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Hierarchy of Coherent Vortices in Developed Turbulence and its Role in Transport Phenomena

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We investigate turbulent flows of neutral fluids. Here, we emphasize that turbulence is not random but composed of coherent vortices with various sizes. For example, developed turbulence at a high Reynolds number away from solid walls consists of a hierarchy of counter-rotating pairs of vortex tubes; and smaller-scale vortices are stretched and amplified in straining fields around larger-scale vortices. [1] Our recent numerical simulations showed that the similar hierarchy of coherent vortices existed in various kinds of turbulent flows such as a turbulent boundary layer, [2] turbulent channel flow [3] and a turbulent wake behind a cylinder (figure 1). This similarity in the hierarchy of coherent vortices may be the origin of the small-scale universality of turbulence.

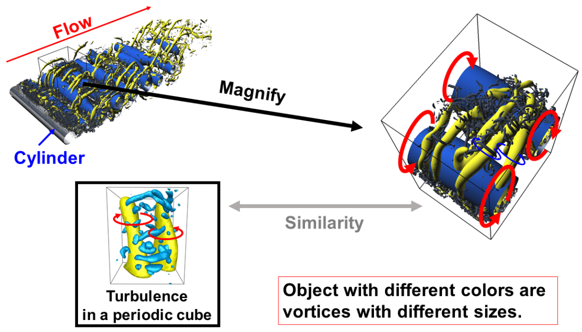

Figure 1 Hierarchy of coherent vortices in a wake behind a cylinder. The hierarchy of vortices is similar to those in turbulence in a periodic cube.

We can describe some transport phenomena in terms of the hierarchy of coherent vortices. An example is the clustering of small particles in turbulence. If the mass density of particles is much heavier (or lighter) than the surrounding fluid, particles tend to accumulate around (or inside) vortices. However, when the Reynolds number is high enough, vortices with various sizes simultaneously exist, and therefore, it was non-trivial to describe the clustering of particles in high-Reynolds number turbulence. To solve this issue, we have developed a theory [4] based on the equation of motion for small solid particles. The important quantity is the relaxation time τ_p of the particle velocity, which is determined by the mass-density ratio between particle and fluid, the particle size and the fluid viscosity. Note that vortices with different sizes swirl with different time-scales. Since particles cannot respond swirling flow faster than τ_p, particles with different τ_p form clusters with different sizes. We can apply this idea to turbulence of different kinds. An example is the particle clustering in the turbulent channel flow (figure 2). It is evident that particles with smaller τ_p form smaller clusters than those with larger τ_p.

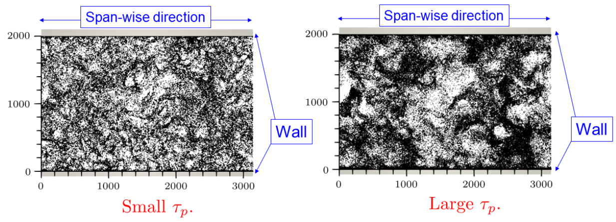

Figure 2 Particle clustering in turbulent channel flow. [5]

Another example is turbulence attenuation due to solid particles. When we add small heavy particles with large τ_p to turbulence, vortices can be created behind them (figure 3) because of large relative velocities between particles and fluid. These particle-size vortices bypass the energy cascade and enhance the energy dissipation, leading to the attenuation of turbulence. Recently, we developed a theory [6] which describes the condition and degree of the turbulence attenuation. This theory is also based on the knowledge of the hierarchy of coherent vortices in turbulence.

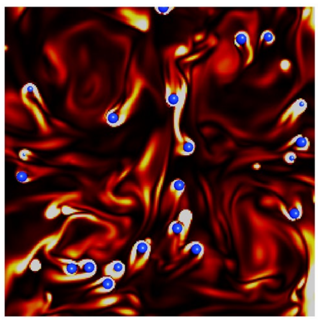

Figure 3 Heavy small particles (blue spheres) with large τ_p in turbulence. The colormap indicates the vorticity magnitude. [6]

References

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