Turbulence Microscales Variations due to Interaction with Shock Wave

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Introduction

In addition to the velocity distribution, combustion and/or mixing processes are characterized by the distribution of the scalar quantities like temperature, density or concentration [1]. The turbulence of the scalar field is superimposed to the turbulent velocity field. While particle image velocimetry provides information about the velocity fields [2], the line-of-sight speckle technique can be used for quantitative measurements of the instantaneous density (temperature) fields in flows. A light beam passing through the test field is disturbed due to the inhomogeneous distribution of the refractive index in the flowing fluid. Speckle photography method is sensitive to the light deflection from its original direction. The line-of-sight speckle photography is very advantageous for quantitative determining of refractive index fields in turbulent flows [3]. The aim of the experiments presented herein is to investigate the changes of statistics of turbulence in the gas flow downstream of a turbulence grid caused by high heating rate due to interaction with a shock wave.

Experiments

The optical arrangement for measuring the light deflection angles by means of speckle photography is shown in Fig.1, see [4]. An expanded, parallel beam of laser light is transmitted through the test section. A lens focuses a plane in the test section onto a ground glass plate. A second imaging lens focuses a plane at distance L from the ground glass onto the photographic plate. On this plate a speckle pattern is recorded that is existent in the plane at the small distance L from the ground glass plate. Two speckle patterns are superimposed by recording two exposures on the same photographic plate. After photographic development, the specklegram is scanned and interrogated with a thin laser beam. By measuring the Young's interferometric fringe spacing and the fringe direction it is possible to determine two components of the speckle displacement at each specklegram interrogation point. These values can be easily converted into the components of the deflection angle of the light passed through the turbulent field.

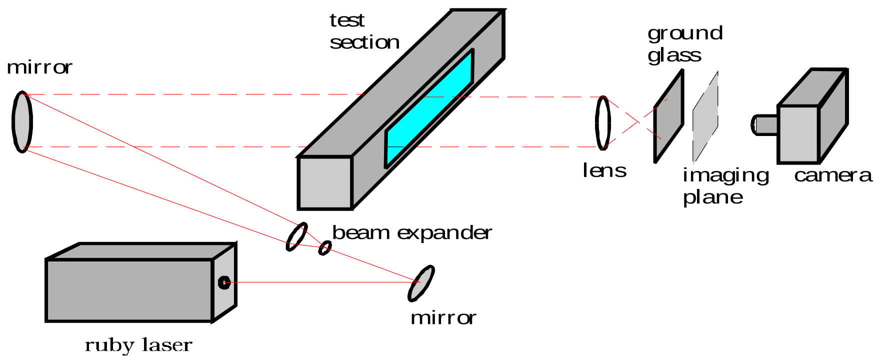

Fig. 1. Optical set-up for speckle photography diagnostics of turbulent flow

The experiments were performed with unsteady air flow in a shock tube of the Essen University having a quadratic cross-section of 100 by 100 mm^2. The shock propagates into the tube of quadratic cross-section where it reflects at the closed end. Integrated in the mechanism used for destroying the diaphragm is a turbulence grid, so that the air expanding from the compression tank must pass through the grid. Thereby, a turbulent air flow with density fluctuations is generated in the shock tube, and the front of the turbulent regime coincides with the contact front that moves with the local air velocity and separates the air which was originally in the low pressure side from that in the compression tank.

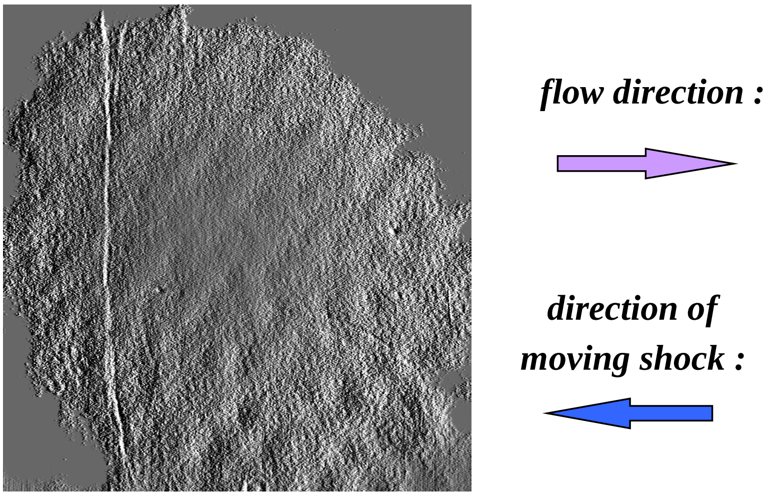

Fig. 2. Specklegram showing a shock wave propagating normally through the turbulent gas flow with fluctuating density.

A plane in the speckle field, normal to the optical axis and at a distance of about 10 mm from the ground glass is imaged onto the photographic plate where the speckle patterns are recorded. With the pulse length of the illuminating ruby laser being approximately 50 ns, we freezed in the specklegram the instantaneous distribution of the deflection angles $\varepsilon(x,y)$ as caused by the turbulent density field.

The double-exposed speckle photograph is developed and then interrogated with a thin He-Ne laser beam in order to determine the local speckle displacement $\Delta(x,y)$, respectively the local light deflection angle $\varepsilon(x,y)$, via the method of Young's fringes. This evaluation is performed with an automated system that, with the hard- and software presently used, can evaluate 2500 data points per hour. In most cases we evaluate a specklegram on a grid of 100 $\times$ 100 data points, so that approximately 4 hours are needed for the analysis of one specklegram (double-exposure). The interrogation is done in steps of 0.2 mm which corresponds to the diffraction limit of spatial resolution in our system, given by $\sqrt{\lambda L_1}$, with λ being the laser wavelength and L_1 being the depth of the optical test section in the direction of light propagation (z-axis).

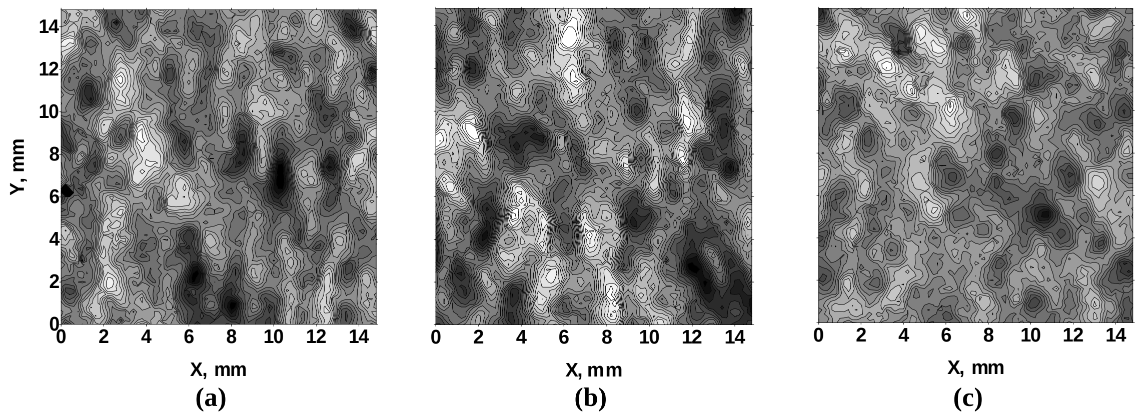

Fig. 3. Deflection angle isolines for three different positions: (a) 10 cm ahead of shock (or 0.26 ms before arrival of shock); (b) 20 cm behind shock (0.5 ms after arrival of shock); (c) 88 cm behind shock(2.2 ms).

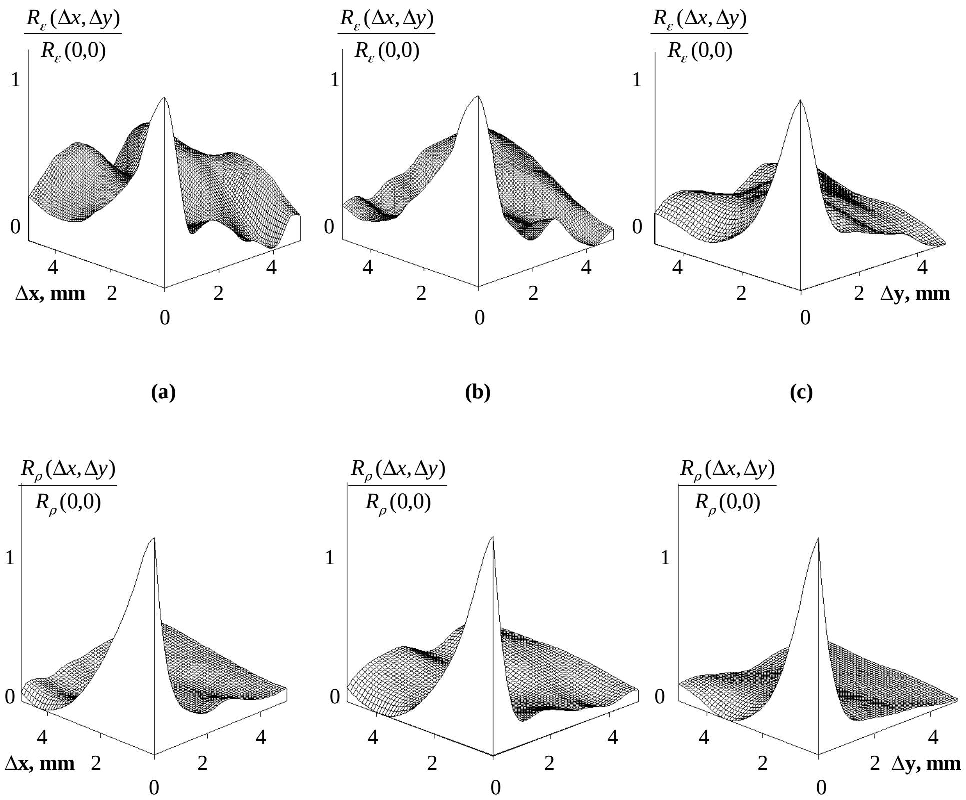

Fig. 4. Two-dimensional correlation functions of the light deflection angles (top) and density (bottom) for three cases shown in Fig. 3.

Statistical analysis

These observations can be quantified by determining the spatial correlation function R_ε of the deflection angles in the x-y plane according to

$$R_\varepsilon(\xi,\eta) = \left\langle \vec{\varepsilon}(p,q)\cdot\vec{\varepsilon}(p+\xi,q+\eta)\right\rangle \quad (1)$$

The non-dimensional spatial correlation functions of the deflection angles are presented in Fig. 3. As we can see, the turbulence in the flow ahead of the shock is anisotropic, and it remains so for the first short period after the passage of the shock wave, with a slight increase in size of the structures. It is evident that different states of turbulence develop downstream of the shock, depending on the extent of loss-of-equilibrium degree as caused by the shock compression. The tendency towards an isotropic state at some distance from the shock is understandable, because the flow velocity behind the reflected shock wave is nominally (under pure gasdynamic aspects) zero. In our interpretation of the visible results, however, we have to pay attention to the fact that all optical signals are integrated along the path of the light through the test section. A direct comparison with results of numerical simulations is therefore not possible. Such a comparison would require a conversion of the 2D optical data into 3D quantities describing the turbulence characteristics of the density field.

Using relations between density gradients and deflection angles, Erbeck and Merzkirch [3] has formulated a connection between 3D density and 2D deflection angle correlations. For isotropic turbulence the 3D density correlation function can be expressed through the deflection angle correlation functions in the following form:

$$R_\rho(r) = \frac{1}{\pi L_1 K^2}\int_r^\infty \frac{1}{\sqrt{\tau^2 - r^2}}\left\{\int_0^\tau R_{\varepsilon q\|}\left(\tau^*\right)d\tau^*\right\}d\tau \quad (2)$$

and

$$R_\rho(r) = \frac{1}{\pi L_1 K^2} \int_r^\infty \frac{\tau}{\sqrt{\tau^2 - r^2}} R_{\varepsilon q \perp}(\tau) d\tau \qquad (3)$$

These expressions are very similar to the Abel integral transform, when a 2D distribution is reconstructed by using 1D line-of-sight data about a parameter being sought. In our particular case, using Erbeck-Merzkirch integrals (2), (3) the 3D density correlation function in a turbulent field can be reconstructed using 2D correlation functions of deflection angles of the light passed through the flowfield. The usual assumption of 2D isotropy in 3D flow is used for this reconstruction. The results of the reconstruction are shown in Fig. 4 (down).

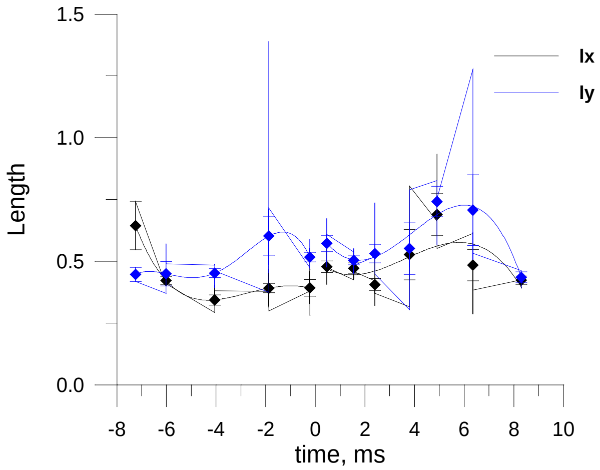

Fig. 5. Temporal turbulence microscales variations due to interaction with a shock front. The time of the shock wave passage corresponds to the instant of time t=0.

Both macro- and micro- scales of turbulence can be determined using obtained density correlation function:

$$L_{\rho i} = \int_0^\infty \frac{R_{\rho i}(r_i)}{R_{\rho i}(0)} dr_i; \qquad \lambda_{\rho i} = -2\frac{R_{\rho i}(0)}{R''_{\rho i}(0)}. \qquad (4)$$

The results of the evaluations are shown in Fig. 5. The obvious elongation of the turbulent structures in the y-direction for cases (a) and (b) shown in Fig. 3 is expressed by the higher values of the correlation functions in this direction. This significant difference of the correlations in x- and y-direction confirms the high degree of anisotropy of the turbulent scalar field at these positions. At a larger distance behind the shock (position (c), Fig. 3) the turbulence is almost isotropic. The more rapid decrease of the correlation in y-direction, as compared to cases (a) and (b), is an indication of the decrease in size of the turbulent structures.

References

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