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Do scalar fluctuations in turbulent shear flows possess local universality?

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Research note

Kolmogorov introduced the concept that small scales of motion in high-Reynolds-number turbulence are statistically homogeneous, isotropic and universal, and derived certain quantitative results. The original paper, about four pages long, has been enormously influential even in fields besides turbulence. There have been later modifications of the original ideas, some by Kolmogorov himself, but the broad expectation has always remained that some type of universality prevails at small scales. It is also believed that the same basic ideas can be extended to scalar fields advected by turbulence, and that the universal behavior of the small-scale velocity field would manifest "naturally" or "obviously" in the scalar field. The main purpose of the talk was to examine the degree to which local isotropy and universality apply to scalar fields.

Specifically, the problem considered was this: Consider a high-Reynolds-number turbulent flow in which the motion can be decomposed without ambiguity into a time average (or the "mean") and the superimposed turbulent fluctuation. The mean flow is taken to possess a strong spatial variation, or shear, in one direction; this is also the direction of inhomogeneity in the turbulence structure. Into such a flow inject a scalar – for simplicity, at a length scale comparable to that of the energy-containing motion of turbulence. A measure of this latter scale is the correlation, or "integral", length scale. We assume that the scalar is passive in that the turbulence dynamics is not influenced by its presence. Low levels of heating or small doses of a dye injected into the flow provide two examples. The scalar field established under such circumstances will have a mean field and a fluctuation field. The questions we sought to address were: At high Reynolds numbers, what are the scaling properties of the fluctuating scalar field at scales much smaller than the injection scale? Are there any properties of the scalar field which are universal, in the sense that they do not depend on details of the manner of injection of turbulent energy and of the scalar itself?

First, the following few brief remarks were made on the velocity field itself. While there is a reasonable collapse of spectra in the dissipative region, unblemished measurements at high enough wave-numbers do not exist, and so one cannot be definitive about universality even for second-order statistics. Local isotropy appears a doubtful proposition, at least in the inertial range and for most Reynolds numbers of practical interest. For high-order moments, the elegance of Kolmogorov's original ideas, which implied a single universal exponent, is definitely lost; instead, we are led to hypothesize an infinity of exponents for which there are no compelling theories. Even though the connection between the physics of vortex stretching and folding on the one hand and the mechanics of cascades on the other remains very vague, experiments permit the belief that the notion of cascades may usefully abstract the scale-invariant process presumed to occur in the inertial range.

As far as it concerns the scalar field advected by sheared turbulence, evidence on the following aspects was presented:

(a) The asymptotic state of the scalar field is reached very slowly in Reynolds numbers. For most Reynolds numbers, diffusive effects seem important even in the "inertial range". There is little credible proof that this asymptotic state is unique.

(b) If local isotropy seemed somewhat dubious for the velocity field, it seems even more so for the scalar field. Existing measurements suggest that local isotropy is not attained in the dissipation range, except perhaps at such extreme Reynolds numbers that are of no practical relevance on Earth.

(c) The small-scale scalar field has a tendency to form a well-defined "structure" in the real space, with its life-time comparable to the large-eddy turn-over time. Indeed, it is an integral part of the large structure itself (as in temperature ramps). Structures of disparate scales directly interact with each other without several intermediate steps.

(d) The predominant mechanism responsible for the elongated structures appears to be the mean or large eddy strain-rate over a large part of the volume occupied by the scalar, probably precluding detailed universality. The average description of the eddy breakdown – if the stretching and folding effect can be called that – is quite unlike the cascade picture usually visualized in Kolmogorov-type scenarios.

Given these, we then asked the following questions: Should we presume that the arguments rooted in Kolmogorov are basically sound and spend our efforts at "modifying" them? Or, should we discard the familiar ground altogether and look for alternatives more faithful to the observed structure? How can we account for structures in real space and model their interactions at different scales? How do we explain the respectable scaling observed at moderate Reynolds numbers? Why is the spectral exponent close to $\frac{5}{3}$ at high Reynolds numbers? What are the minimum conditions under which the $\frac{5}{3}$ law can be observed? What is the correspondence between the structure in the physical space and the scale in the wave-number space?

We argued that an effort at fully understanding these issues would be clearly well-spent. Each of the questions raised above was assessed briefly, and a preliminary model explicitly incorporating the observed structural features was presented.

The complete text of the talk is scheduled to appear in the special Kolmogorov issue of the Proc. R. Soc. London (1991).