

Two-Dimensional Turbulence

The swirling structure of fluid motion has fascinated people since the earliest recorded observations of turbulence by Leonardo da Vinci. Typically turbulent fluid flows occupy the full three dimensions of space, but in certain cases motion in one direction is suppressed and a quasi two-dimensional hydrodynamics remains. The degree to which the third dimension can be ignored depends on the ratio of lateral to vertical scales and on the degree to which imposed forces such as rotation or magnetic field result in strong anisotropy of the flow (i.e., dominance of lateral velocities with respect to vertical velocities).

Two dimensional turbulent experiments and simulations are simple models of atmospheric and oceanic turbulence. 2D turbulence is also of fundamental interest because of the unique turbulent phenomena that are manifest in 2D systems - the inverse energy cascade being a prominent example.

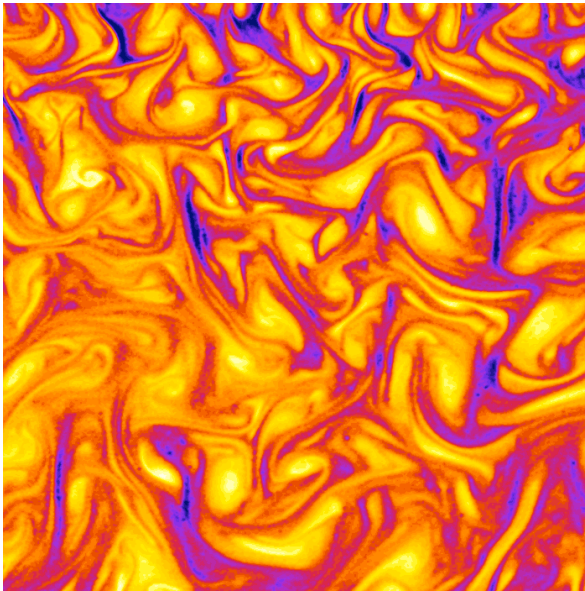


Figure 1 *Grid turbulence visualized by thickness measured by diffuse light scattering.*

Finally, there are a number of significant practical advantages to be gained from studying 2D turbulence: 1) a single velocity field at resolution N^d where N is the number of grid points and d is the dimensionality requires $N^{3/2}$ more storage for 3D flows compared to 2D fields, 2) techniques to obtain velocity field data and to track particles are much simpler to implement for 2D flows, 3) 2D flows are easier to visualize as evidenced by Fig. 1, and 4) the

study of 2D turbulence can act as a development platform for testing novel analysis methods.

We study several types of 2D turbulence systems. The first is a gravitationally-driven soap film channel.¹ The soap film has a typical thickness of between 5 and 30 μm whereas the velocity field varies on the scale of 200 μm up to several cm. Thus, the velocities perpendicular to the plane of the film are small compared to the lateral velocities and the system is quite two dimensional in that respect. Further, the system can be shown in some limits to be a close approximation to a 2D incompressible Navier-Stokes fluid. Although the correspondence is not exact (for example, the film has a typical compressibility of about 10%), this system has been widely used to study 2D turbulence with great success. The other system is a thin horizontal fluid layer, typically a 1-4 mm thick layer of salt water, driven electromagnetically to inject vorticity at a well-defined length scale.

To fully understand 2D turbulence, one must first obtain the fluid velocity field. Experimentally, this is accomplished using particle image velocimetry PIV or a related technique particle tracking velocimetry PTV. Small particles seed the flow and are illuminated by a powerful light source, usually a

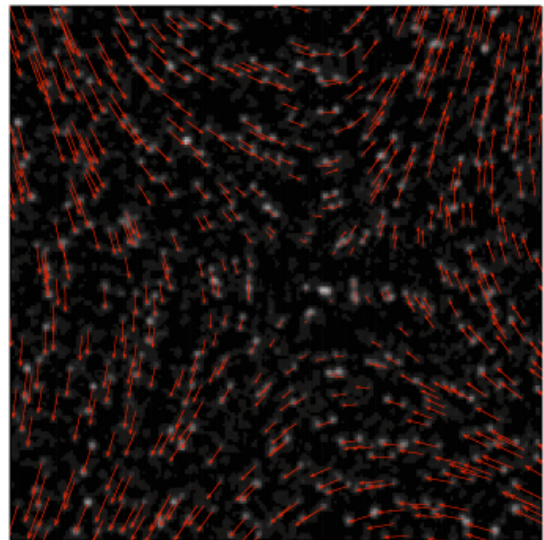


Figure 2 *Particle tracks and velocity vectors from particle tracking velocimetry.*

pulsed laser. In PIV, patterns of particles spanning a small sub-area are matched with a slightly shifted set of particles separated by a well-defined time

interval. The resulting displacement gives an average velocity for that region. Alternately, one can track individual particles between the frames as illustrated in Fig. 2 where two exposed frames are superimposed and red vectors "connect the dots."

The vorticity field which is a measure of the swirl of the flow is derived from the velocity field through spatial derivatives: $\omega(x,y) = \nabla \times \mathbf{v}(x,y)$. An example is shown in Fig. 3 where blue is clockwise circulation and red is counter-clockwise motion. Notice the fine scale filaments of vorticity that are generated by the vigorous stretching and folding mechanisms of the turbulent motion.

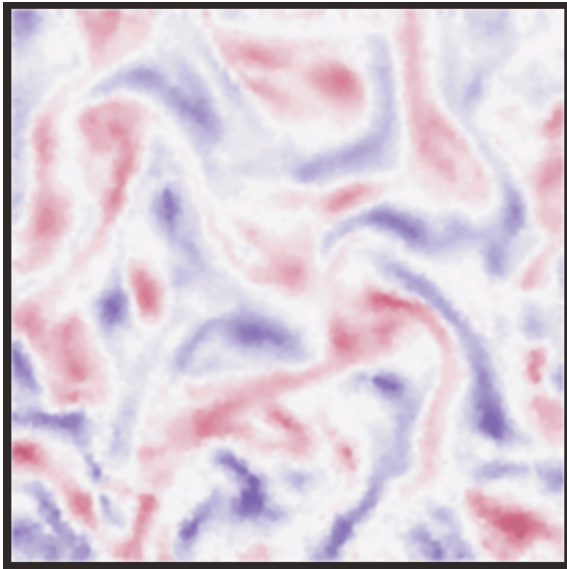


Fig. 3 Vorticity field in grid turbulence

In the soap channel experiments, the flow is so fast, about 1 m/sec, that one can only obtain a set of statistically independent velocity fields. For the stratified layer experiments, however, it is possible to track particles continuously with high spatial and temporal resolution. In Fig. 4, a velocity field composed of short particle tracks is shown. Tracks extending for hundreds of frames can also be obtained. This allows Lagrangian (moving with a fluid element) fluid quantities to be directly measured from experimental data, often for the first time.

Using the data obtained using PTV, we have shown² how structures in the flow are related to the scale-to-scale transfer of energy and enstrophy (the mean-square vorticity). We can measure such transfer directly using filter techniques^{2,3} similar to those

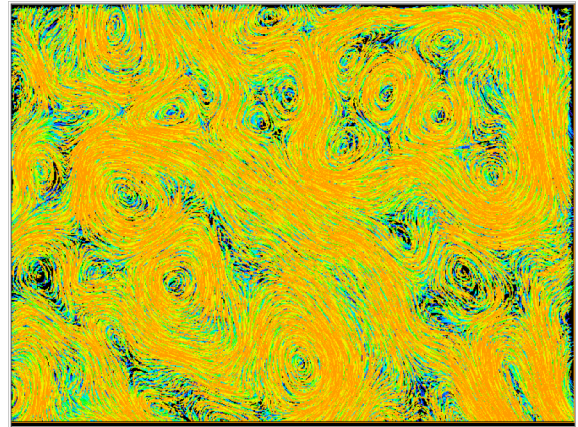


Fig. 4 Raw particle tracks over 4 consecutive frames.

used in large-eddy simulations. We have also performed numerical simulations⁴ that have both motivated our analysis methods and demonstrated consistency between the simulations and the experiments. These experiments are exploring new ground in turbulence by introducing new techniques for extracting inertial transfer quantities and by directly obtaining Lagrangian measures of turbulent motion. Such tools will be decisive in improving turbulence models of important processes such as the mixing of constituents in combustion, in the dispersal of atmospheric and oceanic pollutants, and in applications relevant to national security.

References

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