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Experimental investigation of turbulent structures in a supersonic boundary layer

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Abstract. Turbulence in the supersonic airflows with Mach numbers up to 1.6 was investigated experimentally on a shock tube with a discharge chamber. The radiation of a distributed surface sliding discharge with a duration of 300 ns and area of 10×3 cm^2 was used as a visualizing method. The distribution of the discharge radiation intensity indicates the instantaneous density distribution due to the strong dependence of the intensity on the reduced electric field E/N. Processed result of the obtained experimental photographic images using a mathematical numerical computational program showed that the spatial scales of structural elements of turbulence in the direction of the flow can reach 1.7-5.9 mm.
Key words: supersonic flow, boundary layer, turbulence, surface sliding discharge

1 Introduction

Most of the flows of fluids, gases and plasma in nature and in technical devices are turbulent [1].

With the development of aviation technology in the 20th century, the study of turbulence became popular concerned again. Turbulence is a phenomenon observed in many flows of liquids and gases, and in these flows numerous vortices of various sizes are formed, as a result of which their hydrodynamic and thermodynamic characteristics (speed, temperature, pressure, density) experience chaotic fluctuations and therefore change from point to point and in time irregularly [1]. This definition implies the importance of the sizes of turbulent structures in determining the hydrodynamic and thermodynamic characteristics of the flow, which should be taken into account when solving problems of control and safety of aircraft.

To improve the aerodynamic characteristics of aircraft, except changing the aerodynamic shape of structural elements, plasma of gas discharges (plasma actuators) can be used. At a short distance from the streamlined surface, the air velocity above the plasma actuator increases under the influence of the electric

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field. In this case, the chaotic movement of the turbulent air flow can be suppressed [2]. In this regard, the study of air flows with plasma is of great importance for the active control of turbulence.

One of the ways to study the turbulent structure of a flow is to analyze the information obtained by visualizing the flow.

Experimental studies of turbulence in a supersonic boundary layer have been carried out since the middle of the last century [3, 4]. Mechanism of transition of a laminar boundary layer into turbulent boundary layer is still actively studied. Today it is generally accepted that such a transition is directly related to the stability of the initial laminar flow. To solve the problem of creating effective methods for controlling the boundary layer, it is also necessary to know the mechanisms of initialization of instability. In theoretical works, the theory of hydrodynamic stability is applied, using the wave approach to analyze flows, or direct numerical modeling is carried out [5-7]. In experimental works, the method of controlled disturbances is used and the efficiency of control of the characteristics of turbulent boundary layers is researched. [2-4, 8]. Perturbations of parameters of flow are usually monitored by temperature and pressure sensors. Anemometers measure velocity perturbations. One of the methods for studying the turbulent flow structure is visualization [2-4]. Investigations of various actuators for creating technology for controlling the characteristics of the boundary layer near surfaces have been actively carried out in recent decades [2, 8-10].

The aim of this work is to analyze the structural elements of the boundary layer in the boundary layer of a supersonic flow behind the front of a plane shock wave in a shock tube. In this work, the spatial scales of turbulent structures are determined on the basis of statistical computer processing of photographic images obtained at the facility, consisting of a shock tube and a discharge chamber [9, 10].

2 Experimental conditions

In modern scientific research of turbulence, various methods of visualizing gas-dynamic flows in the boundary layer are used, such as the classical shadow method, schlieren photography, particle image velocimetry (PIV) [2, 4, 9-11]. The obtained spatial flow patterns, as well as continuous measurements of thermodynamic quantities and velocity at different points, can serve as a source of information about instantaneous fields of parameters.

In this work, photographic images of the glow of a surface sliding discharge were obtained on a shock tube (see Fig. 1) with a discharge chamber.

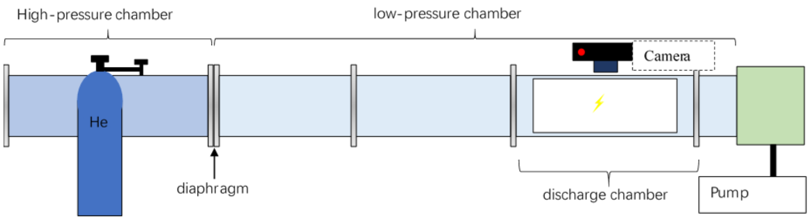


Figure: 1. The experimental set-up diagram.

The shock tube on which the experiments were carried out has a 24×48 mm^2 rectangular cross section, in which it is possible to create air flows with velocity up to 1600 m/s behind the front of shock wave with Mach numbers up to 5 [9]. In the experiments, the turbulent structure of the boundary layer on the channel walls in a supersonic flow behind the shock wave was visualized. The illumination of the flow structure using a nanosecond distributed surface sliding discharge in the discharge chamber was used as a visualizing tool [9, 10].

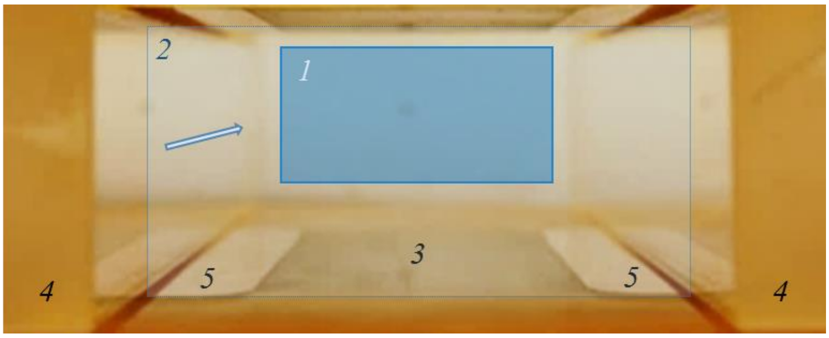


Figure: 2. Flow diagram in the shock tube: 1 – shock wave front, 2 - contact surface, 3 - surface discharge region, 4 - glasses, 5 - discharge electrodes. The arrow shows the direction of flow.

In the shock tube, the boundary layer grows from zero at the shock wave front towards the contact surface [10, 11] (see Fig. 3). The parameters of the boundary layer directly depend on the parameters of the co-current flow behind the shock front (velocity, density, temperature, etc.).

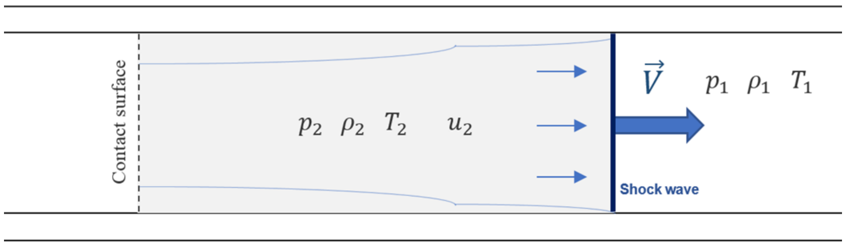


Figure: 3. The co-current flow behind the shock wave in the shock tube channel.

The Rankine-Hugoniot relations can calculate the parameters of the co-current flow behind a plane shock wave with the known Mach number M from the known initial parameters ahead of the shock front [11]:

$$\frac{p_2}{p_1} = \frac{2\gamma_1}{\gamma_1+1}M^2 - \frac{\gamma_1-1}{\gamma_1+1} \quad (1)$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma_1+1)M^2}{(\gamma_1-1)M^2+2} \quad (2)$$

$$\frac{T_2}{T_1} = \left(\frac{2\gamma_1}{\gamma_1+1}M^2 - \frac{\gamma_1-1}{\gamma_1+1}\right)\left(\frac{2}{(\gamma_1+1)M^2} + \frac{\gamma_1-1}{\gamma_1+1}\right) \quad (3)$$

$$\frac{u_2}{a_1} = \frac{2}{\gamma_1+1}\left(M - \frac{1}{M}\right) \quad (4)$$

In the equations for pressure (1), density (2), temperature (3), and velocity of the co-current flow (4), the subscript 1 denotes the parameters ahead of the shock front, and the subscript 2 – behind the shock front (Fig. 3). The γ_1 and a_1 are the heat capacity ratio and the speed of sound ahead of the shock front, M is the Mach number of the moving shock wave, which is equal to the ratio of its velocity V relative to the speed of medium to the speed of sound in this medium a_1. The first three equations are called Rankine-Hugoniot relations.

In experimental physics, it is usual to take the distance from the wall of the streamlined body as the thickness of the boundary layer at which the flow velocity differs by 1% from the external flow velocity. Since in the boundary layer the inertial forces and friction forces are of the same order of magnitude, equating these forces, one can obtain an estimate of the boundary layer thickness for a supersonic flow

$$\delta \propto \sqrt{\frac{\mu l}{\rho U}} \quad (5)$$

The development of the discharge is determined by the local value of the reduced electric field *E/N* (reduced electric field), where *E* is the electric field strength, *N* is the concentration of molecules[10, 12]. The rate of ionization and the concentration of electrons, which determine the discharge current, depend on the *E/N* value. Therefore, density fluctuations affect the local conductivity and the spatial structure of the discharge radiation.

Pulsed sliding surface discharge (plasma sheet) in still air is a system of parallel diffuse and separate brighter channels sliding over the dielectric surface [9, 10] (Fig. 4 a). Sliding surface distributed discharges of size 30×100 mm^2 were initiated on the upper and lower walls of the discharge chamber at a distance of 24 mm from each other in the density range from 0.05 to 0.40 kg/m^3. The discharges were initiated when a pulse voltage of 25 kV was applied. The discharge duration was about 300 ns. The photographic images of the discharge glow were recorded Nikon D50 camera through quartz glasses with 17 cm length, forming the walls of the discharge chamber channel (Fig. 1). The optical axis of the camera was located at a small angle to the plane of the discharge, perpendicular to the direction of flow (Fig. 1).

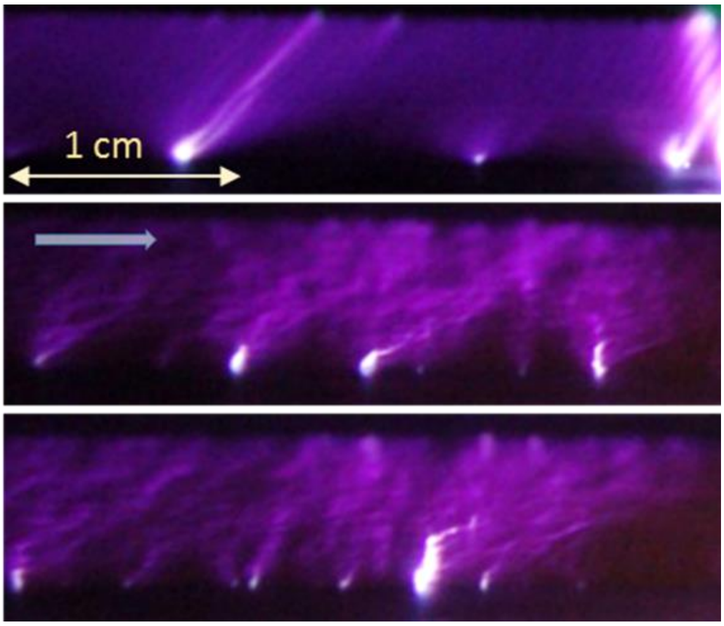


Figure: 4. Photographs of the discharge glow in a discharge chamber in still air (a), in supersonic airflows in turbulent boundary layer (b, c). The arrow shows the direction of flow. M_{flow}=1,52, ρ_2=0.11 kg/m^3.

3 Study of the spatial structure of the discharge glow in

supersonic flows

The photographic images of the discharge glow obtained in the experiments were provided for processing in the form of three series of data with different Mach numbers of the shock wave and the initial parameters of the air ahead of its front. They were obtained in different areas of the boundary layer, at different stages of turbulence development. The initial conditions and calculated flow parameters are given in Table 1):

Table 1

	M_0	M_{flow}	p_1 (torr)	ρ_1 (kg/m^3)	ρ_2 (kg/m^3)	Re ($\cdot 10^5$)	ΔX, cm
1	2.38-2.44	1.17	33	0.056	0.18	2.56	12-25
2	3.6-3.72	1.52	15	0.025	0.11	2.58	6-22
3	4.17-4.48	1.59	7.6	0.013	0.06	1.54	29-36

M_0 – Mach number of the initial shock wave
M_{flow} – the Mach number of the flow behind the shock wave
p_1, ρ_1 – pressure and density ahead of the front of the initial shock wave
ρ_2 – density in the flow behind the front of the initial shock wave
Re – flow Reynolds number
ΔX– distance from the shock front to the glow registration region (see Fig. 5)

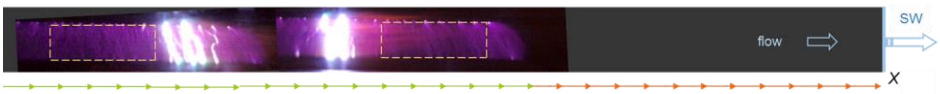


Figure: 5. Images of the discharge glow in first series of experiments at ΔX = 12 and 21 cm. Rectangles outline the processing areas.

To study the nature of turbulence and determine the size of the structural elements of the boundary layer in a supersonic flow, a program was written and used in processing to scan the intensity of the images and convert the intensity to the Fourier spectrum. Before processing the photos were modified manually using Adobe Photoshop (Fig. 6) so that the discharge channels were parallel to the right and left edges of the image.

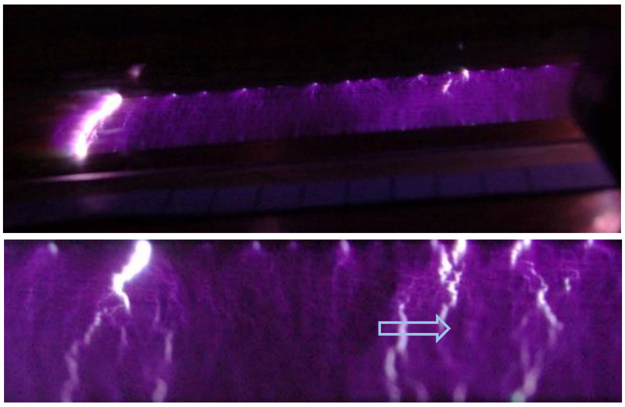
a
b


Figure: 6. Original (a) and modified (b) images. The arrow shows the direction of flow.

Description of the program for processing experimental images

The program is written in the Matlab programming language. Theoretically, this program is based on obtaining the spatial Fourier spectrum of the intensity of the surface discharge glow in the flow. The modified image was used as input for processing to. Then the colorful image can be converted into two-dimensional digital matrix, by the value of which the intensity of the photo image can be determined at every point. Further, the matrix of the obtained image was averaged over the width, after which a graph of the dependence of the intensity on the coordinate (the length of the image along the direction of the flow or in the direction transverse to the flow) was plotted (Fig. 7. a). By using the mathematical instrument – Fourier transform, Fourier spectrum was obtained (the dependence of the intensity on the inverse coordinate 1 / x) (Fig. 7. b).

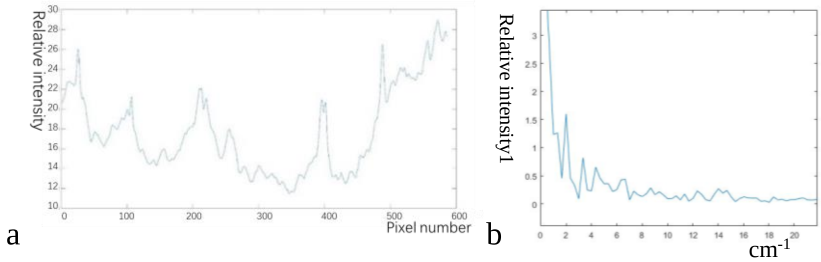
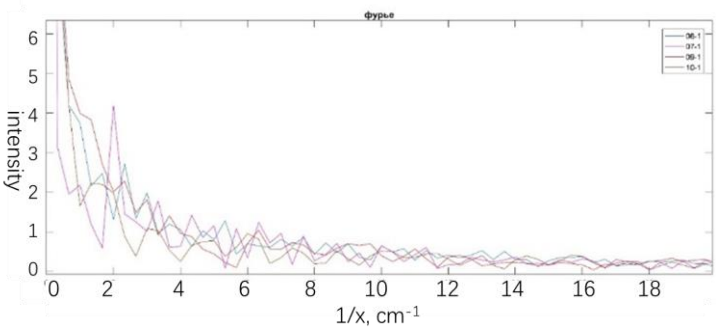


Figure: 7.a) Dependence of the intensity on the *x* coordinate and b) Fourier spectrum (dependence of the relative intensity from the reciprocal length in cm^{-1}) at $\Delta X = 28\ cm$

Results of processing experimental images

When processing photographic images, the dependences of the glow intensity of the discharge region in the direction of the flow and in the direction perpendicular to the flow were obtained. Next, the Fourier transform was performed for the intensity in the program (Fig. 8), and histograms of the frequency distribution for different regions of the flow were plotted for different values of the shock wave departure from the discharge gap ΔX. Significant frequencies were selected from the Fourier spectra and histograms of the dependence of the frequency intensity on the reciprocal coordinate were compiled (Fig. 8). The histograms were normalized so that the same the frequencies for transverse and longitudinal scans were equal.

The analysis of the results of the first series of experiments for different stages of turbulence development showed that the obtained Fourier spectra contain the same frequencies for the transverse and longitudinal scanning directions. They correspond to the same scale of turbulent structures in the boundary layer from 1.3 mm to 5 mm. At the beginning of the turbulent region (near the zone of the laminar-turbulent transition), a larger number of frequencies are observed in the Fourier spectrum, their intensities are close (Fig. 8 a, b). With an increase in the distance of shock wave escape, the number of types of turbulent structures decreases and the intensity of low frequencies becomes higher (Fig. 8 c, d).



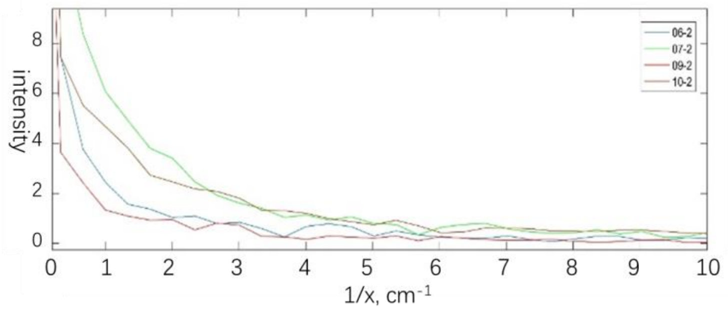


Figure: 8. Fourier spectrum obtained by scanning in the direction of the flow (a) and in the direction perpendicular to the flow (b).

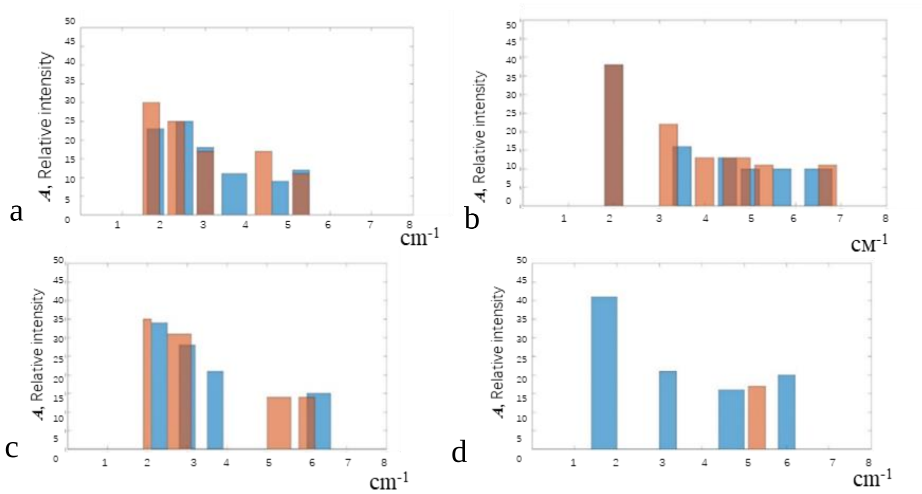


Figure: 9. Histograms of frequency distribution at ΔX= 12 cm (a), 14 cm (b), 21 cm (c) and 25 cm (d). Blue symbols – scanning in the direction of the flow, brown symbols – scanning in the direction perpendicular to the flow.

Conclusions

The paper analyzes the distribution of the glow intensity of a pulsed sliding surface discharge in the boundary layer of supersonic flows in a shock tube. The mathematical tool Fourier transform was used to analyze the turbulent structure of the boundary layer. From the processing results, it can be concluded that the scales of turbulent structures in the boundary layer, determined by scanning the glow intensity of the discharge and the Fourier transform of the signal, reach 5.9 mm. The nature of turbulent structures in the boundary layer under different experimental conditions has common features reflecting the dynamics of the development of turbulence.

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