Journal of Visualization, Vol. 1, No. 1 (1998) 29-35

Quantitative Visualization of the Change of Turbulence Structure Caused by a Normal Shock Wave

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Received 23 July 1997.
Revised 17 November 1997.

***Abstract*:** A speckle photographic technique is used for visualizing the planar distribution of the refractive deflection angles of light transmitted through the compressible turbulent flow in a shock tube. Illumination by a short laser pulse allows to freeze the instantaneous pattern of the deflection angles as caused by the turbulent fluctuations of the gas density. Turbulent structures are visible in the patterns of the deflection angles' isolines. A normal shock wave propagating through the turbulent density field causes structural changes of the observed patterns, which is quantified by determining the spatial correlation functions of the deflection angles.

***Keywords*:** speckle photography, turbulent structures, shock wave.

1. Introduction

Flows having a variable fluid density can be visualized with traditional optical methods, e.g. shadowgraph and schlieren, that rely on the refractive deflection of light passing through the flow (Merzkirch 1987). The information thus available is merely qualitative. Speckle photography, a relatively new optical whole-field method, can provide quantitative information on the planar distribution of the light deflection angles (Merzkirch 1995). In the plane of observation (x-y plane), the two components of the deflection angle, ε_x and ε_y (z designates the direction of the light beam passing through the flow), can be measured simultaneously and virtually at any desired position in the field of view. Thus, a very large amount of quantitative data can be generated with one speckle photograph. A simplified sketch of the optical set-up which includes definitions of the coordinates and the deflection angle is given in Fig.1.

For this type of application, the speckle photographic technique consists of recording on the same photographic plate two specklegrams, one without flow, the second with flow. The displacement of the speckles between the two exposures is measured via the method of Young's fringes (Françon 1979), and it is a direct measure of the deflection angle $\varepsilon = (\varepsilon_x, \varepsilon_y)$. Wernekinck et al. (1985) have demonstrated that ε can be determined even in turbulent flow with fluctuating density. Attempts of analyzing the 3D turbulent field suffer from the fact, common to all line-of-sight methods, that the information is integrated along the path of the light and finally available in 2D form only. Erbeck and Merzkirch (1988) replaced the information missing in the third direction by a turbulence model. With the assumption of homogeneous, isotropic turbulence they could derive statistical quantities, particularly spatial correlation and length scales, describing the turbulence of the investigated flow. In this paper we report on speckle photographic experiments that are conducted in order to explore how a normal shock wave might change the properties of a turbulent flow. Of course, the investigations are restricted to the turbulence scalar field of the fluctuating fluid density.

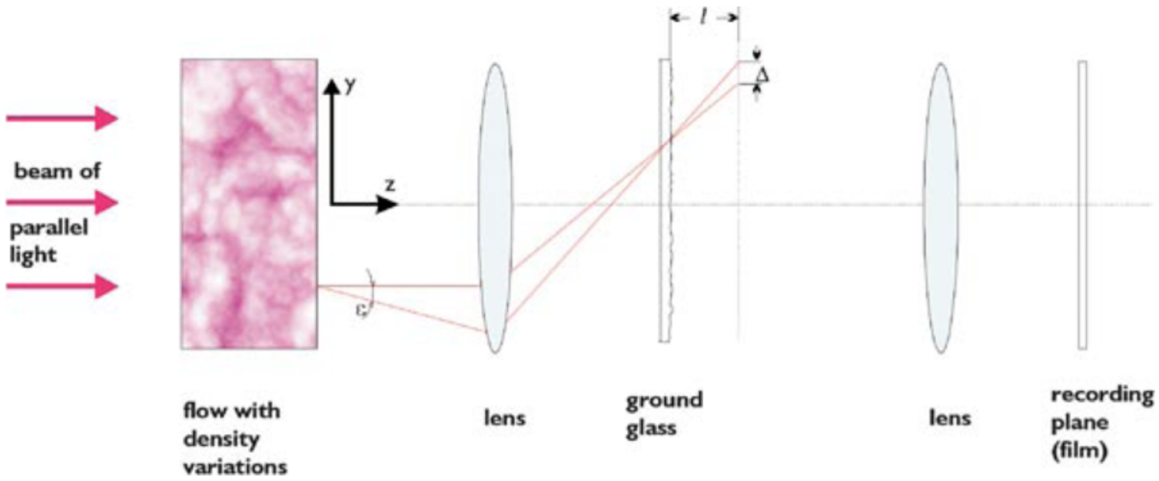

Fig.1. Principal of optical set-up with definition of the coordinates and the deflection angle.

This case was studied already by Keller and Merzkirch (1990) with speckle photographic measurements in a shock tube flow and with the assumptions as described above, but as Lee et al. (1993), Hannapel and Friedrich (1993) and Mahesh et al. (1997) pointed out, this flow is far from having isotropic turbulence. Therefore, we refrain here from attempts to reconstruct the turbulence field, and instead we analyze the visual information on the distribution of the measured deflection angles by statistical means, and we present results on how the visible structures of the turbulent flow change after the passage of a normal shock wave.

2. Experimental Procedure

The experiments are performed with the unsteady air flow in a shock tube having a quadratic cross-section of 100×100 mm^2. A shock wave is produced when the plastic diaphragm separating the compressed air in the compression tank and the low pressure side is destroyed (Fig.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 (Fig.3), 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.

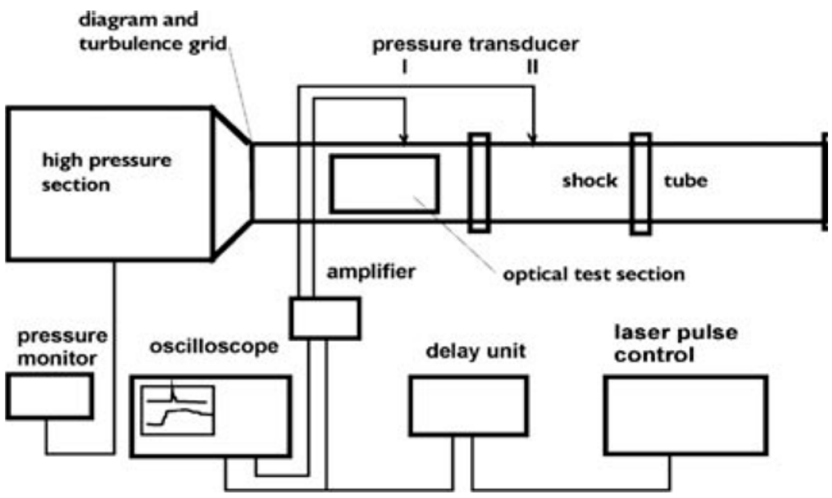

Fig.2. Schematic view of shock tube and measuring equipment.

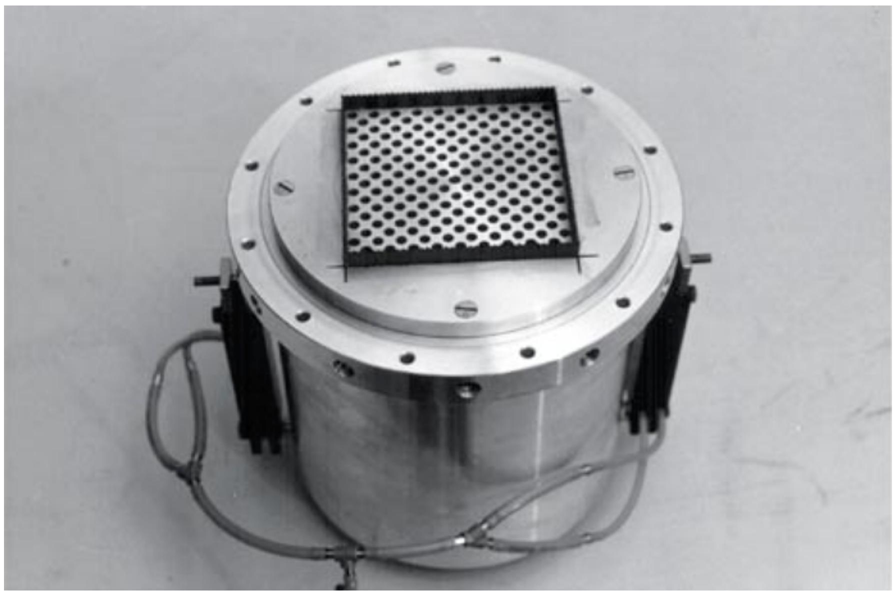

Fig.3. Diaphragm holder with integrated turbulence grid.

At a distance of 0.2 m downstream of the diaphragm/turbulence grid is the optical test section with transparent vertical side walls made of high quality optical glass mounted flush with the plane inner side walls of the shock tube. The side of the glass window is 200 × 100 mm². The expanded parallel laser beam used in the speckle photographic set-up (see below) is directed through the windows of the optical test section, normal to the tube axis. The shock tube is equipped with two piezo pressure transducers (Fig.2). They serve for measuring the pressure increase through the shock wave, the shock velocity, and they provide a signal used for synchronizing the moving shock wave with the laser pulse, i.e. for selecting the instant at which the speckle photograph is recorded.

As an initial condition the air pressure in the low pressure section is always held at atmospheric pressure, while the pressure in the compression tank is such that a shock wave with a shock Mach number $M_s = 1.1$ is produced. This initial condition was chosen so that a comparison of the experimental results with numerical simulations, e.g. those of Lee et al. (1993) can be made in future investigations.

The optical set-up shown in Fig.4 is that described by Wernekinck and Merzkirch (1988); see also Lira (1995). The beam from a pulsed ruby laser is expanded and collimated to form a parallel beam of 10 cm diameter. After having passed horizontally through the optical test section of the shock tube, the laser light illuminates a disk of ground glass, the speckle generating element in the set-up. 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

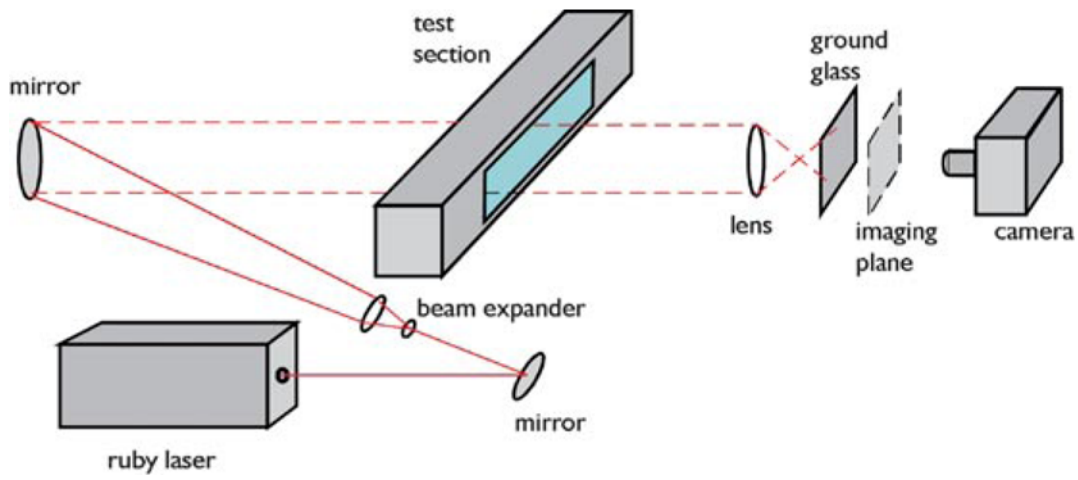

Fig.4. Optical set-up for taking speckle photographic exposures.

speckle patterns are recorded. We image a field of view of about 10 cm in diameter with an imaging ratio of 1:1 onto the photographic plate. The first exposure is taken without flow and it serves as the reference speckle pattern. The second exposure with flow, recorded on the same plate, is taken at a desired instant of time as defined by the instantaneous position of the moving shock wave.

Due to variations of the fluid density occurring in the flow the light rays in the second exposure are deflected with respect to the direction of light propagation in the reference exposure, thus resulting in a (locally inhomogeneous) displacement of the second speckle pattern in comparison to the reference pattern. 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 presently used hard- and software, can evaluate 2500 data points per hour. The major part of the evaluation time is needed for moving the interrogating laser beam mechanically, i.e. by stepping motors, from one interrogation point to the next. In most cases we evaluate a specklegram on a grid of 100 × 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 $\sqrt{\lambda \cdot l_z}$, with λ being the laser wave length and l_z the depth of the optical test section in the direction of light propagation (z-axis).

3. Results

With the pulse length of the illuminating ruby laser being approximately 50 ns, we freeze in the specklegram the instantaneous distribution of the deflection angles ε (x, y) as caused by the turbulent density field. A specklegram that includes the shock wave propagating through the turbulent field is shown in Fig.5. The contrast of this specklegram was enhanced by applying a digital filter, and it resembles the patterns of turbulent compressible flows as visualized by shadowgraphy. Due to its interaction with the density fluctuations the shock is no longer perfectly plane.

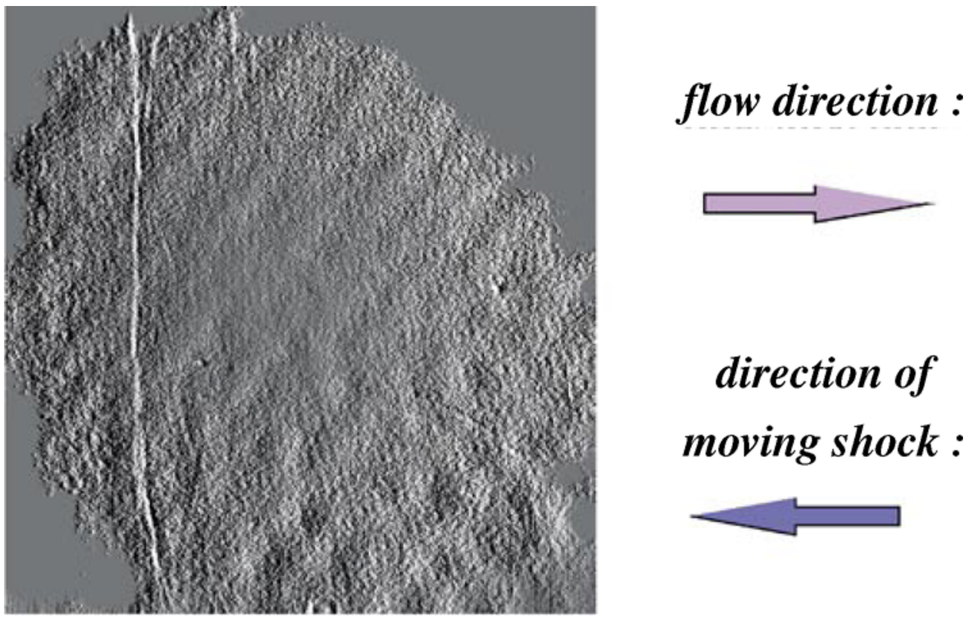

Fig.5. Speckle photograph showing a shock wave propagating normally through the turbulent gas flow with fluctuating density.

An instantaneous distribution of the deflection angles ε (x, y) is presented in Fig.6 in the form of isolines. The two fields of view shown in Fig.6 are the distributions before (left) and after (right) passage of the shock. The distance from the instantaneous position of the shock wave is indicated. The visible patterns can be interpreted as turbulent structures, although one must be aware of the integrating effect of the optical line-of-sight method. Evidently, the structures are more extended in the y-direction than in the x-direction (direction of flow), which can be taken as an indication of the anisotropy of the turbulent field. This anisotropy has also been verified with single-exposure speckle-photographic experiments (Fomin et al., 1996). A further observation is that the amount of light deflection increases after the passage of the shock (right side in Fig.6), which means that the turbulence intensity increases. But in the field of view downstream of the shock wave included in Fig.6 the turbulence is certainly not in an equilibrium state. It is therefore of interest to study the turbulent field at larger distances from the shock.

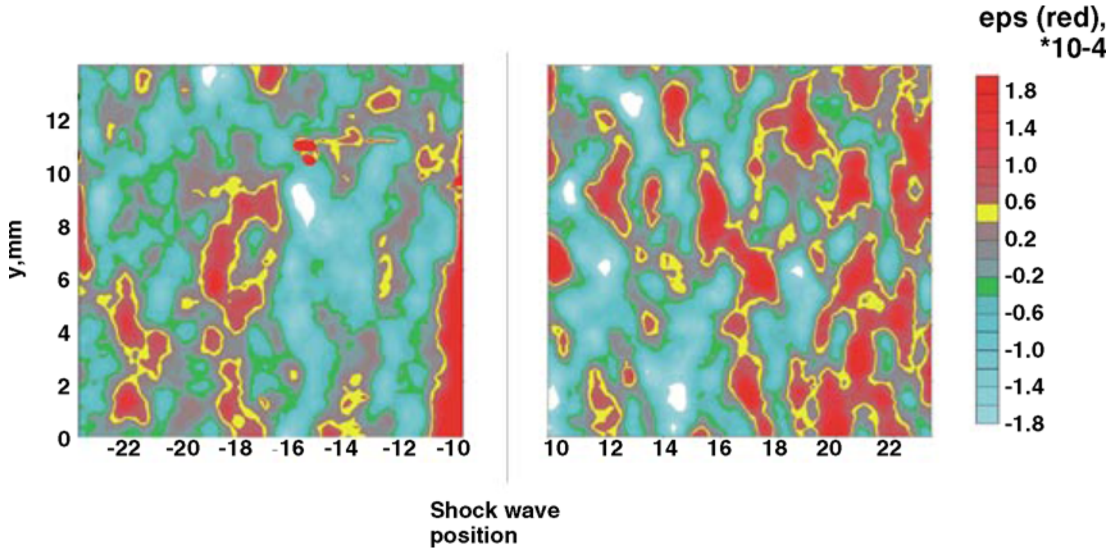

Fig.6. Instantaneous distribution of the light deflection angles $\varepsilon(x, y)$ at two positions downstream (left) and upstream (right) of the moving shock. The shock propagates in the negative x-direction. X-values refer to distance from the instantaneous shock position. Deflection angles ε are measured in radian.

Figure 7 shows instantaneous deflection angle isolines at three different positions. These specklegrams were taken (a) 0.26 ms prior to the arrival of the shock (left), (b) 0.5 ms after the passage of the shock (middle) and (c) 2.2 ms after the passage of the shock (right). The centers of the three sections shown are at a distance from the moving shock of approximately - 10 cm (left), 20 cm (middle) and 88 cm (right). There appears to be a small increase of the size of the visible turbulent structures from position (a) to (b). But at the larger distance (c) from the shock wave the structures are definitely smaller than they are ahead of the shock at position (a), and the turbulence level is also lower at (c) in comparison to (a).

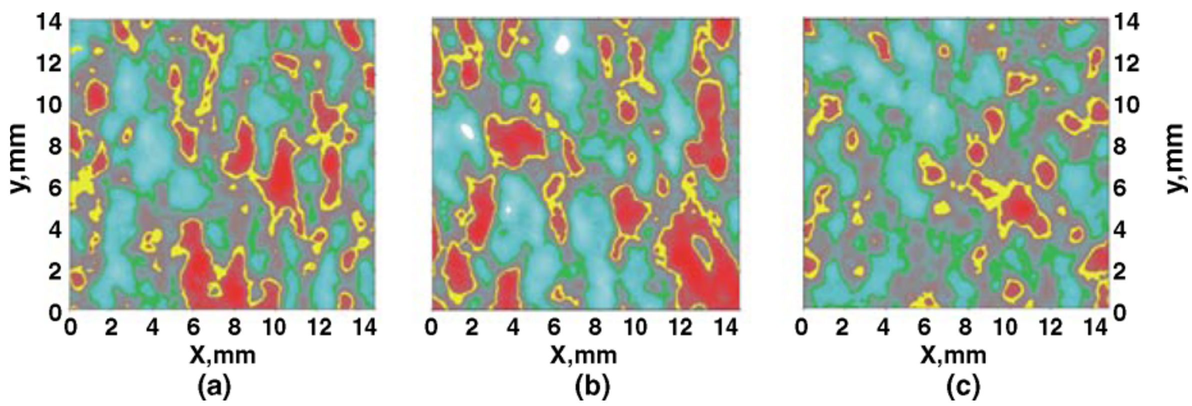

Fig.7. Deflection angle isolines for three different positions:

(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).

Scale of the deflection angles as in Fig.6.

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

$$R_\varepsilon(\Delta x, \Delta y) = \left\langle \varepsilon(x, y) \cdot \varepsilon(x + \Delta x, y + \Delta y) \right\rangle_{AV}$$

where the symbol $\langle .... \rangle_{AV}$ designates an averaging in the x-y plane; Δx, Δy are the correlation distances. The non-dimensional spatial correlation functions for the three cases shown in Fig.7 are presented in Fig.8. A comparison of the correlations in the x- and y-direction and for the three cases investigated reveals the following results:

—The obvious elongation of the turbulent structures in the y-direction for cases (a) and (b) 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) 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.

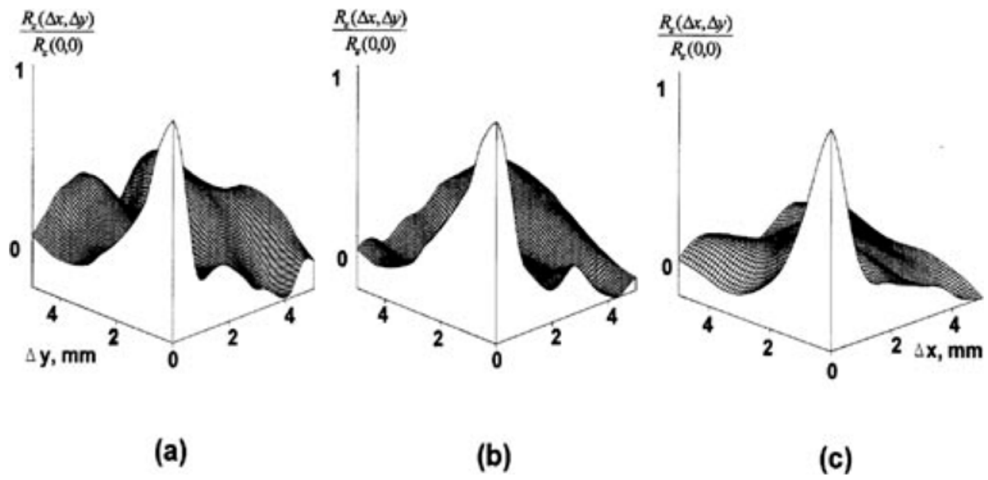

Fig.8. Two-dimensional correlation functions of the light deflection angles ε for the three cases shown in Fig.7.

4. Discussion

The spatial structure of the turbulent scalar (density) field in this compressible flow can be visualized quantitatively with the applied optical specklegram technique. The patterns visible in the distributions of the deflection angle isolines are interpreted as large-scale turbulent structures. The size of the largest structures observed and the mesh size of the turbulence grid are approximately the same. 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 out-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, e.g. of Lee et al. (1993), 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. For this purpose it is necessary to extend the algorithm used by Keller and Merzkirch (1990) to account for anisotropic turbulence.

Acknowledgments

D. Vitkin gratefully acknowledges receipt of a grant from Alexander von Humboldt-Stiftung. A visit of N. Fomin to Universität Essen was made possible within a NATO Linkage Grant Project.

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