

Comparisons of two-phase boundary layer and channel turbulence laden by inertial particles at moderate Reynolds number

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The particle behavior and turbulent modulation of wall-bounded turbulent flow are analyzed by comparing a new simulation of channel turbulence with older simulation of spatially developing turbulent boundary layer at almost identical friction Reynolds number and laden particles with identical inertia and bulk volume fraction. It is found that particle locally accumulate in the wake region of the external boundary layer flow due to more pronounced turbulent/nonturbulent interface effect. Therefore, the particle-turbulence interaction in the outer layer of boundary layer results in stronger turbulent modulation than that in particle-laden channel. This influence not only makes the outer-layer structures more different but may penetrate to the near-wall region of wall turbulence, generating opposite modulation of turbulent mean velocity of the two flows. However, the modulation in second-order statistics and turbulent structures by the presence of inertial particles are qualitatively similar below the logarithmic layer. The similarities/dissimilarities are further explained by comparing the average stress, the turbulent kinetic energy budget and uniform momentum zones/quiescent core.

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I. INTRODUCTION

Two-phase wall turbulence is common in nature and industrial applications, sand/dust storms, sediment transport in water, fluidized beds, to name a few. A distinctive feature of this flow configuration is that the fluid generates mean shear at the solid wall, which results in nonhomogeneous particle transport/distribution [1–3] due to turbophoresis and preferential concentration and significant particle modulation on turbulent statistics and structures [2–6]. Previous studies on particle-turbulence interaction were usually performed in terms of channel and the zero-pressure-gradient spatially developing turbulent boundary layer (TBL) due to their inherent geometrical simplicity. Despite the long-standing controversies about the similarity among the two canonical

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single-phase wall-bounded flows [7–11], there is little attention paid to the similarity/dissimilarity between these two types of particle-laden turbulence.

The extent or existence of similarities between internal (e.g., channel flow and pipe flow) and external (e.g., TBL) single-phase flows have been exhaustively discussed in the past two decades in terms of turbulent statistics and structures. As we know that the asymptotic matching of the inner and outer layers in the classical theory yields the logarithmic mean velocity profile in the overlap region of wall turbulence. However, the ‘universal’ constants and the range of the logarithmic region were found to be not universal and exhibit dependence on the flow geometry [12–17]. Well beyond the log region, there is a stronger wake component of the mean velocity profile in TBL due to the outer intermittency induced by the differences between the potential and turbulent flow regions [18]. Several studies [7–9,11,18] observed that the streamwise velocity fluctuations for internal and external flows are in agreement but TBL exhibits stronger spanwise and wall-normal velocity fluctuations near the wall for the same Reynolds number. However, Jiménez *et al.* [18] and Sillero *et al.* [8] reported a higher streamwise velocity fluctuations in boundary layer that could be explained by the effect of the large-scale intermittency. Whatever, the largest differences in low-order statistics between the internal and external flows are found above the logarithmic layer ($y/\delta \approx 0.3$ – 0.5 , where y is the distance to the wall and δ is the boundary layer thickness for TBL, half-channel height for channel flow and radius for pipe flow) [19,20]. Several comparisons based on experiments also showed that there are obvious important modal differences between the internal and external flows from the outer/core region right down to the wall [14,21]. Especially, the large structures in the outer layer were found to be wider and longer in internal flow than in the boundary layer [7,14,22], which is later explained according to the different dominant momentum transfer process in the outer layer [14,18].

In turbulent channel flows laden with inertial particles, the behavior of particles and turbulence have been studied either experimentally or numerically by many researchers. It is found that their interaction is controlled by many nondimensional parameters such as the particle volume/mass fraction [23], particle Stokes number [24], the ratio of particle diameter to a characteristic flow length scale [25], particle momentum number [26]. One can refer to Gore and Crowe [27], Balachandar and Eaton [28], and Brandt and Coletti [29] for detailed reviews. One of the most interesting result among them is the nonmonotonic modulation of particle Stokes number on turbulence statistics (mean velocity, turbulence intensities, Reynolds stress, and vorticity) and turbulence structures (near-wall streaks, hairpin vortex, and outer-layer large-/very-large-scale motions); see Ref. [20]. This is partly explained by the sketch that particles with different inertia respond efficiently to local structures with similar lifetime [30]. There have been relatively few studies on particle-laden TBL however. Sardina *et al.* [1] presented a direct numerical simulation of spatially developing TBL one-way coupled with inertial particles. They found that the preferential near-wall particle accumulation is similar to that observed in turbulent channel flow while particle behavior characterizes in the outer region are different from channel. For example, the concentration profile of particles with finite inertia has a local minimum at the wall-normal height about the local displacement thickness of the boundary layer and a local maximum at the boundary-layer edge in TBL, which is contrary to the monotonical decrease from the wall to channel center in a channel flow. In the series works of Li *et al.* [31,32], they revealed that inertial particles increases the mean streamwise fluid velocity, the skin-friction coefficient but reduce the boundary layer thickness. However, their studies were also concentrated in the near-wall and log region and similar turbulence modulations as channel for similar particle parameters were reported. Recently, Wei *et al.* [33] found that the geometric and dynamical features of the turbulent/nonturbulent interface in a zero-pressure-gradient turbulent boundary layer is significantly changed by the presence of inertial particles because of the interaction between particles and the outer-layer turbulence structures. In addition, they also reported a local particle concentration peak just beneath the turbulent/nonturbulent interface (TNTI) in their two-way coupling simulation.

Nevertheless, the similarity/dissimilarity of particle-laden internal and external flows is still an open question in spite of the numerous studies on particle-laden turbulent flows. Will the turbulence

modification in particle-laden internal flow be the same as in particle-laden external flow for the same particle inertia? What is the difference and the reason if the answer is no? It should also be noted that understanding these similarity and difference is of great significance at this time as particle-turbulence interaction is now increasingly becoming one of the most important topic in turbulence study. This investigation aims to clarify this issue based on channel and TBL laden with typical inertial particles. The paper is organized as follows. The numerical methods and simulation parameters are described in Sec. II. In Sec. III, we compare the particle distribution, the turbulence statistics and structures in particle-laden channel and TBL. Finally, conclusions are drawn in Sec. IV.

II. NUMERICAL DETAILS AND PARAMETERS

Direct numerical simulations of turbulence are performed for incompressible Newtonian fluid governed by the Navier-Stokes equation and the continuity equation

$$Du/Dt = -\frac{1}{\rho}\nabla p + \nu\nabla^2\mathbf{u} + \frac{1}{\rho}\mathbf{f} \quad \nabla \cdot \mathbf{u} = 0. \quad (1)$$

Throughout the paper, x , y , and z represent the streamwise, wall-normal, and spanwise coordinate, and u , v , and w are the fluid velocities in the three directions, respectively. $\mathbf{u}$ is the velocity vector; t is the time; ρ , p , and ν are the density, pressure, and kinematic viscosity of the fluid, respectively. The governing equations are solved using the same numerical implementation as in Refs. [33,34]. A second-order central difference scheme on a staggered grid is employed to discrete the spatial derivative terms and the simulation is advanced in time by the Crank–Nicholson scheme. The turbulent boundary layer is simulated over a smooth no-slip wall, constant potential flow velocity, spatially periodic spanwise, but with nonperiodic inflow and outflow in the streamwise direction. An auxiliary simulation using a recycling/rescaling technique [35] is performed in advance to generate turbulent inflow conditions. For the main simulation, the Reynolds number $\text{Re}_\theta = U_\infty\theta/\nu$ based on the momentum thickness $\theta = \int_0^\infty U(1-U)dy$ ranges from 300 to 1211, where U_∞ and U are the free-stream velocity and the turbulent mean velocity at wall-normal height y . The computational domain (L_x , L_y , L_z) is set to be $(1536\theta_{\text{in}}, 60\theta_{\text{in}}, 80\theta_{\text{in}})$, where θ_{in} is the boundary-layer momentum thickness at the inlet plane. The mesh is (4096, 400, 256) and the corresponding grid spacing (Δx^+ , $\Delta y^+(\text{min})$, Δz^+) is (5.0, 0.17, 4.19), where superscript “+” indicates the distance based on the wall unit of ν/u_τ and u_τ is the friction velocity at $x/\theta_{\text{in}} = 1267.5$. The data for comparison are taken from the subdomain of $1236 \leq x/\theta_{\text{in}} \leq 1299$ which is centered at $x/\theta_{\text{in}} = 1267.5$ ($\text{Re}_\theta = 1093$) to avoid of the long adjustment process from the inlet. The flow in this subdomain can be approximately considered as a parallel flow because the variation of the boundary-layer thickness for the subdomain stays below $\pm 1.5\%$. Note that the simulation domain is $(51.2\delta, 2\delta, 2.67\delta)$ if scaled by the boundary layer thickness δ at $\text{Re}_\theta = 1093$ ($\text{Re}_\tau = u_\tau\delta/\nu = 402$). For the periodic channel, the no-slip condition is imposed on the upper and bottom wall and the flow is driven by a constant mass flux [36,37]. The computational domain (L_x , L_y , L_z) is set to be $(6\pi\delta, 2\delta, 2\pi\delta)$ (here δ represents the half channel height). The friction Reynolds numbers based on the wall friction velocity u_τ is $\text{Re}_\tau = u_\tau\delta/\nu = 394$. The mesh is (768, 256, 512) and the corresponding grid spacing (Δx^+ , $\Delta y^+(\text{min})$, Δz^+) is (9.67, 0.23, 4.83). The time step of turbulence simulation is $\Delta t^+ = \Delta t u_\tau^2/\nu = 0.075$ to ensure $\text{CFL} < 0.5$ for both flows. The schematics and dimensions for both configurations are shown in Fig. 1.

Particle trajectories are tracked using the widely employed Lagrangian approach. The sub-Kolmogorov-size ($d_{p,K} = d_p/\eta < 1$, where d_p represents the diameter of particle and η represents the Kolmogorov length scale of turbulence on the wall) spherical particles are simplified by point particles that two-way coupled with wall turbulence via a volume-weighting method [38]. Only the drag force $\mathbf{F}_D$ is incorporated in the governing equation of particle motion since the particle-to-fluid density ratio $\rho_p/\rho \gg 1$ (where ρ_p is the particle density) and particles experience a perfectly elastic

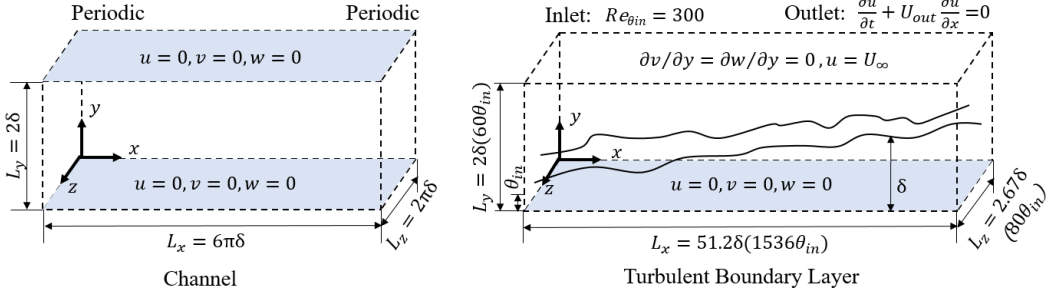


FIG. 1. Schematics of the channel flow and the turbulent boundary layer. The dimensions are not displayed proportionally for clarity.

collision when they meet the solid wall. The particle motion equation

$$\frac{d^2 \mathbf{x}_p}{dt^2} = \frac{d\mathbf{u}_p}{dt} = \frac{\mathbf{F}_D}{\pi d_p^3 \rho_p / 6} = \frac{3}{4} \frac{\rho}{\rho_p} \frac{C_d}{d_p} |\mathbf{u}(\mathbf{x}_p, t) - \mathbf{u}_p| [\mathbf{u}(\mathbf{x}_p, t) - \mathbf{u}_p] \quad (2)$$

is solved using a fourth-order Runge-Kutta method, with a time step consistent with that of the turbulence resolving. $\mu = \rho\nu$ is the dynamic viscosity of the fluid. $\mathbf{u}(\mathbf{x}_p, t)$ is the fluid velocity at particle position $\mathbf{x}_p$ and obtained by trilinear interpolation method. $C_d = 24/\text{Re}_p(1 + 0.15\text{Re}_p^{0.687})$ and $\text{Re}_p = |\mathbf{u}(\mathbf{x}_p, t) - \mathbf{u}_p|d_p/\mu$. Posterior analysis confirms that the Courant-Friedrichs-Lew number $\text{CFL}_p = \max(|\mathbf{u}_p|\Delta t_p/|\Delta|_{\min})$ defined by the modulus of particle velocity $|\mathbf{u}_p|$, time step $\Delta t_p (= \Delta t)$, and the fluid mesh $|\Delta|_{\min}$ remains below 0.5. $\mathbf{f} = -\sum_{n=1}^{N_p} \frac{\mathbf{F}_D^n}{V_j} S(\mathbf{x}^n, \mathbf{x}^j)$, where N_p is the number of particles in the control volume V_j and $\mathbf{F}_D^n$ is the Stokes drag acting on the n th particle located in V_j . $S(\mathbf{x}^n, \mathbf{x}^j)$ is the weight function [31] used for distributing the force $\mathbf{F}_D^n$ on the Eulerian grid $\mathbf{x}^i$ based on the n th particle position $\mathbf{x}_p^n$.

For the two-phase TBL, particles are initially released within the region of $y/\theta_{\text{in}} \leq 36$ with zero-slip local velocities at their released positions. Once particles exit the computational domain from the streamwise outlet plane, the same number of particles are released randomly in the inlet plane to keep a constant particle number of $N_p = 3.3 \times 10^8$ in the simulation domain. The simulation details for the two-phase turbulent boundary layer are presented in Wei *et al.* [33]. The bulk volume fraction in the subdomain $1236 \leq x/\theta_{\text{in}} \leq 1299$ of the two-phase turbulent boundary layer is $\phi_v = 1.23 \times 10^{-5}$. Accordingly, the bulk particle volume fraction of the particle-laden channel turbulence is set to be $\phi_v = 1.23 \times 10^{-5}$, corresponding to a total tracked particle number of $N_p = 8.6 \times 10^8$. Since previous studies [24,33] have proven that particles with inertia of $\text{St}^+ = \tau_p/\tau_f = (\rho_p d_p^2/18\nu\rho)/(\nu/u_\tau^2) \sim \text{O}(10)$ have the most significant interaction with wall turbulence, the particle Stokes number in the two-phase channel turbulence is taken to be $\text{St}^+ = 31$, the same as the highest particle inertia in Ref. [33] (the outer-scale Stokes number of $\text{St} = (\rho_p d_p^2/18\nu\rho)/(\theta_{\text{in}}/U_\infty) = 53$). The parameters for numerical simulations and comparison are listed in Table I.

TABLE I. Parameters for numerical simulations and comparison.

Case	$L_x \times L_y \times L_z$	$\Delta \mathbf{x}^+ \times \Delta \mathbf{y}^+(\text{min}) \times \Delta \mathbf{z}^+$	Re_τ	St^+	$\phi_v \times 10^5$
TBL	$(1536 \times 60 \times 80)\theta_{\text{in}}$ $(51.2 \times 2 \times 2.67)\delta$	$5.0 \times 0.17 \times 4.19$	402	31	1.23
Channel	$(6\pi \times 2 \times 2\pi)\delta$	$9.67 \times 0.23 \times 4.83$	394	31	1.23

Note: The inner-scale parameters for TBL are scaled by the boundary layer thickness δ and friction velocity u_τ at $\text{Re}_\theta = 1093$.

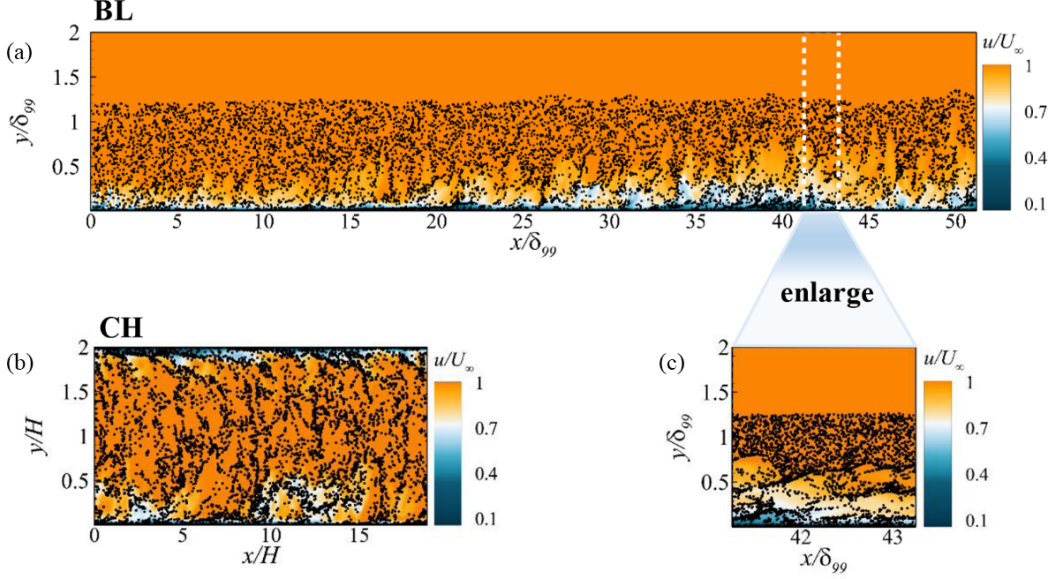


FIG. 2. Instantaneous snapshot of the streamwise turbulent fluctuating velocity and the instantaneous distribution of particles in x - y plane of the two-phase (a) boundary layer and (b) channel. Panel (c) is the enlarged view of the boundary in the range of $1236 \leq x/\theta_{in} \leq 1299$. “BL” represents “boundary layer” and “CH” represents “channel.”

The TBL simulation runs for $10\,000\theta_{in}/U_\infty$ and the postprocessing is performed based on the data sampled during the last $2000\theta_{in}/U_\infty$. The simulation of particle-laden channel turbulence lasts for $T^+ = Tu_\tau^2/\nu = 12\,000$. The analysis is conducted basing on the data sampled during $T^+ = 10\,000$ – $12\,000$ after the particle-laden flows have achieved the statistically steady state, that is, the Shannon entropy hardly changes with time [1,39,40]. Both the particle-free TBL, particle model and the two-way coupling scheme have been verified in Refs. [33,41].

III. RESULTS

Figure 2 shows the instantaneous snapshot of the streamwise turbulent velocity and the instantaneous distribution of particles in x - y plane of the two-phase boundary layer and channel. The same color legends are applied to turbulent velocity in both flows. The contour of fluid velocity in the boundary layer exhibits greater tortuosity in the outer region, indicative of its distinctive intermittent behavior. Meanwhile, large-scale motions traverse the core region in the channel, presenting a distinct feature in the flow dynamics. Particles distribute nonuniformly in the flow field. Various organized structures in the flow fields and for the particle distribution can be observed.

Basing on the two simulation results, we will discuss the distribution of particles and the turbulence modulation by the presence of particles in the two-phase boundary layer and channel turbulence. In the subsequent text, the superscript “+” signifies nondimensionalized quantities scaled by the viscous scale of single-phase turbulence. “ $\langle \cdot \rangle$ ” represents the ensemble average treatment along the horizontal direction and over time for channel while along the spanwise directions and over time for TBL, while “ $\cdot' = \cdot - \langle \cdot \rangle$ ” represents the fluctuation quantity. For example, $u' = u - \langle u \rangle$.

A. Particle distribution

Figure 3(a) illustrates the profiles of particle concentration ϕ . It is clear that particles preferentially accumulate toward the wall since ϕ decays approximatively exponentially with the

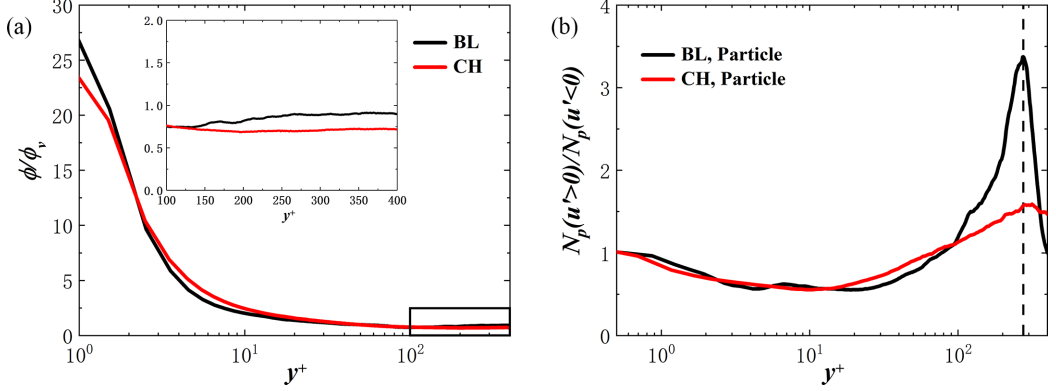


FIG. 3. Profiles of (a) particle concentration (nondimensionalized by ϕ_v) and (b) the number ratio of particles in the high- to low-speed regions.

wall-normal height. The particle concentration is $20 \sim 30$ times the bulk concentration ϕ_v near the wall whereas $< 1.0\phi_v$ in the logarithmic layer. The overall trend is the same for TBL and channel. This also aligns with previous numerical results of two-phase wall turbulence laden with similar inertial particles [39,42,43], in which the accumulation phenomenon, often called turbophoresis, is associated with particle interactions with coherent structures. Despite the same ϕ_v , one can also observe differences in ϕ profiles in the two flows.

Below the buffer layer (except for $y^+ < 2$), the particle concentration in the boundary layer is marginally lower than that in the channel, which is possibly attributed to the lower vertical velocity fluctuation and weak turbophoresis (the turbophoresis velocity is proportional to $d\langle v'^2 \rangle / dy$, see Ref. [44]) in the channel. The inset in Fig. 3(a) enlarges the outer layer to highlight the differences in particle concentrations between the two flows. As shown, the particle concentration in the boundary layer increases with the increase of height here, which is opposite to the monotonic decay of ϕ in channel. At $y^+ \approx 400$, ϕ in TBL is approximately 1.3 times that in the channel. We owe the difference in the outer layer to the higher velocity fluctuation and stronger wake effect in TBL [10,18]. As a matter of fact, Sardina *et al.* [1] found that the particle concentration profile in TBL is characterized by a local minimum at the wall-normal distance approximately corresponding to the local displacement thickness of the boundary layer ($\delta^* \approx \delta/5.5$). Wei *et al.* [33] reported a local bulge (maximum concentration) of the ϕ profile just beneath the turbulent/nonturbulent interface identified by the vorticity magnitude ($0.60 < y/\delta < 0.67$, calculated by the interface height $20.28\theta_{in}$ of the particle-laden TBL and the boundary layer thickness $30\theta_{in}$ of the particle-free TBL). Note that these two results are consistent because the outer maximum of ϕ and near-wall particle accumulation must be accompanied by a local minimum in between. Wei *et al.* [33] believed that this monotonous variation of ϕ for the moderate-inertia particle in TBL is mainly due to the centrifugal effect of the large-scale eddies in the outer layer of turbulent boundary layer and the barrier effect of the potential flow. Nevertheless, this behavior is absent in channel flows.

Figure 3(b) depicts the number ratio of particles in the high-speed [$N_p(u' > 0)$] and low-speed [$N_p(u' < 0)$] regions in x - z plane, as a function of the wall-normal height. Due to the ejection/sweeping of the fluid, the preferential concentration of particles in the horizontal plane is clear visible. $N_p(u' > 0)/N_p(u' < 0) < 1$ when $y^+ < 80$, indicating a low-speed-region distribution of particles and $N_p(u' > 0)/N_p(u' < 0) > 1$ when $y^+ > 80$, indicating a high-speed-region distribution. This is consistent with previous studies [2]. Despite that the consistency can be observed below the logarithmic layer, the profiles of number ratio for TBL and channel are quantitatively different in the outer layer. The peak of $N_p(u' > 0)/N_p(u' < 0)$ is 3.37 for TBL but 1.58 for channel, implying that particles in the outer layer of TBL are more easily distributed in high-speed regions due to the high turbulent intermittency.

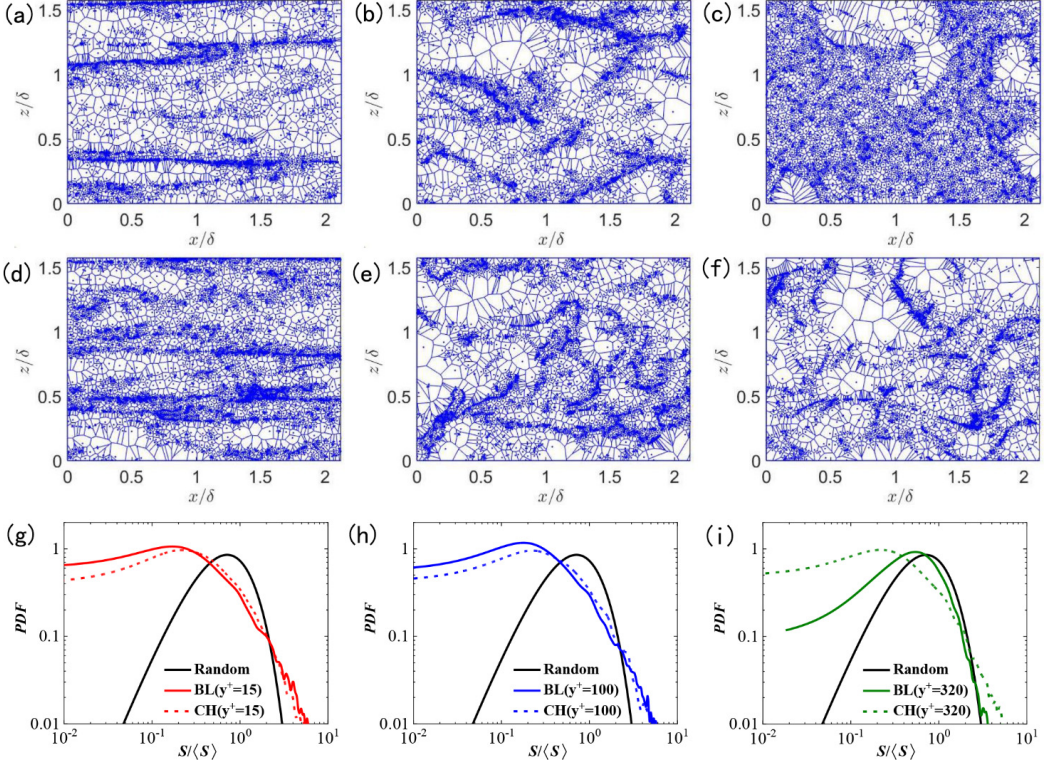


FIG. 4. Instantaneous distribution of particles at various heights of the two flows and the corresponding Voronoi tessellation, as well as the probability density function of the cell area S for the various cases. Panels (a)–(c) are the distributions for turbulent boundary layer. Panels (d)–(f) are the distributions for channel. (a), (d), (g) $y^+ = 15$, (b), (e), (h) $y^+ = 100$, and (c), (f), (i) $y^+ = 320$.

To further investigate the differences in particle clustering between the boundary layer and channel two-phase turbulence, we show the instantaneous distribution of particles at various heights ($y^+ = 15, 100, 320$) from the two simulations and the corresponding Voronoi tessellation in Figs. 4(a)–4(f), as well as the probability density function (PDF) of the cell area S for the various cases. The area is normalized by the average cell area $\langle S \rangle$ and is inversely proportional to the concentration. Again, the area of each individual cell measures the distance to the nearest neighbors [45]. We compare the PDFs of S in TBL and channel flows with that of randomly distributed particles (the black lines) in Figs. 4(g)–4(i). It is well known that particle clustering displays distinct patterns at different heights of wall turbulence. In the buffer layer, particles have streaklike clustering [1, 2, 20, 45], while in the logarithmic layer and above, irregular clouds of particles were observed [2]. This is clear shown from the Voronoi tessellation. We also see from Fig. 4 that the PDFs of $S/\langle S \rangle$ of all cases deviate from the random distribution. However, the local preferential concentration reduces with increasing y^+ . For channel flow, this is attributed to the decreasing anisotropy of the vorticity field in the central region [45]. In the near-wall region ($y^+ = 15$) and logarithmic layer ($y^+ = 100$) of the TBL, the PDFs of $S/\langle S \rangle$ are very close to those in channel, indicating the similarity in particle distribution, though particle clustering is slightly pronounced in the boundary layer. On the contrary, the PDF of $S/\langle S \rangle$ at the height of $y^+ = 320$ in TBL is much closer to that for completely randomly distribution than in channel, implying again a much weaker cluster under the action of local turbulence. This is probably related to the stronger intermittency induced by the differences between the potential and rotational flow regions and smaller turbulent structures in TBL.

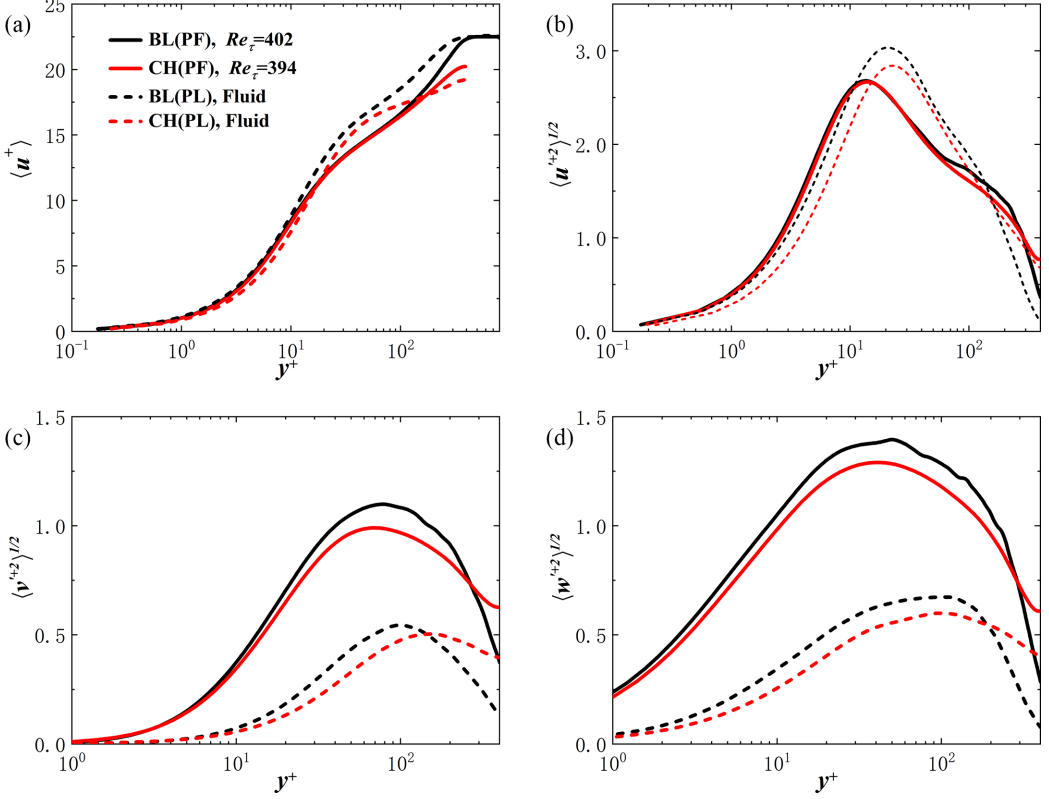


FIG. 5. Statistics of single-phase and two-phase turbulence. (a) Profiles of the mean streamwise turbulent velocity. (b) Streamwise turbulent velocity fluctuations. (c) Vertical turbulent velocity fluctuations. (d) Spanwise turbulent velocity fluctuations. “PF” represents “particle-free case” and “PL” represents “particle laden case.”

[14,18]. Note that the pdf data at $y^+ = 320$ is obtained by using the data within the height range of $y^+ = 320 \pm 10$ because of the low particle concentration in the outer layer.

B. Turbulence statistics

Owing to momentum exchange between phases, turbulence statistics will be significantly influenced. These have been well documented previously, both for channel and for TBL. Figure 5 shows the statistics of unladen and laden turbulence. It is seen from Fig. 5(a) that the mean velocities $\langle u^+ \rangle$ of the two single-phase flows are nearly identical below $y^+ \approx 120$ ($y/\delta \approx 0.3$). In the wake region, the boundary layer has higher mean velocity than channel. Many studies observed the same results [7–11,18]. Essentially, this stems from the intermittent, faster potential flow penetrating deep into the turbulent region in the boundary layer [18]. At the bottom of the buffer layer, particles marginally increase the mean fluid velocity in the boundary layer while decrease it in the channel. The later has been reported in previous studies [2,23,24,46] for similar Stokes number range. The increase of $\langle u^+ \rangle$ in TBL was mentioned in the work of Wei *et al.* [33]. They found that the boundary layer thickness in particle-laden case is apparently decreased and attributed the phenomenon to the entrainment of high-speed flow by the particles in the potential flow region to the turbulent region. As a result, the fluid experiences a negative drag force from the inertial particles and is then always accelerating on average. The impacts of particle on the mean turbulent velocity are significant in the logarithmic layer and above for both flow configurations. Since there are many particles in the

potential region, with high streamwise velocity, the increase of outer turbulent velocity is more pronounced in TBL than in channel. Note that the slight decrease of $\langle u^+ \rangle$ in the outer most region of particle-laden channel is the result of the constant mass flux when driving the channel flow. Nevertheless, a distinct wake region can also be observed here and therefore the velocity profile is noticeably flatter than the unladen case.

Figures 5(b)–5(d) show the velocity fluctuations and Reynolds stress $\langle u'^+ v'^+ \rangle$. The streamwise velocity fluctuation $\langle u'^+ \rangle^{1/2}$ shown in Fig. 5(a) are found to be higher in the outer region of unladen TBL than that in channel, consistent with Ref. [18]. The presence of particles reduces $\langle u'^+ \rangle^{1/2}$ of the two flows near the wall but increases it in the buffer and logarithmic layer. Further away from the wall, the streamwise velocity fluctuations are suppressed by the particles for the parameters studied. However, the degree of modulation in TBL is greater than that in channel, both in the logarithmic region and in the wake region. The more apparent suppression of $\langle u'^+ \rangle^{1/2}$ in the wake region ($y^+ > 130$) of TBL might be ascribed to the higher concentration [see Fig. 3(a)] and the more significant preferential distribution there [see Fig. 3(b)]. The lower particle concentration below the buffer layer ($y^+ < 15 \sim 20$), as shown in Fig. 3(a), is the reason for the less pronounced modulation of $\langle u'^+ \rangle^{1/2}$ within the region of $y^+ < 15$. An interesting result is the more significant enhancement of $\langle u'^+ \rangle^{1/2}$ peak in TBL than in channel and its upward shifting, which was also reported by Ref. [2].

Besides, the addition of particles in wall turbulence leads to the suppression of vertical and spanwise turbulent velocity fluctuations, $\langle v'^+ \rangle^{1/2}$ and $\langle w'^+ \rangle^{1/2}$, throughout the entire height. This is qualitatively consistent with the numerical simulations laden with inertial ($St^+ \sim O(10)$) particles by Refs. [2,31]. While the qualitative impact of particles on turbulence is similar in both flows, there are substantial quantitative differences. Particles have more pronounced effects near the wall but less effects in the outer layer of the channel as compared to the turbulent boundary layer. This is caused by the higher near-wall particle concentration in the channel and stronger preferential concentration in the outer-layer high-speed region of the boundary layer. Indeed, previous studies have already observed that higher particle concentration may lead to a more substantial impact on turbulence.

To further understand the momentum exchange between the two phases, we examine the average stress budget. The whole streamwise momentum budget τ_T can be decomposed into the sum of three terms [47]:

$$\tau_T = \mu \frac{\partial \langle u \rangle}{\partial y} - \rho \langle u' v' \rangle + \int_{\delta}^y \langle f_x(y') \rangle dy', \quad (3)$$

that is, the viscous stress ($\tau_\mu = \mu \partial \langle u \rangle / \partial y$), the turbulent Reynolds shear stress ($\tau_t = -\rho \langle u' v' \rangle$), and the particle-induced extra stress ($\tau_e = \int_{\delta}^y \langle f_x(y') \rangle dy'$), where f_x is the streamwise component of $\mathbf{f}$. Figure 6 illustrates the stress balance given in Eq. (1) from the simulations for particle-laden channel and particle-laden TBL, and normalized by their corresponding particle-free wall stress ($\rho u_\tau^2|_{y=0}$). In single-phase channel turbulence [Fig. 6(a)], the total stress is $\tau_T^+ = 1 - y^+/\text{Re}_\tau$ and is mainly given by τ_t for $y/\delta > 0.2$ [6,47]. The viscous stress τ_μ is the leading term near the wall since the Reynolds stress reduces gradually to zero as $y \rightarrow 0$. The particles significantly reduce the turbulent flux by momentum extraction, which has been reported in numerous experimental and numerical investigations [6,48]. In the region of $y/\delta > 0.2$, the particle stress, although still subleading with respect to the turbulent stress, is very important. It is also one of the important reason for the more uniform mean velocity profile observed in Fig. 5(a). For unladen TBL without the mean pressure gradient, the shear stress on the wall can only be balanced with the fluid inertial force (i.e., convection term of the mean flow), which means that the fluid convection term of mean flow plays a role as the pressure gradient. The total stress τ_T^+ in the boundary layer does not show a linear profile and is higher than that in channel. The viscous stress τ_μ^+ near the wall in particle-laden TBL is even higher than 1, which is contrary to the channel flow. One can observe this phenomenon clearly in the insets of Fig. 6, which are plotted in semi-logarithmic coordinate to address the near-wall stress. The reduced friction for the channel flow and enhanced friction for

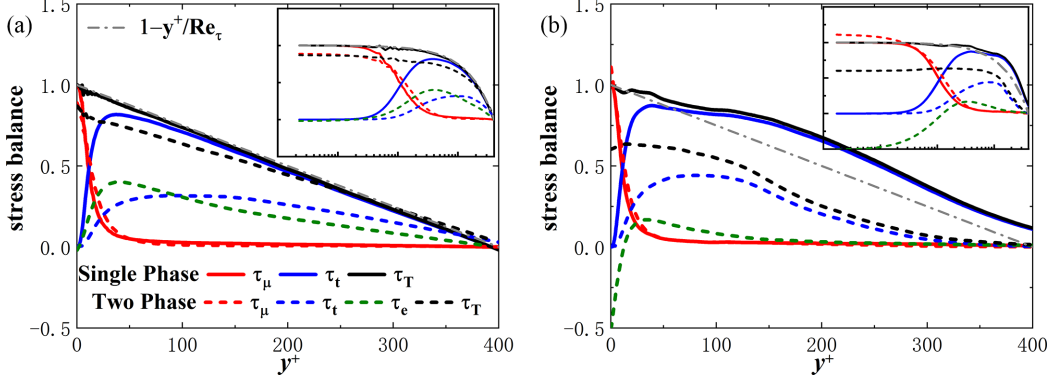


FIG. 6. Profiles of the total, viscous, turbulent, and particle stresses in the (a) channel and (b) boundary layer, normalized by their corresponding particle-free wall stress ($\rho u_\tau^2|_{y=0}$). The insets show the stress profiles in a logarithmic abscissa.

the boundary flow due to the particle effects are in agreement with the modulated mean velocity profiles shown in Fig. 5(a). The particle-induced extra stress τ_e below the buffer layer of TBL has a remarkably negative contribution to the total stress τ_T , which is not observed in particle-laden channel turbulence. Due to the fact that the decrease of the turbulent stress τ_t and the total stress in the outer layer of the laden TBL is more significant than in channel, the increase of the mean velocity is also more significant in the former case.

The differences in the second-order statistics between unladen TBL and unladen channel have been explained by the stronger pressure fluctuations p^+ and faster redistribution of energy in TBL [18]. We further this analysis for particle-laden cases based on and the turbulent kinetic energy budget. The kinetic energy equation can be written as

$$\frac{Dk}{Dt} = P_k + D_k - \varepsilon + B_k. \quad (4)$$

Figure 7 presents the pressure fluctuations $\langle p'^{+2} \rangle^{1/2}$, the premultiplied production term $y^+ P_k^+$, the dissipation term ε^+ , and the particle–fluid interaction term $B_k^+ = \langle u_i^+ f_i^+ \rangle / 2$. Here, the subscript i indicates the streamwise, vertical and spanwise direction when it equals to 1, 2 and 3. Note that the anisotropic modulation of turbulent velocity fluctuation has been reported in many previous studies and explained in terms of the transfer of kinetic energy between the particle and fluid phases and the extra energy dissipation [24,31,46]. We therefore don't show the components of the transport term but just focus on the comparison between the two flows. As shown in Fig. 7(a), the pressure fluctuation in the boundary layer surpasses that in the channel for unladen cases, resulting in higher vertical and spanwise fluid velocity fluctuations because of the faster redistribution by the pressure of the energy to the transverse velocity components in the incompressible turbulence. This is consistent with Jiménez *et al.* [18]. Interestingly, $\langle p'^{+2} \rangle^{1/2}$ decreases and the distinct peaks of $\langle p'^{+2} \rangle^{1/2}$ in the buffer layer of two-phase flows disappear because of the particle-fluid interaction. Consequently, the presence of particles significantly suppresses the vertical and spanwise transport of turbulent kinetic energy in the buffer layer, which is one of the most important reason for the increase of $\langle u'^{+2} \rangle^{1/2}$ near its peak and in the logarithmic layer, as well as the overall decrease of $\langle v'^{+2} \rangle^{1/2}$ and $\langle w'^{+2} \rangle^{1/2}$ in Fig. 5.

The production terms P_k^+ , which only has the streamwise component and pre-multiplied by y^+ to emphasize their outer layers, is generally the same near the wall for the two flows in the absence of particles, as shown in Fig. 7(b), despite $y^+ P_k^+$ in TBL is slightly higher. Instead, $y^+ P_k^+$ in the outer layer of TBL is much higher than that of channel, which helped to explain why the turbulent

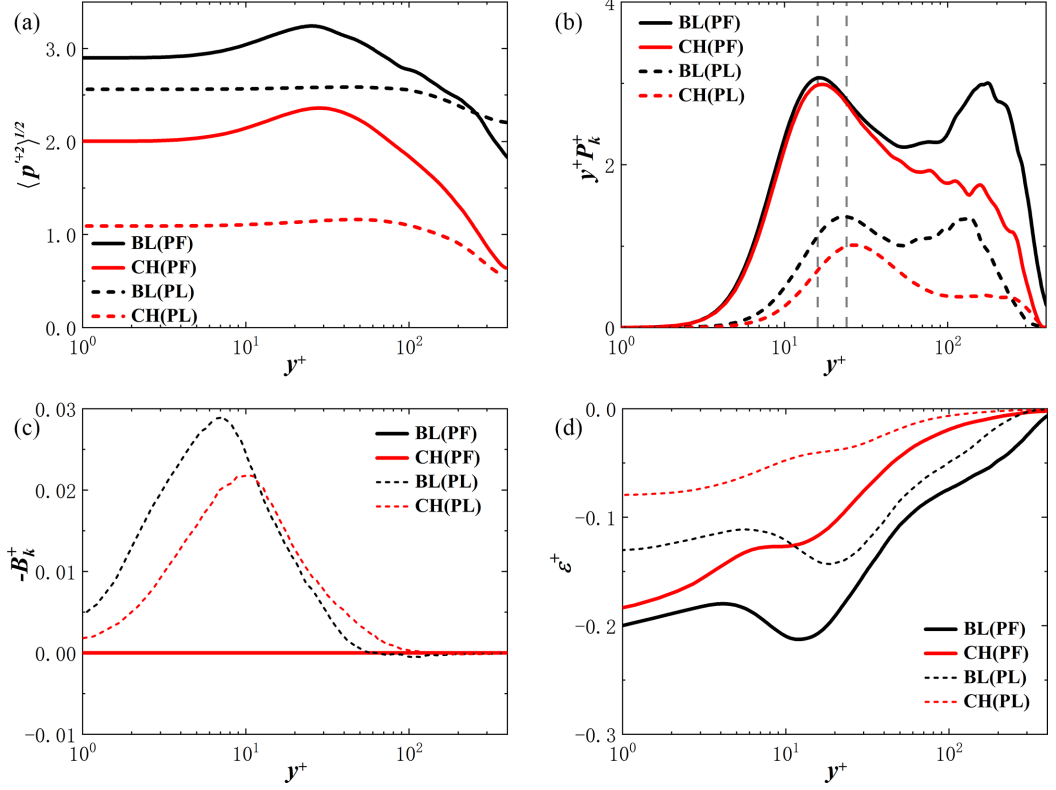


FIG. 7. FIG. 7. (a) Pressure fluctuations, (b) the premultiplied production terms $y^+ P_k^+$, (c) the particle-fluid interaction term $-B_k^+$, and (d) the viscous dissipation term ε^+ of the turbulent kinetic energy budget for unladen and laden TBL/channel.

intensities are also stronger [18]. The presence of particles reduces $y^+ P_k^+$ and has a more significant impact on channel turbulence near the wall ($y^+ < 10$), leading to more significant reduction in the streamwise velocity fluctuation there in two-phase channel (see Fig. 5). However, more significant reduction of $y^+ P_k^+$ on laden TBL is observed in the outer layer ($y^+ > 130$). Similar to the production term, B_k^+ and ε^+ are also contributed by their streamwise components. Particles always behave as a sink because $B_k^+ < 0$ in the two flows, as shown in Fig. 7(c) and generate more viscous dissipation in the outer layer of TBL, as shown in Fig. 7(d), because of the local high concentration there. Nevertheless, the three terms collectively lead to the more clear reduction of $\langle u'^{+2} \rangle^{1/2}$ in the wake region of TBL.

C. Turbulence structures

Wall turbulence is characterized by various coherent structures that are of fundamental importance to the understanding of boundary-layer dynamics. It is well accepted that the presence of inertial solid particles also affects turbulent coherent structures. In this section, we will discuss the effects by checking the instantaneous flow fields and the two-point velocity correlations.

Figure 8 presents the instantaneous snapshots of the streamwise fluctuating velocity u'^+ in the near wall region at $y^+ = 15$. As depicted in the figure, the low-speed fluid frequently develops elongated streaks in the streamwise direction. These low-speed streaks become less meandering and the number of streamwise-elongated streaks decreases in particle-laden cases, which was also

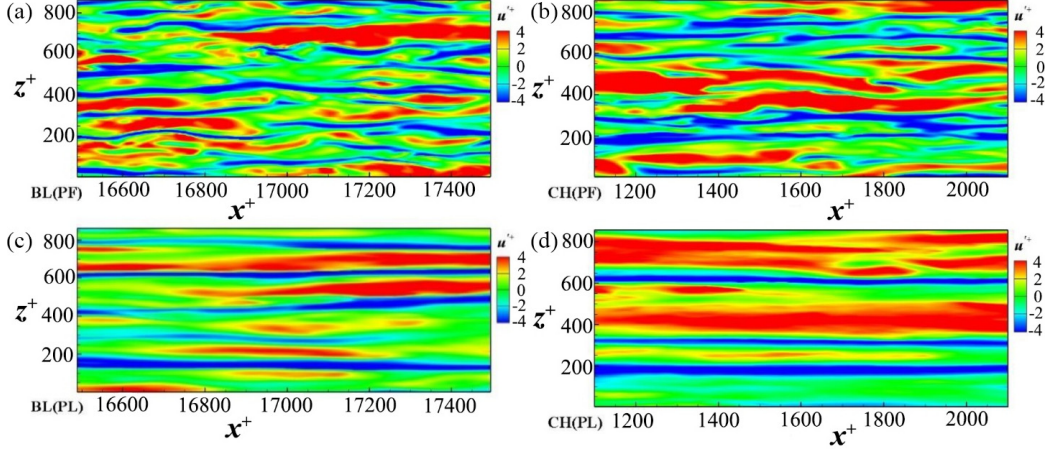


FIG. 8. Instantaneous snapshot of fluid streamwise velocity fluctuation u'^+ at $y^+ = 15$ for (a) unladen TBL, (b) unladen channel, (c) particle-laden TBL, and (d) particle-laden channel.

observed by Refs. [23,31]. The alterations in the near-wall streaks are less pronounced in the two-phase boundary layer than in the channel.

To quantify the low-speed streaks, we calculated the spanwise two-point correlations of the streamwise turbulent velocity fluctuations $R_{uu}(\Delta z) = \langle u'(x, z + \Delta z)u'(x, z) \rangle / u'_{\text{rms}}u'_{\text{rms}}$ at wall-normal position $y^+ = 15$ for the single-phase and particle-laden simulations. Figure 9(a) illustrates the correlations of u' for different spanwise separations in the buffer layer. The location Δz of the minimum in R_{uu} corresponds approximately to half the mean spacing of the streaks. For unladen cases, these low-speed streaks is approximately $\Delta z^+ \approx 100$, consistent with previous studies. The presence of particles alters the mean spacing of low-speed streaks, increasing it to approximately 180 in the boundary layer and 270 in the channel. In two-phase channel turbulence, the notable increase in the spacing of low-speed streaks signifies a weakening of ejections, closely linked to the decrease in streamwise turbulent kinetic energy, as depicted in Fig. 5(b). This weakening leads to a higher concentration of particles below the buffer layer. We also calculate the two-point correlation of particle concentration fluctuation $R_{cc}(\Delta z)$ for TBL and channel. Figure 9(b) indicates that the spacing of particle streaks is generally in agreement with that of turbulence, suggesting that the

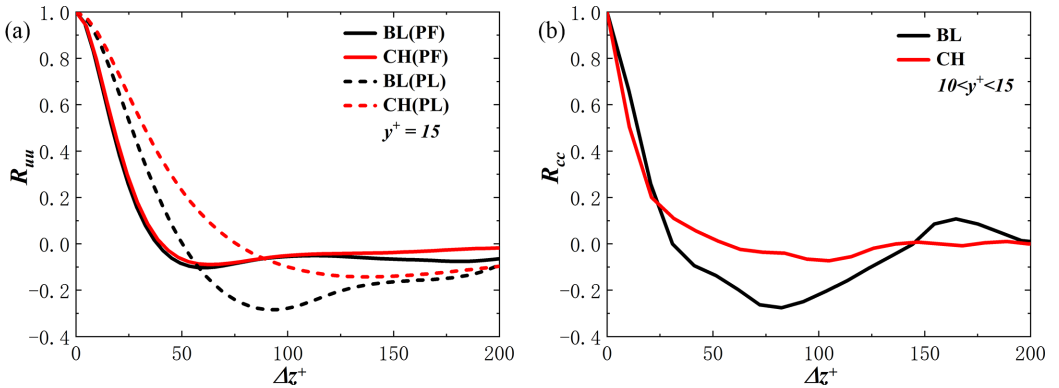


FIG. 9. Spanwise two-point correlations of (a) the streamwise velocity fluctuation at $y^+ = 15$ and (b) particle concentration within the range of $10 < y^+ < 15$.

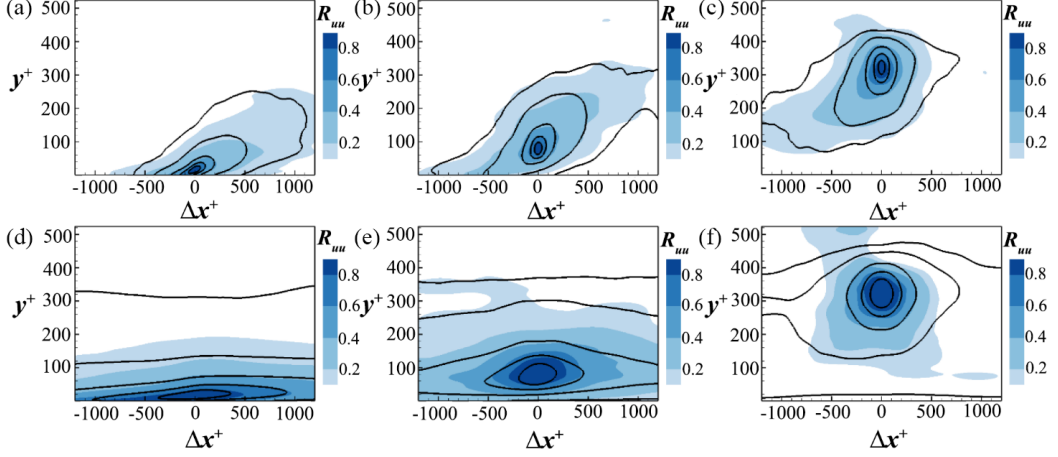


FIG. 10. Two-point correlation $R_{uu}(\Delta x, y)$ in the Δx - y plane for single-phase flows (a)–(c) and two-phase flows (d)–(f) at three typical reference heights $y^+ = 15$ (a), (d), 80 (b), (e), and 320 (c), (f). $R_{uu}(\Delta x, y)$ for TBL is shown in color while that for channel is shown by contour lines.

near-wall turbulent structures dominate the streak formation for particles with studied inertia. Most importantly, more clear valleys of R_{uu} and R_{cc} are observed for TBL, and the magnitudes of the autocorrelations are relatively smaller at the position of valleys, indicating a stronger preferential concentration and more clear turbulent streaks for particle-laden TBL than channel in the near-wall region.

We next discuss two-point velocity correlations in the Δx - y plane to investigate the effects of particles on quasistreamwise vortices at typical reference heights in TBL and channel. Figure 10 shows the $R_{uu}(\Delta x, y)$ results at $y^+ = 15, 80$, and 320 , that is, in the buffer layer, logarithmic layer, and outer layer, respectively, for single-phase flows (upper row) and two-phase flows (bottom row). For comparison, $R_{uu}(\Delta x, y)$ for TBL is shown in color while that for channel is shown by contour lines. In the single-phase flows, they all show similar inclined structures of angle $\sim 25^\circ$ and $\sim 35^\circ$ at $y^+ = 15$ and 80 . However, in the logarithmic and outer layer, the range corresponding to the contour line of $R_{uu} = 0.1$ is longer than that in TBL, which is consistent with Ref. [24] at relatively high Reynolds of $Re_\tau \approx 1000, 2000$. Farther from the wall, it clearly shows that structures in channels are longer than in boundary layer. The structures become relatively thin but long and less inclined in particle-laden turbulence at $y^+ = 15$ and 80 , regardless of flow configurations. The most notable difference in R_{uu} between particle-laden TBL and particle-laden channel are again observed in the outer region. Centering on the same correlation isocontour for the streamwise velocity at $y^+ = 320$ ($y/\delta = 0.8$), $R_{uu} = 0.2$ extends for $\Delta x^+ \approx 1000$ in boundary layers, and for $\Delta x^+ \approx 1800$ in channels. Note that in particle-free TBL and channel, it is $\Delta x^+ \approx 900$ and $\Delta x^+ \approx 800$, respectively. This means that the streamwise extent of coherent structures in the particle-laden channel is more significantly increases (125%) than in boundary layer (11%). In the wall-normal direction, $R_{uu} = 0.1$ spans from $y^+ = 480$ to $y^+ = 20$ in particle-laden channel, penetrating the inner layer, because the energy from the larger outer structures reaches the near-wall layer [24]. However, the lowest position for $R_{uu} = 0.1$ is just $y^+ = 80$ in TBL. This is the result of stronger particle-turbulence interaction in the outer region, see Figs. 3 and 5, and also the reason for the longer particle streaks in the near-wall region of channel; see Fig. 9.

Since the two-point velocity correlation $R_{uu}(\Delta x, y)$ in the outer region demonstrates its significant difference for particle-laden channel and TBL, we further show in Fig. 11 the two-point correlation of the streamwise velocity $R_{uu}(\Delta z, y)$, of the vertical velocity $R_{vv}(\Delta z, y)$ and of the spanwise velocity $R_{ww}(\Delta z, y)$ in the cross-flow (z - y) plane at $y^+ = 320$ ($y/\delta = 0.8$) to discuss the spatial organization of the correlation modulated by particles. Note that the spanwise correlations

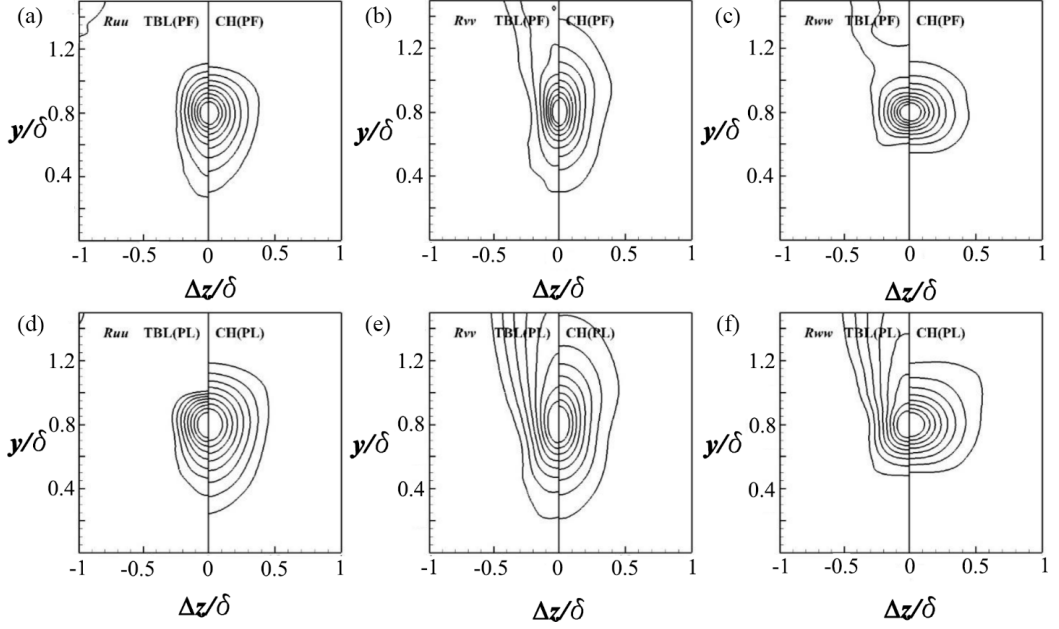


FIG. 11. Two-dimensional $R_{uu}(\Delta z, y)$ in the Δz - y plane of the boundary layer and channel ($y_{\text{ref}} = 0.8\delta$). The outermost contour line is 0.1, and the interval between adjacent contour lines is also 0.1.

are symmetric to Δz . To facilitate a clearer comparison between the two flows, they are presented side-by-side in each panel. For each panel, the left side are for boundary layers, and the right side are for channels.

As depicted in Fig. 11(a), the contour $R_{uu} = 0.1$ in the boundary layer is slightly narrower than that in the channel for single-phase flows. This suggests a marginally smaller spanwise scale of turbulent structures in the outer layer of the boundary layer as compared to that of channel [18,24]. The vertical scale of the correlations are similar in the two flows. However, R_{uu} , R_{vv} , and R_{ww} are different in the vertical direction. The outer contour line of $R_{uu} = 0.1$ and $R_{vv} = 0.1$ both spread downward to 0.3δ . Nevertheless, R_{ww} is thinner in the wall-normal direction than either R_{uu} or R_{vv} and more square in the outer layer [24]. It is evident that the addition of particles significantly influences the outer-layer structures and increase the difference between TBL- and channel-structures. Overall, the spanwise widths of all three correlations are increased. The vertical thickness of R_{vv} and R_{ww} increases, while the variation of that of R_{uu} depends on the flow pattern. The most interesting result is that the vertical range of $R_{uu} = 0.1$ decreases in TBL but increases in channel, indicating that the R_{uu} structures become wider and shorter in TBL but become wider and taller in channel. We attribute this phenomenon to the high-concentration particles in the intermittent outer layer of the boundary layer, which prevents the vertical growth of turbulent structures.

D. Uniform momentum zone/quiescent core

In their pioneering experimental observations, Meinhardt and Adrian [49] identified large, time-varying, irregularly shaped zones with nearly constant streamwise momentum, known as uniform momentum zones (UMZs), throughout the boundary layer. Then, Adrian *et al.* [50] realized that the appearance of uniform momentum zones is a consequence of the vortex packets. They defined different UMZs of boundary layer by using the local peak of fluid streamwise velocity PDF since there are large gradient of streamwise velocity and spanwise vorticity at the boundaries of UMZs. Later, Kwon *et al.* [51] found the channel, like external boundary layers, entrains large regions of

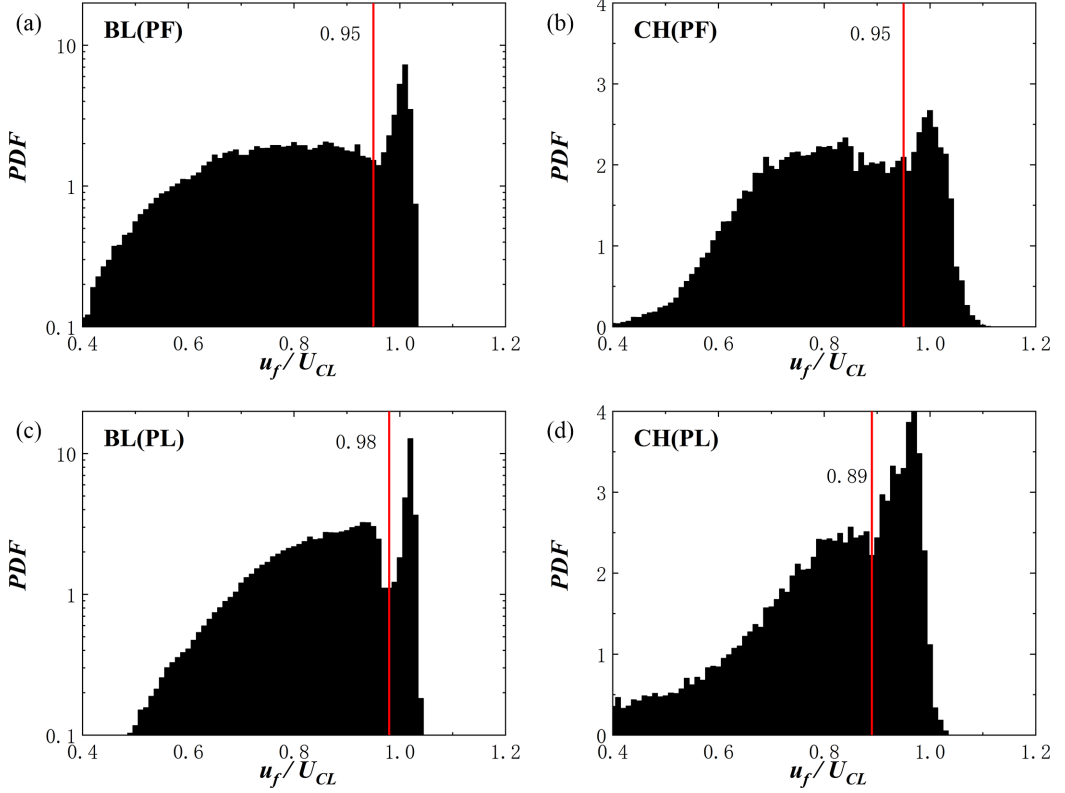


FIG. 12. PDFs of modal velocity in the boundary layer and channel, where the local minimum (red line) represents the boundary velocity of the UMZ/QC.

relatively uniform momentum. This UMZ, in the center of the channel, is called quiescent core (QC) because it has comparatively low turbulence intensity. The structure of the core region resembles the laminar superlayer in the turbulent/nonturbulent interface of TBL [52]. Despite that Jie *et al.* [53] have revealed the strong damp of the rotation of nonspherical particles in the quiescent core of channel through a one-way coupled direct numerical simulation, Jie *et al.* [54] found QC boundary, appeared as a barrier, exerts a substantial influence on transport and accumulation of inertial particle and Wei *et al.* [33]. reported a local accumulation of particles just beneath the turbulent/nonturbulent interface of turbulent boundary layer, the interactions between particles and UMZ/QC, as well as their similarity/dissimilarity, have not been investigated before. This is what we will focus on in this section.

To identify the quiescent core of a turbulent channel flow and uniform momentum zone in TBL, we use a velocity threshold following the approach of Refs. [51,52]. We first get the PDFs of the instantaneous streamwise velocity within a subzone over the streamwise domain length of 2.0δ ; see Fig. 12. For particle-free cases, two peaks are apparent. Each peak corresponds to the modal velocity representative of each UMZ/QC [50,51,55]. Their interface could be defined using the local minimum (red line) as the threshold value. Consistent with previous studies, the threshold velocity of the QC in the particle-free channel is $U_B = 0.95U_{CL}$ (U_{CL} represents the mean fluid velocity at the center of the particle-free channel). The threshold velocity of the outer-layer UMZ in the particle-free boundary layer is also approximately $0.95U_{CL}$, where U_{CL} indicates the free fluid velocity U_∞ at $y = \delta$.

However, the addition of inertial particles increases the threshold velocity in TBL while decreases the threshold value in channel. This is consistent with the modulation of the mean fluid velocity in

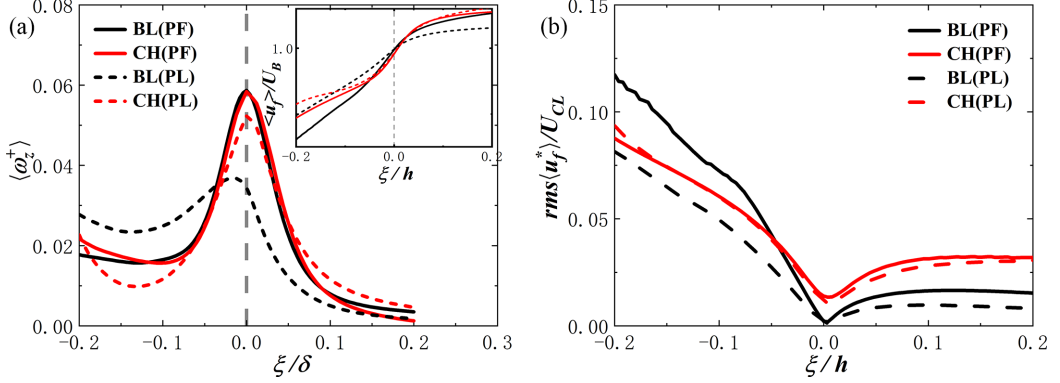


FIG. 13. Conditionally averaged (a) spanwise vorticity and (b) streamwise velocity fluctuation within the range of $\xi \in [-0.2\delta, 0.2\delta]$. The inset of panel (a) shows the conditionally averaged velocity.

the outer layer, as shown in Fig. 5(a). Comparing the mean height of the "enveloped" boundary (as defined by Ref. [51], not shown) of laden and unladen flows shows that the particles decrease the boundary of the outer-layer UMZ from 0.75δ to 0.58δ and that of the QC from 0.62δ to 0.45δ .

It is accepted that the characteristics of the UMZ/QC are particularly marked by a high shear near its boundary and a low-level turbulence in it [51–53,56,57]. The spanwise vorticity $\langle \omega_z \rangle$ (scaled by ν/u_τ^2) and streamwise velocity fluctuation within the range of $\xi \in [-0.2\delta, 0.2\delta]$ are conditionally averaged and plotted in Fig. 13. $\xi = 0$ is the identified UMZ/QC boundary. It is seen that near the boundary of UMZ/QC, the nondimensionalized spanwise vorticity $\langle \omega_z^+ \rangle$ are almost the same in particle-free TBL and channel. They all have peak at $\xi = 0$, indicating a strong shear layer existed at the interface. This is also seen from the conditional streamwise velocity $\langle u_f \rangle$ profiles in the inset of Fig. 13(a). There are steplike jumps in the streamwise velocities as one moves across the interface. Below the boundary, the flow is faster in channel than in boundary layer. Due to the presence of particles, the velocity gradient $d\langle u_f \rangle/d\xi$ and the vorticity $\langle \omega_z \rangle$ significantly decrease throughout the interface layer in TBL, indicating that the UMZ in the outer layer of TBL becomes indistinct. This phenomenon is not as clear in channel. Figure 13(b) plots the conditional turbulence intensity $\text{rms}\langle u_f^* \rangle$ near the UMZ/QC interface. A dramatic decay in the streamwise turbulence intensity, with regard to ξ/δ , is observed for all cases, regardless of the presence of particles or not. By contrast, the UMZ/QC contains a weak level of turbulence. The flow outside of the UMZ/QC constitutes a fully turbulent region. In this region, the decay is faster in particle-free TBL than in unladen channel. For particle-laden cases however, the decrease in $\text{rms}\langle u_f^* \rangle$ is more significant in TBL than in channel. This has already shown in Fig. 5(b). The outer-layer UMZ is believed being induced by the vortex packet [50]. Therefore the reduced $\text{rms}\langle u_f^* \rangle$ and the indistinct UMZ in particle-laden TBL are both associated with the reduced R_{um} structures shown in Fig. 11(a). The effects of particles on the turbulence intensity within UMZ/QC are not remarkable, though $\text{rms}\langle u_f^* \rangle$ does decrease, partly because the particle concentration there is low.

Figures 14(a) and 14(b) display the conditionally averaged particle concentration Φ , scaled by the bulk concentration ϕ_v , inside and outside the UMZ/QC in both TBL and channel. The spatiotemporal averaged particle concentration (the black one) is also provided for reference. Notably, particles outside the UMZ/QC present from the wall to almost δ , whereas particles inside the UMZ/QC are confined to the outer layer. The latter is also the indicative of the significant vertical fluctuations of the boundary of the particle-laden UMZ/QC. As a matter of fact, the boundary ranges from a lowest height $y/\delta \approx 0.25$ to a highest height $y/\delta \approx 1$, regardless of the flow configuration. However, in this range, the ratio of particle concentration inside the UMZ/QC to that outside the UMZ/QC is much higher in TBL than in channel at the same wall distance, see the insets of Figs. 14(a) and 13(b). Particles prefer to reside in the UMZ/QC rather than outside the UMZ/QC and this tendency

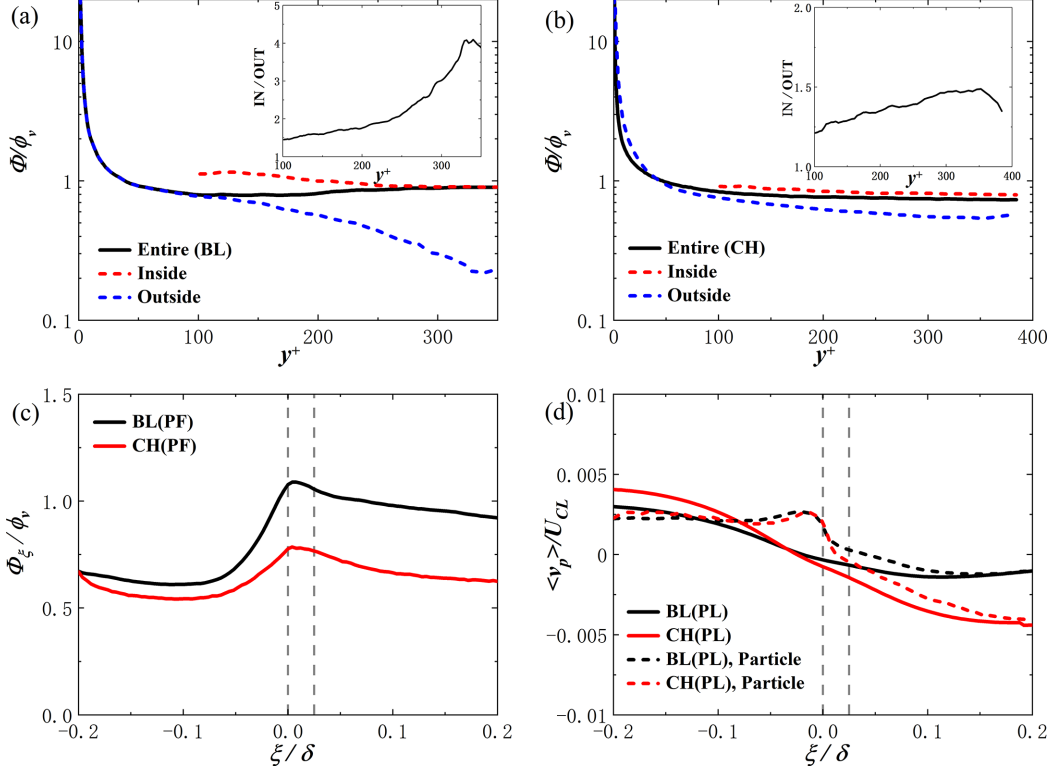


FIG. 14. Conditionally averaged particle concentration inside and outside the (a) UMZ in TBL and (b) QC in channel. (c) Interface-averaged particle concentration in the range of $\xi \in [-0.2\delta, 0.2\delta]$ and (d) the interface-averaged vertical particle velocity within $\xi \in [-0.2\delta, 0.2\delta]$.

is more pronounced in TBL. This is why there is a slight bulge of the mean particle concentration in the wake region of TBL. On the contrary, the inside-outside difference is too small to induce a local accumulation in channel.

Figure 14(c) shows the interface-averaged particle concentration Φ_ξ in the height range of $\xi \in [-0.2\delta, 0.2\delta]$. We see that particles do locally accumulate near the UMZ/QC boundary, though the spatiotemporal averaged particle concentration decay monotonically with the wall-normal distance y/δ , as shown in Figs. 3(a) and 14(b). Jie *et al.* [54] observed similar phenomenon in their one-way coupling simulations of particle-laden channel turbulence. They argued that the centrifugal mechanism causes inertial particles to avoid the vortices around the QC boundary. Thus, the QC boundary, characterized by hairpin packets, acts as a barrier hindering the wall-normal transport of particles, resulting the local accumulation. Wei *et al.* [33] also explained the local accumulation of inertial particles below the turbulent/nonturbulent interface by the combined effect of centrifugal mechanism and potential flow barrier based on their two-way coupling TBL simulation. This is confirmed by the negative conditionally averaged vertical particle velocity $\langle v_p \rangle$ inside the UMZ/QC and positive $\langle v_p \rangle$ outside the UMZ/QC, as shown in Fig. 14(d). Nevertheless, the higher degree of particle accumulation near the UMZ/QC in turn explains the lower vorticity $\langle \omega_z \rangle$ there and hence the indistinct UMZ in particle-laden boundary layer.

IV. CONCLUSIONS

The interphase interaction in particle-laden wall turbulence are usually studied on the basis of channel and spatially developing flat-plate boundary layer. Although the extent or existence

of similarities between internal channel and external boundary layer flows has been exhaustively discussed in the past two decades, the similarity/dissimilarity for particle-laden cases attracts less attention.

In this paper, a two-way coupled direct numerical simulation is conducted in a horizontal channel laden with moderate-inertia ($St^+ = 31$) small, solid spherical particles. The simulated results, together with our previous simulation data of a spatially developing turbulent boundary layer laden with particles of the same inertia, are employed to discuss the similarity/dissimilarity between particle-laden channel and TBL. The corresponding friction Reynolds number of single-phase turbulence are $Re_\tau = 394$ and 402, respectively.

Although the particle concentration decays approximatively exponentially with the wall-normal height in both flows due to turbophoresis, the differences are observed throughout the turbulence region. The concentration profiles do not collapse in the near wall and outer region. The biggest differences are observed in the wake region where there is a local bulge of the ϕ profile in TBL due to the centrifugal transport of particles by outer large-scale eddies and the potential flow barrier. This is not observable in channel. The statistical and Voronoi analysis demonstrate that particles with the studied inertia prefer to cluster in high-speed region in the outer layer of wall turbulence. However, this phenomenon is more pronounced in TBL. On the contrary, the low-speed-region distribution below the logarithmic region are almost the same for both flows.

Below the buffer layer and in the wake region, particles modulate the turbulent mean velocity in an opposite way, that is, the mean velocity is increased in TBL but reduced in channel. Instead, particles enhance the mean turbulent velocity in the logarithmic region in both flows. The streamwise velocity fluctuation is decreased in the near-wall region, increased in the logarithmic region and decreased again in the wake region in both flows. In the vertical and spanwise direction, the velocity fluctuations are completely suppressed by the inertial particles. Nevertheless, the modulation is more apparent in outer layer of TBL. The dissimilar modulation is explained by the average stress budget, pressure fluctuation and turbulent kinetic energy budget. We see the profiles of total stress in channel and TBL are essentially different and modulated more significantly in TBL. The less decrease of the pressure fluctuations and turbulent-kinetic-energy production terms explain the less pronounced reduction of the streamwise turbulent kinetic energy near the wall and more enhancement in the buffer/logarithmic region of TBL. In addition, the two-point correlations of the turbulent velocity fluctuations show that the spanwise spacing of the near wall streaks are more notably increased by the presence of particles with studied inertia in channel. Meanwhile, the streamwise extent of coherent structures in the outer region is increased by 125% in channel and 11% in boundary layer.

The above results about the modulations in the outer layer are further confirmed by analyzing the uniform momentum zone and quiescent core, which is believed to be a consequence of the large-scale vortex packets. We find that the presence of particles decreases the threshold velocity for the identification of uniform momentum zone and quiescent core, and lower the interface of these low-turbulence-intensity regions. Most importantly, the velocity gradient and the vorticity more significantly decrease throughout the interface layer in TBL, indicating that the uniform momentum zone in the outer layer of TBL becomes more indistinct than that of channel. The difference of particle inside/outside the uniform momentum zone and quiescent core explains the more clearly visible local accumulation of particles in the outer layer of TBL.

The simulations are limited in relatively low Reynolds number and particle Stokes number. Since recent studies have revealed the nonmonotonic interactions between inertial particles and wall turbulence with regard to Re_τ , St , and volume fraction, the comparisons performed in this work should be further extended to larger parameter space.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they contain sensitive personal information. The data are available from the authors upon reasonable request.

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