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EXPERIMENTAL EVIDENCE OF A PHASE TRANSITION IN A TURBULENT SWIRLING FLOW

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Phase transitions are ubiquitous in physical systems and generally are associated to symmetry breakings. Symmetry breaking also governs transition to turbulence, that usually proceeds, as the Reynolds number Re increases, through a sequence of bifurcations breaking successively the various symmetries of the flow [1]. Finally, at large Re, it is commonly admitted that all the broken symmetries are restored in a statistical sense. However, recent studies have disturbed this vision raising intriguing features such as finite lifetime turbulence [3] and possible existence of turbulent transitions [4, 5, 6]. Consequently, despite turbulent flows are intrinsically out-of-equilibrium, one may wonder whether the observed transitions can be interpreted in terms of phase transitions. In this work [7], we introduce a susceptibility to symmetry breaking in a von Kármán turbulent flow and investigate its evolution as Re increases from 150 to 10^6 using stereoscopic Particle Image Velocimetry (SPIV). We observe a divergence of susceptibility at a critical Reynolds number $Re = Re_\chi \simeq 90\,000$ which sets the threshold for a turbulent "phase transition". Moreover, this divergence is associated with a peak in the amplitude of the fluctuations of the flow instantaneous symmetry.

Our experimental setup consists of a Plexiglas cylinder filled up with water-glycerol mixtures. The fluid is mechanically stirred by a pair of coaxial impellers rotating in opposite directions (Fig. 1(a)). SPIV measurements provide time series of the 3 velocity components in a meridian plane. Denoting the impellers rotation frequencies f_1 and f_2, the control parameters are the Reynolds number $Re = \pi(f_1 + f_2)R^2/\nu$, where ν is the fluid viscosity, and the rotation number $\theta = (f_1 - f_2)/(f_1 + f_2)$, which controls the asymmetry of the forcing conditions.

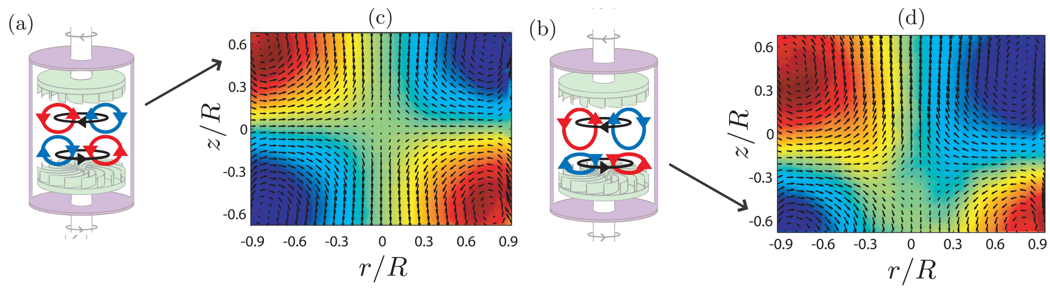

Figure 1: (a) and (b) Flow topologies and (c) and (d) corresponding experimental maps of mean velocity field at $Re = 800\,000$ for (c) $\theta = 0$ ($\overline{I} = 0$) and (d) $\theta = -0.0147$ ($\overline{I} < 0$). The color maps the azimuthal velocity u_φ whereas the arrows map the (u_r, u_z) field.

When $\theta = 0$, the experimental system is symmetric with respect to any $\mathcal{R}_\pi$-rotation exchanging the two impellers (Figs. 1(a) and (c)): the problem conditions are invariant under π-rotation around any radial axis passing through the center of the cylinder. When $\theta \neq 0$, the experimental system is no more $\mathcal{R}_\pi$-symmetric, the parameter θ measuring of the distance to the exact $\mathcal{R}_\pi$-symmetry. Depending on θ, the flow can respond by displaying different symmetries (Fig. 1): (i) the exact $\mathcal{R}_\pi$-symmetric flow composed of two toric recirculation cells separated by an azimuthal shear layer located at the equator, when $\theta = 0$; (ii) an asymmetric two-cells flow, the shear layer being closer to the slowest impeller, when $\theta \neq 0$. In order to quantify the distance of the flow to the $\mathcal{R}_\pi$-symmetry, we use the normalized and space-averaged angular momentum $I(Re, \theta, t)$ as order parameter: $I(t) = \frac{1}{\mathcal{V}} \int_\mathcal{V} r dr d\varphi dz \, \frac{r u_\varphi(t)}{\pi \, R^2 \, (f_1 + f_2)}$ where $\mathcal{V}$ is the volume of the flow. An example of time variation of $I(t)$ at $\theta = 0$ in the turbulent regime is provided in Fig. 2(Left). Then, using this ensemble averaged order parameter, we define a susceptibility of the flow to symmetry breaking as: $\chi_I = \partial\overline{I}/\partial\theta|_{\theta=0}$.

In the laminar case, when $\theta = 0$, $\overline{I} = 0$ due to the symmetry of the flow. In contrast, as θ drifts away from 0, the value of the angular momentum $\overline{I}$ becomes more and more remote from zero as the asymmetry of the flow grows. The symmetry parameter $\overline{I} = I(t)$ evolves linearly with θ (Fig. 2(c)) and the susceptibility is $\chi_I \simeq 0.24$. Increasing the Reynolds number, one expects to reach fully developed turbulence around $Re = 10\,000$. Therefore, even when $\theta = 0$, the $\mathcal{R}_\pi$-symmetry is of course broken for the instantaneous flow. However, as usually observed for classical turbulence, this symmetry is restored for the time-averaged flow. Then, as in the case of the laminar flow, when θ is varied, we observe the breaking of the $\mathcal{R}_\pi$-symmetry of the mean flow. In Fig. 2(c), we see that, at $Re = 800\,000$, in the close vicinity of $\theta = 0$, $\overline{I}(\theta)$ evolves actually much more rapidly with θ than in the laminar case. Therefore, turbulence seems to enhance dramatically the sensitivity of the flow to symmetry breaking. In Fig. 2(a), we see that the susceptibility actually grows by more than two orders of magnitude between $Re = 150$ and $Re \simeq 90\,000$, before decreasing by a factor 4 between

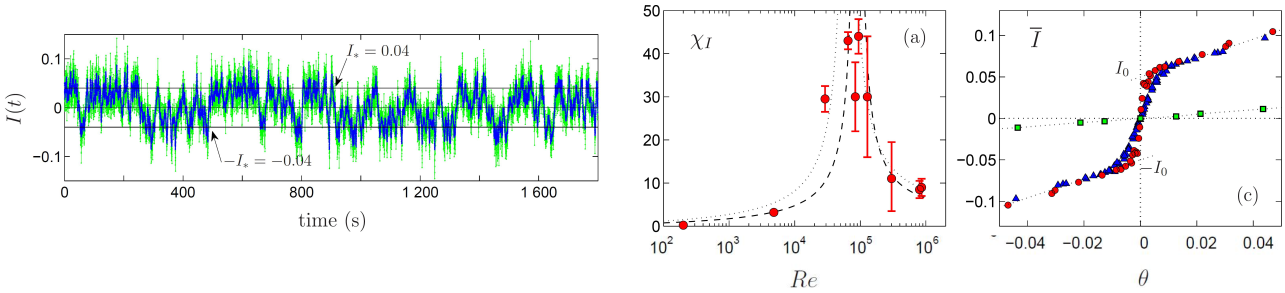

Figure 2: Left: Angular momentum $I(t)$ as a function of time for $Re = 43\,000$ and $\theta = 0$. Green dots are PIV data sampled at 15 Hz and blue dots correspond to 1 Hz low-pass filtered data. Eye-guiding lines have been drawn at $I(t) = \pm I_* = \pm 0.04$. Right (a): Susceptibility χ_I as a function of Re at $\theta = 0$; (c) angular momentum $\overline{I}$ as a function of θ for $Re = 150$ (green □), $Re = 65\,000$ (red ∘) and $Re = 800\,000$ (blue △).

$Re \simeq 90\,000$ and $Re = 800\,000$. These results suggest a critical divergence for $\chi_I(Re)$ near $Re = Re_\chi \simeq 90\,000$.

For higher $|\theta|$, we observe a crossover in the curve $\overline{I}(\theta)$ very close to $\theta = 0$, at $|\theta_r| \simeq 0.9\,10^{-3}$, for $Re = 65\,000$ (Fig. 2(c)). For $|\theta| > |\theta_r|$, we recover the laminar slow evolution of $\overline{I}$ with θ which is quite independent of Re at large Re, so that we can extrapolate this linear behaviour to $\theta = 0$. This extrapolation describes the ideal behaviour at critical $Re = Re_\chi$ if χ_I diverges: a jump of $\overline{I}$ between $-I_0$ and $+I_0$ where $I_0 \simeq 0.05$. This can be interpreted as a spontaneous "turbulent momentization" I_0 at $\theta = 0$ by analogy with the spontaneous magnetization M_0 at zero external field for ferromagnetism in the usual para-ferromagnetic transition.

A signature of this momentization can be seen on the instantaneous angular momentum $I(t)$ for Re near the peak of susceptibility and $\theta = 0$ (Fig. 2Left). Indeed, one observes that $I(t)$ does not remain near zero (its mean value) but shows a tendency to lock preferentially on the plateaus $\pm I_*$ with $I_* \simeq I_0$. The global angular momentum actually fluctuates very much along time with two separate time scales: fast fluctuations related to "traditional" small scale turbulence and time intermittencies corresponding to residence time of few tens of seconds. If one performs a time average over one of these intermittent periods only, one obtains a time localized "mean" flow, which breaks spontaneously the symmetry, analogous to what is obtained for true mean flows when $\theta \neq 0$. The previous experimental results set a strong connection between the spontaneous symmetry fluctuations of the flow near the peak of susceptibility and the mean flow response to the system symmetry breaking: the interpretation of the large fluctuations of $I(t)$ in terms of multistability suggests that the strong observed linear response of the mean flow (Fig. 2(c)) with respect to θ in the close vicinity of $\theta = 0$ is the result of a temporal mixing between the metastable states in different proportions.

Despite bifurcations with symmetry breaking are commonly found in natural turbulent flows, the corresponding theoretical tools are still today not well settled. Existing studies of phase transitions in the presence of fluctuations generally considers systems in which an external noise is introduced [8] and not intrinsically fluctuating systems. Our turbulent system, in which we access both to the spatiotemporal evolution of the states and the mean thermodynamic variables, appears as a a unique tool to study out-of-equilibrium phase transitions in strongly fluctuating systems.

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