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MECHANICS

Grid Turbulence and Its Interaction with a Shock Wave[1]

O. I. Dokukina*, E. N. Terentiev, L. S. Shtemenko, and F. V. Shugaev

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Abstract– Turbulent fluctuations of density and pressure in air and argon in a shock tube have been investigated as well as their interaction with a shock wave reflected from a perforated plate at the end of a shock tube. Air and argon were used as test gases. The Mach number of the incident shock was 1.9–3.9, that one of the reflected shock was 1.4–2.4. The turbulent length scale behind the incident shock was measured as well as that one behind the reflected shock. The last value is a few times less than the former. It was established that there is overpressure in the turbulent flow behind the reflected shock. The value of the overpressure is 12% in argon and 9% in air.

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The interaction between a shock wave and turbulence is a substantially non-linear process. The two phenomena mutually affect each other. The shock wave amplifies turbulent fluctuations [1] while turbulence increases the thickness of the shock wave [2]. The problem under consideration is of interest for shock propagation through a non-uniform medium as well as for ecology (propagation of *N*-wave through the turbulent atmosphere). The turbulent length scale is one of the main parameters that characterizes a turbulent flow and determines its ability to mix as well as the amplitude of fluctuations.

Recently the turbulent length scale of density fluctuations was determined for shock Mach numbers close to unity and at the pressure equal to 1 atm [3–5]. The value of the length scale was about 0.5 mm. Specle interferometry was used.

Turbulent fluctuations in supersonic flows of air in nozzles were investigated in [6] for two values of the flow Mach number: M = 2 and M = 2.5. Thermoanemometric technique was used. The amplification of the fluctuations of velocity, density and pressure after the interaction with an oblique shock wave was determined. Phenomena which occur when a shock wave falls on the boundary between two media of different density were analysed in [7]. The process of mixing and the onset of turbulence were studied.

[1] The article was translated by the authors.

Moscow State University, Moscow, Russia
**e-mail: shugaev@phys.msu.ru*

We have studied experimentally the interaction between a shock wave and a turbulent gas flow. The experiments were fulfilled in a shock tube of rectangular cross-section of 40 × 60 mm^2 area. The length of the canal was 3 m. Turbulent flow was created with the aid of a grid. Vortex rings appeared in the flow behind the grid. The grid had 150 orifices 3 mm in diameter. The distance between the grid and the test section was 700 mm. The incident shock was planar at the test section. The incident shock reflected from a perforated plate at the end of the shock tube. After that there was an interaction between the reflected shock and the turbulent flow. As known, grid turbulence is at a maximum extent similar to the homogeneous isotropic turbulence. The turbulent flow is not an isotropic one behind the reflected shock.

Pressure fluctuations were measured with the aid of a pressure transducer. Its sensitivity was 4.439 mV/kPa. Density fluctuations were measured with the aid of a laser-schlieren technique. A He–Ne laser beam of 1 mm in diameter with Gaussian profile intersected normally the test section and was detected by a double split differential photodiode. The output signals were recorded by a digital oscilloscope as well as those ones from the pressure transducer. The shock velocity was measured at different bases (10–40 mm) by means of signals from the photodiode and from the pressure transducer. The Mach number of the incident shock was 1.9–3.9, the Mach number of the reflected shock was 1.4–2.4. The initial pressure in the test section was 1.0–8.7 kPa. Air and argon were used as test gases. As known, [8, 9] there is no interaction between a shock wave and a boundary layer on the walls of the shock tube in case of argon. So we should not take into account that interaction and its influence on the experimental data. The reflected shock wave has a complicated shape in case of air due to the interaction between the shock and the boundary layer. The shape of the reflected shock varied during its propagation through the test section. As a result, the shock velocity varied: it increased and then diminished. The reflected shock is nearly planar in argon.

When the laser beam intersects the turbulent flow, the beam intensity varies due to diffraction of light on the turbulent fluctuations. We assume the gas in the test section to be a phase screen. When there is no flow the beam falls on the center of the sectioned photodiode, and the output signal is absent. When the gas flow intersects the beam, the output signal appears. To calibrate the setup we moved the photodiode along a line parallel to the shock tube axis in the absence of a gas flow.

The Maxwell equations in the scalar case were used in order to calculate the laser beam intensity on the surface of the photodiode. The output signal $V(t)$ is as follows [10]

$$V(t) = \int_{-\infty}^{+\infty} F_{opt}(s - vt)\Delta n(s)ds, \quad (1)$$

where Δn is the variation of the refractive index, $F_{opt}(\xi)$, v, and ξ are the response function, the flow velocity, and the displacement of the beam relative to the center of the photodiode, respectively. Equation (1) is a convolution. The function $\Delta n(s)$ can be found with the aid of the Fourier transform.

The response function is as follows

$$F(\xi) = -C_{cal}(0.5\sqrt{0.5\pi/a_1}/a_0)\{-i\exp(q_1)\sigma_1 + i\exp(q_2)\sigma_2\},$$
$$q_1 = 0.5i\psi(-a_1 - i(a_2 + a_3) - r\exp(-i\psi))\xi^2,$$
$$q_2 = -0.5i\psi(-a_1 + i(a_2 + a_3) - r\exp(i\psi))\xi^2,$$
$$\sigma_1 = \mathrm{erf}(q_3q_5) - \mathrm{erf}(q_3q_6) - \mathrm{erf}(q_3q_7) + \mathrm{erf}(q_3q_8),$$
$$\sigma_2 = \mathrm{erf}(q_4q_9) - \mathrm{erf}(q_4q_{10}) - \mathrm{erf}(q_4q_{11}) + \mathrm{erf}(q_4q_{12}),$$
$$q_3 = \exp(-0.5i\psi)\sqrt{r},$$
$$q_4 = \exp(0.5i\psi)\sqrt{r}, \quad q_5 = -i\xi + a_3l_2/r,$$
$$q_6 = -i\xi + a_3l_1\exp(i\psi)/r, \quad q_7 = -i\xi - a_3l_1\exp(i\psi)/r,$$
$$q_8 = -i\xi - a_3l_2\exp(i\psi)/r, \quad q_9 = -i\xi + a_3l_2\exp(-i\psi)/r,$$
$$q_{10} = i\xi + a_3l_1\exp(-i\psi)/r, \quad q_{11} = i\xi - a_3l_1\exp(-i\psi)/r,$$
$$q_{12} = i\xi - a_3l_2\exp(-i\psi)/r,$$
$$\alpha = 2/k, \quad a_0 = 1 + \alpha a, \quad a_1 = 1/a_0, \quad a_2 = \alpha a a_1,$$
$$a_3 = 0.5k/b, \quad r = (a_1^2 + (a_2 + a_3)^2)^{0.5}, \quad \psi = \arctan((a_2 + a_3)/a_1), \quad (2)$$

where C_{cal} is a calibration constant, a and b being the distance between the laser and the test section and between the test section and the photodiode, respectively. The quantity l_1 is the width of the sensitive cell of the photodiode, the quantity l_2 is the distance between two sensitive cells.

The refractive index depends on the gas density

$$\frac{n-1}{\rho} = G, \quad \Delta\rho = \Delta n/G, \quad (3)$$

where ρ is the gas density, G is the Gladstone–Dale coefficient.

Acoustic disturbances have been observed in the turbulent flow, their frequency being much less than that of the turbulent fluctuations. These low-frequency disturbances were filtered with the aid of the discrete Fourier transform. High-frequency signals were analyzed by means of statistical methods. Correlation functions of density and pressure fluctuations were found behind the incident shock as wells their phase trajectories. The amplitude of the high-frequency fluctuations in argon was 0.2–1% of the density behind the incident shock, the shock Mach numbers being 1.9–3.1. The absolute values of the fluctuations varied from 0.27×10^{-6} g/cm^3 to 3.2×10^{-6} g/cm^3. The amplitude of the turbulent fluctuations increases if there is increase either in the shock Mach number or in the gas density behind the incident shock. In air the relative amplitude of the density fluctuations was 0.1–1.5% if the shock Mach number varied from 1.9 to 3.9. The absolute value of the density fluctuations was equal to 0.1×10^{-6} g/cm^3 (min) and 0.64×10^{-6} g/cm^3 (max). In argon the relative amplitude of the pressure fluctuations at the same values of the Mach numbers was 1–2.4%, for air 1–4% . The absolute amplitude being 0.33–0.67 kPa. The appropriate values were 0.28 and 1.1 kPa in case of air.

These data were compared with the results in [6]. The appropriate data are as follows [6]. The relative amplitude of the density fluctuations is 1.96%, that one of the pressure fluctuations is 2.74% (M = 2). In our experiments the relative amplitude of the density fluctuations is 1.5%, that one of the pressure fluctuations is 4% (M = 1.5). As seen, the appropriate data are close to each other, though the conditions of the experiments are different. The main difference is the size and the number of the orifices in the grid. This circumstance may have an influence on the amplitude of the turbulent fluctuations. It is incorrect to compare our results concerning the amplitude of the fluctuations with those in [6]. In our experiments the Mach number M of the planar shock was M = 1.5–3.9 while only oblique shock waves were used in [6]. But there is a qualitative similarity. In both cases the amplitude of the pressure fluctuations increases as the shock Mach number grows. But the quantitative results are different. There was found a six-fold increase in the amplitude in [6] (at M = 2.5) while the appropriate value in our experiments is suited to the conditions at the shock front. This fact coincides with the results of [1].

The length scale was determined from the correlation function for the turbulent fluctuations. We found temporal correlation functions and a correlation time τ in $\mu\sigma$. The length scale R was determined from the following expression: $R = v\tau$, where v is the flow velocity behind the shock wave.

Figure 1 shows the correlation function for the air density behind the incident shock against distance. The number of fluctuations is equal to N. The length scale is 0.89 mm.

We used the Taylor hypothesis (the so-called frozen turbulence).

As known, vortex rings are sources of pressure fluctuations. Acoustic disturbances appear if the pressure varies. These disturbances were recorded with the aid of the pressure transducer. Frequency filter for the pressure fluctuations remains only the same frequency band that coincides with that one for the density fluctuations.

Figure 2 represents the length scale of the density turbulent fluctuations against the Mach number of the incident shock. Dark squares refer to air, light triangles refer to argon. As seen, the length scale varies from 0.3 to 0.6 mm when the Mach number varies from 1.9 to 3.1 for argon. It varies from 0.35 to 0.7 mm in the same interval of the Mach numbers for air. It is equal to 1.1 mm for M = 4.

The length scale for pressure fluctuations is just the same as for the density fluctuations in case of argon and air. The length scale for the turbulent fluctuations is 12–20% greater in air than in argon (M = 1.9–4). It is of interest to investigate turbulent length scale in flows of other gases (for instance, in carbon dioxide and sulphur tetrafluoride).

The fact that the turbulent length scale depends on the shock Mach number can be explained in the following manner. Namely, the conditions of formation of vortex rings behind the grid are different. They are determined by the gas velocity and its pressure. The turbulent length scale is reduced 5–10 times behind the reflected shock.

The amplitude of the pressure and density fluctuations is also reduced behind the reflected shock. One can see this fact from the phase trajectories of the turbulent fluctuations. Figure 3 shows the 3D phase trajectories related to the pressure fluctuations in argon behind the incident shock as well as behind the reflected one. The horizontal axis refers to time in microseconds. The two rest axes refer to the amplitude of the pressure fluctuations (z-axis) and to the velocity of their variation (y-axis). The amplitude of the pressure fluctuations at first grows and then diminishes. (Large pressures refer to a reflected shock wave.)

The reduction of the amplitude of the pressure fluctuations can be explained as follows. Acoustic disturbances appear due to the interaction between vortex rings behind the incident shock. They become more intensive behind the reflected shock. Resonant scattering of acoustic waves on vortex rings takes place [9]. The vortex rings become unstable and break down into smaller ones. This circumstance results in the diminishing in the amplitude of the pressure and the density fluctuations and to the reduction of the turbulent length scale.

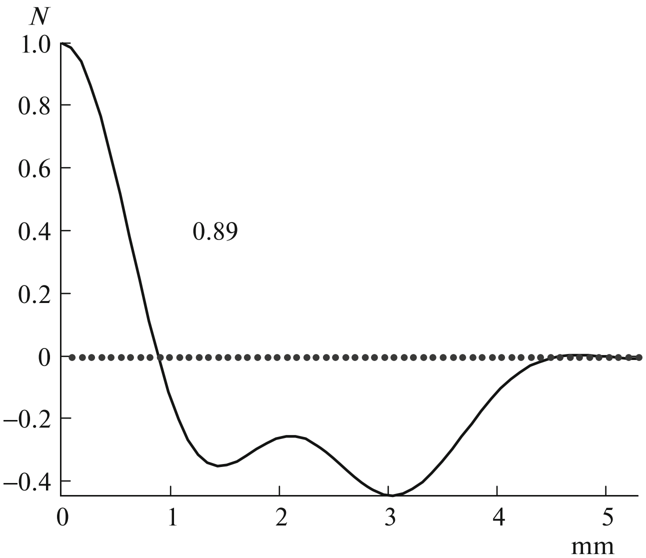

Fig. 1. Correlation function for the density fluctuations behind the incident shock wave in air. The length scale is equal to 0.89 mm.

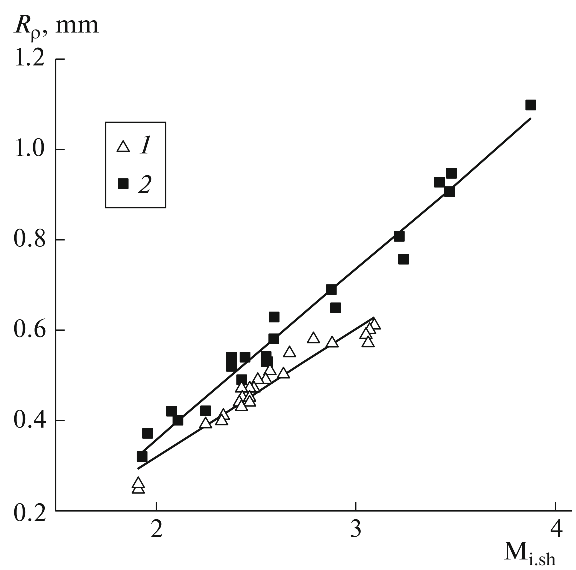

Fig. 2. The turbulent length scale R_ρ in (*1*) argon and (*2*) in air against the Mach number of the incident shock.

The pressure P_3 behind the reflected shock was measured. The value P_3 is 12% greater in the turbulent flow of argon than that one in the laminar flow, ceteris paribus. The corresponding value is equal to 9% for air. Figure 4 represents the value P_3 for argon against

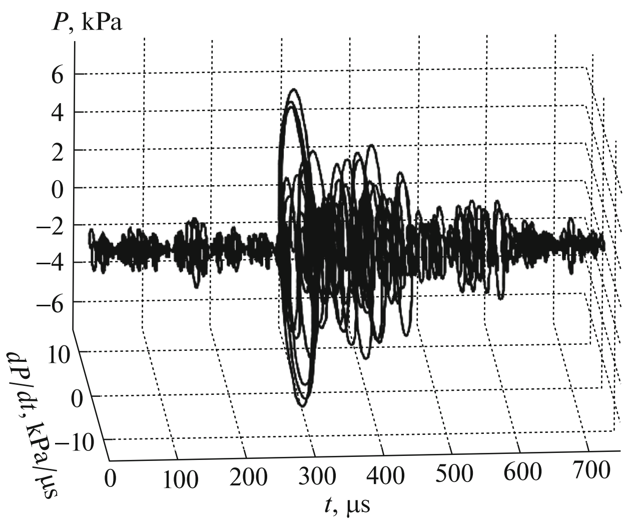

Fig. 3. 3D phase trajectory for the pressure fluctuations in argon behind the incident shock as well as reflected shock.

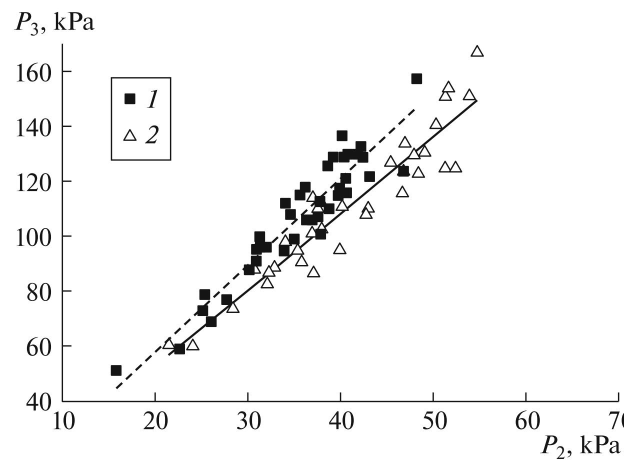

Fig. 4. The pressure P_3 behind the reflected shock in argon against the value of P_2 before the reflected wave: (*1*) turbulent flow, (*2*) laminar. The solid lines are drawn by the method of least squares.

P_2, being the pressure ahead of the reflected shock. Dark squares refer to the turbulent flow, light triangles refer to the laminar one. Lines are drawn by the method of least squares. As seen, the pressure in the turbulent flow behind the reflected shock exceeds that one in the laminar flow (e.g. in the absence of the grid that creates turbulence), ceteris paribus. This overpressure may be caused by additional heating due to acoustic radiation which arises in the interaction of the vortex rings. The additional heating leads to an increase in the velocity of the reflected shock in the turbulent flow compared to the velocity in the laminar flow. So, in argon the Mach number of the reflected shock is 6% greater the Mach number in the laminar flow. It corresponds to the increase of the pressure.

Thus, in the experiments it was established a reciprocal influence on each other a shock wave and turbulent flow.

Vortex rings become unstable in the interaction with a shock, they emit additional acoustic disturbances and then break down in smaller ones, e.g., the process of mixing is enhanced.

Acoustic waves heat the gas behind the shock waves. This fact results in an increase of the pressure and of the shock velocity. Thus, the turbulent fluctuations increase the shock strength.

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