EXPERIMENTAL INVESTIGATION OF LARGE-SCALE NON-DECAYING ROTATING TURBULENCE

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Abstract Laboratory experiments on rotating turbulence have been conducted to explore the formation of columnar vortices in a forced steady-state environment. Forcing was achieved by means of co-rotating impellers situated at the top and bottom surfaces of a large cylindrical tank of height 2 m and diameter 2 m. As the impellers rotated the fluid, the turbulence generated, characterized by the root mean squared (rms) velocity $|\boldsymbol{u}|$, was controlled using symmetrically located baffles on the inner walls of the tank. By varying the rms velocity $|\boldsymbol{u}|$ and bulk rotation rate Ω, the flow was investigated over a range of in-plane Rossby numbers, $|\boldsymbol{u}|/2\Omega l$. 2D Particle image velocimetry (PIV) was carried out for a plane normal to the axis of rotation at the center of the tank, and was utilized to compute velocity fields and streamlines which revealed the emergence of columnar eddies, as is often seen in decaying experiments on rotating turbulence. PIV results were used to deduce the parameters affecting the structure, frequency of occurrence and life cycle of these columns. The tendency of columns to be predominantly cyclonic and the effect of columns on bulk rotation rate were also analyzed.

INTRODUCTION

The study of turbulence in rotating systems has largely been focused on the case of temporal decay of turbulence. With the exception of Hopfinger et al. [1], who used fixed oscillating grid frequencies to force turbulence to stationary states, much of the early experimental work [2] and most later works [3, 4, 5] were concerned with the time evolution of the flow from some specified initial state, as the aim was to observe the formation and axial elongation of columnar vortices characteristic of such rotating flows. This linear growth in length scales associated with columnar eddies has been documented in recent experiments by Davidson et al. [4] and Staplehurst et al. [5]. Even though the large-scale nature of these structures is frequently noted [6], experiments thus far have been limited to shallow tanks or small-scale apparatuses [7], where columns inevitably reach confined boundaries and result in the formation of highly dissipative Ekman layers [2]. In this paper, we address these gaps in knowledge by experimentally studying large-scale steady state dynamics of rotating turbulence. The apparatus used gives us control over the fluctuating velocity $|\boldsymbol{u}|$ and rotation rate Ω, allowing us to investigate the factors affecting the life cycle of columnar eddies at different stationary forcing conditions. The use of impellers to rotate the flow implies that unlike most experiments (which use solid body rotation), wall effects are present here. In this regard, the setup used is similar to that of Pinton et al. [8], but on a much larger scale.

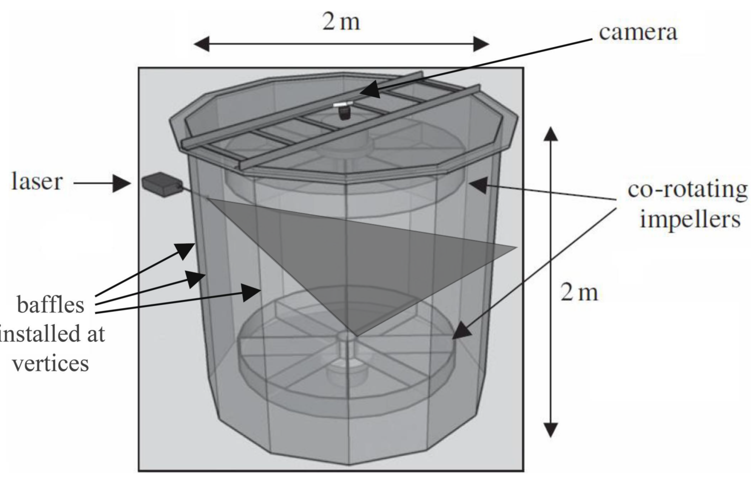

Figure 1. Schematic of apparatus used to conduct PIV measurements on rotating turbulence. (Adapted from Worth and Nickels [9])

METHODOLOGY

The experiments were conducted in a large mixing tank facility at the Department of Engineering, University of Cambridge designed for high Reynolds number homogeneous isotropic turbulence [9]. As shown in Figure 1, the co-rotating impellers drive the flow and turbulence is generated primarily with the aid of 12 baffles installed symmetrically inside the

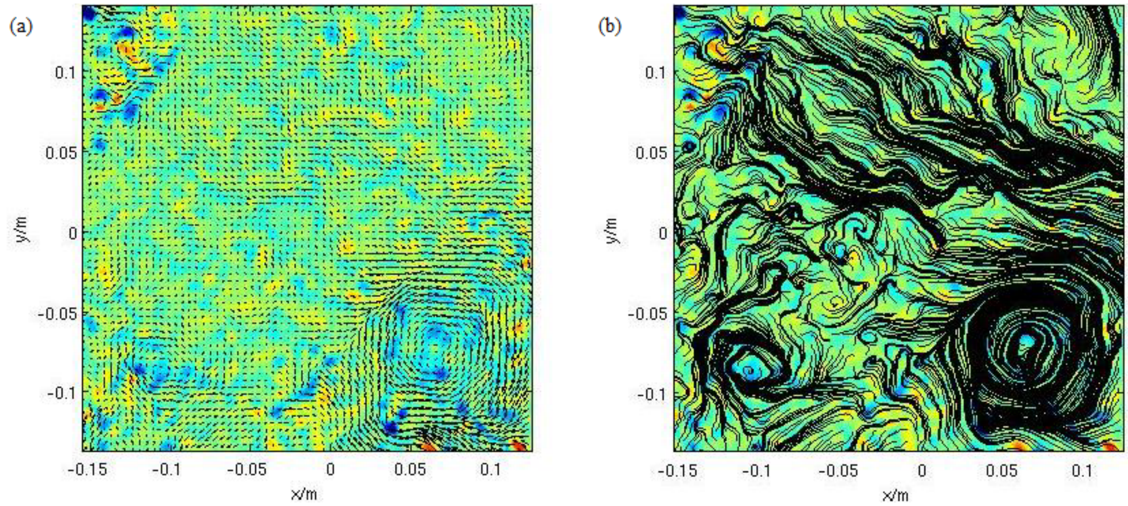

Figure 2. A cyclonic columnar vortex corresponding to impeller rotation rate = 4.00 rpm and number of baffles = 6, illustrated using (a) instantaneous velocity vector field with the mean removed (for clarity, only every second vector is shown here), and (b) streamlines. (Note that the background rotation is oriented clockwise.)

tank, all of which can be removed and reinstalled as desired. It was found that, by symmetrically altering the number of baffles, the value of rms velocity, $|\boldsymbol{u}|$, can be changed as well. The symmetric configurations of baffles used in this work are 12 (all), 6 (half) and 3 (quarter). To conduct the PIV, the fluid (water) was seeded with 10 μm silver coated Pliolite particles. A horizontal cross-section of the fluid was illuminated by creating a laser sheet with a Continuum Surelite laser and a stationary high-speed Photron SA1 camera was used to capture the motion of particles in the illuminated field from the centre of the top of the tank. A field of view of 30 $\times$ 30 cm was used, and the final interrogation window size had 16 $\times$ 16 pixels with an overlap of 8 pixels. The spatial resolution obtained was x = 4.6875 mm (based on the interrogation window size), which is of the order of the laser sheet thickness. A sample rate of 1 Hz was used to record successive camera images. PIV data was obtained for impeller rotation rates of 0.67, 1.33, 2.67 and 4.00 rpm. At each combination of rotation rate and baffle configuration, 1000 velocity fields were ensemble averaged. The PIV computations were performed with the software Davis 7.2, and the statistical analysis of the velocity fields was done in Matlab.

RESULTS

Figure 2 shows a typical cyclonic columnar vortex of a characteristic size of about 5 cm revolving with the bulk rotation. In the full paper, we will present the frequency of occurrence, lifetime and size of these eddies at different stationary forcing conditions. Analyses of the PIV data also demonstrate that because of the radial increase of the root mean squared velocity $|\boldsymbol{u}|$ (more turbulence generated near baffles), the local in-plane Rossby number grows radially across the fluid at any fixed rotation rate. The overall level of turbulence generation is also seen to rise with the number of baffles as expected. However, it is observed that as the baffle number increases, the bulk rotation rate increases above the impeller rotation rate, which corroborates the findings of Pinton et al. [8 - Fig. 6]. This results in a smaller radial increase in local Rossby numbers at higher baffle configurations. The full paper will contain discussions on the role of columns in increasing the bulk rotation rate as well as the preferred range of Rossby numbers for column formation.

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