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TEMPERATURE FIELD BEHIND PARALLEL-LINE HEAT SOURCE IN TURBULENT FLOW

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ABSTRACT

An interaction of the free turbulent shear flow and the steady temperature field, which develops to the homogeneity in the planes that are perpendicular to the main stream, was studied. The temperature field was generated by parallel thin heated wires. The isotropic grid turbulence is supposed. Heated wire generates large cross temperature gradients whereas unheated one does not affect the flow. Development of the temperature field was investigated experimentally.

INTRODUCTION

The variation of the intensity of turbulence with distance downstream of a grid in the homogeneous isotropic turbulence has been investigated many times since the experiments reported by Simmons and Salter (1934). Fundamentals of turbulent flow were summarized eg. by Hinze (1959). Variance of the downstream component of the fluctuating velocity should follow the decay power-law.

NOMENCLATURE

u	[m/s]	fluid velocity
T	[K]	fluid temperature
θ^2	[K^2]	variance of temperature fluctuation
Iu	[-]	intensity of turbulence
Iu_0	[-]	intensity of turbulence in the channel without grid
x, y	[m]	Cartesian coordinates
a	[m]	distance between grid generator and the mandoline
Re_M	[-]	Reynolds number based on a mesh length of a grid
E	[V]	anemometer output voltage
Nu, Re	[-]	Nusselt and Reynolds numbers of the hot-wire probe
T_w	[K]	operating temperature of the probe sensor
I_w	[A]	operating current of the probe sensor
A_w, B_w, n_w, m_w	[-]	parameters of the heat-transfer law
d_w, l_w	[m]	diameter and length of the probe sensor
ρ, λ, μ		thermophysical properties of fluid
M	[m]	mesh length of a grid
A, n	[-]	parameters of the turbulence-intensity decay
B, m	[K^2, -]	parameters of the temperature-variance decay

A comprehensive study of the decay by Comte-Bellot and Corrsin (1966) indicated that $Iu = A[(x-x_0)/M]^{-n}$, 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.

Similarly to the velocity, also heat and other passive scalars develop in a turbulent flow. The decay of a scalar is of great importance in modelling of turbulent flows. The variation of the temperature fluctuation downstream has been measured in the experiment.

EXPERIMENTAL SETUP

Experiments were performed at a blow-down tunnel. Cross section of the channel is of a width of 0.1 m and a height of 0.25 m. The channel downstream the mandoline is 1 m in length.

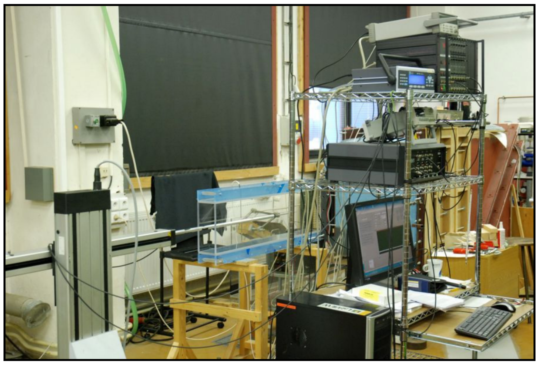


Figure 1 Blow-down tunnel

The tunnel has 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 was about Iu_0=0.002 in the working section input.

A scheme of the turbulence generator and the mandoline in the channel is in Fig. 2.

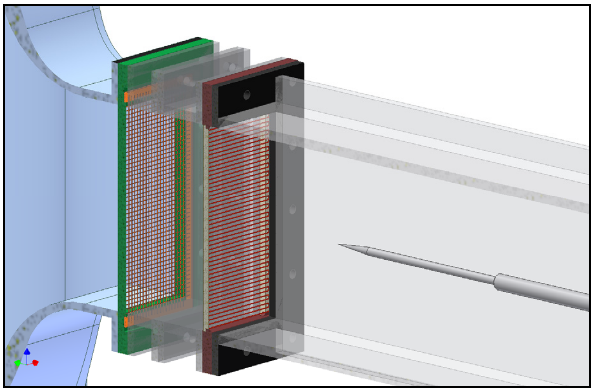


Figure 2 Experimental arrangement of the grid and the mandoline

The turbulence-generating grid GT-1.07/5 was placed after contraction. It was made of rods of diameter 1.07 mm and its mesh length M was of 5 mm. The solidity of the grid was 0.37. The grid generates an intensity of turbulence Iu=0.031 in the x/M=50.

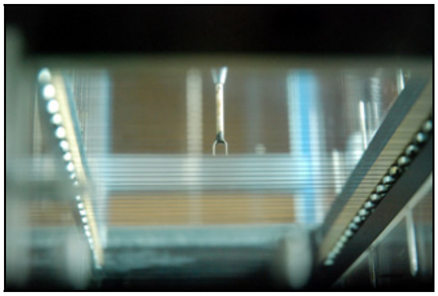


Figure 3 The dual-wire probe behind the mandoline (view from the top)

The thermal field was 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 (1978).

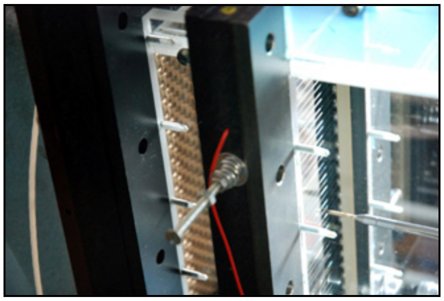


Figure 4 The grid with the mandoline downstream

The nickel-chromium wire was of diameter of 0.25 mm. Spacing between wires was set to be equal to a mesh length M=5 mm. Wires were oriented horizontally. Springs on the sides of flange were used to keep wires under tension to prevent sagging. A power consumption of a mandoline was of 0.7 kW giving an increase of mean temperature of ΔT=2.5 K. Distance of the mandoline from the grid was in a region of a=(4-28) M.

A dual probe with two sensors was used for the velocity and temperature measurement. The probe (Fig. 5) is composed from two parallel wires (space between wires is about 0.5 mm). The first sensor W1 has a tungsten wire of the diameter d_{w1}=5 μm and the active length l_{w1}=1.25 mm; the second sensor W2 has a tungsten wire of the diameter d_{w2}=2.8 μm and the length l_{w2}=4.8 mm.

The wire W1 was operated in CTA mode (wire temperature is T_{w1}=493 K) and the wire W2 in CCA mode (I_{w2}=2 mA).

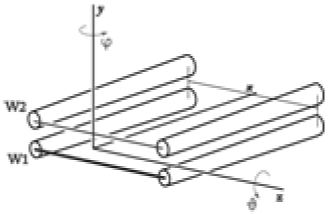


Figure 5 Sensors of a dual probe

A cooling law of Collis and Williams, modified by Koch and Gartshore (1972), was used for hot-wire measurements:

$$Nu \left(\frac{T_m}{T}\right)^{m_w} = A_w + B_w \, Re^{n_w} \quad , \tag{1}$$

where the Nusselt and the Reynolds numbers are defined by equations:

$$Nu = \frac{R_w E^2}{\pi l_w \lambda_m \left(R_A + R_w\right)^2 \left(T_w - T_a\right)} \quad ; \quad Re = \frac{d_w u \rho_m}{\mu_m} \quad . \tag{2}$$

E is an output voltage of the anemometer, and l_w and d_w are its length and diameter respectively, R_w denotes the operating and R_A is a sum of leads resistance, which is connected in series with R_w. The density ρ, thermal conductivity λ and molecular viscosity μ are evaluated for the mean film temperature T_m=0,5(T_w+T_a).

Wires were calibrated in the rig with variable flow temperature. From data in the range of velocities U=(2-24) m/s, wire temperatures T_w=(450-510) K and flow temperatures T=(290-320) K were evaluated calibration constants A_w, B_w, n_w,, m_w for sensor W1 (eq. 1). Sensor W2 was calibrated in the same range of velocities and flow temperatures in CCA mode I_w=2 mA.

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).

Two RTD thermometers Pt100 were employed for mean temperature measurements. 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.

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. From time series of hot/cold-wire measurements were evaluated: the velocity u, the temperature T, and the variance of temperature fluctuation $\overline{\theta^2}$.

Variance of temperature fluctuation is defined as follows:

$$\overline{\theta^2} = \mathrm{Var}(T) = \frac{1}{N}\sum_{k=1}^{N}\left(T_k - \overline{T}\right)^2 \quad . \tag{3}$$

Developments of the temperature-variance on the centreline of the channel behind a mandoline are shown in Graph 1.

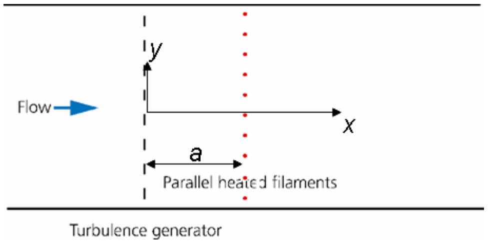
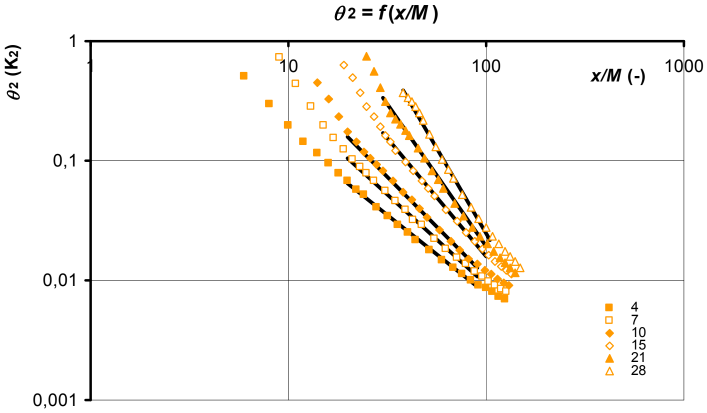


Figure 6 Coordinate system

There are six configurations: distances between grid and mandoline were set a=(4;7;10;15;21;28) M. Origin x=0 is taken at the plane of the grid generator (see Fig. 6).



Graph 1 Downstream decay of the temperature variance $\overline{\theta^2}$ (K^2); U=4.0 m/s; T≈391 K; heated mandoline ΔT=2.5 K; Centreline y=0; a/M=(4;7;10;15;21;28)

Solid lines in the graph represent best fits of the formulae (4) on the data. It should be pointed out that a power-law fitting was made in the region approximately x/M=20-100. Data in the beginning region (x/M<20) are sensitive on the precise vertical adjustment of the mandoline. To obtain similar starting shape of curves for all configurations it is essential to keep horizontal traversing exactly in the same position with respect to mandoline wires. Inaccuracy of about 1 mm (0.2M) caused considerable differences.

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

$$\overline{\theta^2} = B\left(\frac{x}{M}\right)^{-m} \quad . \tag{4}$$

Evaluated coefficient B and exponent m are given in the Tab. 1.

	GT-1.07/5					
a/M (-)	4	7	10	15	21	28
B (K^2)	3.4	9.7	24.5	145	1020	12500
m (-)	1.32	1.51	1.68	1.98	2.36	2.85

Table 1 Parameters of the temperature-variance decay

The decay rates compare well with results of Sirivat and Warhaft (1982). They reported measurement of thermal decay in approximately isotropic grid turbulence with exponents from 1.84 to 2.95 (depending on the configuration of a grid and a mandoline).

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. The exponent varying from 1.32 if the mandoline is placed close to the grid (a/M=4) to 2.85 if the mandoline is further downstream of the grid (a/M=28) at Reynolds number Re_M=1180.

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