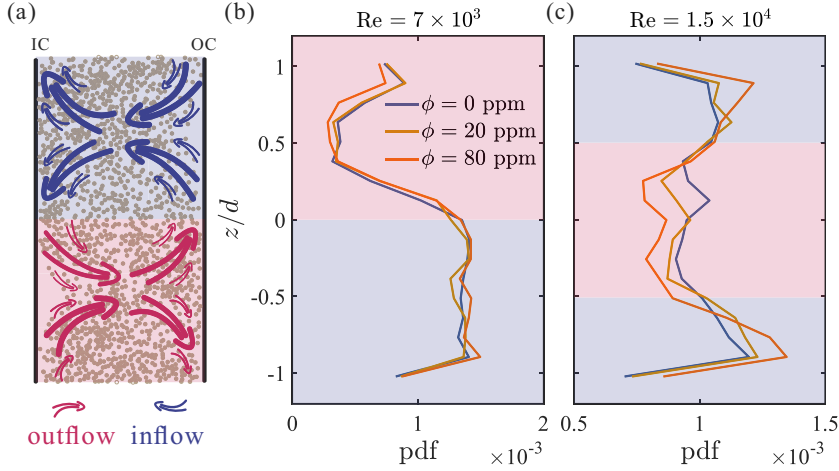


FIG. 9. (a) Sketch of the effect of Taylor vortex on the particle distribution. Axial dependence of spherical particle distribution at $Re = 7 \times 10^3$ (b) and $Re = 1.5 \times 10^4$ (c). The data are sampled over a cylindrical shell with thickness about $0.1d$ centered at $(r - r_i)/d = 0.05$. The blue and cyan shaded regions denote inflow and outflow dominated areas. The particle volume fraction $C_p = 1\%$.

distribution becomes less strongly peaked near the walls. This behavior suggests that polymer elasticity weakens the near-wall trapping of spherical particles. Near-wall turbulent coherent structures and wall-normal velocity fluctuations can transport particles toward and away from the wall, thereby maintaining the exchange of particles with the near-wall particle layer [59]. Polymer additives, on the other hand, suppress Reynolds shear stress, near-wall Görtler vortices, and plume emission in TC turbulence [39], thereby weakening the turbulent feeding of the near-wall particle layer. At the same time, the elastic normal stresses can induce lateral particle migration in the direction of decreasing absolute shear rate [60–62]. In the present TC geometry, where the shear rate is largest near the IC, this mechanism tends to drive particles away from the high-shear inner-wall region. The combined effect is therefore a reduction of the wall-localized spherical-particle concentration at sufficiently high Re and Wi .

The effect of polymer on spherical particle distribution can also be appreciated from the axial distribution, from which the role of Taylor vortices in the particle distribution can be clarified. Figure 9 shows the axial distribution of spherical particles sampled in a near-IC cylindrical shell centered at $(r - r_i)/d = 0.05$ with a thickness of approximately $0.1d$. At the lower Reynolds number, as shown in Fig. 9(b), the axial distribution of particles in Newtonian TC turbulence exhibits distinct peaks and valleys as a result of the strong Taylor vortex. The inset of Fig. 6(b) shows the axial dependence of the normalized mean radial velocity at the middle gap, which clearly demonstrates the presence of a coherent Taylor vortex at low Re . The sketch in Fig. 9(a) illustrates that Taylor vortices generate alternating inflow and outflow regions, which provide organized large-scale transport of particles in the r - z plane. Inflow and outflow drive particles toward and away from the IC, leading to higher and lower local density of particles close to IC [15,63]. The axial distributions for different polymer concentrations remain similar, again indicating that polymer additives have only a weak influence on the particle organization in this regime. In this case, the particle distribution is mainly controlled by the coherent Taylor-vortex circulation, while the polymer-induced elastic effect is not strong enough to reorganize the particle local distribution.

The situation changes at the higher Reynolds number shown in Fig. 9(c). In the Newtonian case, stronger turbulent fluctuations tend to mix particles along the axial direction and weaken the axial modulation imposed by Taylor vortices. When polymers are added, however, the turbulence is suppressed, as indicated by the reduced Reynolds shear stress in Fig. 6(b). This suppression

weakens the random turbulent mixing that would otherwise homogenize the particle distribution. Consequently, the coherent transport by Taylor vortices becomes more apparent, and the axial particle distribution becomes more nonuniform. Please note that the Taylor vortices in Fig. 9(c) exhibit a shift in the axial direction compared to the lower Reynolds number case [see Fig. 9(b)], as also observed in [64]. In this sense, Taylor vortices and turbulence have competing effects on the axial distribution: Taylor vortices organize particles into axially modulated structures, whereas turbulence tends to smear out this organization. Polymer additives reduce the latter effect at high Re , allowing the Taylor-vortex-induced modulation to be more clearly observed.

Figures 8(c) and 8(d) show the radial distributions of oblate particles. Compared with spherical particles, the polymer effect on the radial distribution of oblate particles is weaker. At $Re = 7 \times 10^3$, the curves for different ϕ nearly overlap, similar to the spherical case. At $Re = 1.5 \times 10^4$, only a mild modification of the radial distribution is observed: the overall profile remains close to the Newtonian one, with no strong polymer-induced depletion of the near-wall region. This weaker sensitivity may be related to the orientation dynamics of oblate particles [16,43]. Oblate particles can preferentially align with the local shear and azimuthal mean flow, thereby reducing the effective disturbance imposed on the carrier flow and weakening the local polymer stretching around the particles. As a result, the elastic modification of their radial migration is less pronounced than for spherical particles.

The prolate-particle distributions shown in Figs. 8(e) and 8(f) are even less affected by polymer concentration. For both Reynolds numbers, the radial profiles remain nearly unchanged when ϕ is increased from 0 to 80 ppm. This indicates that the radial organization of prolate particles is dominated primarily by finite-size particle dynamics and Taylor-vortex transport rather than by polymer elasticity. A possible explanation is that prolate particles can align with the azimuthal flow direction for a significant fraction of time, which reduces their effective cross-stream blockage and weakens the near-field deformation of the polymer solution [16,43]. Their elongated geometry also enhances rotational and orientational dynamics, which may prevent the formation of a strong, persistent wall layer. Therefore, among the three particle shapes investigated here, spherical particles exhibit the strongest polymer-induced redistribution, whereas oblate and especially prolate particles show weaker sensitivity to polymer concentration.

Figures 8 and 9 demonstrate that the effect of polymers on particle distribution is strongly shape dependent and Reynolds-number dependent. At low Re , where Wi is small and the turbulent transport is only weakly affected by polymers, particle distributions are nearly unchanged for all particle shapes. At high Re , polymers suppress turbulent mixing, making the competition between elastic migration, particle-wall layering, and Taylor-vortex transport more evident. This effect is most pronounced for spherical particles, which generate stronger local disturbances and more robust near-wall accumulation, while nonspherical particles are less sensitive presumably due to their preferential alignment and orientation dynamics.

IV. CONCLUSIONS

We have experimentally investigated drag modulation by finite-size particles in viscoelastic TC turbulence with only the IC rotating. The working fluids are a Newtonian glycerol-water solution and dilute PAM solution with polymer concentration in the range $0 \leq \phi \leq 80$ ppm. Three particle shapes, namely oblate, spherical, and prolate particles, are considered while keeping the particle volume fixed. By combining global torque measurements with particle-distribution measurements, and by using velocity statistics from our previous PIV measurements, we examined how finite-size particles, polymer additives, particle shape, turbulence, and Taylor vortices jointly determine the angular momentum transport and particle distribution.

The main findings form a consistent physical picture. The global torque measurements first show that finite-size particles and polymers act through competing pathways of angular momentum transport. Particles enhance drag by introducing additional particle-induced stress and particle Reynolds stress, whereas polymers reduce drag by suppressing turbulent Reynolds stress. When

particles and polymers are added simultaneously, the combined response cannot be described by a linear superposition of the two separate effects. Instead, the flow undergoes a transition from a particle-dominated regime at lower Reynolds number to a polymer-dominated regime at higher Reynolds number. This transition is further clarified by measuring the particle-induced drag penalty in the viscoelastic fluid. At low Reynolds number, where polymer elasticity only weakly modifies the turbulence, increasing polymer concentration strengthens the local particle-polymer interaction and therefore increases the drag penalty. At high Reynolds number, however, polymers strongly suppress turbulent fluctuations; as a result, the interaction between particles and the carrier turbulence is weakened, and the particle-induced drag penalty decreases at high polymer concentration.

This coupling picture is further supported by the particle-shape and particle-distribution measurements. Spherical particles generate larger torque than oblate and prolate particles, suggesting that they produce stronger local disturbances and particle-related stress. The difference between particle shapes becomes more pronounced in the viscoelastic fluid, suggesting that polymer elasticity amplifies the shape dependence by making the flow sensitive to the local deformation generated around the particles. The particle-distribution measurements provide a spatial view of the same mechanism. At low Reynolds number, polymer addition has little influence on the radial particle distribution, consistent with its weak effect on the turbulence. At high Reynolds number, polymers reduce the near-wall accumulation of spherical particles and make the axial distribution more nonuniform, because turbulent mixing is suppressed and the organization by Taylor vortices becomes more evident. The weaker response of oblate and prolate particles is presumably due to their preferential alignment and orientation dynamics.

The present observations are also consistent with previous particle-resolved studies of viscoelastic channel flows, which showed that finite-size particles suppress turbulent momentum transport while enhancing particle-related and polymeric stresses, thereby weakening or even reversing the drag-reducing effect of polymers [36–38]. Our results demonstrate experimentally that the balance between these competing contributions is not fixed, but varies with Reynolds number and polymer concentration, leading to the transition between particle-dominated and polymer-dominated regimes. Moreover, the present TC configuration reveals that this coupling is further modulated by particle shape and by the coexistence of turbulence with persistent Taylor vortices.

Several open questions remain. First, the present work infers the polymeric contribution mainly through global torque and velocity statistics; direct measurements or simulations of the local polymer stress around finite-size particles would be valuable for identifying the microscopic origin of the particle-polymer coupling. Second, the orientation dynamics of the nonspherical particles were not measured, and the strength of the Taylor vortices could not be quantified in the two-phase flows. Simultaneous measurements of particle position, orientation, and carrier-flow velocity would therefore help clarify the shape-dependent mechanisms and directly quantify the coupling between particles and Taylor vortices. Finally, fully resolved numerical simulations of finite-size particles in viscoelastic TC turbulence would allow the different angular momentum fluxes in $J_{mp,v}^\omega$ to be separated quantitatively, and would provide a more complete picture of how particles, polymers, turbulence, and Taylor vortices interact across different parameter regimes.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

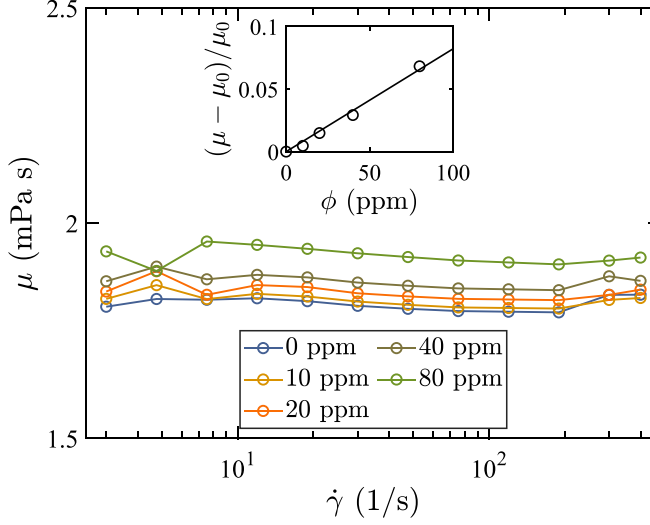


FIG. 10. Shear viscosity of the polymer solution used in this study. Inset: normalized polymer contribution to the shear viscosity as a function of concentration ϕ . μ_0 is the viscosity of the solvent. The solid line is a linear fit to the experiment data with slope $[\eta] \approx 8.2 \times 10^{-4}$. The overlap concentration can be estimated as $\phi^* = 0.77/[\eta] \approx 940$ ppm.

APPENDIX A: SHEAR VISCOSITY OF THE POLYMER SOLUTIONS

The shear viscosity of the polymer solutions is measured by the Discovery Hybrid Rheometer (TA instruments) equipped with a cone-plate geometry, whose diameter is 40 mm and angle is 2° . Figure 10 shows the measured shear viscosity μ over $3 \leq \dot{\gamma} \leq 300$. The measurements show that the viscosity varies only weakly over a large range of shear rate with the maximum variation less than 3%, confirming that shear-thinning effects are negligible for the polymer solutions used in this study.

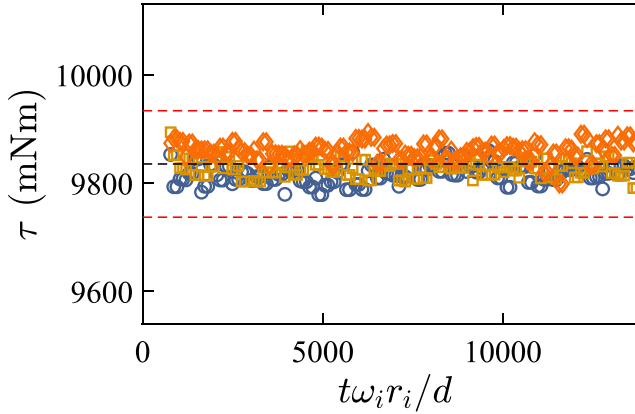


FIG. 11. Time series of the measured torque from three repeated experiments using the same polymer solution at the highest Reynolds number $Re = 2 \times 10^4$ ($Wi = 4.3$). The polymer concentration $\phi = 80$ ppm. Horizontal black dashed line: average torque over the three experiments. Horizontal red dashed lines: 1% deviation from the average torque.

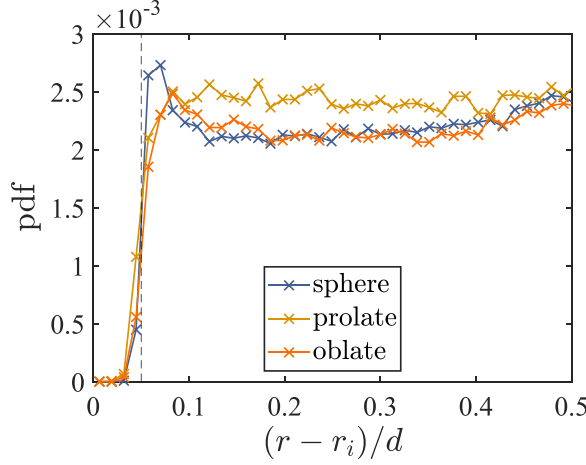


FIG. 12. Comparison of particle radial distribution for the three particle shapes investigated at $Re = 7 \times 10^3$ in the Newtonian case.

APPENDIX B: POSSIBLE DEGRADATION OF POLYMERS

In this study, the explored Weissenberg numbers ($1 < Wi < 5$) are relatively small, thus the degradation of polymer additives would be very weak. To provide quantitative check of the stability of the solution during the experiments, three successive measurements at $Re = 2 \times 10^4$ performed under the same condition are shown in Fig. 11. It can be found that no systematic increase in torque with experimental time can be detected, and the three data sets overlap within the experimental uncertainty with deviation less than 1% shown as the two horizontal red dashed lines in Fig. 11. Since mechanical degradation would reduce the polymer drag-reduction effect and consequently cause a systematic increase in torque, the observed repeatability indicates that polymer degradation is negligible over the duration of the present measurements.

APPENDIX C: COMPARISON OF PARTICLE RADIAL DISTRIBUTION

Figure 12 presents a direct comparison of the radial distributions of the three particle shapes, demonstrating that spherical particles exhibit a pronounced near-wall concentration peak, whereas such a peak is much weaker or absent for the oblate and prolate particles. This observation is consistent with previous numerical studies of finite-size nonspherical particles [51].

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