Simulation of shock wave produced by detonation of high-explosive charge in a conical shock tube

Medvedev S P¹, Khomik S V¹, Ivantsov A N¹, Anderzhanov E K¹, Tereza A M¹, Mikhailin A I² and Silnikov M V¹,²

¹N.N. Semenov Federal Research Center for Chemical Physics, Russian Academy of Sciences, Moscow, Russia
²Special Materials Corp., St. Petersburg, Russia

E-mail: podwal_ac@yahoo.com

Abstract. Specific features of the flow during the detonation of high-explosive charge in a conical shock tube are revealed by analyzing the results of numerical simulation. It is established that the main difference between the flow in conical geometry and the spherical case is associated with a change in the flow parameters behind the shock wave due to interaction with the bounding surface (cone wall). Comparative analysis of the calculated results shows that the real performance factor of the conical shock tube can vary both over the length and cross-section of the tube.

1. Introduction
Spherical shock waves (SSW) are formed in the surrounding space as a result of rapid (explosive) energy release in a local volume. SSWs are widespread in various fields of nature and technology. Sources of a spherical explosion have a wide spectrum in size and power – from a weak spark discharge to a supernova explosion. In connection with anthropogenic accidents and terrorist attacks, the study of explosion of condensed explosives (HE) is of particular relevance. Full-scale experiments using HE are useful, but have a number of limitations. In the field testing, it is difficult to achieve good reproducibility of pressure wave parameters. Additional difficulties arise when it is necessary to perform comprehensive measurements, such as optical registration of the flow. It is also necessary to take into account that HE explosions are subjected to regulatory restrictions and require specially equipped sites or explosive chambers. For these reasons, in addition to field tests, it is advisable to conduct experiments under well-controlled conditions.

An alternative approach to modeling blast waves is to conduct experiments using shock tubes. However, despite its universality, traditional shock tubes with a fixed cross-sectional area are poorly adapted to simulate the practically important case of the formation and propagation of spherical shock waves during the HE explosion [1]. In this regard, the modeling of SSW on conical shock tubes (CST) is of scientific and practical importance [1-5]. In this case, the HE charge of mass \( W_{\text{CST}} \) is located at the apex of the cone. The main advantage of such a scheme is that a given shock wave intensity is achieved with a \( W_{\text{CST}} \) value much smaller than the mass of the corresponding spherical charge \( W_{\text{Sph}} \). According to [2,6], the \( W_{\text{Sph}}/W_{\text{CST}} \) ratio characterizing CST is the performance factor \( K_p \), which is determined by the angle of the cone \( \alpha \):

\[
K_p = \frac{W_{\text{Sph}}}{W_{\text{CST}}} = \frac{2}{1 - \cos \left(\frac{\alpha}{2}\right)}
\]

(1)
An important advantage of a conical shock tube is also the possibility of using pressure sensors integrated flush into the wall, as in a traditional shock tube. In addition, CST can be placed in a laboratory room and equipped with standard optical flow visualization systems.

In conical geometry, the walls are parallel to the streamlines of a spherical flow. Nevertheless, in spite of such “ideal” prerequisites, the formation of a boundary layer in the wall region and triple shock wave configurations, as well as multiple reflections of compression and rarefaction waves, can affect the flow parameters and pressure profile of the shock wave. Identification of the mentioned effects is an important task for proving the methodology for studying spherical shock waves using CST. The experimental results, for example, the parameters of the blast waves measured by pressure sensors, do not provide information on the distribution of pressure, density, temperature, flow velocity over the entire length of the pipe and in cross sections. In this work, the features of the flow in a conical shock tube during the HE explosion are revealed by analyzing the results of numerical simulation.

2. Materials and methods
The object of simulation was a CST-38 conical shock tube of 1 m in length with an angle of 38 deg. In experiments [7, 8] it was demonstrated the effectiveness of the CST for simulation of explosion load from various sources such as compressed gases and two-phase (bulk) media, and boiling liquids.

Numerical modeling was performed using the GAS DYNAMICS TOOL (GDT) gas-dynamics calculation package [9]. Using the modified method of large particles, the GDT implements the procedure for solving the problem of HE explosion and subsequent propagation of a shock wave into the surrounding space. The package was tested earlier on the interaction of detonation and shock waves with permeable barriers [10, 11], flat channels [12] and obstacles [13]. Numerical modeling was performed in a three-dimensional formulation. The computational domain of 470x174x174 mm³ included a CST segment with a size of 1/4 cross section with two planes of symmetry. A non-reflecting boundary condition was set at the outlet. The size of the computational cell s = 1 mm. To resolve specific features of the near-field flow of explosion, some calculations were performed at s = 0.1 mm. An HE charge of radius r₀ = 7 mm simulated PETN at a density of 1600 kg/m³, a detonation velocity of 7800 m/s and an initial adiabatic index of γ = 3. Note, that PETN, among other high explosives, has a minimum critical size of detonation initiation and for this reason it can be considered for use in CST. The shock wave propagates in the air under normal conditions. The simulation results for the CST were compared with the calculated flow field in the case of the explosion of the same spherical HE charge in open space.

3. Results and discussion
The parameters of the shock wave during the explosion of the HE charge change in a much wider range than, for example, in gas explosions. Figure 1 represents the flow pattern and the spatial distribution of pressure at various time intervals after the initiation of detonation of the HE charge. As can be seen, at the initial stage at t = 4 μs and a distance of about 4 charge radii, the shock front retains a shape close to spherical. The boundary of detonation products, which is identified by the distribution of the adiabatic index, moves directly behind the shock front. As can be seen from the pressure profiles in the right part of Figure 1, the amplitude of the shock wave at a time of 4 μs is about 200 bar, however, the maximum pressure is reached near the center of the explosion. The flow in the direction of the center of the explosion in the case of CST leads to the appearance of transverse pressure waves, which manifest themselves in the form of pressure spikes exceeding 1000 bar. In addition, it should be noted that the pressure distribution at the axis of the tube (curve 2) and along the wall (curve 3) differ from each other. This effect is due to the deceleration of the shock-compressed gas on the wall and the formation of the boundary layer. An analysis of the calculation results shows the presence of transverse compression and rarefaction waves, which are absent during spherical expansion in an unconfined space.

In the middle zone of the explosion at t = 35 μs (Figure 1), the front of the shock wave in the CST is elongated along the axis of the cone. The boundary of detonation products does not stop at a distance of 10r₀, as is the case in the spherical expansion. Redistribution of pressure leads to formation of the “jet” of detonation products along the axis of the cone.
Figure 1. The flow field and the spatial distribution of pressure at various time interval after the initiation of detonation of the HE charge. S - explosion in unconfined space, C - explosion in a CST. Symmetry axis of the CST is on the horizontal distance axis. Pressure contours step, bar: 100 (4 µs), 3 (35 µs), 0.1 (650 µs). Pressure-distance curves: 1 - explosion in unconfined space, 2 - pressure along the axis of the CST, 3 - pressure along the wall of the CST.

In the considered cases of the near- and middle-zone of the explosion, the amplitude of the shock wave on the axis of the cone corresponds to the spherical case. The flow pattern changes in the far field of the explosion at $t = 650$ µs (Figure 1). The overpressure at the front of the shock wave in the CST becomes less than at explosion in unconfined space.
The revealed features are confirmed by considering the pressure-time dependences shown in Figure 2. In the middle zone of the explosion at a distance of about $14r_0$ (Figure 2 a), the largest amplitude of the shock wave appears on the CST axis. In the far field at $62r_0$ (Figure 2 b), the amplitude of the shock wave in the CST is less than in an explosion in unconfined space. Thus, it is observed a non-monotonic change in the amplitude of the shock wave along the length and cross section of the CST.

Another characteristic feature is the significant difference in the pressure profile on the wall and on the axis of the conical shock tube, which is especially pronounced near the charge. It should also be noted the practical absence of the rarefaction phase of the blast wave in the CST compared with an explosion in open space.

Evaluation of the real performance factor of the CST can be done on the basis of the representation of the parameters of the shock wave in universal reduced coordinates. Figure 3 represents the calculated and experimental dependences of the shock overpressure $\Delta P$ on the reduced distance $R = r/(W_{SPH})^{1/3}$. The observed good agreement between the results of 3D calculations of a spherical unconfined explosion of the PETN charge with experimental data [14] serves as a validation of the GDT numerical procedure. As can be seen, the performance factor of CST-38 corresponds to Eq. (1) in the near and middle zone at $R<2$. A decrease in the value of $K_p$ is observed in the far field. Figure 3 also represents the data of [2] for explosion of the TNT charge in a $22^\circ$-conical shock tube. Comparison of the present results with data of [2] and also of [6] shows that a decrease in the angle of a cone leads to a decrease in the efficiency of the conical shock tube.
Figure 3. The calculated and experimental dependences of the shock overpressure on the reduced distance. 1-3 – approximations of the experimental results for PETN [14], 4 – numerical simulation of unconfined explosion of the PETN charge, 5 – CST-38 simulation, 6 – standard data for spherical TNT explosion, 7 – experimental data for CST [2].

4. Concluding remarks
The results of three-dimensional numerical simulation demonstrate that the blast waves generated by detonation of the HE charge in the conical shock tube have a profile corresponding to spherical shock waves in unconfined space. It is established that the main difference between the flow in conical geometry and the spherical case is associated with a change in the flow parameters behind the shock wave due to interaction with the bounding surface (cone wall). The revealed flow non-uniformity manifest themselves in the form of pressure pulsations and in the practical absence of a rarefaction phase. Comparative analysis of the calculated results shows that the real performance factor of the CST can vary both over the length and cross-section of the tube. The results of the performed investigation can be used in planning experimental modeling of spherical explosions in conical shock tubes.

Acknowledgments
This study was financially supported by the Russian Science Foundation, grant No. 19-19-00554.

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