Small-scale universality in the spectral structure of transitional pipe flows

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INTRODUCTION

Kolmogorovian turbulence at very large Reynolds numbers

Every turbulent flow looks different. Yet, many will look the same when placed under a magnifying glass; the statistics of the small scales are universal, irrespective of the particular flow. This is the key insight of Kolmogorov’s phenomenological theory of turbulence (1–3). The theory is built on Richardson’s imagery of an “energy cascade” (4): The energy progressively cascades from large scales to smaller scales to even smaller scales and so forth, until it is dissipated viscously at the smallest scales.

Kolmogorov crystallized this imagery into quantitative predictions (1–3). At each step of the cascade, the nonlinear interactions that mediate the scale-to-scale transfer of energy also cause a progressive loss of sensitivity to the large-scale attributes of the flow. The larger the Reynolds number, Re, the broader the separation between large and small scales and, consequently, the lesser the influence of the large scales on the distant small scales. Considering turbulent flows at “very large Re” (1) and in regions far from boundaries, Kolmogorov posited that whereas the large scales can be inhomogeneous, anisotropic, and unsteady, the statistics of small scales turn homogeneous, isotropic, and steady. Kolmogorov called this property of small scales “local isotropy” (1).

For this domain of small scales, Kolmogorov made the bold hypothesis—the “first similarity hypothesis”—that their statistics depend only on the kinematic viscosity, \( \nu \); the energy dissipation rate per unit mass, \( \epsilon \); and the wave number, \( k \). This hypothesis, in the domain \( k \gg L^{-1} \) (where \( L \) is a large scale, e.g., pipe diameter), leads to a universal function for the energy spectrum, \( E(k) \), which embodies the spectral structure of the velocity fluctuations; specifically

\[
E(k) \approx \frac{\nu^2}{\eta} F(\eta k)
\]

where \( \eta \equiv (\nu^3/\epsilon)^{1/4} \) is the viscous dissipation scale (also known as the Kolmogorov scale) and \( F(\eta k) \) is a universal function—a mathematical signature of small-scale universality (1). At this juncture, we also mention Kolmogorov’s “second similarity hypothesis,” according to which, in a subdomain of small-scale universality—the “inertial range,” \( L^{-1} \ll k \ll \eta^{-1} \)—\( E(k) \approx \epsilon^{2/3} k^{-5/3} \) [i.e., \( F(\eta k) \approx (\eta k)^{5/3} \)], the “5/3 law.” Notwithstanding its prestige, we emphasize that it is conformity to the universal \( F(\eta k) \) that signals small-scale universality, regardless of the specific functional form of \( F \). In discussing small-scale universality, we limit our attention to \( E(k) \), which is a second-order statistical measure, although Kolmogorov’s theory also extends to higher-order statistics.

To test Kolmogorov’s predictions, field observations, experiments, and simulations have naturally reached toward flows with ever larger Re (5–7). Furthermore, these studies have often sought to draw as close as possible to ideal conditions, meaning homogeneity, isotropy, and steadiness in the large scales as well. The evidence in all cases is overwhelmingly in favor of Kolmogorov’s predictions, and although there are well-known deviations (anomalous scaling) for higher-order statistics (8), his original framework remains the most lucid and empirically tested description of turbulence at very large Re.

Unexpectedly, recent studies have shown that Kolmogorov’s theory prevails even at moderate values of Re (9, 10). Evidently, the realm of Kolmogorovian turbulence is much broader than previously anticipated. In this study, we put the limits of this realm to an extreme test by considering flows that are far removed from any turbulent flow studied heretofore. They are relatively low Re, inhomogeneous (segmented along the flow direction and fully circumscribed by walls), and unsteady (the segmented regions change with time) transitional pipe flows (11).

Transition to turbulence in pipe flows

Pipe flows are linearly stable (12–14). But for finite-amplitude perturbations, the flow can remain laminar up to arbitrarily large Re (by definition, \( Re \equiv UD/\nu \), where \( U \) is the mean flow velocity and \( D \) is the pipe diameter). For \( Re \lesssim 1600 \), irrespective of the perturbations, the flow is laminar throughout the pipe. At higher Re, the existence of laminar flow is predicated on the perturbations being small. For perturbations of finite amplitude above a critical threshold [which decreases with increase in Re (12)], other flow states become manifest. At the onset of transition, laminar flow becomes axially inhomogeneous, with plugs of laminar flow alternating with “flashes” of eddying flow (11–13). Flashes come in two states. For \( 1600 \lesssim Re \lesssim 2250 \), flashes take the form of arrowhead-shaped, discrete lumps...
flow states are triggered. For slugs (at $Re < 2700$), the flow state depends on whether the finite-amplitude perturbation is applied briefly or continuously. For the former, slugs persist; for the latter, the flow turns to fully developed turbulence throughout the pipe. In Fig. 1, we illustrate this sequence of flow states.

**Study**

We focus on flash flow or flow inside flashes. For reference, we note that even for fully turbulent pipe flows, small-scale universality appears to have been tested (and found to hold) only for $Re ≥ 24,000$ (15); whether small-scale universality holds for $Re < 24,000$ is not known. Now, flashes span values of $Re$ that are an order of magnitude lower. They appear, on the basis of their macroscopic features, qualitative as well as quantitative, clearly distinct from turbulence (16, 17). Above, we have discussed a few qualitative features, e.g., the arrowhead shape of puffs. Complementing the distinctions highlighted by the qualitative features, quantitative features draw attention to the role of $Re$. For example, the lifetime statistics for puffs splitting and the lifetime statistics for puffs fading away markedly change depending on whether the $Re$ is above or below a critical $Re$ (12, 14); the speeds of the front and back interfaces of the expanding slugs vary systematically with $Re$ (16, 18). To wit, given the low $Re$ and marked differences with turbulent flows, a priori, it appears unlikely that flash flows could partake in the signature universality of Kolmogorovian turbulence.

We examine flash flows with a combination of experiments and direct numerical simulations (DNS). For the experiments, we use a 20-m-long, smooth, cylindrical glass pipe of $D = 2.5 \text{ cm} ± 10 \mu \text{m}$ with water as the working fluid. For the DNS, we use the open-source, hybrid-spectral code Openpipeflow (19). Details about the experiments and DNS can be found in (20).

We first focus on the flow along the centerline of the pipe (we consider off-centerline flow later). For the experiments, we measure a time series of the axial velocity and radial velocity, $u(t)$ and $v(t)$, respectively, where $t$ is time, using a laser Doppler velocimeter (LDV) (see Materials and Methods). We invoke Taylor’s frozen turbulence hypothesis to transform the velocity time series to the velocity spatial series (see the Supplementary Materials). (For flash flows, it is not obvious a priori that Taylor’s hypothesis is valid. We discuss this issue in detail in the Supplementary Materials; here, it suffices to note that Taylor’s hypothesis holds for flash flows.) For the DNS, we directly obtain the velocity spatial series. Note that for transitional flows, the velocity series from experiments and DNS include flashes and laminar plugs. We disentangle the flashes using an indicator function (see Fig. 2). Having identified the regions of flash flow, we are ready to proceed.

**RESULTS**

**Local isotropy**

In accord with the sequence of arguments in Kolmogorov’s analysis (1), before considering small-scale universality, we first test for local isotropy. To that end, we study a scale-by-scale measure of isotropy: $E_{ix}(k)$, the cospectrum of $u$ and $v$ (21), whose dimensionless form, known as the spectral coherency (22), is defined as $H_{ix}(k) ≡ |E_{ix}(k)|^2 / (E_{ix}(k)E_{xy}(k))$, where $E_{ix}(k)$ and $E_{xy}(k)$ are the (one-dimensional) energy spectra of the axial and radial components, respectively, and $k$ is the

![Fig. 1. A schematic “state diagram” for pipe flows. The abscissa is Re, and the ordinate is a qualitative measure of the perturbation. For laminar flow, puffs, and slugs (at Re ≤ 2700), the measure of the perturbation is primarily its amplitude. When the amplitude is below a critical value (which decreases with increase in Re), the flow stays laminar; when the amplitude exceeds this critical value, the other flow states are triggered. For slugs (at Re ≥ 2700) and turbulence, the measure of the perturbation, in addition to its amplitude exceeding the critical value, is whether the perturbation is applied briefly (which yields slugs) or continuously (which yields turbulence). Corresponding to each flow state, we show representative experimental time series of the axial velocity at the pipe centerline.

![Fig. 2. An illustrative example of identifying slugs using LDV data. To identify the regions of slug flow (or, in general, flash flow), we define an indicator function $I(x)$, where $x$ is the axial distance, using squared off-axis velocity components (see the Supplementary Materials). Because the magnitude of the off-axis velocities are small for laminar plugs but substantial for flashes, the flashes can be robustly identified by putting a threshold on $I(x)$. In the example here, we show simultaneous spatial series of the axial velocity, $u(x)$, and the indicator function, $I(x)$. The slugs correspond to $I(x) ≥ 6$ (marked by gray bars), where the threshold $δ$ (dashed line) is set as 3 SDs above the mean laminar value of $I(x)$ (20, 27).
axial wave number. (We compute the energy spectra and the co-
spectrum using the velocity spatial series attendant to flash flows
and turbulent flows; see the Supplementary Materials.) This measure
is built on the idea that for the scales where the velocity components
become statistically independent, there is no preferred direction in
the attendant flow. In choosing this measure, we follow the well-
known exposition on local isotropy by Saddoughi and Veeravalli (22),
who concluded that $E_{\varepsilon\varepsilon}(k)$ is “the most sensitive indicator of local
isotropy.” Specifically, $H_{\varepsilon\varepsilon}(k) \ll 1$ at large $k$ signals local isotropy.

In Fig. 3A, we show $|E_{\varepsilon\varepsilon}(k)|$, along with the corresponding $E_{\varepsilon\varepsilon}(k)$ and
$E_{\varepsilon\varepsilon}(k)$, for a representative puff flow, slug flow, and turbulent
flow. In Fig. 3B, we show the corresponding $H_{\varepsilon\varepsilon}(k)$. For all flows,
across the whole domain of $k$, $|E_{\varepsilon\varepsilon}(k)|$ assumes values an order of
magnitude lower than the corresponding $E_{\varepsilon\varepsilon}(k)$ and $E_{\varepsilon\varepsilon}(k)$. This
comparison is rendered quantitative by $H_{\varepsilon\varepsilon}(k); \forall k$. We find that $H_{\varepsilon\varepsilon}(k) \ll 1$
for all $k$. At the pipe centerline, the flows not only are in good accord
with local isotropy but also manifest isotropy at the large scales.

**Small-scale universality**

Having verified local isotropy, we test for small-scale universality, as
embodied by Eq. 1. In Fig. 4A, we show $E(k)$ for several representative
puff flows, slug flows, and turbulent flows from our experiments and
DNS, along with a few high-Re $E(k)$ from the Princeton superpipe
experiment (15, 23). [In our analysis of $E(k)$, we restrict our attention
to $E_{\varepsilon\varepsilon}(k)$. Focusing on this most commonly studied component
of the energy spectrum allows us to compare our results with those
from other studies at very large Re. Hereafter, we refer to $E_{\varepsilon\varepsilon}(k)$ simply as $E(k).$] Each $E(k)$ is a distinct curve whose shape depends
on the particular flow realization (specifically, on the values of
$D$ and $v$). Spanning a range of Re, from $1600$ to $512,000$, these spectra
differ widely and betray no sign of universality. In Fig. 4B, we rescale
$E(k)$ simply as $k^3$. This measure of the energy spectrum allows us to compare our results with those
from other studies at very large Re. Hereafter, we refer to $E_{\varepsilon\varepsilon}(k)$ simply as $E(k).$ Each $E(k)$ is a distinct curve whose shape depends
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from other studies at very large Re.

Note that unlike the 5/3 law, Eqs. 1 and 2 are not predicated on
having a broad inertial range, which necessitates a small ratio $\varepsilon/\eta$, which, in turn, necessitates a particularly large value of $\eta$ (see Eq. 2). For pipe flows, the 5/3 law becomes clearly apparent (23) only for $Re > 80,000$, well above the values of $Re$ at which flashes have been observed. By contrast, Eqs. 1 and 2 can hold, in principle, at the values of $Re$ of our experiments (note, however, that whereas the 5/3 law can be tested by using a single flow realization at very large

**Fig. 3. Testing local isotropy for centerline flow.** (A) Plots of $|E_{\varepsilon\varepsilon}(k)|U^2/D$ versus $kD$ (dotted lines), $E_{\varepsilon\varepsilon}(k)U^2/D$ versus $kD$ (solid lines), and $E_{\varepsilon\varepsilon}(k)U^2/D$ vs. $kD$ (dashed lines) for a representative puff flow, slug flow, and turbulent flow from our DNS. Note the ordinate axis: for ease of comparison, we show the set of spectra plots for each flow separately. (B) Plots of $H_{\varepsilon\varepsilon}(k)$ versus $kD$ (dashed lines) corresponding to the flows in (A). For reference, we replot the $E_{\varepsilon\varepsilon}(k)$ (solid lines). Note that $H_{\varepsilon\varepsilon}(k) \ll 1$ for all $k$. 

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Fig. 4. Testing small-scale universality (Eq. 1) for centerline flow. (A) Plots of spectra, $E(k)$ versus $k$, for several representative puff flows, slug flows, and turbulent flows from our experiments and DNS; we also show a few high-Re turbulent flows from the superpipe experiment (15, 23). (B) Plots of rescaled spectra, $\eta E(k)/\nu^2$ versus $\eta k$, corresponding to the flows in (A). Irrespective of the type of flow, the rescaled spectra at high $\eta k$ collapse onto $F(\eta k)$, in good keeping with small-scale universality (Eq. 1) [we take the $\eta k \gtrsim 10^2$ region of the rescaled spectrum from superpipe flow at $Re = 512,000$ as a proxy for $F(\eta k)$]. At $Re \gtrsim 80,000$, the rescaled spectra conform not only to small-scale universality but also to the 5/3 law. Inset: The scaling of data points ($\eta k^*$, $Re$) is also in accord with the Kolmogorovian framework. We compute $k^*$ by putting a threshold on the deviation of the rescaled spectra from $F(\eta k)$. The dashed line—the least-squares fit to the prediction $\eta k^* = 34.7Re^{-3/4}$—represents $\eta k^* = 34.7Re^{-3/4}$, which, from the fit of Fig. 5, yields $k^* = 5D^{-1}$. 

Fig. 5. Scaling of the Kolmogorov scale. Data points ($\eta D$, $Re$) for centerline flow. The data are in good keeping with Eq. 2, irrespective of the type of flow. The dashed line—the least-squares fit to Eq. 2—represents $\eta D = 6.88Re^{-3/4}$. The ratio $\eta D$ is a measure of the separation between the large and small scales; the separation broadens with an increase in $Re$. Note that even for puff flow at $Re = 1600$, $\eta D = 0.027 \ll 1$, signaling a broad separation of scales.

Re, a test of Eqs. 1 and 2 requires many flow realizations that span a broad range of $Re$). In the previous section, we showed that Eq. 1 holds for our experiments; next, we turn to testing Eq. 2.

In Fig. 5, we test Eq. 2 using data points corresponding to puff flows, slug flows, and turbulent flows from all our experiments and DNS, along with several data points corresponding to high-$Re$ turbulent flows from the Princeton superpipe experiment (15, 23). Irrespective of the type of flow or the value of Re (which spans about two decades), the data points conform to the Kolmogorovian scaling of Eq. 2 [in all cases that we studied, the Taylor microscale Reynolds number $Re_{\lambda} \gtrsim 60$, for which we find that Eq. 2 holds, in accord with previous studies that find the dissipation anomaly requires $Re_{\lambda} \gtrsim 20$ to 50 (9, 25)]. Returning to $\eta k^*$, using Eq. 2, we predict that $\eta k^* \propto \eta D \propto Re^{-3/4}$. In the inset of Fig. 4B, we verify this prediction.

Off-centerline flow

Thus far, we have restricted our attention to the flow along the pipe centerline. While our finding that flash flows conform to the Kolmogorovian framework, even if this holds only at the centerline, is unexpected, it is natural to ask whether this framework also extends away from the centerline. Two challenges become immediately apparent. First, the pipe geometry makes the flow progressively more inhomogeneous as the wall is approached. Second, whereas the mean shear at the centerline is zero, it monotonically increases away from the centerline, and because mean shear engenders anisotropy, the increased mean shear makes the flow progressively more anisotropic as the wall is approached. Consequently, whether off-centerline flash flow, or even turbulent flow, will exhibit local isotropy and small-scale universality is unclear. We now turn our attention to these considerations. (Because our experimental measurements are restricted to the centerline, here, we use only our DNS data.)

To test for local isotropy, in Fig. 6A, we show $H_{\eta\sigma}(k)$ for a representative puff flow, slug flow, and turbulent flow at three wall-normal positions, $y$, that span $0.05 \leq y/D \leq 0.5$. In each flow and for all the positions, $H_{\eta\sigma}(k) \ll 1$ at high $\eta k$, signaling local isotropy. By contrast, at low $\eta k$, for positions away from the centerline, $H_{\eta\sigma}(k) \ll 1$ no longer holds, signaling that the large scales are anisotropic.

Having verified local isotropy, we test for small-scale universality (Eq. 1). In Fig. 6B, we show the rescaled spectra, $\eta E(k)/\nu^2$ versus $\eta k$, for several representative puff flows, slug flows, and turbulent flows, spanning the wall-normal positions $0.05 \leq y/D \leq 0.5$. For all flows, regardless of the type and the value of $Re$, and over the whole span of positions, the rescaled spectra at high $\eta k$ collapse onto the same
universal function $F(\eta k)$ as we noted in Fig. 4B. The framework of small-scale universality truly has a broad purchase (for additional discussion, see the Supplementary Materials).

**DISCUSSION**

In summary, we have shown that the spectral structure of the small-scale fluctuations in flash flows, like those in conventional turbulent flows, is governed by Kolmogorov’s phenomenological theory of turbulence, with the implication that flash flows, aside from being restricted to relatively low Re, are statistically indistinguishable from conventional turbulent flows. This finding harks back to the early studies on transitional flows and fully turbulent flows, which treated them as part of the same tapestry before later developments sundered them into divergent fields (26). Our findings notably broaden the scope of Kolmogorovian turbulence, extending its realm much beyond the restricted domain of idealized flows at very large Re, suggesting that the theory may truly be universal.

Our findings also provide a critical missing piece of empirical evidence in support of recent studies that seek the universality class of transitional pipe flows. In a number of experimental and computational studies (27–29) published in 2016, compelling evidence has been adduced in support of a 30-year-old conjecture by Pomeau (30) to the effect that the subcritical transition in pipe flows and other shear flows belongs to the directed-percolation universality class of nonequilibrium phase transitions. Yet, in a comment on those studies (31), Pomeau cautioned that “the arrowhead patterns observed in early experiments on boundary layers are sufficiently regular to denote a bifurcation to a turbulence-free state.” (Recall that puffs, too, are shaped like arrowheads.) That is to say, if flashes were nonturbulent, then they could hardly be the agents of a transition to turbulence, and the experimental and computational evidence of directed percolation would be severed from the turbulent regime. Our findings show that flash flow is but turbulent flow; thus, flashes endow the transitional regime with the requisite link to turbulence.

We submit that the tools of high-Re turbulence can be brought to bear upon flashes and that new insights into the transition to turbulence may be gained by approaching the transition from above, from higher to lower Re, complementing the usual approach from below. For example, invoking the spectral link (32, 33) and using Eq. 2, we can predict that the fluid friction corresponding to the flashes obeys the Blasius scaling, as indeed has been recently verified using experiments and simulations (20). With elegant simplicity, Kolmogorov’s phenomenal insight, from 1941, into the mechanics of complex turbulent flows at very large Re continues to also illuminate problems far removed from its original scope.

**MATERIALS AND METHODS**

**Velocity measurements**

We used an LDV (Dantec FiberFlow) to measure the time series $u(t)$ and $v(t)$. The LDV was stationed at a distance of 465D (1162.5 cm) from the entrance of the pipe [see the Supplementary Materials in (20) for details of the experimental setup]. At this location, the pipe was housed inside a rectangular acrylic encasement filled with water; this was to reduce optical distortion (see fig. S1) [this design is similar to that used in (34)]. Despite the optical encasement, there was still a small correction to $v(t)$, which, via ray tracing (35), we estimated to be $v_{\text{real}}(t) \approx 1.026 v_{\text{measured}}(t)$. To conduct LDV measurements, we seeded the water in the pipe with 10-μm-diameter, silver-coated, density-matched particles. The typical data rate was >300 Hz, and the typical length of a time series was ≈1000 s.

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/4/eaaw6256/DC1

Supplementary Text

Fig. S1. Velocity measurements.

Fig. S2. Test of Taylor’s hypothesis.

Fig. S3. Effect of the choice of the value of $\delta$ on the value of $\eta$.

Fig. S4. Effect of detrending in puff flows.
Fig. S5. Ratio tests for isotropy.
Fig. S6. Testing the validity of the isotropic formula in computing $\eta$ for centerline flow.
Fig. S7. Dissipation spectrum.
Fig. S8. $\eta/D$ versus Re.
Fig. S9. Effect of mean shear on small scales.

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