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EXPERIMENTAL CHARACTERISATION OF TURBULENT FLOW RÉGIME IN THE THREE-DIMENSIONAL ROTATING-DISK BOUNDARY LAYER

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Fully developed turbulent flows are known to display some universal features when bounded by a solid wall. The flow due to a large disk rotating in otherwise still fluid undergoes transition from laminar to turbulent dynamics at a nondimensional radius $R \simeq 500$. The turbulent régime prevailing beyond this critical radius is unusual in several respects [4, 3, 2, 1]: it is sandwiched between a solid moving surface and the outer fluid at rest, and it develops in the radial direction while the main flow and shear components are in the azimuthal direction.

The aim of the experimental work presented here is to characterise some features of this particular turbulent boundary layer.

1 Experimental setup

The experimental setup consists of a 50 cm diameter glass disk that is rotated at constant angular speeds, up to 1500 rpm. Disk rotation and viscosity produce a three-dimensional boundary layer of constant thickness $\delta = \sqrt{\nu/\Omega_d}$ (a typical value is $\delta = 400 \mu\text{m}$), where ν is the kinematic viscosity and Ω_d the disk rotation rate. Non-dimensional (based on δ) radial and azimuthal coordinates R and Z are introduced; non-dimensional azimuthal velocities V are used, based on the local linear disk velocity $R\delta\Omega_d$.

Flow measurements are carried out by constant-temperature hot-wire anemometry. The hot wire is positioned by a computer-controlled high-precision two-axes traversing mechanism and provides azimuthal velocity time series. These time-series are processed to obtain the flow characteristics, in particular the mean-flow velocity profiles and the spectral analysis.

2 Mean-flow velocity profiles

Azimuthal mean velocity profiles are obtained by averaging the hot-wire measurements for 100 disk revolutions at each location. From these measurements it is observed that the mean-flow profiles very closely follow the analytic profile for $R \leq 480$ and that weak mean-flow corrections prevail over the range $490 \leq R \leq 540$. For $R \geq 550$, strong mean-flow distortions develop that progressively extend to beyond $Z = 15$ by $R = 600$. Such boundary-layer thickening is characteristic of the development of a turbulent boundary layer. In figure 1, mean-flow velocities for $550 \leq R \leq 650$ are plotted against Z using a logarithmic scale. It is found that the velocity profiles are nearly linear in $\log Z$ for $R \geq 600$, which is the characteristic low of the wall of fully turbulent boundary layers. Velocity profiles for $R \leq 590$ are not linear in $\log Z$, suggesting that the flow is not yet fully turbulent and still in the transitional régime. Thus, we conclude from the mean-velocity measurements that the flow begins transition around $R \simeq 540$ and is fully turbulent by $R \simeq 610$.

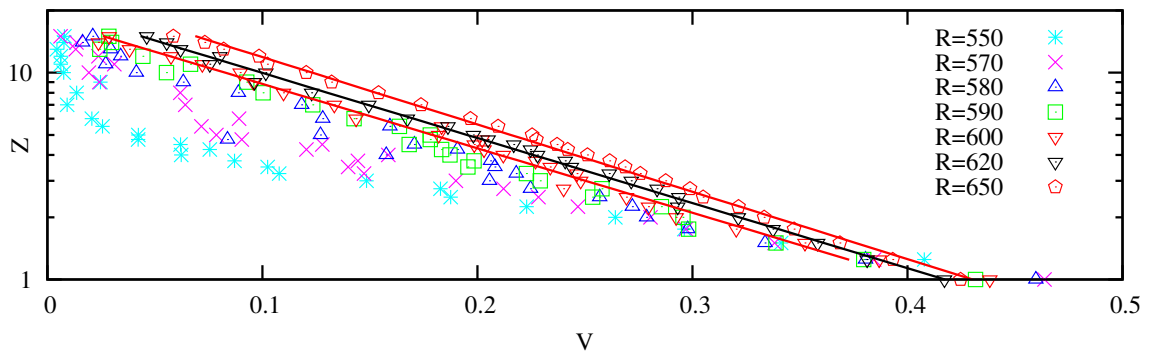


Figure 1: Mean-flow velocity profiles of the transitional and fully turbulent flow régimes plotted against Z on a logarithmic scale. Solid lines are linear fits to the data in the range $1 \leq Z \leq 16$ for $R = 600, 620$ and 650 (slopes are respectively $dV/d\ln(Z) = -0.139, -0.138$ and -0.133). The root-mean-square error of each fit is around 0.005.

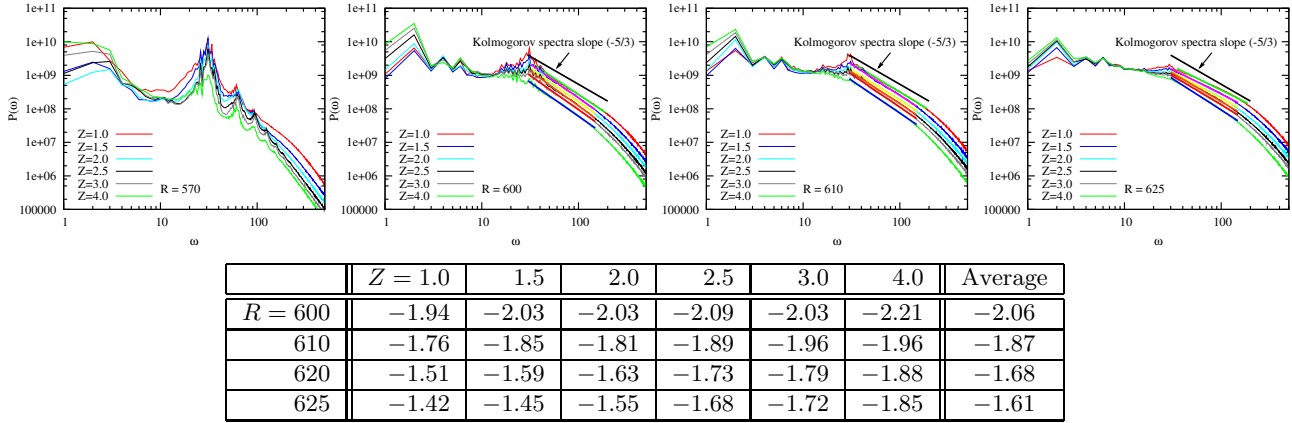


Figure 2: Log-log plots of spectra in turbulent régime. For $R \geq 600$, linear fits are computed for data in the range $30 \leq \omega \leq 200$ and shown together with a reference line of slope $-5/3$. The slope values shown in the table have a root-mean-square error of around 0.05.

3 Spectral analysis

Fourier spectra are calculated to show the frequency content of the azimuthal velocity time series at different non-dimensional radii and disk normal positions. In figure 2, spectra corresponding to the transitional and fully turbulent régimes are plotted using a log-log scale to bring out a possible power-law behaviour. For $R = 570$, the modal peak and its harmonics is still apparent, whereas at $R = 600$ and above, the peak is absent and there is a linear range extending over a good fraction of a decade in frequency upwards from where the peak would occur. The figure shows linear fits to the data in the range $30 \leq \omega \leq 200$ for $R \geq 600$. Such linear behaviour corresponds to spectral power laws with exponents equal to the slopes of the lines, listed in the table. For reference purposes, the figure also shows a straight line with the Kolmogorov slope $-5/3$. It is seen that these power-law exponents are not far from the Kolmogorov value, particularly at the largest values of R where the turbulence is most developed. Also apparent from the table, the power-law exponent depends on both R and Z , tending to decrease in absolute value as R increases and to increase with Z .

4 Discussion

A possible explanation of these variations, more qualitative than quantitative, refers to the physics of the turbulent energy cascade from large to small scales which forms the basis of Kolmogorov's theory. Large scales, here corresponding to frequencies at and below $\omega \simeq 30$, break down to smaller and smaller scales, which leads to the $-5/3$ law by dimensional analysis when assuming a constant rate of energy supply from the large scales.

Imagine following a packet of turbulence as it is convected by the mean flow. If the energy supply rate from the large scales increases with time, the energy flux was lower in the past and, given that the cascade takes a certain time, we expect the spectral energy of the small scales to be less than it would have been had the energy supply been constant, hence a steeper slope on the log-log plot. This suggests larger absolute values of the exponent in the presence of an increasing supply rate, and smaller ones for decreasing supply rate. In the table of figure 2, the absolute value of the Z -averaged exponent is seen to be higher than $5/3$ for the first three values of R . This is to be expected since the turbulent intensity, and hence the energy supply rate, increases with R in the transitional region. Both $R = 600$ and $R = 610$ have exponents above $5/3$ for all Z , suggesting an increasing supply rate at all distances from the disk. This is reasonable because the turbulence is developing up to $R = 610$. For $R = 620$ and $R = 625$, the exponent is less than $5/3$ towards the disk and greater than $5/3$ at higher Z . This suggests a decreasing supply rate near the disk and an increasing one further out.

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