DOI: 10.13009/EUCASS2019-548

Boundary layer evolution in channel behind the shock wave

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Abstract
Optical methods and digital image processing is used for study of boundary layer developement on the glass wall and also other two walls in shock tube channel behind the flat shock wave. PIV, high-speed shadowgraphy and pulse volume discharge visualization method are used. Laminar-turbulent transition, striped structures in turbulent flow were visualized in near surface flow. Data on flow velocity distribution evolution and structure in time was obtained for flow behind shock wave with Mach number 1,5 - 4,7 up to 15 millisecond.

1. Introduction

Shock tubes are gas dynamic facility being used since the middle of the last century in experimental high speed gas dynamics [1-5]. They are useful for the investigation of shock waves interactions, reflections. Detonation processes, low temperature plasmas were studied in shock tubes of different types [6, 7].
As far as flow behind flat shock wave in shock tube is rather homogeneous and has fixed parameters according to Rankine-Hugoniot equations, shock tube may also be used as small wind tunnel of short-time flow duration. Models streamlining, boundary layer development, oblique shocks formation, were studied with the help of special equipment with high time resolution [6, 8, 9]. The data of flow evolution in time is very important for these experiments.
The shock tubes with a squared cross section with built-in windows allow to visualize the flow inside with different optical methods. Schlieren and shadow methods are the main tool in supersonic gas flow visualization. High-speed digital cameras now allow recording the evolution of the flow during several milliseconds with high space resolution and microsecond time intervals. Its quite enough for recording of all the gas dynamics processes in shock tube.
The shock tube we used is composed of high-pressure and low-pressure sections, including test camera, which are initially separated by a diaphragm. The rupture of the diaphragm generates a flat shock wave, which moves into the low-pressure section. The high-pressure gas is expanded into the low-pressure section of the shock tube as a soon as the diaphragm ruptures. An expansion wave is generated moving at the speed of sound from the diaphragm position into the high-pressure section. Contact surface is the interface separating the high-pressure (helium) and low-pressure (air) gases and moving to the high-pressure section.
The position of a laminar–turbulent transition is usually determined by measuring and processing the signals from sensors. By using the laser knife technique, it is possible to visualize flow structures in boundary layers of considerable thickness. Boundary layer imaging using the glow of a nanosecond pulsed sliding surface discharge allowed to determine the position of the laminar–turbulent transition with rather good precision [10].
The possibility of shock tube experiments for the investigations of boundary layer evolution in supersonic and transonic flow behind the shock wave has been proved by the analysis of obtained results. Optical methods based on digital technologies and digital image processing were used. Gas flows during 15 μs after shock wave passage have been considered.

1.1 Experimental setup

A specially made test chamber was mounted in the shock tube with a rectangular profile of 2.4 x 4.8 cm2. 2 side walls were quarts windows 17-cm-long for flow visualization. Also special pulse volume discharge was used for gas discharge flow visualization (Fig.1). Boundary layer developed in channel flow behind the flat shock wave with Mach number range from Ma=1.5 to Ma=4,6.

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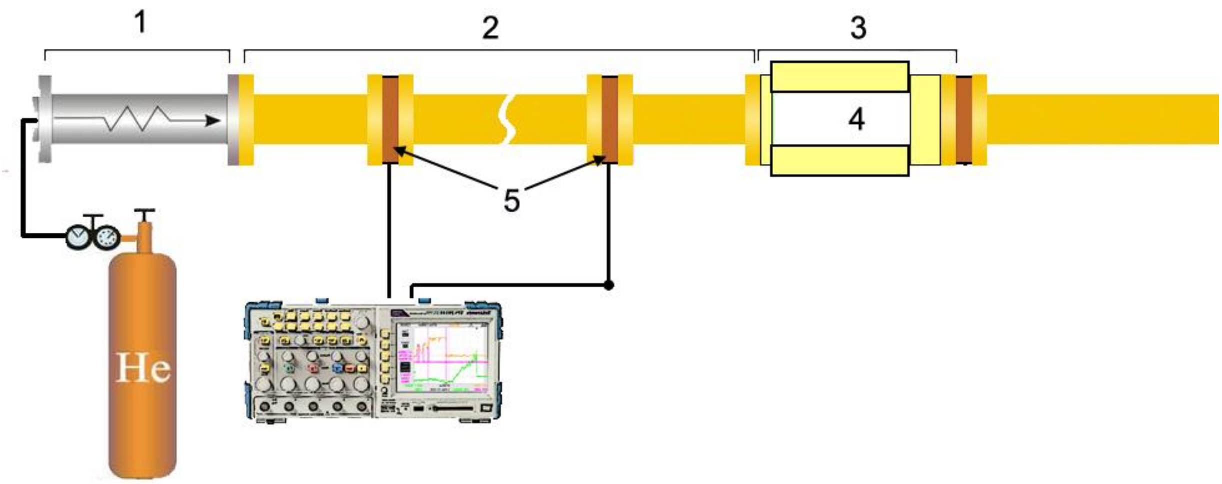

Figure 1: Scheme of shock tube (1 - high – pressure section, 2 - low – pressure section, 3 - discharge chamber, 4 – plasma electrodes, 5 – pressure sensors)

Flow visualization with high speed shadowgraphy was focused on the boundary layer which formed on the side walls (windows). Particle image velocimetry (PIV) method was used for visualization and quantitative analysis of flow at centerline of the camera and boundary layer on the upward and downward walls.
Laminar-turbulent transition on glass surface (side walls) and on top and bottom walls was studied both with PIV and pulse volume discharge visualization method.
Pulse volume discharge with pre-ionization by plasma electrodes can be initiated in test camera at any moment of flow with shock wave [7-9]. The top and bottom walls of the chamber were the plasma sheets which produced the ultraviolet glow for the preionization of the spatial discharge area in flow region of 10 cm length. The discharge current duration, was 200 ns, it is much lower than the characteristic time of gasdynamic processes in flow in the shock tube. The discharge glow is quite homogeneous all over the discharge section in quiescent air. If the discharge was initiated in flow behind the shock, the discharge glow visualized flow inhomogeneities including structures of the turbulent boundary layer; separation zones on the boundary layer.

2. Results and discussions

Laminar-turbulent transition time was analyzed on both types of walls; flow relaxation and turbulent boundary layer evolution in 13 mc after the shock had passed was studied with three visualization methods.
It is known that boundary layer behind the shock wave being laminar first then grows and turns to turbulent (Fig.2). The critical Reynolds number determining the transition from a laminar flow to a turbulent depends on the homogeneity of flow, the surface roughness, flow velocity etc.

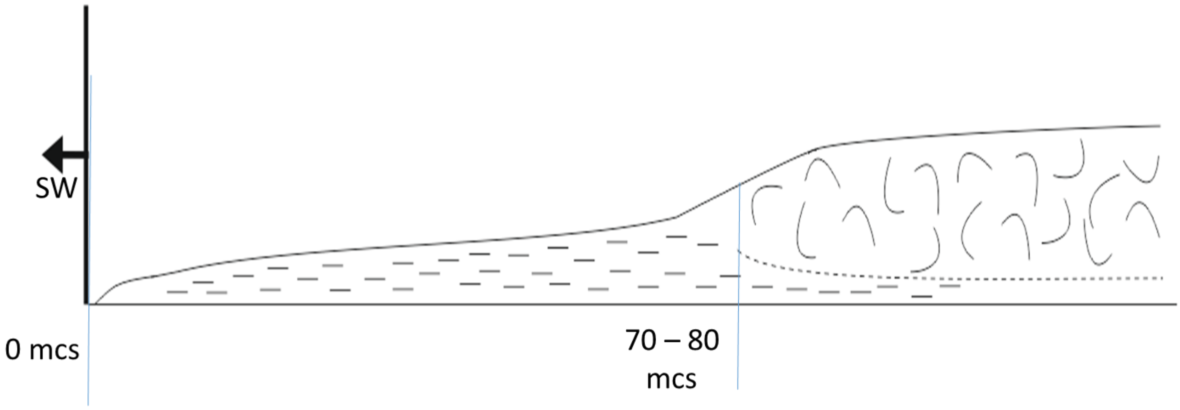

Figure 2: Scheme of laminar-turbulent transition

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2.1 Shadow imaging.

The shadow flow visualization method - was used for two purposes:

1. Determination of the flow velocity by angle of incline of the oblique conical shock wave, that appears behind the obstacle on the bottom;
2. Boundary layer evolution in time and space visualization.

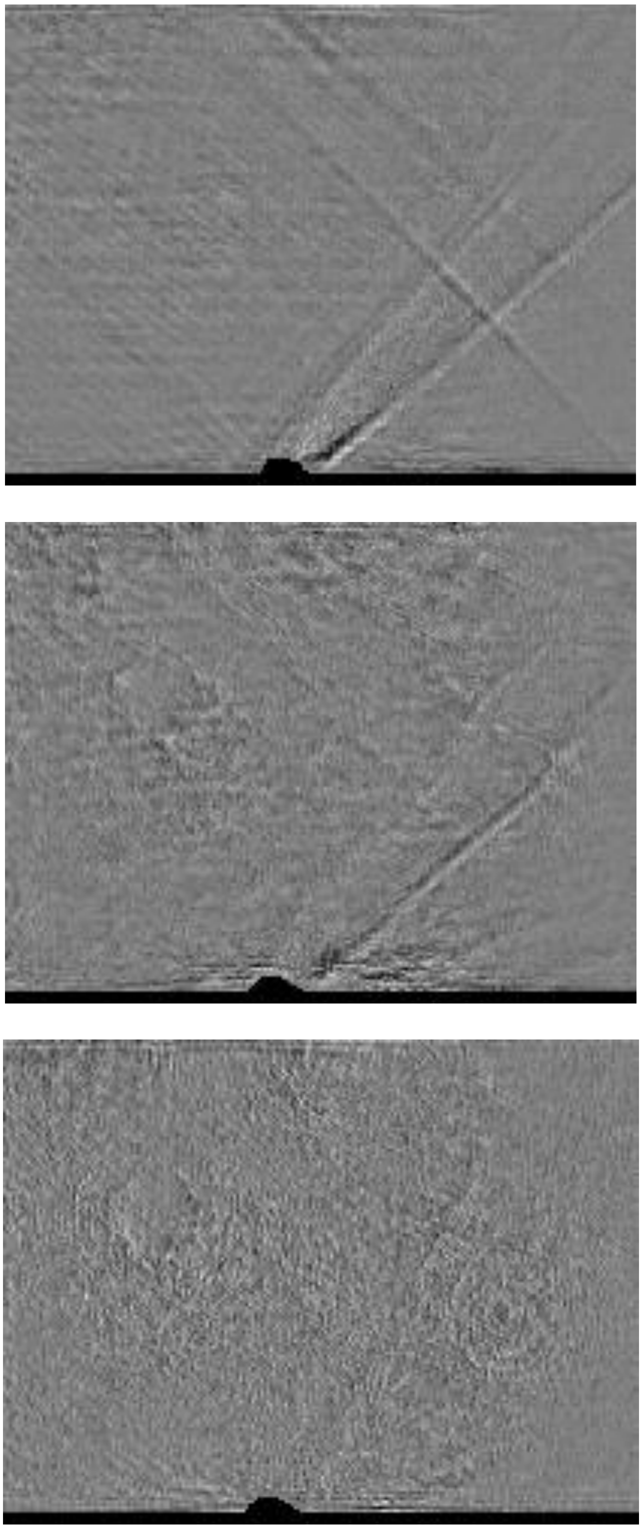

Figure 3: Oblique shock wave and sound wave at different time moments 70 µs, 590 µs and 1590 µs, respectively

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High speed camera registration rate extents up to 500,000 frames per second. We are detecting a passing shock wave and the flow behind it. The boundary layer is located on the nearby glass of the test chamber, optical system is focused on it. For the first 15-30 mcs the flow on images is smooth. The striped structures, which arise in the boundary layer are visualized some time after the shock wave passage, (Fig. 3, rate 100 000 frames per second). Later we see that the flow becomes completely turbulent in the boundary layer and that includes not only on the side walls, but also on the upper and lower walls. The exact times for different Mach numbers have been measured for this transition. Instant Mach number of the flow was determined by angle of inclination of the oblique shock wave. When the oblique shock wave disappears is may show the moment of transition from supersonic to subsonic flow. These data can be measured due to advantages of high speed shadow visualization.

2.2 Pulse discharge imaging.

The method of visualization by pulsed volume discharge was used also. When a pulsed volumetric discharge with pre-ionization by ultraviolet radiation from plasma sheets is initiated in the flow, then there is a redistribution of the discharge glow in the area of inhomogeneity. Laminar boundary layer is homogenious; turbulent layer in perturbed. Here we can see two images of flow after laminar-turbulent transition (Fig.4). The first image is an oblique shock wave formed behind an obstacle at the bottom of the channel and the breakdown mode. The second one is the breakdown mode, in which the breakdown is carried out on the turbulent structures of the boundary layer on the glass. The image shows lengthened stripes visualized from the discharge afterglow in flow direction. These are the same striped structures that appear on the glass after some time. Here we see the scale of these striped structures – plasma is concentrated in lower density local areas. It is clear that this method works only once per experiment, because after each initiation of the discharge in the flow, the conditions and even the structure of the flow itself change significantly [7]. The discharge plasma afterglow exposure time is here 1-5 mcs.

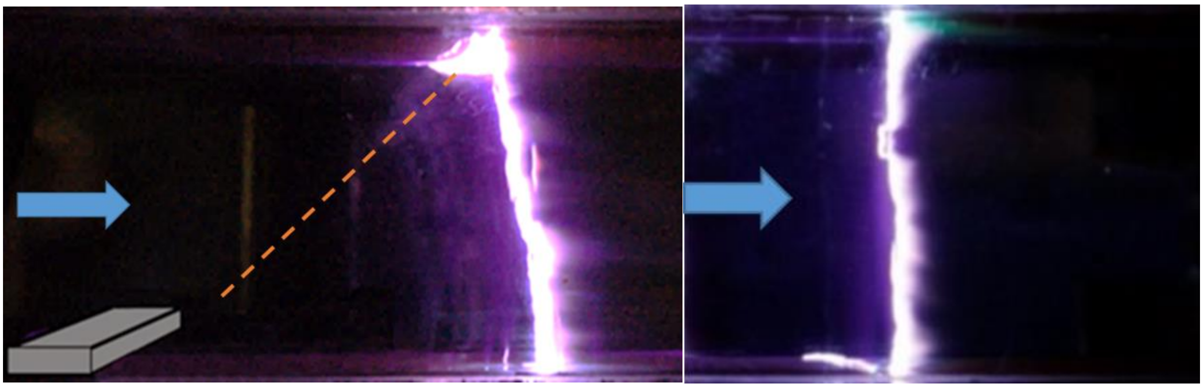

Figure 4: Visualization of boundary layer on chamber window: supersonic flow with obstacle (t = 630 mks) and without obstacle (700 mk), respectively

2.3 PIV imaging.

The third method is the Particle Image Velocimetry (PIV) method. The section was illuminated by a laser sheet in the longitudinal direction in the symmetry plane of the flow of the shock tube channel (Fig.5). A very complex seeding scheme in low pressure section was developed. We obtained images of the incident shock wave with a small Mach number of the flow and images of late stages of flow development.

This method as a new for shock tubes flows. It turned out that even after 3, 4, 5 ms after the shock wave had passed, high values of the flow rate remained with a developed boundary layer on all four walls. However, this flow is suitable for measurements in a gas-dynamic flow. Fig.6 presents instant three single images of flow velocity field 0.27, 5.7 and 14.5 ms after shock wave had passed, respectively. It was shown that after 12 mcs all the flow is turbulent and slow.

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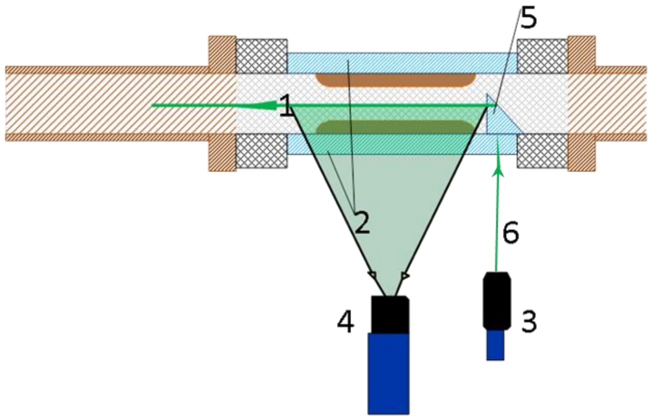

Figure 5: Scheme of PIV registration (1 – laser beam, 2 – quartz glasses, 3 – laser, 4 – camera, 5 -prism, 6 - laser beam)

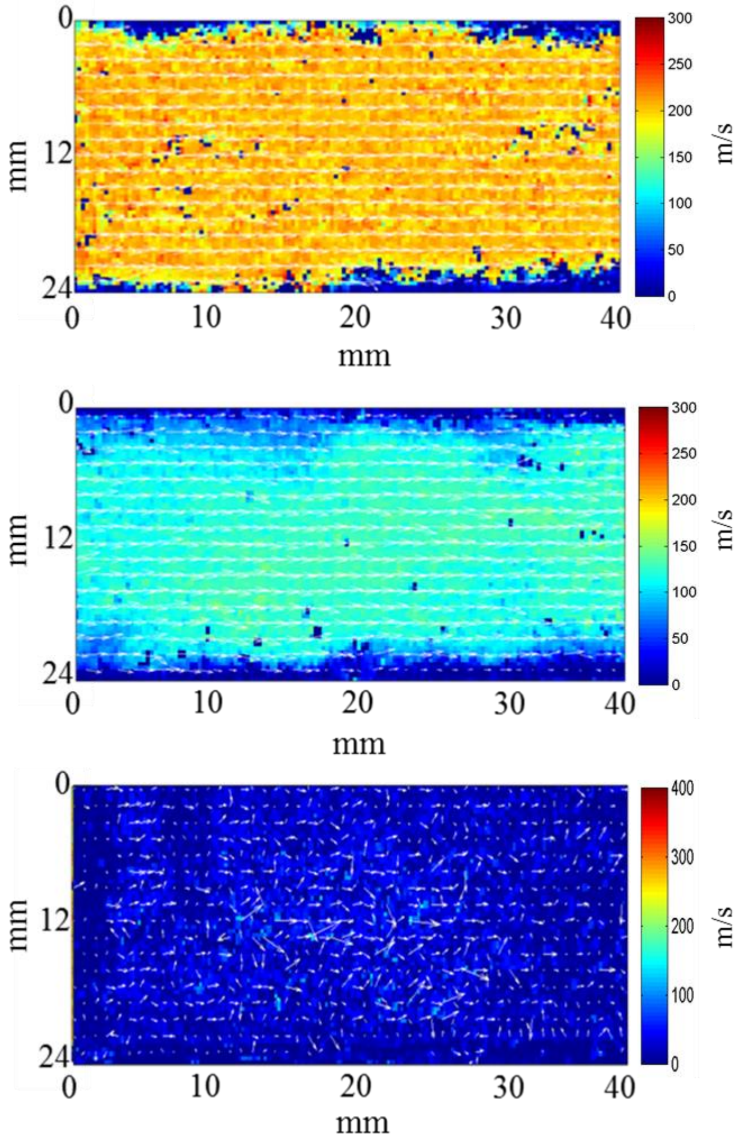

Figure 6: Single images of flow velocity field.

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3. Summary

Three panoramic digital optical methods were used for study of boundary layer developement on the glass wall in shock tube channel behind the flat shock wave. Particle Image Velocimetry (PIV), high-speed shadowgraphy and pulse volume discharge visualization method are used. Laminar-turbulent transition, striped structures in turbulent flow were visualized in near surface flow. Data on flow velocity distribution evolution and structure in time was obtained for flow behind shock wave with Mach number 1,5 - 4,7 up to 15 millisecond. It was shown that even 5 ms after the shock wave had passed, high values of the flow velocity remained in the centerline channel area with thick turbulent boundary layer. So the devise may be used for study of millisecond – lasting processes.

Acknowledgment

This work was supported by the RSF grant 18-19-00672.

References

[1] Bazhenova, T.V., Golub, V.V., Gvozdeva, L.G. et al. 2014. Half a century of continuous shock interaction investigations in the Joint Institute for High Temperatures of Russian Academy of Sciences. In: *Shock Waves.* 24, 347.

[2] Nishida M.: Chapter 4.1 Shock tubes and tunnels. In: Ben-Dor, G., Igra, O., Elperin, T. (eds) 2001 Handbook of Shock Waves, vol. 1: Theoretical, Experimental and Numerical Techniques, Academic Press, New York.

[3] F. V. Shugaev and L. S. Shtemenko 1998 *Propagation and Reflection of Shock Waves* (World Sci., Hong Kong, Singapore, New Jersey, London,.

[4] *Igra O, Seiler F. 2015 Experimental Methods of Shock Wave Research 478.* Igra**,** Ozer, Seiler, Friedrich (Eds.).

[5] E. Y. Koroteeva, I. A. Znamenskaya, F. N. Glazyrin, N. N. Sysoev. 2016. Numerical and experimental study of shock waves emanating from an open-ended rectangular tube *Shock Waves"* Vol. 26, no. 3, pp 269–277.

[6] N. A. Fomin. 2010. 110 years of experiments on shock tubes" Journal of Engineering Physics and Thermophysics December, Volume 83, Issue 6, pp 1118–1135

[7] D. Igor, Z. Irina, K. Dmitry, K.-z. Tahir. 2017. When shock is shocked: Riemann problem dynamics at pulse ionization of a shock wave" *Physics of Fluids*. Vol. 29, no. 10.

[8] I. A. Znamenskaya, T. A. Kuli-zade, V. N. Kulikov, S. P. Perminov. 2011. Transonic 3d non-stationary flow visualization using pulse transversal discharge" *Journal of Flow Visualization and Image Processing*. Vol. 18, no. 3. pp 214–224

[9] I. A. Znamenskaya, I. E. Ivanov, I. A. Kryukov, T. A. Kuli-Zade. 2002. Pulsed volume discharge with preionization in two-dimensional gasdynamic flow", *Journal of Experimental and Theoretical Physics*. Vol. 95, no. 6. pp. 1033–1039

[10] I. A. Znamenskaya, D. F. Latfullin*, and I. V. Mursenkova. 2008. Laminar–Turbulent Transition in a Supersonic Boundary Layer during Initiation of a Pulsed Surface Discharge Technical Physics Letters, 2008, Vol. 34, No. 8, pp. 668–670