Dispersion of patterns written in turbulent air

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What in Fig. 1 looks like an unsuccessful capital letter H is a small (6 mm size) structure that was written in a turbulent air flow. The writing is done by fusing the O₂ and N₂ molecules of air into NO molecules in the focus of a strong UV laser beam. By crossing these beams several times, a letter H was made which has both small and large length scales. The NO molecules were made visible by making them fluoresce a while (30µs) later using a second UV laser [1].

Fig. 1 Pattern of NO molecules written in a strongly turbulent jet flow, made visible by laser-induced fluorescence, 30 µs after it was written. The thin line is a fit for finding the intersections. The horizontal extent of the figure is 6 mm, the Gaussian width of the lines is ¼ 100 µm.

Molecular tagging is a technique to create tracers at will in a turbulent flow by selective excitation of molecules or, in our case, by the creation of new molecular species. In contrast, the traditional seeding by particles suffers from the problem that in order to resolve the smallest scales and thus to find 2 particles close together, the seeding density must be prohibitively high.

In our experiments, strong turbulence (Rₐ ≈ 450) emanates from a jet (diameter 10 mm), with measurements done 0.4 m downstream where the turbulence is homogeneous and approximately isotropic.

The width (σ ≈ 100 µm) of the lines that make the pattern in Fig. 1 is a few times the Kolmogorov length (η = 17µm), so that the widening of the lines is a microscope on molecular mixing. The delay time between writing and reading varies from 0.1τₜ to 5τₜ, during which the lines widen both due to molecular diffusion and due to turbulence at these small (≈ 5η) scales. The turbulent spreading is exponential, σ (t) ≈ σ₀ exp(t / τᵣ), and we find a spreading rate γ = 0.26 ± 0.01. It is the first time that this small-scale Lyapunov exponent has been measured in turbulence.

Fig. 2 The increase of the root-mean-squared separation of the nodes of the H with time very accurately follows the Batchelor prediction (full line).

In the structure of Fig. 1 the distance ε between the crosses encompasses the inertial range (Δ/η ≈ 200). For the relatively short delay times between writing and reading, the increase of the separation is in the Batchelor regime

\[ \langle \Delta(t)^2 \rangle = \Delta(0)^2 + \frac{7}{3} C \epsilon^{2/3} \Delta(0)^{2/3} \tau^2, \]

with ε the dissipation rate, and C the Kolmogorov constant for the second order structure function. As Fig. 2 illustrates, the separation of the nodes of the letter H very accurately follows the Batchelor prediction. This is surprising because these nodes are extended clouds, and not mathematical points.

Although the flow is incompressible, written patterns are not, and turbulence causes clustering of the passive tracers (molecules) that make the written line. These concentration fluctuations are very intermittent, with scaling behavior that is very different from the self-similar Kolmogorov one.