IN-TECH Conference
Ljubljana 2017

INTERNATIONAL CONFERENCE ON INNOVATIVE TECHNOLOGIES

IN-TECH2017

LJUBLJANA, SLOVENIA 11. - 13. 9. 2017

Organized by:
World Association for Innovative Technologies

Proceedings

International Conference on Innovative Technologies

IN-TECH 2017

Ljubljana

Proceedings

IN-TECH 2017

Proceedings of International Conference on Innovative Technologies

Editors:

- Pepelnjak Tomaž – Slovenia
- Car Zlatan – Croatia
- Kudláček Jan – Czech Republic

IN-TECH 2017 Organization committee:

- Car Zlatan – Croatia
- Kudláček Jan – Czech Republic
- Pepelnjak Tomaž – Slovenia
- Drašnar Petr – Czech Republic
- Zoubek Michal – Czech Republic
- Pakosta Michal – Czech Republic
- Plestenjak Tanja – Slovenia
- Andelic Nikola – Croatia
- Blazevic Sebastian – Croatia

Publisher: Faculty of Engineering, University of Rijeka

Printed by: TISK AS, s.r.o., Jaroměř, Czech Republic

Printed in 100 copies.

IN-TECH 2017 International Conference on Innovative Technologies runs from 11. 9. 2017 to 13. 9. 2017 in Ljubljana, Slovenia.

E-mail: info@in-tech.info
URL: http://www.in-tech.info

ISSN 0184-9069

DETERMINING TURBULENT PROPERTIES IN GRID GENERATED TURBULENCE BASED ON HOT-WIRE DATA

N. Szaszák[1], Sz. Szabó[1] and P. Bencs[1]

[1] Dept. of Fluid and Heat Engineering, University of Miskolc. H-3515 Miskolc-Egyetemváros, Hungary
Tel.: +36 46 565 154, Fax: +36 46 565 471, e-mail: aramszn@uni-miskolc.hu

Keywords: grid turbulence; isotropic turbulence; hot-wire anemometry; energy spectrum; Kolmogorov microscales

Abstract: This paper deals with the determination of several turbulence quantities in the case of nearly isotropic, homogeneous grid turbulence. Grids placed in wind tunnels upstream of the test section are used to produce flow with roughly isotropic and homogeneous decaying turbulence for wind tunnel investigations. Passive grids without moving parts can produce relatively low turbulent intensity while active grids with moving parts are applied to create much more intense turbulence. Such flows can then be used for measurements which demand flow with predetermined turbulent properties, for instance validation of results of computational fluid dynamics (CFD) simulations. Therefore, first the characterization of the achievable turbulence has to be carried out. For this purpose, a kind of hot-wire measurement technique, constant-temperature anemometry, was applied. The time series of instantaneous velocity-component samples (in longitudinal as well as in one transversal direction) downstream of a novel type active grid were processed in MATLAB® script made for this purpose. Using the script with an appropriate number of samples of velocity components with sufficiently high sampling rate, the following turbulent properties can be derived: turbulence intensity in one and three dimensions, turbulence kinetic energy, isotropy ratio, integral time-scale, turbulence energy spectra, dissipation rate of turbulent kinetic energy, Kolmogorov microscales, Taylor microscale, turbulence Reynolds number, and Taylor-Reynolds number.

Introduction

Much of the flow occurring in natural and industrial processes is turbulent flow. The fine structure of such flows can be measured and described in laboratory tests and through numerical simulation. When using numerical data, it must be validated through comparison with measured data. Wind tunnels are crucial devices whose main purpose is to create flow so that various turbulence properties can be measured. Turbulence generating grids are used in order to create turbulence in wind tunnels; there are passive and active grid types. A passive grid has no moving parts, and can increase the turbulence intensity to a limited extent [1]. Much greater intensity on a wider scale can be achieved using an active grid [2] whose moving parts (controlled motion from external energy sources) disturb the flow. Active grids, however, are quite complex structures, and thus high in cost. Another alternative to these complicated and expensive grids [2,3] exists; the type of grid that we have developed offers a much more economical solution [4] that uses the mechanical energy of the main flow (moving boundary layer) to move the grid elements. Along with developing the grid, a computational procedure was also worked out for using the measurement data to provide the largest possible number of characteristic turbulence parameters dealt with in the literature. This paper introduces the main elements of the computational procedure, using the newly developed grid as an illustration and giving examples of the various properties calculated using the computational procedure.

A Definition of Turbulence

A clear and concise definition of the physical process of turbulence is essential to its study. A compilation and discussion of definitions can be found in [5]. Many of these definitions are vague, such as ‘a motion in which an irregular fluctuation (mixing, or eddying motion) is superimposed on the main stream’ [6] or ‘a fluid motion of complex and irregular character’ [7]. One definition, given in [8], is that turbulence is ‘a field of random chaotic vorticity’. However, the words ‘random’ and ‘chaotic’ imply that no formal mathematical solution – which would be necessarily deterministic – can exist. Probably the most exact brief definition of turbulence is ‘the general-solution of the Navier-Stokes equation’ [9]. A more general definition is suggested in [10]: ‘a system with a main cross flow containing secondary intermittent streaming, at some angle to the direction of the main flow and with which it interacts’.

Evaluation of turbulence

Defining turbulence is no simple task, as can be seen above, and the evaluation of turbulence measurements requires complex calculations. Here we attempt to summarize the main steps in the turbulence evaluation/post-processing. The computational procedure introduced here was designed for quantifying properties of turbulent flow induced by the turbulence generating grid built into a wind tunnel. Measurements were carried out at fixed points using constant-temperature hot-wire anemometry (CTA) and a two-dimensional probe; this allowed samples to be taken for each measuring point at a sampling frequency of several kHz for streamwise (u) and transverse (v) instantaneous velocity components. Thus, a time series of u and v components was obtained for each point. These time series were then used in determining turbulence properties. Based on recommendations in the literature, measuring points were placed downstream of the grid at a suitable distance (starting from 10 M, where M is the mesh spacing (M=25 mm)), as this allows us to assume that due to local isotropy the standard deviations of the transverse velocity component are equal: $v_{std}=w_{std}$, where w is the z component, perpendicular to the main flow. This approach is applied when deriving the equations.
The definition of turbulent kinetic energy is

$$k = \frac{1}{2} \cdot (u_{std}^2 + 2 \cdot v_{std}^2), \quad (1)$$

where u_{std} is the standard deviation of the streamwise velocity component and v_{std} is the standard deviation of the transverse velocity component. Turbulent kinetic energy is defined as the turbulent energy per unit mass of fluid; thus, time series with larger standard deviations indicate flow with higher turbulent energy.

The turbulence intensity, which is obtained by the ratio of standard deviation of velocity and the mean velocity, is a general characteristic of the main flow. The streamwise turbulence intensity is widely used in the literature, defined as

$$T_u = \frac{u_{std}}{u_m} \cdot 100\%, \tag{2}$$

where u_m is the time-mean value of the streamwise velocity component.

When the turbulence intensity is based on all three velocity components, then the denominator by definition contains the average velocity of the main stream (mean velocity), since the time-mean of the velocity components perpendicular to the main stream vanishes. Hence the turbulence intensity is obtained as

$$T_{u,v,w} = \frac{\sqrt{\frac{1}{3}(u_{std}^2 + 2 \cdot v_{std}^2)}}{u_m} \cdot 100\%. \tag{3}$$

The integral time scale *ITS* can be calculated from the autocorrelation function of the velocity component in the direction of the main stream as

$$ITS = \int_{t=0}^{t(u_{\mathrm{ac}}=0)} u_{\mathrm{ac}}\, dt, \tag{4}$$

where u_{ac} is the autocorrelation value of the velocity component in the direction of the main flow. The integration should be started from t=0 and should be continued until the autocorrelation function $u_{ac}(t)$ becomes zero.

The integral length scale *ILS* is a value characteristic to the largest size of vortices in the flow. For wind tunnel measurements, this value can be approximated as the inner diameter of the wind tunnel. The value of *ILS* can be determined with the *ITS* and the average main flow velocity u_m as

$$ILS = ITS \cdot u_m. \tag{5}$$

The wide range of vortices in turbulent flows can be distinguished from each other by their characteristic sizes. The time series of velocity components in the direction of and perpendicular to the main stream can be converted into a frequency domain by Fourier transform, which can then be converted into power spectral density functions ($PSD_u(f)$, $PSD_v(f)$). This function gives the characteristic energy spectrum of the turbulent flow as functions of frequencies f present in the flow. In the literature, however, researchers prefer to give the energy spectrum as a function of wave number κ. The wave number is proportional to the number of vortices of given size in unit length, and is calculated as

$$\kappa = \frac{2\pi}{u_m} \cdot f. \tag{6}$$

The energy distribution of eddies of different sizes present in the turbulent flow gives useful information about the turbulence. That is why the energy spectrum E is an especially important characteristic of turbulence and can be calculated using the power spectral density function:

$$E_i(\kappa) = \frac{u_m}{2\pi} \cdot HPSD_i(f), \text{ where } i=\{u,v\}. \tag{7}$$

The three-dimensional energy spectrum function $E_{3D}(\kappa)$ using the isotropy assumption can be calculated as

$$E_{3D}(\kappa) = E_u(\kappa) + E_v(\kappa) + E_v(\kappa). \tag{8}$$

The dissipation rate of the turbulent kinetic energy ε is also an important feature of turbulence because the Kolmogorov scales (characterizing the smallest dissipative eddies in the flow) can be determined by ε, among others. The dissipation rate can be determined using the energy spectrum as

$$\varepsilon = 2 \cdot \nu \cdot \int_0^\infty (E_{3D}(\kappa) \cdot \kappa^2) d\kappa. \tag{9}$$

The dissipation rate is used for the determination of Kolmogorov length scale η, which is characteristic of the size of the smallest eddies in the flow, and is defined as

$$\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}, \tag{10}$$

where ν is the kinematic viscosity of fluid. It can be seen in this equation that η is a universal quantity. This length scale depends only on the viscosity and the dissipation rate. The value of η for laboratory wind tunnel measurements with sufficiently high turbulence Reynolds numbers is between 10^{-4} and 10^{-3} m.

When the Reynolds number is large enough, an inertial subrange $E_{in}(\kappa)$ can be observed in the turbulent energy spectrum $E_{3D}(\kappa)$. The larger eddies break up into smaller eddies, and the inertial forces dominate over dissipative forces, meaning that dissipative forces can be neglected. This domain ($ILS^{-1} \ll \kappa \ll \eta^{-1}$) is characterized by the exponent of (-5/3) in the energy spectrum curve. Based on [11] this domain can be approximated as

$$E_{in}(\kappa) \approx A \cdot \varepsilon^{\frac{2}{3}} \cdot \kappa^{-\frac{5}{3}}, \tag{11}$$

where A=1.5 is a universal constant.

Making quantities dimensionless allows us to compare various types of measured data. Non-dimensional quantities are used in the case of energy spectra, too. Wave length non-dimensionalised by the Kolmogorov length scale is given as

$$\kappa^* = \kappa \cdot \eta. \tag{12}$$

The energy spectrum function is made dimensionless using the quantity $(\nu^5\ \varepsilon)^{\frac{1}{4}}$:

$$E_{3D}{}^* = \frac{E_{3D}}{(\nu^5 \cdot \varepsilon)^{\frac{1}{4}}}. \tag{13}$$

Figure 1 shows an example for the dimensionless energy spectrum. The dots in the figure are hypothetical and the curve is based on Eqs. (11) and (13) and shows a good fit for the data points.

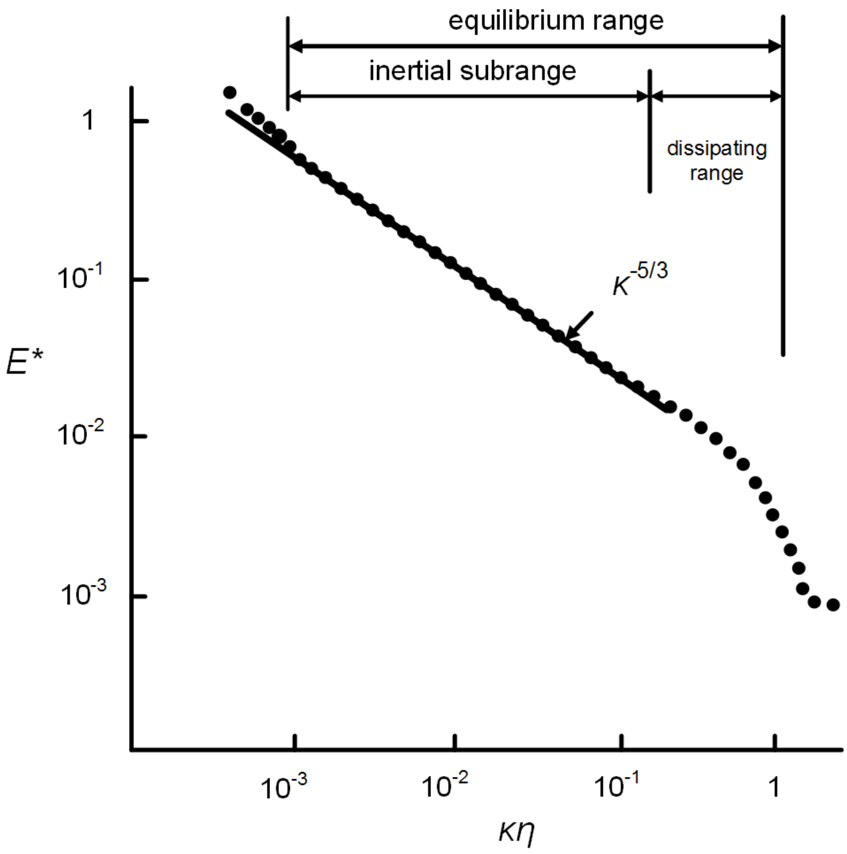

Fig. 1 A typical wavenumber spectrum observed in the ocean, plotted on a log-log scale. The unit of *E** is arbitrary, and the dots represent hypothetical data [11].

Based on these calculated quantities some further quantities describing turbulence can be determined. Based on [12] the definition of the length scale *LS* for larger vortices in the flow is

$$LS = \frac{k^{3/2}}{\varepsilon}. \tag{14}$$

Using the definition of *LS* the Taylor microscale λ_g can also be determined. This intermediate scale is characteristic for vortices larger than those described by the Kolmogorov length scale. The dynamics of these vortices is strongly influenced by the fluid viscosity. The Taylor microscale λ_g can be calculated as

$$\lambda_g = \sqrt{10} \cdot \eta^{\frac{2}{3}} \cdot LS^{\frac{1}{3}}. \tag{15}$$

The turbulence Reynolds number Re_L can be defined as the product of the square root of turbulent kinetic energy *k* and length scale *LS* divided by kinematic viscosity ν. Taking also into account Eq. (14) Re_L can be written as

$$Re_L = \frac{k^{\frac{1}{2}} \cdot LS}{\nu} = \frac{k^2}{\varepsilon \cdot \eta}. \tag{16}$$

Taylor-Reynolds number Re_λ is a dimensionless quantity used in the Taylor microscale. In grid turbulence this is probably the most important quantity to judge whether the fully developed turbulence stage has been reached or not. The magnitude of this quantity is related to the width of the inertial subrange in the energy spectrum. The larger the value of Re_λ the wider the wave number spectrum in the inertial subrange. The aim of this investigation is to reach fully developed turbulence, which is when the gradient of the physical quantities (except for that of the pressure) vanishes in the flow. The Taylor-Reynolds number can be calculated as

$$Re_\lambda = \left(\frac{20}{3} \cdot Re_L\right)^{1/2}. \tag{17}$$

Hence it can be seen that the Taylor-Reynolds number is proportional with the square root of the turbulence Reynolds number.

Results

To carry out the computations a computer code was developed for the software package MATLAB. Based on this code we are able to evaluate a variety of turbulence parameters of the flow generated by a turbulence generator. As an example, the variation of the Taylor-Reynolds number along the centerline of the wind tunnel downstream of the grid is shown in Fig. 2. Measurements were carried out downstream of the grid at 10, 15, 20, 25 and 28 times of the mesh spacing *M* (=25 mm) for mean flow velocities u_m= 3, 4, 5 and 6 m/s.

It can be seen in the figure that Re_λ is practically zero for u_m=3 m/s. It seems that at this velocity value the grid cannot obtain enough energy from the main flow to ensure fluttering. At the higher mean flow values investigated, the tapes of the grid were fluttering. Naturally the intensity of fluttering and turbulence intensity increase with u_m, resulting in up to a two-order-of-magnitude increase in Re_λ. The Re_λ values belonging to the higher velocity values (fluttering cases) decrease in the flow direction downstream of the grid. This is most likely due to the decrease in turbulent kinetic energy and its dissipation rate and also due to the change in the Kolmogorov length scale (Eq. (17)).

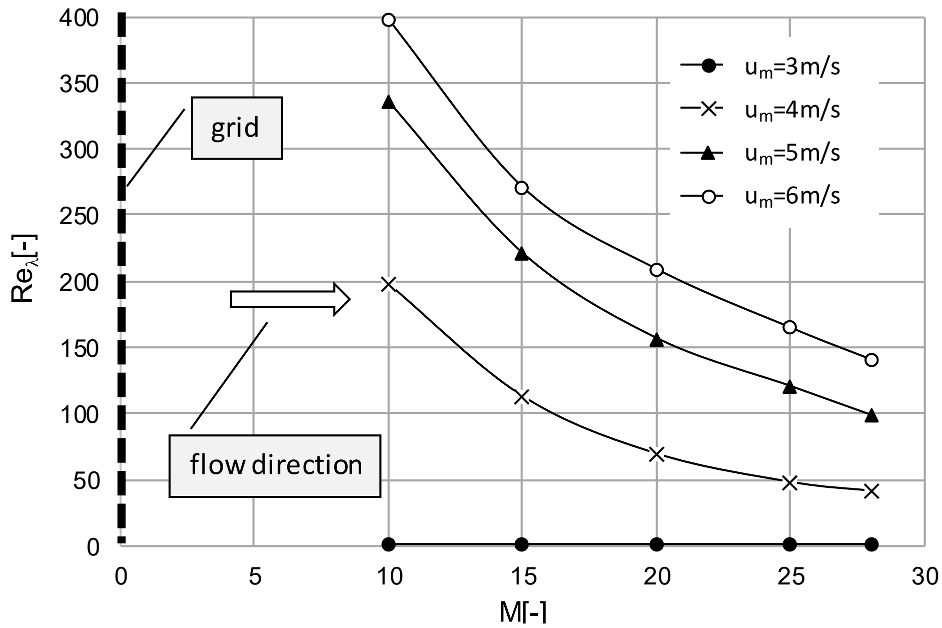

Fig. 2 Variation of the Taylor-Reynolds number along the centerline of the wind tunnel at different mean velocity values

Conclusion

The task of a turbulence generator is to create turbulent main flow of given properties for use in wind tunnel measurements. In order to assess the different types of turbulence generators, it is important to determine the characteristic parameters for the fine structure of the generated flow. The computational procedure that we have developed – using the CTA measuring technique to obtain *u* and *v* velocity components for each measuring point – allows us to calculate a number of important characteristics of turbulence at each measuring point. As a result of the measurements and calculations, even the spatial distribution of the turbulence properties becomes possible. The method is very complex, yielding numerous relevant values. Using these values both the properties of the turbulent flow field and those of the turbulence generator generating the flow field can be analyzed. A MATLAB® script was prepared to carry out the calculations. The method was used successfully for the investigation and comparison of different turbulence generators. As an example the variation of the Taylor-Reynolds number for an active turbulence generator developed by the authors [4] has been shown along the centerline of the wind tunnel at different mean velocity values. The study determined the limits of application of the grid and also the spatial distribution of turbulence parameters generated by the grid.

Acknowledgment

The described research was carried out as part of the EFOP-3.6.1-16-00011 "Younger and Renewing University – Innovative Knowledge City – institutional development of the University of Miskolc aiming at intelligent specialization" project implemented in the framework of the Szechenyi 2020 program. The realization of this project is supported by the European Union, co-financed by the European Social Fund.

References

[1] Md. Kamruzzaman, L. Djenidi, R. A. Antonia: Behaviours of Energy Spectrum at Low Reynolds Numbers in Grid Turbulence, *International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering*, World Academy of Science, Engineering and Technology, Vol:7, No:12 (2013), pp. 1385-1389.

[2] M. Hiderahu: Realization of a large-scale turbulence field in a small wind tunnel, *Fluid Dynamics Research*, IOP Publishing, North-Holland, Vol. 8.(1991), pp. 53-64.

[3] H. S. Kang, S. Chester, C. Meneveau: Decaying turbulence in an active-grid-generated flow and comparisons with large-eddy simulation, *Journal of Fluid Mechanics*, Cambridge University Press, UK, Vol:480 (2003), pp. 129-160.

[4] N. Szaszák, P. Bencs, Sz. Szabó: Experimental investigation of the effects of tensile force on the characteristics of turbulence downstream of a novel active grid, *Advances and Trends in Engineering Sciences and Technologies II: Proc. of the 2nd International Conference on Engineering Sciences and Technologies*, CRC Press/Balkema, (2017) pp. 261-266.

[5] A. Tsinober: *An informal introduction to turbulence*, Vol. 63. (2001), Springer Science & Business Media

[6] H, Schlichting,, J. Kestin [Trans.]: *Boundary layer theory* , 4th ed. New York, MacGrawHill (1960).

[7] B. J. Bayly, S. A. Orszag and T. Herbert: Instability mechanisms in shear-flow transition*, Annual review of fluid mechanics*, 20(1) (1988), pp. 359-391.

[8] P. G. Saffman: Vortex interactions and coherent structures in turbulence, *In: Transition and Turbulence: Proceedings of the Symposium on Transition and Turbulence in Fluids, Madison, WI, October 13-15, 1980. (A82-12438 02-34) New York, Academic Press, 1981, p. 149-166.*

[9] P. Bradshaw: *An introduction to turbulence and its measurement: thermodynamics and fluid mechanics series*, Elsevier, (2013).

[10] T. K. Tuoc: *A theory of turbulence, Part 1: Towards solutions of the Navier-stokes equations*, arXiv preprint: 0910.2072, (2009).

[11] P. K. Kundu, and L. M. Cohen: *Fluid mechanics, 3th edition,* (Academic, Calif., 1990).

[12] S. B. Pope: *Turbulent Flows*, Cambridge Univ. Press (2000).