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Velocity and Temperature Decay in Turbulent Flow behind Parallel Heat Sources

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Abstract. Paper deals with the velocity and temperature field generated by a system of parallel heated wires placed in grid-generated turbulent flow. Development of the temperature field was studied for a number of configurations of grid generator and line heater was investigated experimentally. Decay of the temperature fluctuations was evaluated from thermoanemometry measurements.

1 Introduction

An early study of the variation of the turbulence intensity with distance downstream of a grid in the homogeneous isotropic turbulence has been reported in 1934 by Simmons and Salter [1]. Since that time many experiments has been carried out. Variance of the downstream component of the fluctuating velocity should follow the decay power-law. Passive scalars, similarly to the velocity, also develop in a turbulent flow. The decay of a scalar is of great importance in modelling of turbulent flows (eg. [11]).

The variation of the temperature fluctuation downstream has been measured in the experiment. Turbulence is generated by a grid and the temperature field by parallel thin heated wires, which produce large cross temperature gradients.

2 Experimental setup

Experiments were performed in a blow-down tunnel.

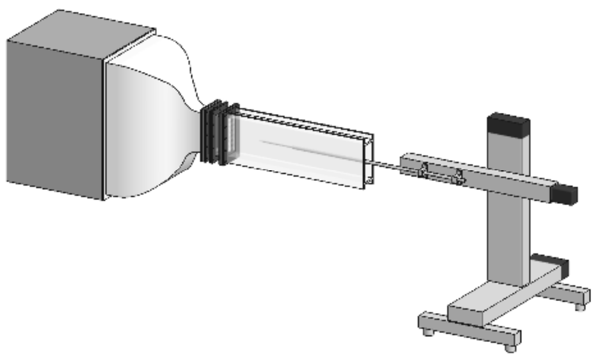

Fig. 1. Experimental setup of a channel and a probe traversing system

Cross section of the channel is of a width of 0.1 m and a height of 0.25 m. The channel downstream is 1.0 m in length. There are placed a turbulence-generating grid and a mandoline behind contraction. Figure 1 shows a scheme of experimental arrangement.

The tunnel has a rectangular cross section with filled corners, honeycomb and a system of damping screens followed by contraction with ratio of 16. The time-mean velocity departures from homogeneity in planes perpendicular to the tunnel axis are of order tenth of percent with the exception of corners, where corner vortex starters could be detected. The natural turbulence level is about $Tu_0 = 0.12$ % in the working section input.

2.1 Turbulence grid generators

Four grids were manufactured with the same solidity ratio of 0.37. Grids A and B were made of circular rods whilst grids C and D were made of square ones (see figures 2 and 3).

Fig. 2. Grid GT-B

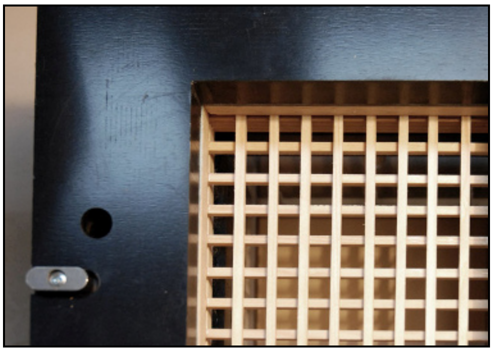

Fig. 3. Grid GT-C

Intensity of turbulence at a distance x/M = 50 behind the grid is denoted Tu_{50}. Table 1 shows grid parameters.

Table 1. Parametres of turbulence grid generators

Grid	*Rod* (mm)	*M* (mm)	Tu_{50} (%)
GT-A	dia 1.02	5	0.26
GT-B	dia 1.57	5.75	0.32
GT-C	3×3	11	0.55
GT-D	5×5	18.5	0.35

2.2 Mandoline

The thermal field is generated by a mandoline, placed downstream the grid. A mandoline is a system of fine parallel wires; used as a line heat source by Warhaft and Lumley [6]. Distance of the mandoline from the grid was in a region of a = (20-150) mm (figure 4).

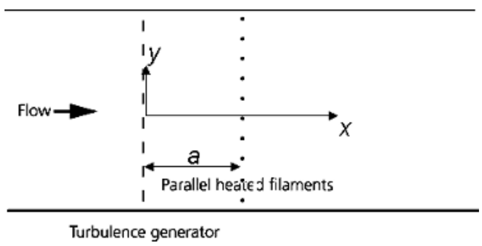

Fig. 4. A grid with a mandoline

The mandoline consists of nickel-chromium wires of diameter of 0.25 mm. Spacing between wires is 5 mm. Wires are oriented horizontally. Springs on the sides of flange are used to keep wires under tension to prevent sagging.

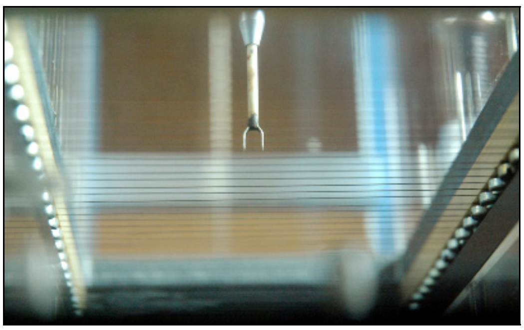

Fig. 5. The mandoline (view from top)

A power consumption of a mandoline was set to 0.7 kW giving an increase of mean temperature of ΔT=2.5 K. Two RTD thermometers Pt100 were employed for indicating of a mean temperature rise ΔT. The first one was inserted in the inlet of the tunnel - upstream the damping screens. The second one was placed near the outlet of the channel – downstream the mandoline, which indicated a mean heated-flow temperature.

2.3 Dual wire probe

A dual probe with two sensors was manufactured for the velocity and temperature measurement. The probe is composed from two parallel wires (space between wires is about 0.5 mm). The first sensor W1 (tungsten wire; diameter d_{w1} = 5 μm; active length l_{w1} = 1.25 mm) was operated in CTA mode (wire temperature is T_{w1} = 493 K); the second sensor W2 (tungsten wire; diameter d_{w2} = 2.8 μm; length l_{w2} = 4.8 mm) was operated in CCA mode (I_{w2} = 2 mA).

The probe was calibrated in the rig with variable flow temperature T = (290-320) K in the range of velocities u=(2-24) m/s. Wire temperatures were set T_{w1} = (450-510) K.

The CTA system DANTEC Streamline and the A.A.Lab.System AN-1003 CCA bridge were used for operating wires. The output signals are then digitalized using the A/D transducer (National Instruments data acquisition system, sampling frequency 25 kHz, 16 bit).

3 Results

The measurement was carried out at a mean test-section speed u = 4.0 m/s; a grid Reynolds number was about Re_M = 1180 for GT-A. There were set up several distances between grid and mandoline (a/M) for each grid.

An intensity of turbulence Tu and a variance of temperature fluctuation $\overline{\theta^2}$ were evaluated from time series of hot/cold-wire measurements. The turbulence intensity and the variance of temperature fluctuation are defined as follows:

$$Tu = \frac{1}{\bar{u}}\sqrt{\mathrm{Var}(u)} = \frac{1}{\bar{u}}\sqrt{\frac{1}{N}\sum_{k=1}^{N}\left(u_k - \bar{u}\right)^2} \quad , \qquad (1)$$

$$\overline{\theta^2} = \mathrm{Var}(T) = \frac{1}{N}\sum_{k=1}^{N}\left(T_k - \bar{T}\right)^2 \quad . \qquad (2)$$

A comprehensive study of the decay by Comte-Bellot and Corrsin [5] indicated that $Tu^2 = A[(x-x_0)/M]^{-n}$, where x is a downstream coordinate and x_0 represents a virtual origin. Coefficient A and exponent n appeared to depend on the particular geometry and Reynolds number Re_M. Virtual origin is used to account for the fact that effective origin of the velocity fluctuation may not coincide with location of the grid. Typical values are in the range of x_0/M = 0÷15 ([2], [5]). Determination of x_0 is usually made by condition for a minimum of the root mean square of the difference between measured values and corresponding values of power law. Mohamed and

LaRue [9] recomputed some of previous experiments for $x_0 = 0$ and concluded on typical value of decay exponent $n = 1.1$-1.4.

Exponents of all used grids in experiment are nearly the same. Velocity fluctuation decay is shown for grid GT-D (graph 1). The grid GT-D gives a turbulence-decay exponent $n = 1.12$ and parameter $A = 0.0012$ for $x_0 = 0$. Origin of x-coordinate is taken in a plane of the grid.

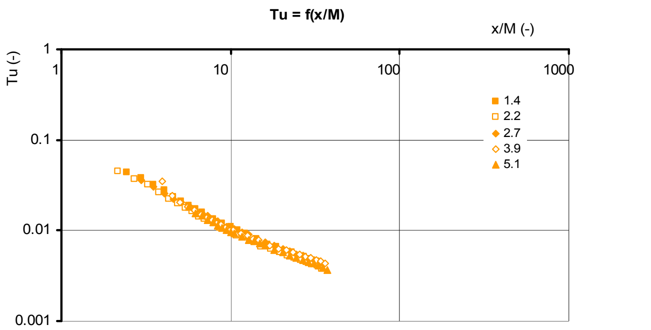

Fig. 6. Graph 1. Downstream decay of the turbulence Tu (-); GT-D; $u = 4.0$ m/s; T ≈ 391 K; heated mandoline $\Delta T = 2.5$ K; $y = 0$; $a/M = (1.4;2.2;2.7;3.9;5.1)$

Developments of the temperature-variance on the centreline of the channel behind a mandoline are shown for grids GT-A, GT-B, GT-C and GT-D in following graphs. In graphs 2, 3, 4 and 5 an origin of x-coordinate take place at the location of the mandoline.

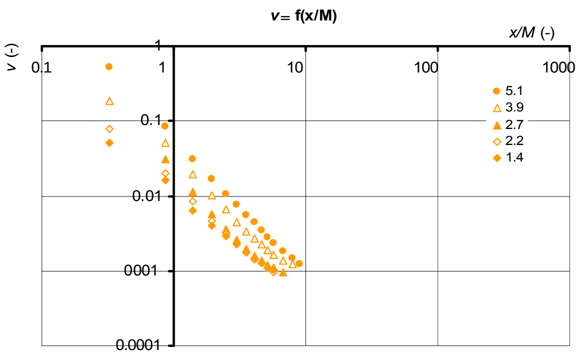

Fig. 7. Graph 2. Downstream decay of the temperature variance $v = \overline{\theta^2} / \Delta T^2$ (-); GT-A; $u = 4.0$ m/s; T ≈ 391 K; $\Delta T = 2.5$ K; $y = 0$; $a/M = (4.4;7.4;10.4;15.4;21.4)$

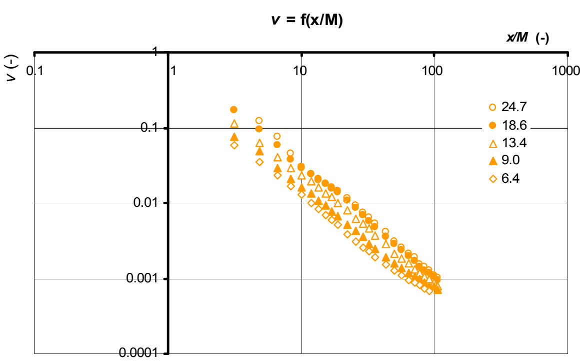

Fig. 8. Graph 3. Downstream decay of the temperature variance $v = \overline{\theta^2} / \Delta T^2$ (-); GT-B; $u = 4.0$ m/s; T ≈ 391 K; $\Delta T = 2.5$ K; $y = 0$; $a/M = (6.4;9;13.4;18.6;24.7)$

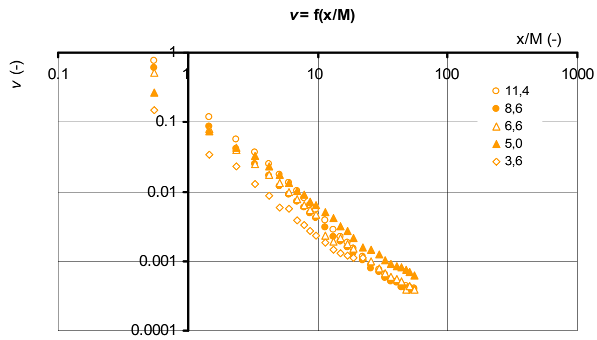

Fig. 9. Graph 4. Downstream decay of the temperature variance $v = \overline{\theta^2} / \Delta T^2$ (-); GT-C; $u = 4.0$ m/s; T ≈ 391 K; $\Delta T = 2.5$ K; $y = 0$; $a/M = (3.6;5;6.6;8.6;11.4)$

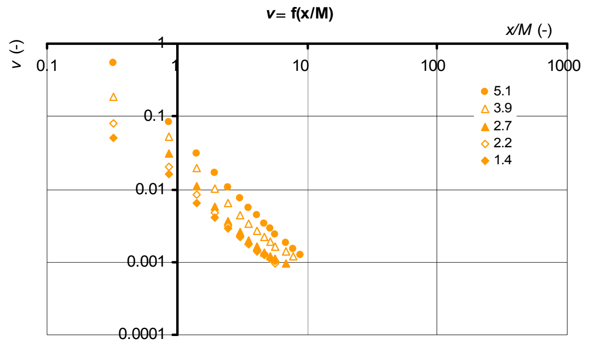

Fig. 10. Graph 5. Downstream decay of the temperature variance $v = \overline{\theta^2} / \Delta T^2$ (-); GT-D; $u = 4.0$ m/s; T ≈ 391 K; $\Delta T = 2.5$ K; $y = 0$; $a/M = (1.4;2.2;2.7;3.9;5.1)$

A decay of a scalar in turbulent flow can be expressed by a power law; the temperature-variance decay is described in the form:

$$\frac{\overline{\theta^2}}{\Delta T^2} = B\left(\frac{x}{M}\right)^{-m} \quad . \tag{3}$$

The variance of the temperature is normalised by square of a mean temperature rise; there are two reasons for that. First, it make left side of eq. (3) nondimensional. Second, in spite of trying to keep constant condition for every tests, small departures from adjusted velocity and mandoline heat power occured; we believe that the eq. (3) compensates in certain region these phenomenas. Evaluated coefficients B and exponents m which represent best fits of the formulae (3) on the data are given in the tab. 2.

Table 2. Parameters of the temperature-variance decay

	GT-A				
a/M (-)	4.4	7.4	10.4	15.4	21.4
B (-)	0.18	0.33	0.46	0.64	1.11
m (-)	1.23	1.30	1.31	1.37	1.41
	GT-B				
a/M (-)	6.4	9.0	13.4	18.6	24.7
B (-)	0.29	0.39	0.63	0.99	1.20
m (-)	1.37	1.38	1.44	1.49	1.53
	GT-C				
a/M (-)	3.6	5.0	6.6	8.6	11.4
B (-)	0.06	0.14	0.15	0.16	0.24
m (-)	1.35	1.37	1.54	1.60	1.67
	GT-D				
a/M (-)	1.4	2.2	2.7	3.9	5.1
B (-)	0.011	0.014	0.019	0.032	0.061
m (-)	1.41	1.58	1.69	1.69	1.83

The decay rates compare well with results of Warhaft and Lumley [6] and Sirivat and Warhaft [7]. They reported measurement of thermal decay in approximately isotropic grid turbulence with exponents from 0.86 to 2.95 (depending on the configuration of a grid and a mandoline and level of heating).

4 Conclusion

Development of the temperature fluctuation produced by a mandoline downstream a grid has been investigated experimentally. The results show that the variance of temperature follows power-law decay. By moving the mandoline away from the turbulence-grid generator the thermal-variance decay increases. Four grids were used in the experiment. The exponent is varying from 1.23 to 1.83. For each grid can be stated that the exponent is lower if the mandoline is placed closer to the grid and higher if the mandoline is further downstream of the grid. Reynolds number Re_M = 1180 for grid GT-A and Re_M = 4370 for GT-D respectively.

Acknowledgement

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