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The decay power law in turbulence generated by grids

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Abstract

It is well known that turbulence in the flow can be characterized by two main parameters: the intensity and scale (such as macro- or microscale of length, time or speed). Turbulence in wind tunnels can be generated by a variety of means (placed perpendicularly to the flow) like passive and active grids, most often grids of round or square wires, perforated plates and so on. The aim of this study is to gain a detailed knowledge of the degree of turbulence isotropy and homogeneity in the flow behind the grids of variable geometry. For this purpose, skewness and kurtosis of the velocity fluctuations and also transverse variation for five grids of different parameters were determined. Additionally, some new results on the influence of the initial conditions of turbulence generation on the decay law of turbulence are given.

Keywords: Turbulence generation; Turbulence intensity; Grid; Isotropy; Homogeneity

1 Introduction

Recently there is a renewed interest in generation of turbulence of more broader range of characteristics like scales and more specific parameters, e.g., zero shear stress. Therefore new methods of its generation are used. The methods of turbulence generation can be divided into passive (regular static grids, fractal grids) and active (jet, grid with wings).

Turbulence homogeneity improvement can be attained by the active grids that

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are equipped with controllable nozzles [1]. Compared with the passive case, the downwind-jet active grids has a smaller pressure drop across it and gives a smaller turbulence level. The upwind-jet grid gives a larger static pressure drop, larger turbulence level and scales, which is much like that commonly observed behind passive grids of higher solidities. According to the authors, a coflow injection grid generates turbulence with a greater degree of isotropy and homogeneity than it would be in the case of passive grid or counterflow injection grid. Other authors [2] used the turbulence generator consisting of grid bars with triangular wings that rotate and flap in a random way. They have explored the evolution of grid turbulence with Reynolds number. Their experiments, made with the use of such active grid, appeared to be first to bridge the gap between the low-Reynolds-number laboratory studies of grid-generated turbulence and the high-Reynolds-number experiments done in the atmosphere and the oceans. Their results suggest that much can be learned about the behaviour of turbulence at high reynolds number (Re) using a small wind tunnel.

New experimental results of decaying turbulence were presented in [3], to highlight the similarities and differences between turbulent flow behind regular grid, and the turbulence generated by fractal square grid and to compare them with measurements made by [2]. Their investigations also examine the homogeneity and isotropy of the decaying turbulence. They noted that the study of freely decaying turbulence requires experiments where a wide range of Reynolds number can be achieved by modifying the initial conditions.

2 Experimental rig

The investigation was carried out in the subsonic wind tunnel of low level of turbulence, $Tu < 0.08\%$ and velocity up to 100 m/s [26]. The enhanced level of turbulence was generated by five wicker grids of following dimensions named appropriately:

1) G1: $d = 0.3$ mm, $M = 1$ mm,
2) G2: $d = 0.6$ mm, $M = 3$ mm,
3) G3: $d = 1.6$ mm, $M = 4$ mm,
4) G4: $d = 3.0$ mm, $M = 10$ mm,
5) G5: $d = 3.0$ mm, $M = 30$ mm,

where d is the diameter of wire, and M is the mesh size. The coordinate system for the turbulence intensity and scale measurements is fixed to the grid with x coordinate parallel to the mean velocity of flow. The investigation consisted of measuring the average velocity profiles and the velocity fluctuations by means of the 55P15 thermoanemometry probe of DANTEC [27,28]. Data were transferred to the PC via a data acquisition card NI 6040. The velocity of the incoming stream was also a variable parameter during the investigations. For each grid, it was equal to:

1) G1: $U = 10, 15$, and 20 m/s that corresponds to the Reynolds number, given by the formula (4): $\mathrm{Re}_M = 1350, 2020$, and 2700, respectively

2) G2: $U = 10, 15$, and 20 m/s, $\mathrm{Re}_M = 3250, 4750$, and 6100

3) G3: $U = 6, 10, 15$, and 20 m/s, $\mathrm{Re}_M = 4600, 7500, 11150$, and 14650

4) G4: $U = 6$, and 10 m/s, $\mathrm{Re}_M = 8800$, and 14700

5) G5: $U = 4$, and 6 m/s, $\mathrm{Re}_M = 9000$, and 15000.

3 Turbulence intensity behind the grid

3.1 Isotropy and homogeneity of turbulence

In general, the turbulence intensity is defined as the ratio of standard deviation to the mean flow velocity, U. If the velocity field is described by the coordinate system x_i, where x_1 is an axis oriented in the direction of the mean flow velocity ($U = U_1$, $U_2 = U_3 = 0$), a ratio

$$Tu_i = \frac{\sqrt{\overline{u^2}_i}}{U} = \frac{u_i'}{U} \,, \quad , i = 1, 2, 3 \,, \tag{6}$$

where $i = 1$ corresponds to the longitudinal turbulence intensity and the two others to the components of the transverse intensity. In case of isotropic turbulence their characteristics do not depend on the spatial orientation of the coordinate system.

One of the methods to assess the isotropy of turbulence is to determine the skewness factor in the flow velocity distribution [4,5]:

$$S(u) = \frac{\overline{u^3}}{\overline{u^2}^{3/2}} \,, \tag{2a}$$

where u is the mean flow velocity fluctuation, and overbar denotes the mean value. The turbulence is isotropic, if the skewness factor is zero and hence, the probability density function of the variable u has normal distribution.

In a similar way to the concept of skewness, kurtosis is a descriptor of the shape of a probability distribution. The measure of kurtosis ia a fourth central moment of mean velocity divided by the standard deviation to the fourth power:

$$K(u) = \frac{\overline{u^4}}{\overline{u^2}^{4/2}} \ . \tag{2b}$$

When $K(u) = 3$, the probability distribution is normal, while for $K(u) < 3$ or $K(u) > 3$, kurtosis are called platykurtic distributions (flat) or leptokurtic distributions (focused), respectively. According to [4], the distribution can be considered as normal to the value of $K(u) = 2.86$ or $K(u) = 2.85$ [6].

As a method to investigate the homogeneity of the flow behind the grid, transverse variation can be used [5]. It is the difference of the root mean square of the downstream velocity, $\overline{u^2}^{1/2}$, and the centreline value normalized by the centreline value, $\overline{u^2}_0^{1/2}$:

$$V(u) = \frac{\overline{u^2}^{1/2} - \overline{u^2}_0^{1/2}}{\overline{u^2}_0^{1/2}} \ . \tag{3}$$

The experiments show that the lower is the Reynolds number, based on the mesh size, M, the closer to homogeneous is the flow behind the grid;

$$\mathrm{Re}_M = U_M M/v \ , \tag{4}$$

where $U_M = U_\infty/(1-S)$ is an averaged flow velocity at the grid mesh.

There is an initial distance wake region downstream of a grid where the flow is strongly inhomogeneous. This is due to the fact that initially isolated bar wakes increase their size and coalesce to form a truly homogeneous flow. Experiment of Roach [7] shows that the area where the turbulence is inhomogeneous, depends on the mesh size and the flow can be considered to be homogeneous by ten mesh lengths downstream of a grid. However, different authors give different assumptions. For example in [8] we can read that the homogeneity of the flow depends on the grid parameters and on the surface roughness of the grid elements; the value of the distance from which turbulence can be considered to be nearly homogeneous is $x/M = 95$. As noted in [9], the turbulence homogeneity depends on the shape of the grid elements and also on the grid fill factor (5). For example for $S \approx 0.4$ (quite small fill factor) the homogeneous turbulence was obtain for $x/M = 40$. Other authors [10], for the grid with mesh size $M = 1.27 \times 10^{-2}$ m, obtained the homogeneity of the flow by 80 mesh lengths downstream of a grid.

One of the methods to gain isotropic turbulence is to achieve high Reynolds number that is difficult with the use of 'conventional' (or static) grids. Turbulence isotropy and homogeneity improvement can be attained by the active (or dynamic) grids that are equipped with controllable nozzles. This technique has been used for example by Makita [11,12] and improved by Mydlarski and Warhaft [2,13], where a Taylor Reynolds number of the order of 700 was achieved [13]. Another method for generating isotropic turbulence is by using a closed vessel stirred with fans. This method was first developed by Semenov [14]. Later, similar setups based on Semenov's concept were developed by different authors, for example [15] or [16]. An attempt to gain isotropic turbulence at low Reynolds number was recently made by Birouk *et al.* [17]. For this aim an experimental apparatus, a turbulence chamber 'box', was used to generate an isotropic turbulent flow field in the center of the chamber, even though the Reynolds number achieved in this experiment is considered to be small, $\mathrm{Re}_\lambda = u'\lambda/v < 100$, where λ is a length Taylor microscale.

3.2 Decay power law

An important parameter describing the grid is the grid fill factor determined from the equation

$$S = 1 - \beta = 1 - \left(1 - \frac{d}{M}\right)^2 , \tag{5}$$

where $\beta = F_1/F_0$ is the ratio of the area unoccupied by the grid rods, F_1, of diameter d, and the total grid area, F_0; M is the grid mesh size. Roach [7] gives a very simple formula for the level of turbulence, depending on the diameter of the grid wire, d:

$$Tu = c\left(\frac{x}{d}\right)^{-n} , \tag{6}$$

where x is an axis oriented in the direction of the mean flow velocity. In accordance with the Roach's experiments, a value of the experimental factor c is usually equal to approximately 0.8, and $n = 5/7$. Another equations used to determine the decay of turbulence behind a grid were given by Mikhailova *et al.* [18]:

$$Tu = c_1\left(\frac{x}{M}\right)^{-n_1} , \qquad (7a) ,$$

$$\frac{Tu}{\sqrt{S}} = c_1\left(\frac{x}{M}\right)^{-n_2} , \qquad (7b) ,$$

where constant values c_1, n_1 and c_2, n_2 are determined experimentally. In accordance with the data of different authors, cited by Mikhailova *et al.* [18], the exponent n_1 takes values 0.5 to 0.7. In expression (7b), $c_2 = 86$, $n_2 \approx 0.95$ in the initial wake region (for $7 \leq x/M \leq 20$), and $c_2 = 41$, $n_2 \approx 0.7$ in the main region (for $x/M > 20$) in the wake downstream of the wicker grids [19]. Finally, Comte-Bellot *et al.* [20], following for example Batchelor and Townsend [21], gives the power law for the data on $1 - \overline{u^2}$:

$$1/Tu^2 = U^2/\overline{U^2} = A/((x - x_0)/M)^m \ , \tag{8}$$

where x is the coordinate, positive in the downstream direction with origin at the grid, x_0 – the virtual origin, A and m – the decay coefficient and exponent determined experimentally, respectively . One can find different values for the decay exponent, determined in many experiments by different authors, e.g., 1, 10/7, 6/5, 1.43 or $1.16 \leq m \leq 1.37$ [5]. As noted in [22], the value of m is determined by arbitrarily chosen distance x_0 from the grid to a conventional origin of the coordinate system, where $1/Tu = 0$.

4 Investigation results

First of all, isotropy and homogeneity of the flow behind the grid were investigated. Figures 1a and 1b present the skewness factor, $S(u)$, for grids G2 and G5, depending on x/M. Figure 1a shows the results for velocities $U = 15$ and 20 m/s, which correspond to the Reynolds numbers $\mathrm{Re}_M = 4750$, and 6100. Directly behind the grid, for $x/M = 30$, skewness factor is different from zero, but does not exceed 13% at the highest point. Then tends to zero, which indicates that the probability density function of the variable u' approaches the Gaussian distribution. From $x/M = 150$ we observe the skewness factor not exceeding 5%. Directly behind the grid G5 (Fig. 1b) the flow is strongly anisotropic. At a distance of $x/M = 1.5$ from the grid, $S(u) = -0.27$ for $\mathrm{Re}_M = 9000$, and $S(u) = -0.09$ for $Re_M = 15000$. The skewness factor is negative because of the bar wakes velocity fluctuations that are smaller than the average velocity flow fluctuations. From $x/M = 15$ we observe the skewness factor increase and for $x/M = 30$ it is still very high, $S(u) = 16\%$.

Kurtosis for the grid G2 oscillates around a value of 3. At the distance of $x/M = 30$ from the grid distribution is leptokurtic but $K(u)$ does not exceed a value of 3.1. Then it decreases slightly which means a distribution becomes more flat. The smallest value of kurtosis, $K(u) = 2.79$, is at distance of $x/M = 255$ for $\mathrm{Re}_M = 6100$. A quite different distribution of kurtosis is given by a flow velocity for the grid G5. At the beginning $K(u)$ is small, about 2.6 for $\mathrm{Re}_M = 9000$. Then increases slightly and gains a value of 2.99 at $x/M = 36$ for $\mathrm{Re}_M = 15000$.

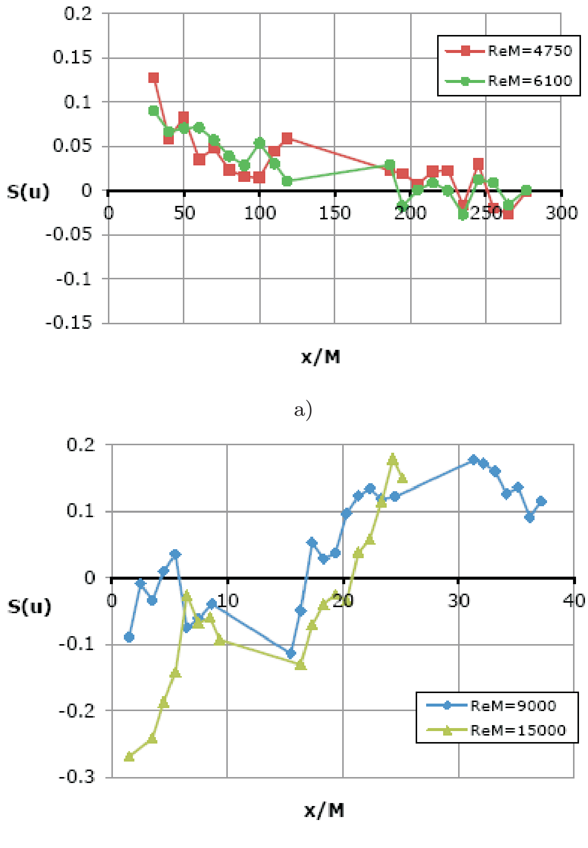
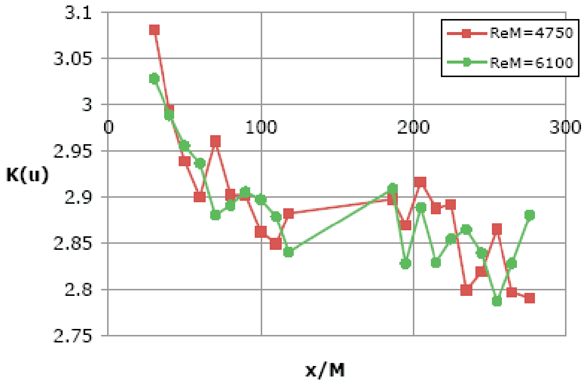
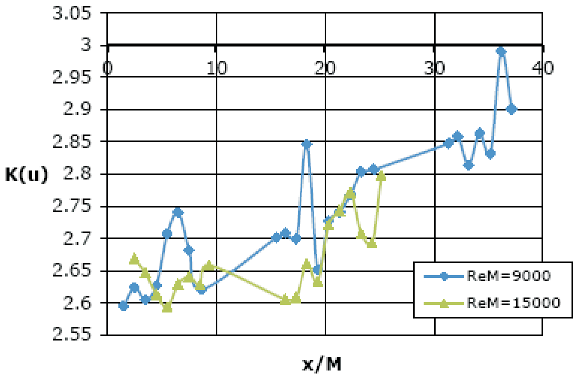


Figure 1: Skewness factor for a) grid G2 and Reynolds numbers ReM = 4750 and 6100, b) grid G5 and Reynolds numbers ReM = 9000 and 15000.

Figures 3 and 4 present transverse variation as a function of x/M, where y is the coordinate normal to the velocity vector. Figure 3 relates to the grid G2 and Reynolds number $\mathrm{Re}_M = 6100$. Measurements were made at three distances from the grid: $x/M = 30$, 63, 97. For a distance of $x/M = 97$, $V(u)$ does not exceed 4% (for $x/M = 30$ and $x/M = 63$ it does not increase much), so it can be assumed that the turbulence is homogeneous at this point. Figure 4 shows the case of grid G5 and Reynolds number $\mathrm{Re}_M = 15000$. At a distance of $x/M = 3$ the difference between the flow behind the mesh and the flow tracing the wire is clearly visible. As the distance from the grid increases we can see the transverse variation reduction, but the flow is still far from homogeneous (about 20%). So



a)



b)

Figure 2: Kurtosis for: a) grid G2 and Reynolds numbers $\mathrm{Re}_M = 4750$ and 6100; b) grid G5 and Reynolds numbers $\mathrm{Re}_M = 9000$ and 15000.

we can agree with Valente and Vassilicos [3], who claim that for regular grids the turbulent flow should be considered inhomogeneous in transverse planes for $x/M < 25$ (or even more; as shown in Fig. 3, $V(u)$ exceeds slightly the value of 4% for $x/M = 30$).

The best correlation describing the decay of turbulence behind the grid was obtained for the Eq. (8). The results of the investigation for five wicker grids of different dimensions are shown in Fig. 5 and the values of A, m and x_0/M – in Tab. 1. Making correlation for all grids together, we get: $A = 32.8$, $m = 1.49$ and $x_0/M = 1$. The correlation coefficient is equal to 0.992. The values of skewness, kurtosis and transverse variation for other grids one can find in [25].

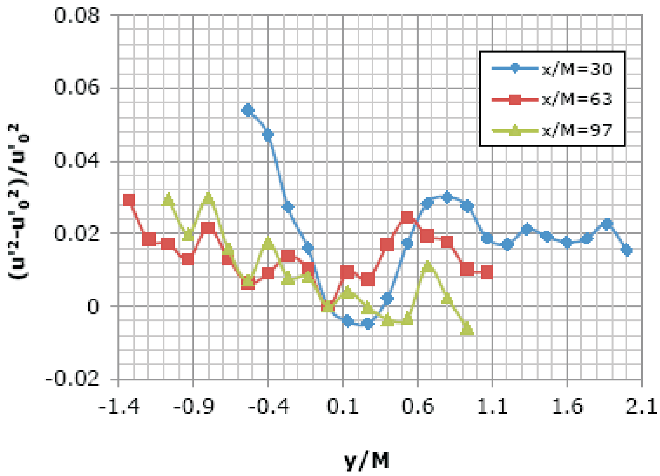


Figure 3: Transverse variation for grid G2 and $Re_M = 6100$.

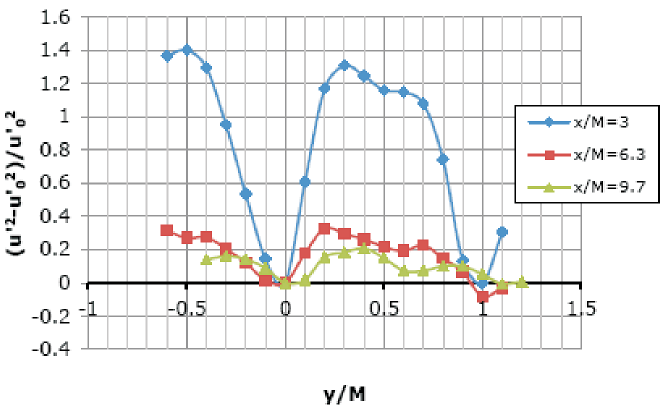


Figure 4: Transverse variation for grid G5 and $\mathrm{Re}_M = 15000$.

The results for correlations (7a) and (7b) are presented at Fig. 6 and 7. Correlations at Fig. 6 are made separately for each grid and the coefficients c_1 and n_1 are presented in Tab. 2. As we can see, c_1 and n_1 increase consequently with the grid dimensions, except for the grid G5, which generates neither isotropic nor homogeneous turbulence.

It is worth mentioning that the results for the correlation given by Roach as the formula (6), suggest the decay coefficient c and the exponent n both depend

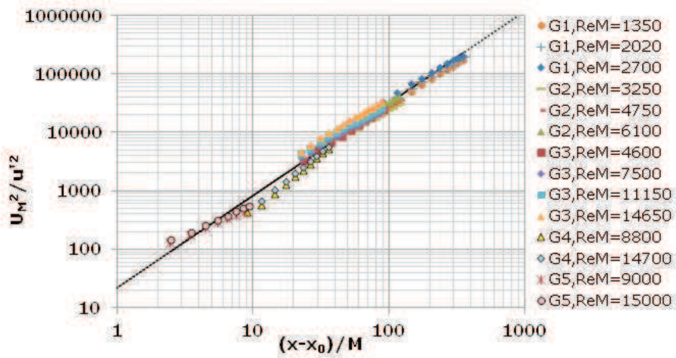


Figure 5: The decay power law (8) behind grids.

Table 1: Values of A, m, and x_0/M at formula (8) for different grids.

Grid	A	m	x_0/M
G1	85.3	1.33	11
G2	44.4	1.41	-3
G3	142.3	1.18	6
G4	3.4	2.03	-2
G5	41.6	1.12	-0.3

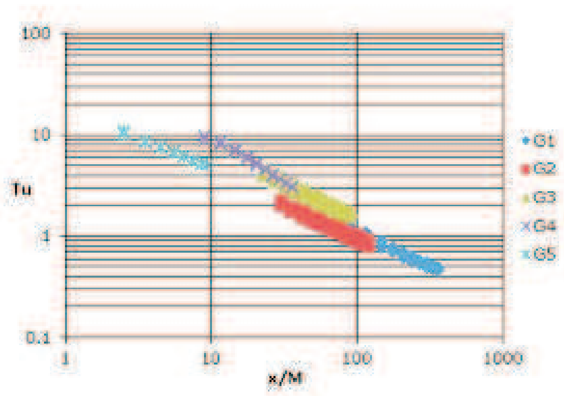


Figure 6: The decay power law (7a) behind grids.

Table 2: Coefficient c_1 and exponent n_1 at the formula (7a) for different grids.

Grid	c_1	n_1
G1	4.4	0.354
G2	19.2	0.656
G3	36.6	0.684
G4	63.6	0.839
G5	17.8	0.572

on the Reynolds number based on grid dimension, M:

$$c = \varphi_c \mathrm{Re}_M^{-zc} \qquad n = \varphi_n \mathrm{Re}_M^{-zn} \ . \tag{9}$$

Recent experiments seem to confirm this assumption (Figs. 8a and 8b). (The same correlation was made for the Reynolds number based on the rod diameter, d.) The factors zc, zn (which were avaraged for all grids) and ϕc, ϕn are shown in Tab. 3. The factors φ_c and φ_n increase consequently with the grid dimensions, again with the exception of the Grid5.

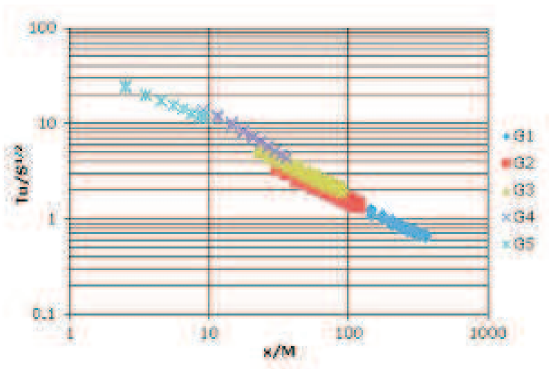
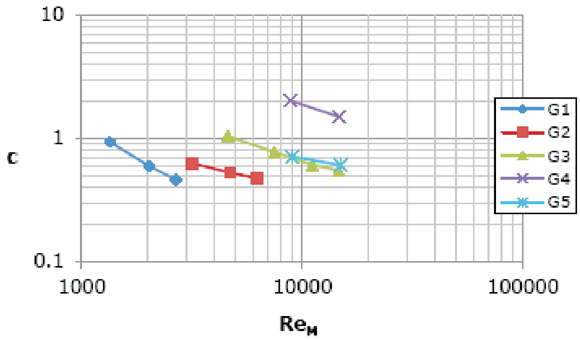


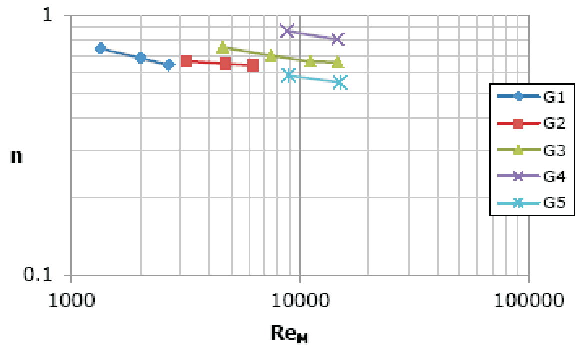
Figure 7: The decay power law (7b) behind grids.

5 Conclusions

To investigate the isotropy and homogeneity of turbulence in the flow behind different grids the skewness factor of the flow velocity distribution function and



a)



b)

Figure 8: Coefficient c (a) and exponent n (b) of the power law (6) behind grids.

Table 3: Factors from expressions (9) for different grids.

Grid number	φ_c	zc	φ_n	zn
G1	51.2	0.58	1.78	0.12
G2	70.6		1.86	
G3	137.1		2.14	
G4	388.2		2.68	
G5	148.1		1.82	

also the transverse variation were determined. The results showed that there is an initial distance in the bar wakes to which the flow is strongly anisotropic and inhomogeneous. The effect of wake is the stronger, the greater are the parameters

M and d (mesh size and diameter of wire)of the grid.

Few different correlations of decay power law were tested. The most accurate seems to be relation (8), which has the greatest correlation coefficient. It requires indeed the determining of the virtual beginning of the turbulence. Referring to relation (6) there is a prediction the decay coefficient c and the exponent n both depend on the Reynolds number based on the grid dimensions.

These results will be used to assess the influence of the different characteristics of turbulence on the laminar-turbulent transition in the boundary layer of a flat plate. An exact method to determine the onset of the transition one can find in [23], [24] or [25].

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