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EXPERIMENTAL EXPLORATION OF QUASI-2D TURBULENCE CLAMPED BY BOUNDARY LAYERS

Duda D.[1], Yanovych V.[2], Klimko M.[3], Mrázová A.[4], Uruba V.[5], Tomášková T.[6]

Abstract: *Many flows in nature and technical applications are quasi-two-dimensional. This means that one dimension is significantly shorter than the other two. Examples include atmospheric and oceanic circulation, flow between the fins of a cooler, and protoplanetary discs. The two-dimensionality leads to an inverse energy cascade, pumping energy from small scales towards larger ones. This effect, predicted by Kraichnan, leads to the formation of a large-scale energy condensate.*
We performed a simple experimental study of decaying grid turbulence clamped by boundary layers. We observed that the large-scale condensate appears when the layer thickness is comparable to the mesh parameter of the grid. In contrast to an ideal inviscid case, the condensate weakens with thinner layers. We explain this as the effect of boundary layers, which dissipate energy at large scales and, on the other hand, pump small-scale structures (e.g., hairpin vortices) into the main flow.

Keywords: Turbulent flows, Turbulent transitions, Quasi-two-dimensional turbulence, Large-scale condensate, Particle Image Velocimetry

1. Introduction

Turbulent flows are involved in many natural and technical applications we encounter every day. Many of these flows are quasi-two-dimensional (Alexakis, 2023), meaning that one dimension is significantly smaller than the other two. More specifically, this third dimension is smaller than the characteristic size of the turbulent structures of the flow. Examples include flow between densely packed fins of a passive cooler, oceanic (Callies and Ferrari, 2013) and atmospheric (Izakov, 2013) circulation, and planet formation in protoplanetary disks (Brož et al., 2021). Each of these categories contains its own specific effects (e.g., Coriolis force in planetary flows, Lorentz force in plasma, boundary layers in solid walls), which make them unique. However, a common issue is the two-dimensionality of large-scale flow leading to an inverse energy cascade (Kraichnan, 1967) and the formation of a turbulence condensate (van Kan et al., 2019; Alexakis and Biferale, 2018; Alexakis, 2023).

Vortices in 2D flow have less possibilities of interaction with each other – in fact, they can only orbit or merge. On the other hand, the 3D turbulence offers much more possibilities, the vortices are stretched by the turbulent velocity field and they can change their topology via reconnections.

In 3D, rich vortex interactions lead to prevailing energy transport from larger scales to smaller ones (note that the opposite is not prohibited, just less probable), while in 2D, the energy is predominantly transported

[1] Assoc. Prof. RNDr. Daniel Duda, Ph.D.: Faculty of Mechanical Engineering, University of West Bohemia in Pilsen, Street Univerzitní 22; 306 14, Pilsen; CZ, dudad@fst.zcu.cz
[2] Assoc. Prof. Vitalii Petrovych Yanovych, DrSc.: Faculty of Mechanical Engineering, University of West Bohemia in Pilsen, Street Univerzitní 22; 306 14, Pilsen; CZ, yanovych@fst.zcu.cz
[3] Ing. Marek Klimko, PhD.: Faculty of Mechanical Engineering, University of West Bohemia in Pilsen, Street Univerzitní 22; 306 14, Pilsen; CZ, klimko@fst.zcu.cz
[4] Bc. Anna Mrázová: Faculty of Mechanical Engineering, University of West Bohemia in Pilsen, Street Univerzitní 22; 306 14, Pilsen; CZ, mrazovaa@students.zcu.cz
[5] Prof. Ing. Václav Uruba, CSc.: Institute of Thermomechanics, Czech Academy of Sciences, Street Dolejškova 15, 180 00, Prague; CZ, uruba@fst.zcu.cz
[6] Ing. Tetjana Tomášková, Ph.D.: Faculty of Electrical Engineering, University of West Bohemia in Pilsen, Street Street Univerzitní 26; 301 00, Pilsen; CZ, tomaskot@fel.zcu.cz

towards larger scales. This inverse energy flux leads to the formation of a large-scale *condensate* (Müller et al., 2020), which has been observed experimentally in superfluid helium by Varga et al. (2020). Well-known atmospheric features like zonal flows or hurricane formation can be explained in this way, see Boffetta (2023). The physical phenomena occurring in thin layer turbulence are studied mainly numerically or theoretically (Celani et al., 2010), because there are not many such systems that are pure enough and accessible to experimental investigations.

Numerical simulations (Celani et al., 2010; Benavides and Alexakis, 2017; Müller et al., 2020) suggest that there exists a transition regime between a purely inverse energy cascade (typical for 2D turbulence) and the forward (or direct) energy cascade in dependence on the dimensionless aspect ratio $Q = \ell_f/H$ (ℓ_f is the length-scale of forcing, H is height of the layer). In this regime, a bidirectional cascade appears, bounded by two critical values of Q, denoted Q_{2D} and Q_{3D}.

2. Wind tunnel measurement

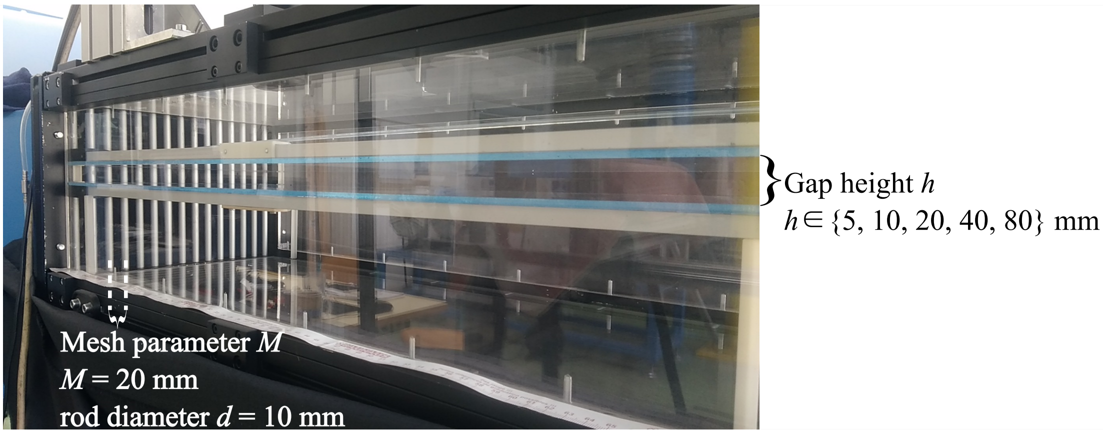

Fig. 1: Photograph of the wind tunnel at the University of West Bohemia in Pilsen. In this experiment, the decaying turbulence past a grid of cylindrical parallel rods of diameter $\mathrm{d} = 10\,\mathrm{mm}$ *is limited by using pair of transparent polypropylene plates. The aspect ratio Q is calculated by using mesh parameter* M *and the gap height* h *as* $Q = M/h$*, where* $M = 20\,\mathrm{mm}$ *is fixed, while the gap height changes among the discussed cases. The observed area lies* $235\,\mathrm{mm}$*, i.e.* $11.75M$ *past the grid (smaller FoV starts at* $279\,\mathrm{mm}$*). Velocity between plates is* $4.0 \pm 0.1\,\mathrm{m/s}$*, the uncertainty is caused by indirect wind tunnel power control.*

The amazing results of Benavides and Alexakis (2017) inspired us to perform an experiment in order to determine whether those fascinating quasi-2D features are limited to ideal case without boundary layers, or if they can be reproduced even in the "dirty" conditions of real life with boundary layers and the forcing limited to a simple passive grid upstream. From a practical point of view, this experimental setup is closer to the case of flow between cooler fins than to cases of planetary flows or rotating plasma discs.

The experiment was performed at the wind tunnel of the University of West Bohemia in Pilsen (Yanovych et al., 2019). The flow was turbulized using a grid made of regularly spaced rods perpendicular to the main area (i.e., the axes are parallel to the shortened dimension), see Fig. 1. The flow velocity was measured using the Particle Image Velocimetry (PIV) technique without temporal resolution. To increase the range of spatial resolution, we observed the same plane using two cameras from the top and bottom of the wind tunnel at different distances (thus with different resolutions, see Fig. 2b).

Figure 2b displays the in-plane vorticity. This vorticity is calculated using a central-second-order differentiation scheme, which already includes some smoothing over the neighbouring grid cells. Therefore, the length scale probed by this differentially calculated vorticity changes with the changing size of the Field of View (FoV). Arrows represent the velocity deviations from the local field-averaged value, as discussed by Duda and Uruba (2019).

At first glance at Fig. 2, the instantaneous structures do not offer direct insight into the changing nature of turbulent structures. However, a more detailed look at the $Q = 4$ case shows that there are three large-scale vortices apparent in the larger field of view (FoV), while the smaller FoV displays random droplets of

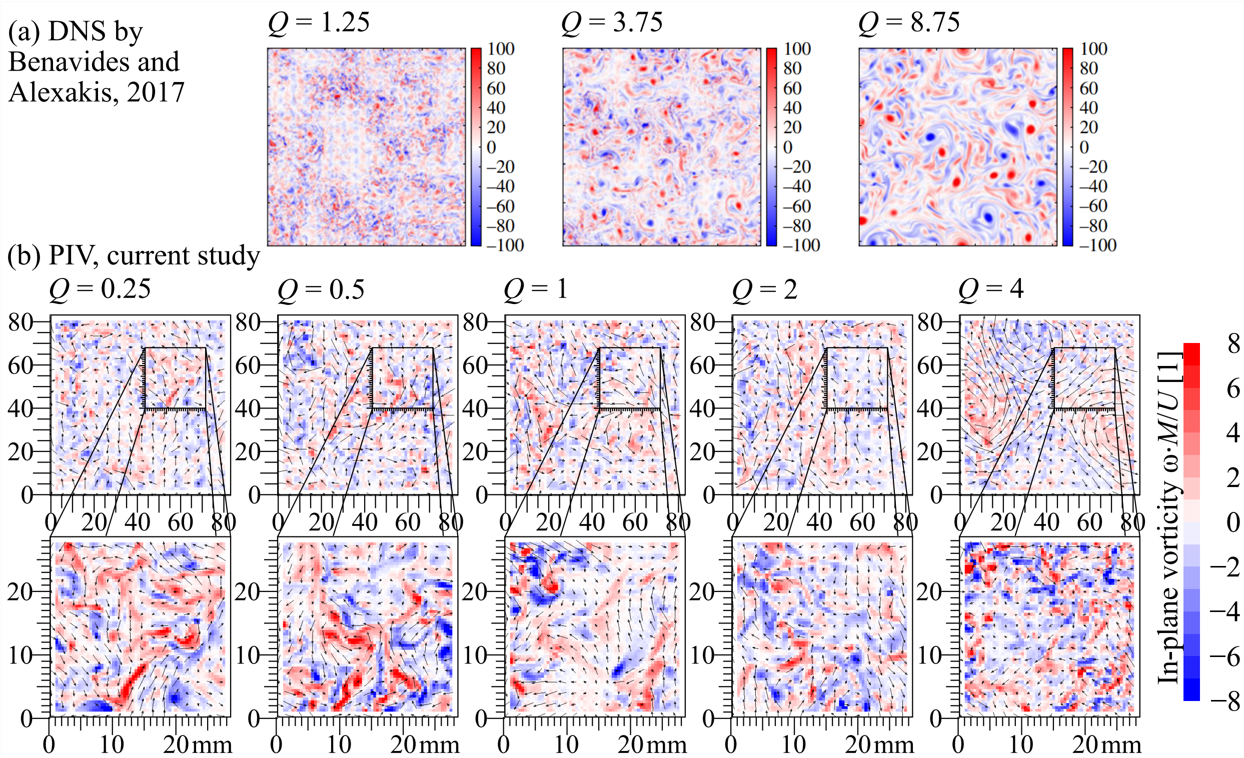

Fig. 2: (a) The 2D-vorticity from Direct Numerical Simulation (DNS) calculated by Benavides and Alexakis (2017). (b) Example of instantaneous vorticity fields measured by PIV. The distance from the grid (i.e. shift of zero at the x-axis of the larger FoV) is $235\,\mathrm{mm}$, i.e. $11.75M$.

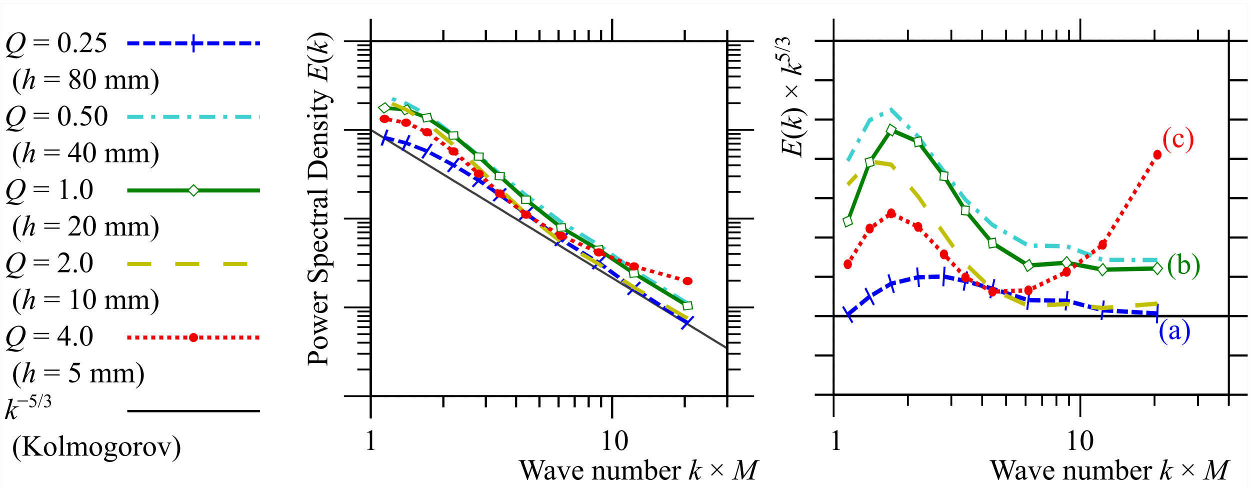

*Fig. 3: **Left** the power spectral density calculated as energy of band-pass filtered spatial data as discussed by Duda and Uruba (2019). **Right** the spectrum multiplied by $k^{5/3}$, hence the ideal Kolmogorov turbulence is displayed as a horizontal line (black line). When we increase Q (make the gap narrower), we can first observe (a, blue dashed line) almost ideal turbulence in the wide gap. When the layer is thinner (b, green line with squares), a large-scale turbulence condensate appears. However, as the gap becomes even thinner (c, red dotted line), the experimental limitation appear, and this large-scale condensate is damped by boundary layer, which is a source of energy at smaller length scales.*

positive and negative vorticity. In thicker layers (smaller Q), the small FoVs more often display elongated spots connected with vortices oriented non-perpendicularly to the FoV.

The large-scale condensate is fully displayed in terms of energy spectra, Fig. 3. It peaks at intermediate Q, while at too thin layer, the boundary layers become important damping those large-scale flows. Note that the boundary layers are impossible to omit in experimental study. Very interesting can be the dependence on Reynolds number, which has not been measured yet.

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3. Conclusions

Using a simple experimental setup, we partly reproduced the fascinating results of Benavides and Alexakis (2017). We observed the formation of a large-scale turbulence condensate when the turbulence becomes thin. However, the boundary layers damp such a condensate when the gap is even thinner. Thus, the large-scale condensate theoretically connected with 2D turbulence exists only in a limited range of experimentally available conditions. The direction of energy flux is not discussed in this limited conference contribution. We hope to publish it elsewhere in the future.

Acknowledgments

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