VORTICES STABILITY AND INVERSE CASCADES IN A 3D TURBULENT VON KÁRMÁN FLOW

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Summary We analyse recent results in a fully turbulent 3D flow between two counterrotating impellers in a cylindrical container. The averaged flow exhibits spontaneous symmetry breakings, and coherent structures are created in the shear layer. The dynamics of this flow presents inverse cascades towards the very low frequencies, and its origin is explained.

INTRODUCTION

Since the seminal work of Kolmogorov in 1941 [1, 2] the transfer of energy towards the small scales through a cascade with a power law of -5/3 has been observed in many 3D flows. Nevertheless this success, there are many topics that remain open. One of them is the creation and origin of coherent structures, with large scales that are even larger than the injection scales. In 1967, Kraichnan[2, 3] proposed a new approach in 2D turbulence where the energy could be transferred towards large scales. In this approach, two different magnitudes were conserved, the energy and the enstrophy. Other cases of inverse cascades have been found in quantum fluids and wave turbulence.
Here we present evidence of an inverse cascade in a fully developed turbulent flow in 3D, where the transfer is due to the transport of angular momentum from the small to the large scales. In this flow, the shear layer between two helical flows oscillates with very slow frequencies, and coherent structures are created.

Experimental setup

The experimental volume is a closed cylinder with diameter D=20cm placed horizontally (see Fig.1). Two impellers of diameter D_{prop}=17.5cm are located at L=6cm from both cylinder ends, the propellers are distinguished using the labels N ($z = +H/2$) and S ($z = -H/2$). The disks have 10 curved blades (2cm tall and 4.85cm of curvature radius) and the distance between them is set at H=20cm. The impellers rotate in opposite directions, and are powered by two independent motors (maximum power of 1.5 kW) regulated through a computer. The stability of the impeller velocity is below 0.1% . The rotation frequency of the propellers can be adjusted between $f_{N,S}$=0.5-12.5Hz generating a maximum torque of 15 Nm. The cylinder is placed inside a square tank of 150l of volume filled with water at 21 °C to reduce optical distortions. This volume of fluid ensures a high thermal inertia so the temperature evolves slowly. A 1D Laser Doppler Velocimetry (LDV) system is used to measure three components of the velocity field (radial v_R, azimuthal v_θ and axial v_Z) with a measurement volume size of $1.3 \times 0.3 \times 0.3$ mm^3, a 1cm of spatial resolution and temporal resolution up to 100kHz. For the measurements we use tracer particles with size of 14 μm and density ρ = 1.65 g/cm^3. The Reynolds number defined as $Re = RV_{prop}/\nu$ using the rim velocity of the propellers $V_{prop} = \pi D_{prop} f$ varies in the range Re $\sim 10^3 - 10^6$. A detailed description can be found in [4, 5].

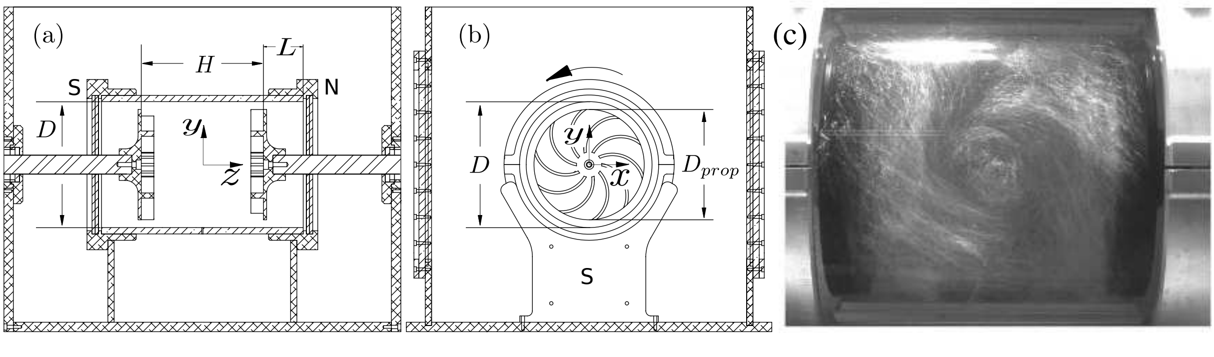

Figure 1. Experimental setup (a) Frontal view of the cylinder placed inside the square tank. The north propeller is at $z = H/2$ and the south propeller is at $z = -H/2$. (b) Section of the cylinder displaying the south propeller (view from the north impeller). The rotation direction of the south impeller is counter clock wise. (c) Frontal view of the flow. The impellers are the black disks located on the left and rights ends, and partially hidden by the air bubbles used as tracers. We can observe a large coherent vortex in the shear layer.

RESULTS

When the impellers are placed in counterrotation (opposite angular velocities, but the same frequency), they aspire the fluid at the axis, and eject it towards the wall with opposite angular velocities. The fluid returns by the lateral wall, and a

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shear layer appears near the equator where both circulations meet. For small Re the shear layer is exactly at the equator, but for $Re > 10^4$ a bifurcation of the basic flow appears and the separation layer between both flows is displaced from the equator. For $Re = 10^5$ the fluid is in a fully developed turbulent regime, whit a turbulence intensity of 50% (see [4, 5]). In figure 1(c) we have presented a picture of the flow that appears in this configuration. Two possible solutions are available where the vortices move with opposite azimuthal directions, and the system jumps random and spontaneously between these two solutions (what we call reversals). The spectrum of the time-series of the different velocity components present different power laws for different frequencies ranges and in different locations (see 2(c)).

For large frequencies, we obtain the classical Kolmogorov cascade. For very low frequencies, we get a -2 slope, that corresponds to the reversals between both solutions (as described in [4], not presented here). But for small frequencies, just below the injection frequency, we get an inverse cascade with -1/3. We can observe the creation of coherent structures (figure 1(c)) that lie near the wall at the shear layer. The radial extension of these vortices is obtained, and their dynamical behaviour is recovered from the slow frequencies (below the normalized injection frequency) of the spectrum presented on figure 2(c). We can determine the evolution of the velocity field corresponding to the vortices as it appears in figure 2(a), compatible with the vortices observed in figure 1(c).

This flow has been studied as a bench test of turbulence characteristics by other authors. For example, the kurtosis of the velocity distributions close to the geometrical centre of the container has been determined and, depending on the component of the velocity field and on the experimental setup, varies between 2.6 to 3.3. In this experiment we have identified the source of these deviations from the Gaussian shape (i.e. see figure2(b) and the evolution of the kurtosis along the axis). If reversals are allowed, the kurtosis of the whole series is 2.5-2.6 but if one of the states is fixed[5] then its value increases to 3.3. Finally, splitting the original data series on slow and fast frequencies, we can recover Gaussian distributions (K=2.9 for the slow and K=3.0 for the fast frequencies) of an original series with kurtosis 2.6.

In this configuration there is a transfer of angular momentum between different layers (z=const) [6]. The dimensional analysis predicts an inverse cascade for the conserved magnitude compatible with the results presented here. Some years ago a similar scaling was proposed[7] in order to explain the creation of large structures in the atmosphere, but in this situation it was proposed as a behaviour in an inviscid fluid, where there is a transport of helicity in a flow with an averaged zero helicity and Gaussian distributions.

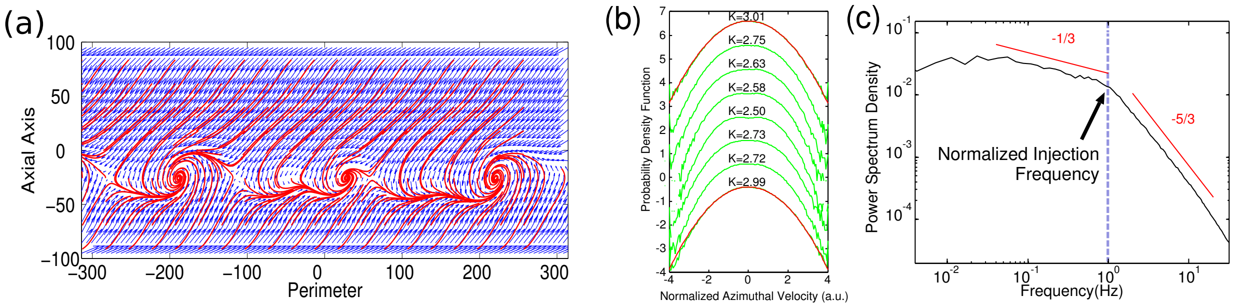

Figure 2. (a) Reconstruction of the vortices in the cylindrical shell $r = 0.9$. (b) Velocity distributions for different z. The red line correspond to a Gaussian shape. The different graphs have been shifted for clarity. The kurtosis of each distributions is presented. (c) Spectrum of the axial component at the centre ($r = 0, z = 0$).

CONCLUSIONS

We have presented a system where the dynamics of a shear layer in a fully 3D turbulent flow produces coherent structures and an inverse cascade, whose origin is related to the angular momentum transport.

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