Digital processing of shadowgraph images taking into account the diffraction of light at a shock front

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Abstract. The aim of the study is to determine the shock wave position in experimental shadowgraph images and to evaluate the accuracy by digital image processing. The experimental images were obtained with the shock tube with a rectangular channel. The shadowgraph optical system formed a parallel light beam. It passed through the plane-parallel quartz glasses of the shock tube test section. The process synchronization system at the facility allows registering the shadowgraph images of unsteady flows with shock waves with a high-speed camera or with a single frame camera. The obtained spatial intensity profiles were used to determine the coordinates of gas-dynamic discontinuities at different stages of the flow evolution. Shadowgraph patterns were analysed taking into account diffraction at the shock front in case of a laser light source.

1. Introduction

The direct shadowgraph technique is applied in various science and technology fields for to obtain images of transparent optically inhomogeneous objects. They are characterized by a spatial change in the refractive index [1, 2, 3, 4]. It is used to determine gas density and temperature spatial distributions in aerodynamics, physics of combustion and explosion and plasma physics [1, 3]. In optical technologies it is applied to control the quality of optical elements [5]. The classical shadowgraph technique involves obtaining a shadowgraph picture on the screen when parallel light rays pass through the inhomogeneity [1, 5]. The light beam from the light source is formed into a parallel beam and directed through the area of interest. The inhomogeneity causes the optical beams to deviate from the original direction, leading to a redistribution of the intensity in the visualization field and forming a non-uniformly illuminated field on the screen. The small difference between the refractive indices of the object leads to a shadowgraph pattern observation. The shadowgraph technique is highly visual and informative. It allows obtaining high-quality information about the distribution of the refractive index in the research object based on the analysis of shadowgraph patterns. First of all, the coordinates of regions with a sharp change in the value of the refractive index (shock waves, contact surfaces, boundaries of vortices and regions of turbulence), as well as the zone of opacity, can be determined. Shadowgraph research assumes that the absorption of probe radiation can be neglected. The wavelength of the probe light should be much less than the characteristic size of the investigated inhomogeneity. In this case, the propagation of beams can be described by Geometric Optics [5]. Optical schemes of shadowgraph registration differ from each other in the elements of forming optics, image registration systems and methods of protection from the plasma’s radiation [1, 2, 6, 4, 7, 8].
The shadowgraph image of the heterogeneity for stationary objects can be observed directly on the screen. On the other hand, high-speed shadowgraph registration is widely applied to study fast processes in gas and plasma flows. Observation of density variations accompanying shock wave displacement in the order of several millimeters requires high-speed imaging of shadowgraphs with the exposure time less than one microsecond. Traditionally, pulsed light sources such as flash lamps have been used for high-speed shadowgraphy, but flash times of microseconds are difficult to achieve a high-quality light pulse [1, 2]. Continuous wave lasers provide good beam profiles and are suited for shadowgraphy. The required time resolution in the order of one microsecond can be provided by a high-speed shutter or imaging device [7]. The use of a pulsed laser eliminates the problem of pulse width and makes it possible to obtain a high-quality single image of a moving shock wave. However, diffraction effects can be significant when the laser wavelength is comparable to the characteristic length scale of density gradients. For atmospheric pressure air, the shock front thickness is of a micrometer which close to the laser wavelength. The diffraction patterns in experimental laser shadowgraph images makes their processing more difficult [2, 7, 9]. The aim of this study was to determine the position of shock waves on experimental shadowgraph images based on digital processing and to evaluate the accuracy of the processing, taking into account the diffraction of light at a shock front.

![Figure 1. Experimental setup: shock tube (1); test section (2); piezoelectric pressure sensors (3-5); light source (6); high-speed camera/photo camera (7); delay generator (8); high-voltage block (9); imaging PC (10).](image)

2. Experimental setup and shadowgraph system

The investigations were carried out in test section of shock tube of rectangular cross-section 24 × 48 mm² [3, 10, 11]. Plane shock waves with Mach numbers $M = 1.9 - 3.6$ propagated in a shock tube channel at initial air pressure $p_0 = 5 - 60$ Torr. Two opposite walls of the test section were the quartz glasses within a length of 17 cm (see figure 1). The velocity of the shock wave was measured also the synchronization of processes in experiments was provided using signals of piezoelectric pressure sensors. The combined volume discharge was initiated in the presence of a plane shock wave in a test section [10]. Two surface sliding discharges were created on the upper and lower walls of the chamber at a distance of 24 mm from each other which provided the volume
preionization. The volume discharge of 300 ns duration was realized at voltage of 25 kV and discharge current \( \sim 1 \text{kA} \). The length of the discharge region along the direction of motion of the shock wave was 100 mm. The discharge was initiated at different positions \( x_0 \) of the shock front in the discharge volume; the end of the electrodes was taken at \( x = 0 \) (see figure 1). In the presence of a shock wave in the discharge volume, the discharge is localized in front of the shock wave at \( x_0 < x < 0 \) [10].

High-speed shadowgraphy was used to study the plane shock wave movement and the flow pattern evolution after the pulse volume discharge. Shadowgraph images of the gas-dynamic flow field were recorded with a high-speed camera with a frame rate of up to 525,000 fps and one microsecond exposure time. Light from a source was collimated by an optics and passed through a test field perpendicular to the glasses of a test section (figure 1). The pulse laser (with 532 nm wave length, 6 ns pulse duration) or continuous wave laser (532 nm) or flash lamp (1000 \( \mu \text{s} \) pulse duration) were used as light sources.

3. Image processing
Shadowgraph images were processed with the intensity scanning program in MATLAB. The first step was in the analyzing of plane shock shadowgraph images in the discharge chamber channel (figure 1). A clear part of the shock wave experimental image with the size of \( 10 \times 5 \text{ mm}^2 \) was selected far from the upper and lower boundaries to exclude the influence of edge effects. The selected part was scanned to obtain the light intensity distribution of the image in the horizontal direction (\( x \)-axis). The width for \( y \)-direction processing was varied. Within the selected area, the intensity values were averaged over the strip width and the dependence of the intensity on the \( x \)-coordinate was plotted in dimensional units. Then the coordinate of the maximum of the intensity gradient along \( x \)-axis was determined. The coordinates of the maximum and minimum intensity were determined with the accuracy of 0.15 mm.

![Shadowgraph images with shock wave front (top row), enlarged fragments (middle row) and intensity \( x \)-profiles (bottom row) for \( M = 2.05, p_0 = 304 \text{ Torr} \) (a), for \( M = 2.20, p_0 = 50 \text{ Torr} \) (b), for \( M = 2.10, p_0 = 25 \text{ Torr} \) (c). A flash lamp was a light source (a) or a laser (b, c). The exposure time is 1 \( \mu \text{s} \) (a, b) and 6 ns (c). The shock wave moves from left to right. The width of the processing area along the \( y \)-axis is 2 mm.](image)

*Figure 2.* Shadowgraph images with shock wave front (top row), enlarged fragments (middle row) and intensity \( x \)-profiles (bottom row) for \( M = 2.05, p_0 = 304 \text{ Torr} \) (a), for \( M = 2.20, p_0 = 50 \text{ Torr} \) (b), for \( M = 2.10, p_0 = 25 \text{ Torr} \) (c). A flash lamp was a light source (a) or a laser (b, c). The exposure time is 1 \( \mu \text{s} \) (a, b) and 6 ns (c). The shock wave moves from left to right. The width of the processing area along the \( y \)-axis is 2 mm.
Figure 2 shows the examples of image processing. The experimental images were obtained due to the lamp (a) and the laser with a wavelength of 532 nm (b, c) as a source. The rectangles show the processing areas in the original shadowgraph images (top row). The selected areas of $10 \times 5 \text{ mm}^2$ in magnified scale are in the middle row. The intensity profiles along the $x$-axis are presented in the bottom row. The exposure time in the shadowgraph frames of high-speed shooting is $1 \mu\text{s}$ (figure 2(a), (b)). The exposure time for the photo image (figure 2(c)) is 6 ns. The diffraction pattern is clearly visible in figure 2(c). Its width is more than 3 mm. Here the shock wave moves $\sim 0.004 \text{ mm}$ during 6 ns. The shockwave location accuracy is determined by the diffraction pattern and the non-parallelism of the light beam [9]. At an exposure of $1 \mu\text{s}$ (figure 2(b)) diffraction appears insignificantly near the shock front. The accuracy of determining the coordinate of the front is reduced due to the displacement of the shock wave by 0.70 mm during the registration of the shadowgraph pattern. In the shadowgraph picture (figure 2(a)) the accuracy of determining the coordinate of the shock front is also determined by the front displacement during the registration time.

4. Numerical simulation

The numerical method for obtaining the light intensity distribution on the screen consists of three stages. The first one is to obtain the density profile of a plane shock wave for a given Mach number and gas parameters ahead of the shock wave. On the one hand, the Mach number of the shock wave in the considered experiments is near 2. On the other hand, at the experimental pressures ahead of the shock wave, the internal structure is not determinative for the final intensity distribution [9]. These two factors allow the application of the classical Navier-Stokes-Fourier equations to obtain the density profile for a shock wave here [12]. The numerical scheme for the shock wave structure problem is the same as in [13, 14]. The distribution of the relative refractive index is reconstructed from the obtained profile using the Gladstone-Dale approximation [15, 16].

The next step is to calculate the optical path and deflection of the incoming light to the first window of the shock tube test chamber after it has passed through the shock wave [17, 5]. It allows obtaining the phase and light intensity distribution on the second window of the shock tube test chamber. The last stage consists in calculating the final picture of the light distribution on the screen. The points with phase and amplitudes obtained in the previous stage are the sources of secondary waves, the result of which is summed up at each observation point in accordance with their optical paths [18, 19, 20].

As was demonstrated in [9], in the presence of divergence in the laser beam, the result of the shadowgraph image strongly depends on the shock wave position relatively to the center of the beam. Figure 3(a) presents three numerical results of the light intensity on the screen for different positions of the shock wave. Black line represent the case when the shock wave center position ($x_s$) coincidences with the laser beam center. Blue and red lines represent the cases of right and left shock wave positions correspondingly ($x_s = 15 \text{ mm}$ and $x_s = -15 \text{ mm}$). The Mach number in this case is $M = 2.1$. The degree of the laser beam divergence is chosen the same as in [9]. The presented deviation of light intensity is calculated as follows

$$I = \frac{I - I_0}{I_0}. \tag{1}$$

As it can be seen from the presented comparison in figure 3(a), a parallel laser beam is preferable to exclude such a strong influence of the position of the shock wave relative to the center of the laser beam.

If we talk about the one-frame shockwave fixation variant (figure 2(c)) with small exposure time (6 ns), the movement of the shock wave can be neglected. This allows to speak about fixing the "instantaneous" intensity distribution on the screen. This leads to the presence of a diffraction pattern
in the shadowgraph image [9]. The figure 2(b) shows a snapshot where the exposure time is much longer (1 μs). Diffraction effects in this case are smoothed due to significant displacement of the shock wave. The figure 3(b) shows the results of a numerical calculation of the instantaneous intensity distribution on the screen for the Mach number \( M = 2.2 \) and its averaged distribution. The averaged numerical result was obtained for the shock wave displacement by 0.7 mm (from \( x = -0.35 \) mm to \( x = 0.35 \) mm). The resulting intensity averaging leads to the expected result. The diffractive nature of the shadow image is smoothed, the intensity extrema decrease in absolute values. The position of the minimum of light intensity inside a plane shock wave depends on its thickness [9]. The comparison of the experimental figures 2(b) and 2(c) confirm this numerical result.

![Numerical results](image)

**Figure 3.** Numerical results. Different shock wave positions (a). Instantaneous and averaged intensity distributions (b).

5. *Image analysis after a pulse volume discharge*

High-speed shadowgraphy showed the dynamics of shock-wave configurations after discharge. When the initial plane shock wave breaks down, two shock waves and a contact surface are formed [10]. The shock-wave configuration changes with time because of the motion of waves. Surface discharges initiate shock waves moving in the transverse direction to the shock fronts and affecting the structure of the flow.

The sequence of shadowgraph images after the volume discharge is shown in figure 4. Shadowgraph images show central part of 24 mm height channel of \( 16 \times 8 \) mm size near the plane of symmetry of the flow. The shock-wave configuration formed after the breakdown of initial shock front is concentrated in a narrow region [10]. In the first frame, the initial shock wave moves to the right at a speed of 780 m/s. The second frame corresponds to discharge initiation moment. The next frames show the formation and movement of several shock-wave structures after the discharge. For the conditions of this experiment, the shock wave SW1 (a right boundary of configuration) moves to the right as well as a contact surface C. The shock wave SW2 (a left boundary of configuration) moves to the left opposite to the flow direction [10]. Obviously, this structure is clearly visible in frames 3 and 4, where the shock waves and the contact surface are at a distance of several millimeters from each other. This distance is close the width of the diffraction pattern (see figure 2(b)). Shock waves from surface discharges influence the plane shock fronts and contact surface 6.6 μs after the discharge as visible in frame 4.
6. Concluding remarks
The obtained numerical results allowed to explain the qualitative difference between the experimental data obtained at different exposure times. High-speed shadowgraph recordings of supersonic flows with plane shock waves were analyzed by digital processing as well as after interacting with volume discharge in the shock tube channel. The experimental data of shock waves dynamics are obtained from shadowgraph recordings in different initial conditions in shock tube. The accuracy of determination of shock waves positions is evaluated based on digital processing, taking into account the diffraction of light at a shock front.

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Figure 4. The sequence of high-speed shadowgraph images of flow field after the interaction of plane shock wave with volume discharge. Shadowgraph images of $16 \times 8 \text{ mm}^2$ area are taken for $M = 2.27$, $p_0 = 50$ Torr, $x_0 = -10$ mm at 1 µs exposure time; a continuous wave laser was a light source. The frame rate is 300,000 fps.
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