PREFERENTIAL CONCENTRATION OF PARTICLES IN COMPRESSIBLE TURBULENCE

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Abstract The behavior of particles in compressible turbulence has been seldom investigated to date despite its importance in many natural and industrial flows. Direct numerical simulations of particle-laden compressible isotropic turbulence are performed to study the preferential concentration of particles and the underling mechanisms. It turns out that heavy particles tend to concentrate in regions of low enstrophy and high fluid density (i.e, strain regions between vortex rings), especially the particles of Kolmogorov scale, which show the largest number density. Due to the compressibility, fluid particles do not distribute uniformly as in incompressible case, but show a tendency to bunch up in high density zones. The preliminary result might give some insights into compressible turbulent transport, dispersion and mixing as well as the subgrid-scale modeling for large-eddy simulation of particle-laden compressible flows.

NUMERICAL METHODS

High-order compact finite difference method and the localized artificial diffusivity technique [1] are employed to solve the governing equations for isotropic compressible flows in a cubic domain $[0, 2\pi] \times [0, 2\pi] \times [0, 2\pi]$. The motions of particles in the flow are integrated by using Maxey and Riley's approximation [2] for incompressible flow. When the particle is much smaller than the Kolmogorov length scale, i.e., $d \ll \eta$ and much heavier than the fluid, i.e., $\rho_p \gg \rho$, the particle can be considered to be a point-particle. Therefore, the control equation for particles can be simplified in the form

$$\frac{dx_{p,i}}{dt} = v_{p,i} \tag{1}$$

$$\frac{v_{p,i}}{dt} = \frac{u(x_{p,i}) - v_{p,i}}{\tau_p} \tag{2}$$

As suggested by Parmar *et al.* [3], the above equation is also suitable for particles in compressible flow under the assumption of point-particle except for the definition of particle's response time τ_p. Here, $\tau_p = \frac{1}{Re}\frac{\rho_p d^2}{\mu_f}$, where μ_f is not a constant as in incompressible case, but varies with the time and location [5].

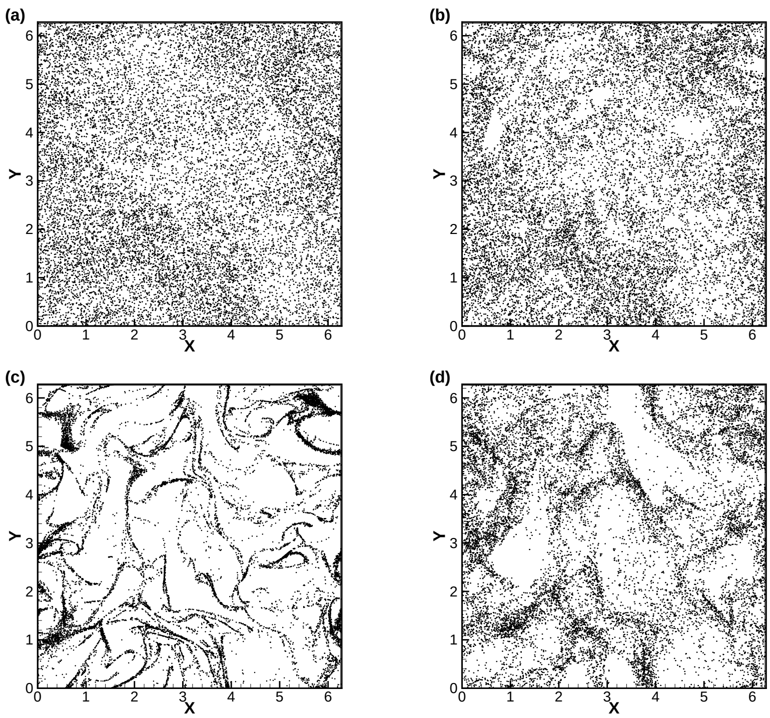

Figure 1. Pointwise particle distribution in a slice with thickness of about 2η: (a) Tracer, (b) St=0.1, (c) St=1.0, and (d) St=5.0.

RESULTS AND DISCUSSION

As is well known, particles may accumulate in particular regions even in isotropic turbulence, which is referred to as preferential concentration [4]. In compressible turbulence, we observe the similar phenomena.

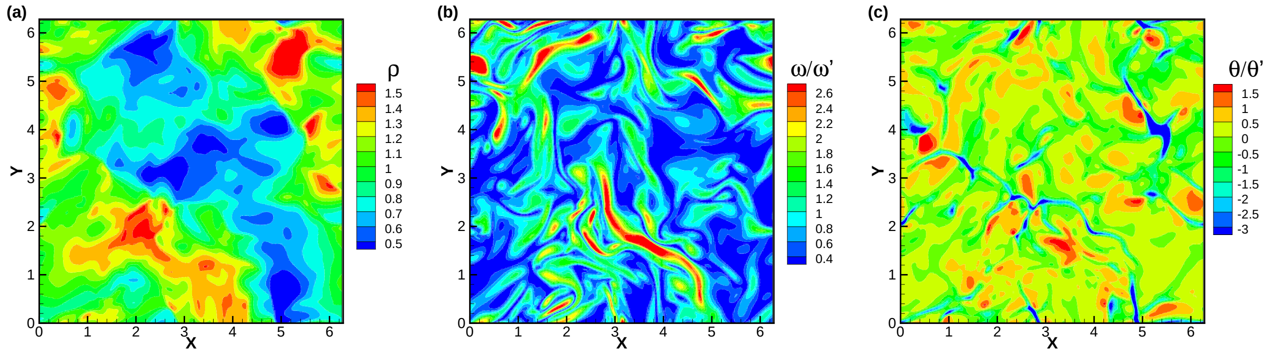

Figure 2. Instantaneous contours in the same slice as in figure 1 for (a) density, (b) vorticity magnitude, and (c) dilation.

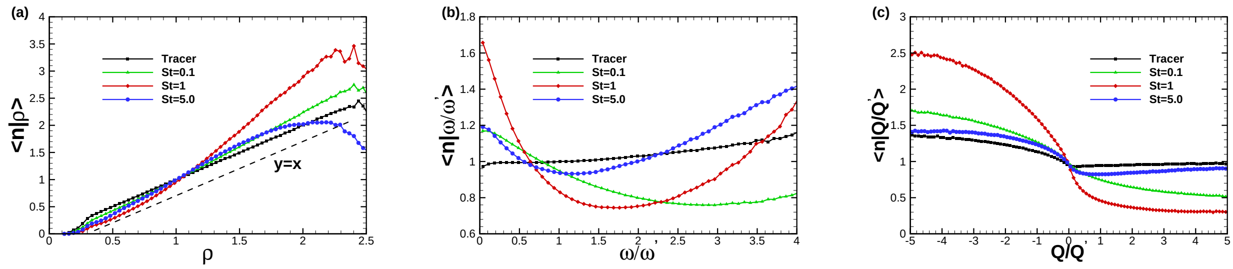

Figure 3. Averaged particle number density conditioned on (a) density, (b) vorticity magnitude, and (c) Q.

We have shown in Fig. 1 the instantaneous pointwise distribution of four different particles in a slice with thickness of about 2η. Fig. 2 shows the instantaneous contours of fluid density, vorticity magnitude and dilation in the same slice as in Fig. 1. From Fig 1 (a) and Fig. 2 (a) and (c), it can be seen that tracers are more likely to bunch up in high density zones, i.e., the downstream of the shocklets. Fig. 1 (c) and Fig. 2 (b) indicate that particles with intermediate St number ($St = 1.0$) have the strongest correlation with low-vorticity field. The small St number ($St = 0.1$) particles are able to respond quickly to the fluid motion and behave similarly to tracers (Fig. 1 (b)). The distribution of large St number ($St = 5.0$) particles seems to have increasing correlation with strong-vorticity regions (Fig. 1 (d)).

The quantitative conclusion can be further demonstrated by statistical analysis. Shown in Fig. 3 (a), (b) and (c) are the averaged particle number density conditioned on fluid density, vorticity magnitude, and Q. Here $Q = \frac{1}{2}(\frac{1}{2}\omega^2 - S^2 + \theta^2)$ is the second invariant of velocity gradient tensor in compressible flow. It is obvious that both tracers and heavy particles tend to be located in zones of high fluid density (see Fig. 3 (a)). The mean number density of tracers correlates with fluid density linearly as expected. For intermediate St number (e.g., $St = 1.0$), the mean particle number density in low-vorticity zone is the highest, which is in agreement with that in incompressible case. As St increases, concentration of particles can also be observed in relatively high-vorticity zones (Fig. 3 (b)), and becomes increasingly so for large St number case (e.g., $St = 5$). It may be attributed to the effect of compressibility. Nevertheless, the mean particle number density conditioned on Q monotonically decreases with increasing Q. Note that Q is different from that in incompressible turbulence. It contains the dilation effect as well as the vorticity and strain rate information.

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