MEASUREMENT OF TURBULENCE PROPERTIES

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ABSTRACT

The aim of the research is to investigate anisotropic turbulence intensities, id est to investigate the distribution of Reynolds stresses and energy spectra in a square cross-section channel, downstream of a semi-active jet turbulence grid generating anisotropic turbulent airflow. In addition to the semi-active jet turbulence grid, another type of turbulence grid was developed and experimentally investigated. This grid contains vertical, flexible strips of aluminum (in this case, there are no perpendicular (horizontal) grid elements), which vibrate at a frequency depending on the velocity of the main airflow. Besides the investigation of the velocity- and turbulence intensity distributions, another main objective of the research is to measure the von Kármán energy spectrum when the turbulence cannot be considered isotropic. This aspiration of ours is justified by the knowledge gap present in the literature in this specific field. Monin has carried out a theoretical study to extend and generalize the von Kármán – Howarth isotropic principal stress equation to the anisotropic regime. The proposed new experimental work aims to provide a solid experimental background for verifying and validating the physical correctness of the Monin equation, which may result in a new theoretical understanding and perception of the major issues and the nature of anisotropic turbulence. Since the anisotropic energy spectra are expected to exhibit different characteristics from the isotropic Kolmogorov spectra, these new experimental results may contribute to the development of new anisotropic and engineering turbulence models that can be used in industrial applications.

Keywords: turbulence, measurement, Reynolds, boundary-layer

1. INTRODUCTION

There are different types of turbulence grids (active, passive, semi-active, etc.) facilitated in laboratory wind tunnels to generate appropriate turbulence. These grids are usually placed upstream of the measurement section of the wind tunnel to produce the appropriate flow parameters. Investigations can occur where the base airflow is already turbulent, in which cases turbulence grids can be used to improve turbulent properties, such as the turbulent kinetic energy. A passive turbulence grid is a non-moving grid placed in a wind tunnel. In a general dynamic sense, however, they can also be considered active grids [1]: e.g. the layers within the boundary layer possess uncertain motions. In the study of isotropic turbulence, the first (probably [2]), which began several decades earlier, occurred in a passive form of a turbulence generating grid. The role of contraction in the isotropy of passive grid-induced turbulence was investigated by Comte-Bellot & Corrsin [3]. The publication of Comte-Bellot is probably the most important one on grid experiments [4]. Flow measurements in grid-generated turbulence are the most important experiments in the theory of turbulence that provide appropriate boundary conditions and proper data to validate turbulence models. The Reynolds number of the grid (or Taylor Reynolds number) depends on the dimensions of the passive grid and largely on the generated turbulence [5]. It is important to mention that experiments with active grids that facilitate moving borders ([6] vibrating grids), or grids capable of increasing the average momentum of the flow have become more prominent in the last few decades [7]. Additionally, turbulence grids called "jet grids", which change the average flow rates through secondary jets, have promising potential among active grids. Jet grids generate high intensity turbulence, and at the same time they can maintain an appropriate level of homogeneity. This results in higher Reynolds numbers and thus makes the broadening of existing experiments feasible [8]. The motivation of the presented work was to achieve an almost homogeneous flow with a medium mean velocity (about 3 m / s) and a relatively

high turbulent kinetic energy (about 0.5 m^2 / s^2), which is typical among meteorological results. However, such a result has been produced using a passive grid combined with a fluctuating wind tunnel fan speed [9]. Recently, the most common active grids are equipped with rotating blades introduced primarily by Makita and Miyamoto [10]. Subsequently, a more detailed study described the performance of the active grid and presented some characteristics of induced homogeneous quasi-isotropic turbulence (Makita (1991)). The properties of turbulence decomposing behind the active lattice (Makita [11]) were compared with the results of the high-vortex simulations by Kang et al. 2003 [8], and their results suggested that an update of Comte-Bellot & Corrsin, 1971 [4] is required. Larssen and Devenport constructed this type of grid, which is probably the largest grid developed so far that combines different stages of the development of turbulence grids [12].

2. TURBULENCE PROPERTIES

Turbulence is certainly not an easy phenomenon to define. It is ubiquitous and is experienced in our everyday lives. Some prime examples of turbulent motions are the evolution of the flow regimes around vehicles, buildings, airplanes etc. Processes insight internal combustion engines, piston engines, gas turbines are also highly turbulent. Some examples of visualized turbulent flows can be seen in Fig. 1. The chaotic and often unpredictable nature of turbulence makes it a highly complex field of research. Many statistical and empirical models have seen the light in the course of centuries; nevertheless, a full understanding of the phenomena is yet to exist. Issues related to fluid flow appear in most fields of engineering practice. Many, if not most, flows of engineering are turbulent, hence the turbulent flow regime is not just a theoretical interest but a practical problem source.

Figure 1. Turbulence in everyday life

Turbulent flows possess different properties. They can have seemingly irregular velocity and pressure fluctuations in all three dimensions of the space, regardless of the original flow being two-dimensional. The time history of the velocity at a certain point can be rather unpredictable and random. The irregularities often obtain a certain form. These structures, called eddies, can be the form of a vortex, a mushroom, a wave etc. Turbulence is normally self-sustaining, once initiated, it continues without diminishing. In addition, turbulence mixes fluids, thus it has a strong diffusive effect. Most researches describe turbulence as the motion state of the flow.

The rate of turbulence depends on the relation of inertia force and viscous force, which is described by the Reynolds number. If inertia forces are below viscous forces, we are talking about laminar flow. When inertia forces are higher, the flow becomes turbulent. For laminar flows a low Reynolds-number, for turbulent flows a high Reynolds-number is associated.

By definition, the Reynolds number can be written as:

$$Re = \frac{\rho \cdot v \cdot L}{\mu}$$

Where ρ, v, L, μ stand for fluid density, characteristic velocity, a characteristic length scale and dynamic viscosity respectively.

The main properties of turbulent flows are:

I. Irregularities. The effects of turbulence make the flow seemingly irregular and even random. A complete description of the flow using deterministic approach is extremely complicated, therefore they are usually described statistically. Turbulent flows are always chaotic, but not every chaotic flow can be called turbulent.

II. Diffusivity. The diffusivity of the turbulence results in enhanced mixing and increased impulse-, heat- and mass-transfer rates.

III. High Reynolds numbers. Turbulent flows almost always occur at high Reynolds numbers.

IV. Three-dimensional. Turbulent flows rotate and are three-dimensional. There are non-zero vortexes and a high degree of volatility is typical of them. Mechanisms such as stretching three-dimensional vortexes play a key role in turbulence.

V. Dispersion. Turbulent flows are always dissipative. Kinetic energy is converted to heat due to viscous shear stresses. Turbulent energy dissipates quickly with lack of an energy source.

VI. Continuum. Turbulence is a continuity phenomenon that is governed by the equations of fluid dynamics.

3. ANISOTROPIC TURBULENCE

Anisotropic turbulence raises a knowledge gap when it comes to reliable measurement data. John Laufer [13, 14] put a circular cross-channel under investigation. The working medium in case of his investigations was air, and he measured the awakening Reynolds stresses near the wall, but the range of Reynolds-numbers he used is too tight to draw reliable statistical data from for developing turbulence models. He used Hot Wire Anemometry (HWA) to execute the flow measurements at Re = 50 000 and at Re = 500 000.

Nikuradse [15] investigated the flow evolution in a circular cross section pipe with different relative roughness walls. The working medium in his investigations was water, and observations were made on the loss of head, velocity distribution, discharge quantity and water temperature. Nikuradse, however, did not measure the Reynolds-stresses; therefore, his results can solely be used to compare different velocity profiles.

The question might arise: why would having a broader knowledge with more results be important? Since then, different investigations – involving Laser Doppler Velocimetry, Laser Doppler Anemometry etc. – were executed, however the range of Reynolds-numbers is rather tight.

Therefore, it would be expedient for us to measure the velocities and the velocity fluctuations at as many Reynolds numbers with varying wall roughness as possible. First, the Reynolds numbers at which Laufer did his investigations is going to be in focus, so to check how much his results correlate to ours. Then the Reynolds-numbers that were observed by Nikuradse in a circular channel will be investigated, but instead in a rectangular cross channel. Quantities necessary to determine the Reynolds stress tensor and the near-wall energy spectrum will be measured and recorded in every case; namely the average velocities and velocity fluctuations in 3D.

This is where the anisotropy of the flow will become significant; we measure the velocity fluctuations u'_1, u'_2, u'_3 and determine $u'_{1\,average}$, $u'_{2\,average}$, and $u'_{3\,average}$. At the wall, these averages will be different. Near the wall, there is a peak value perceived by many investigations. It is not yet clear whether this peak really exists, or is an indefinite measurement error. Many simulations – including Large Eddy Simulations, Direct Numerical Simulations – were executed to estimate the behaviour of fluids near walls, however,

such results are not applicable to be used as references. The knowledge gap in the field occurs when an anisotropic turbulence model is based on the results of other simulations – which, although accurate, are not equivalent to reliable measured data.

If a turbulence model can estimate the velocity profile well, and, say, the pressure profile decently, but when it comes to the stresses, the model fails, then the model itself is not reliable. The turbulent kinetic energy and the dissipation will be incorrect, and turbulence is basically dissipation of energy. If a turbulence model can not estimate the dissipation properly, then that model is flawed. However, how do we know – without a reference –, that our model is good? The answer is we do not know. Hence, a reference is needed, and crating this reference base is one of the main purposes of this work.

Most engineers payed attention to the velocity and pressure profiles, since they have practical importance. However, knowing the velocity field and the pressure distribution is not enough to develop anisotropic turbulence models. They do not provide enough information to draw any long-term conclusions about the statistical nature of the flow.

4. MATERIALS AND METHODS

The investigations of the evolving velocity profile took place downstream of the turbulence generator (strip grid) in a pressurized low velocity open ended wind tunnel. The cross section of the measurement zone is a 400x400 mm square. Air velocity can be altered by changing the speed of the axial fan. Maximal velocity with the current setup is around 22 m/s. The measurement is located at the end of the wind tunnel as seen in Fig. 2. The turbulent kinetic energy of the flow downstream of the strip grid can be changed by relaxing or tightening the tensioners, and by changing the angle of the strips using the strip guides. The strips are made of aluminium and they measure 0.5 mm in thickness and 5 mm in width.
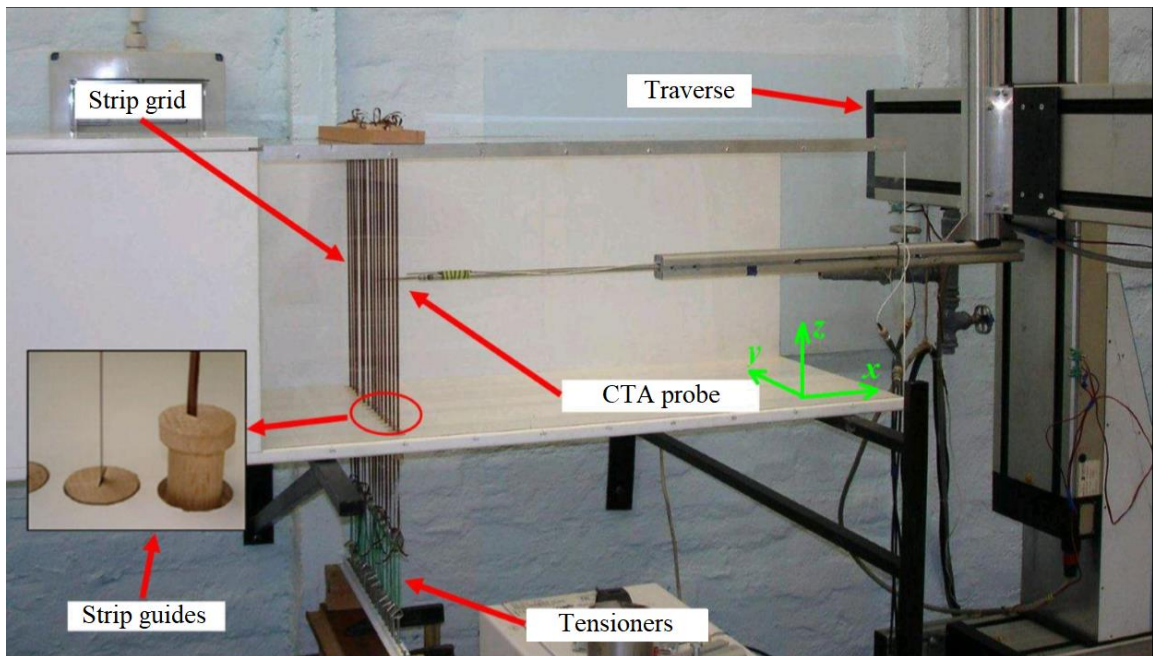

Figure 2. Open type wind tunnel

Using two dimensional CTA (Constant Temperature Anemometry) probes, two velocity components can be recorded with high frequency sampling at the same time. Since the results will be normalized down the line, by simply turning the probe by 90 degrees, the remaining velocity component can be measured. Although not at the same time, the velocity components should theoretically give a reliable representation of the velocity field; and since u will be measured in both cases, v and w can be normalized during data processing.

The main importance of the investigation is to measure the velocity fluctuations close to the wall in case of different Reynolds numbers and flows with different turbulence intensities. The sampling frequency was chosen to be 80 kHz for the first measurements, though this number will most likely be raised in the future. The probe has a built-in temperature measuring node which records the ambient temperature in each step. The probe makes velocity profiling possible on a wide range of velocity scales, from relatively low to high velocities (from 0.2 m/s to around 0.8 Mach).

Figure 3. DANTEC CTA (Constant Temperature Anemometer)

4.1. Velocimetry using LASERs

Two dimensional LDV (Laser Doppler Velocimetry) system is available at our disposal to measure two velocity components in a single point. The farthest measurement point from the optics can reach up to 750 mm. The velocity range of the LDV system is [0.3; 25] m/s with a maximal laser performance of 3 W. The obtained data is recorded and analysed by Flowsizer LDV software.
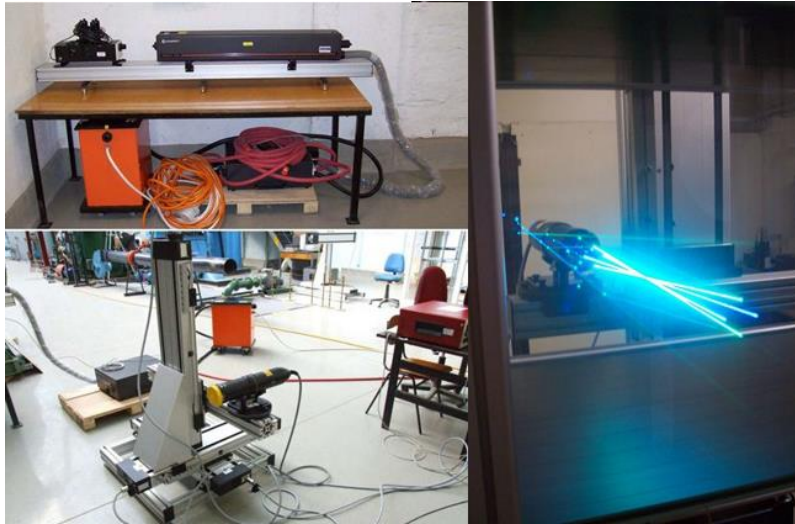
Figure 4. TSI LDA (Laser Doppler Anemometer)

4.2. Two-dimensional PIV systems

Through two-dimensional PIV investigations, the velocity profile of a single plane can be obtained using high frequency, high resolution cameras. The size of the measurement plane can reach up to 300x300 mm with a velocity range of [0.3; 25] m/s. One camera is sufficient to record the two-dimensional evolution of the velocity profile in a plane assuming the flow itself is two-dimensional. In our case, we can facilitate a MP PIV camera with a 135 mJ impulse laser. To record and analyse the data, Insight 4G PIV software is used.
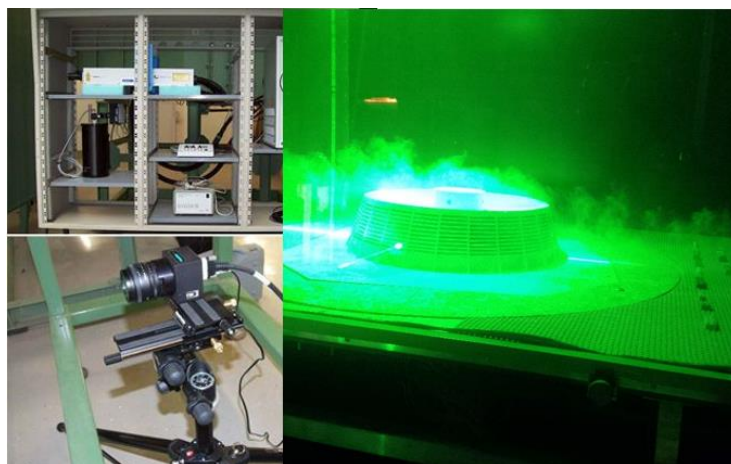

Figure 5. TSI PIV (Particle Image Velocimetry)

5. RESULTS

Preliminary tests were executed with maximum fan speed and a sampling frequency of 4 kHz and a sample number of 80 000 per point. The CTA probe was moved from the bottom side of the wind tunnel (3 mm) up to the axis of symmetry with 0.5 mm steps.

The investigation was therefore executed along a vertical line, which was 500 mm downstream of the strip turbulence grid (around 20M with M being the spacing between individual strips).

Fig. 3 shows the energy dissipation of the flow. The mean velocity of the flow is 4.735 m/s. With the equivalent diameter being 0.4514 m and the kinematic viscosity being $15.06 \cdot 10^{-6}$ m^2/s, the Reynolds number in this case is 141 924.
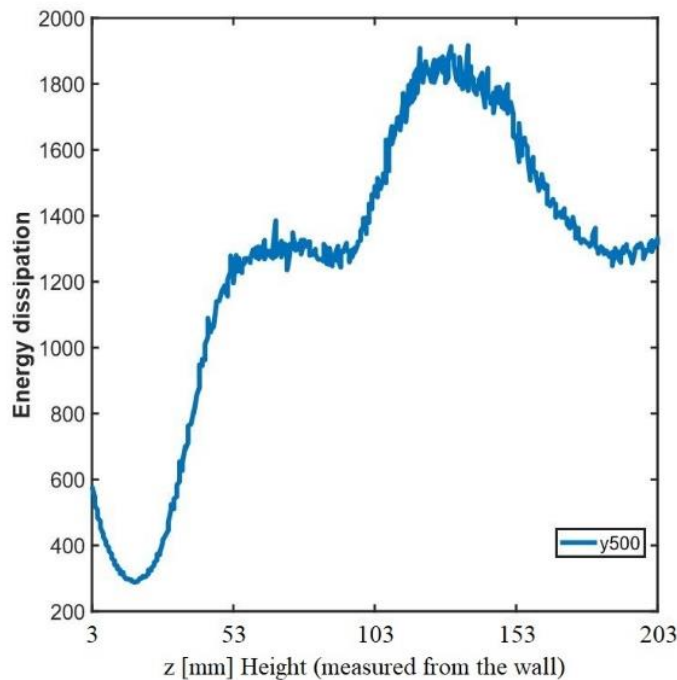
Figure 6. Energy dissipation as a function of distance from the wall

The results show us that the strip turbulence grid generates a rather inhomogeneous turbulence field; the fluctuations (seen as vertical oscillations on the diagrams) occur as we get farther from the wall. This is because the turbulence grid is fixed at the top and at the bottom, hence the amplitude of the vibrations increase as we get farther away from the wall, and theoretically peaks in the middle of the channel.
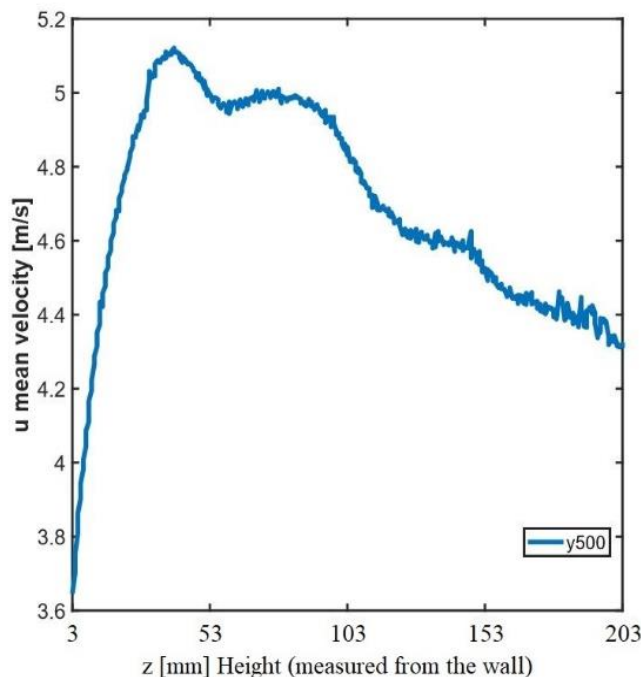
Figure 7. Mean velocity "u" as a function of distance from the wall

6. CONCLUSIONS

After a comprehensive literature overview a lack of experimental data has been discovered in the form of Reynolds stresses near planar surfaces. A novel type of semi-active jet turbulence grid is already developed [16], as well as passive strip grid which are currently facilitating during our investigations. Our intention is to continue the development of turbulence grids in parallel with our investigations regarding flow evolutions near planar surfaces to enhance our range of scope. Our observations expand to airflows of different Reynolds numbers, flow velocities, relative surface roughness and varying turbulence intensities. It is important to determine as many flow parameters of turbulent flows as possible (such as the velocity fluctuations, length scales, Reynolds stresses, von Kármán energy spectra, etc.) in order to create an extensive database. The preliminary tests show us that the system works, and we can use it to measure the turbulent properties of the airflow. However, in the future, we plan to improve the system to make it suitable to investigate the velocity profiles closer to the wall (between]0; 3] mm), and to achieve a more homogeneous turbulence distribution.

ACKNOWLEDGMENTS

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