Lagrangian Dispersion and Heat Transport in Thermal Convective Turbulence

Authors: Joerg Schumacher
arXive:0803.1634v1 [physics.flu-dyn],
Phys. Rev. Lett., 100 (2008) 134502

Recommended with a commentary by Eberhard Bodenschatz, Max Planck Institute for Dynamics and Self-Organization, Goettingen

Fluid turbulence is generated whenever a fluid is driven sufficiently hard and is thus fundamental to most technological, geophysical and astrophysical flows. Due to those fundamental reasons and also the general quest for an understanding of this intermitted and multi-scale state, fluid turbulence has long been a topic of intense scientific inquiry in the statistical and nonlinear physics branch of condensed matter physics. Progress in the understanding of turbulent flows has been slow. To put it in the words of Richard Feynman, "With turbulence, it's not just a case of physical theory being able to handle only simple cases–we can't do any. We have no good fundamental theory at all." (Omni magazine interview, "The Smartest Man in the World", 1979; available in "The Pleasure of Finding Things Out"). Even now, almost 30 years later, most successful theories rely on models that are guided by the equations of fluid mechanics, but are not derived from first principles. Although much progress was made recently (see for example the reviews in *Annual Review of Fluid Mechanics*) many fundamental questions remain to be understood. Current turbulence research focuses on the following (and incomplete) list of topics:

- boundary layer flows, transition to turbulence and fully developed turbulence.
- turbulent convection and heat transport.
- mixing and dispersion in turbulent flows.
- turbulence statistical properties as a function of turbulence level.
- turbulence in multiphase flows and complex fluids.
- inertial and large particle dynamics in turbulent flows.
- turbulence in compressible flows.
- quantum turbulence.
- magnetohydrodynamic turbulence.

Recently it has become possible not only to study the spatial properties of a turbulent flow, but also the temporal properties. The latter Lagrangian properties are investigated by following the trajectories of fluid particles or tracers. Although high turbulence levels (large Reynolds numbers) in practical flows remain the domain of experiment, the so called Direct Numerical Simulations (DNS) have come long ways. DNS are now investigating sufficiently high turbulence levels under idealized conditions and are beginning to have a scaling range both in the spatial as well as the temporal properties. I have selected this manuscript for my commentary, as it addresses on short four pages some of the very fundamental properties of turbulence.

The paper is concerned with one particularly well investigated turbulent system: a fluid layer that is placed horizontally into the Earth's gravitational field and is confined between two parallel plates, which are heated from below and cooled from above. In this case the control parameters are the non-dimensional temperature difference, *i.e.*, the Rayleigh-number, and the Prandtl number that describes the timescales of thermal diffusion over viscous relaxation. The Prandtl number determines the relative importance of the nonlinear convective derivatives in the momentum and heat transport equations. The Prandtl number is ≈ 1 for gasses, in liquid metals it is much smaller (< 0.05) and for fluids like water or oils it is larger. In general, shear flow effects are more pronounced in fluids with Prandtl number 1 and smaller.

In order to render the problem simpler, it is common to study convection in the Boussinesq–regime, where the temperature difference is sufficiently small so that only the change of density with temperature needs to be taken into account. Thermal turbulent convection is different from other turbulent flows as it is driven by thermal plumes that are ejected from the boundary layers. The system is thus intrinsically anisotropic in respect to the horizontal and vertical coordinates.

This paper presents results from DNS (512x512x257) of a Prandtl number 1 fluid layer, where the vertical boundaries are free–slip and the horizontal boundaries are periodic. The free–slip boundaries are numerically fast, as they allow the use of Fourier-modes in all three directions . Experimentally, however, they are almost impossible to realize. As the paper is mainly concerned with the bulk properties of the thermally driven turbulence, it can be expected that the results carry over to experiments.

The manuscript compares results on the vertical flux of energy with recent experiments by the Lyon group (Gasteuil et al., PRL **99**, 234302,2007). In that experiment neutrally buoyant particles were tracked optically, while the particle was "smart" and tracked the local temperature.

The main results of the paper are

- measurements of the pair-disperion in thermal convection
- a study of the fluid particle acceleration
- the identification of the correlation of vertical flux (product of vertical velocity and temperature fluctuations) with thermal plumes.

Figure 4 in the paper shows that large values of the vertical flux are associated with the thermal plumes emitted from the boundaries. It also shows that the flow can be divided into five horizontal layers of different behavior - the boundary layers, the plume dominated region with larger fluctuation of vertical flux, and the bulk turbulent region with a slight increase in vertical flux towards the middle of the experiment.

Figure 2 shows the analysis of the dispersion of pairs of particles released at approximately two Kolmogorov distances (smallest dynamical scales of the flow). Three scaling regimes were observed that conform with expectations. The most interesting regime is the almost t^3 Richardson-type behavior. The crossover to Richardson type behavior sets in approximately at the Lagrangian de-correlation time of the vertical velocities and crosses over to a t behavior well past the Lagrangian de-correlation time of the horizontal velocities. The Figure also shows that the vertical and the horizontal behavior is quite different. Currently there is no theoretical prediction of these observations and it is unclear why Richardson scaling should be expected for this very anisotropic flow. One important question left for the future is, how the behavior depends on the initial separation. Richardson scaling requires independence of the initial separation. Another interesting question coming to mind is, whether the behavior depends on the location where the particles were released.

In Figure 3 the particle acceleration is shown and was found to be as intermittent as that of mechanically driven turbulence. It was, however, that the PDF is narrower for the vertical components of the acceleration when compared to the horizontal ones. It is interesting that the acceleration and the vertical flux are the most correlated for the largest, but also rarest fluctuations, corresponding most likely to strong thermal plumes.

In summary, this work together with the previous experimental study by the Lyon group opens a new perspective, namely the Lagrangian perspective, on the study of convective turbulence.