# Direct Numerical Simulations of Particle-Turbulence Interactions

**C. Lee**[1,2*]

1: Department of Computational Science and Engineering, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul, Korea.
2: Department of Mechanical Engineering, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul, Korea.
*Correspondent author: clee@yonsei.ac.kr

Particle-laden turbulence has been extensively studied numerically or experimentally for the last 20 years. Answers to fundamental questions such as how particles cluster or how turbulence is modified by particles have been sought. Under a certain circumstance, our level of understanding on the interaction between laden particles and turbulence is satisfactory. For example, we now know that heavy particles tend to cluster in low-rotation and high-straining region due to the sling effect by vortical structures. Small particles enhance turbulence by adding inertia to fluid while large particles suppress turbulence by random movement. However, these observations were made in gravity-free situation. Our knowledge on the interaction between settling particles and turbulence is quite limited although gravity is unavoidable in real situations. Here, we provide new findings on the behavior of settling particles from theoretical and numerical studies.

When heavy particles settle in isotropic turbulence, a new type of clustering is observed. Particles tend to vertically cluster in the strip pattern in the gravity direction when the Stokes number ($St = \tau_p/\tau_\eta$) is of order one or larger and the Froude number ($Fr = v_\eta/g\tau_\eta$) is much smaller than one (Park, 2014). Here, $\tau_p, \tau_\eta, v_\eta$ and $g$ are the particle relaxation time, the Kolmogorov time scale, the Kolmogorov velocity scale and gravitational acceleration, respectively. A plausible mechanism behind this phenomenon was provided from the skew-symmetric distribution of the velocity gradient in the vertical direction, which is a non-Gaussian property of turbulence. This clustering of particles is different from the clustering found in artificial Gaussian turbulence in the presence of gravity in that the latter is found even when gravity is eliminated while our clustering is observed only when strong gravity settles particles. For this parameter regime ($St \sim 1, Fr \ll 1$), theoretical estimates for the particle number density correlation and the Lyapunov exponents are possible since the so-called 'flow of particle' exists due to strong gravity (Fouxon, 2015). $\langle n(0)n(r)\rangle = \left\langle n(0)^2\right\rangle (r/\eta)^{2D_{KY}}$ where $n(r)$ and $\eta$ are the particle number density and the Kolmogorov length scale, and $D_{KY}$ is the Kaplan-Yorke codimension given by $|\sum\lambda_i|/|\lambda_3| = (3\pi/4g)\int_0^\infty E(k)k\ dk$ with $\lambda_i$ and $E(k)$ denoting the Lyapunov exponents and the isotropic energy spectrum of turbulence. When gravity is strong, quick settling prevents the sling effect so that the velocity of particles remain smooth.

When particles sediment in the channel turbulence in the wall-normal direction, turbulence near the top wall and bottom wall is modified differently. Preferential sweeping of the settling particles among the streamwise vortices near the top wall produce clustering of particles and enhance the ejection process so that turbulence is increased and extended to a deeper region in the core, while turbulence near the bottom wall is suppressed by the settling particles towards the wall. An interesting finding is that a large-scale circulatory motion throughout the channel similar to ones typically observed in the turbulent Couette flow is created by the sedimenting particles.

Particle-laden stratified turbulence has not been well studied although many particle-laden flows found in nature is stratified, weak or strong. Even the disturbed motion by a settling sphere in stratified stationary fluid was recently studied mostly for strongly stratified density field such as seawater (Yick, 2009). Our investigation of the flow induced by a settling sphere in linearly stratified fluid with $Pr = 0.72$ (air) and $Pr = 7$ (water) shows that drag increases due to the suppressed vertical motion significantly particularly for small Reynolds numbers. Behavior of settling particles in stratified homogeneous turbulence was also numerically studied. Anisotropic nature of turbulence due to stratification obviously affects particle clustering owing to gravity.

## REFERENCES

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