Influence of diaphragm fragments on the flow in a conical shock tube

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Abstract. In experimental study of spherical shock waves in a conical shock tube, it was found that the amplitude of the shock wave turns out to be less than that calculated on the assumption of instantaneous removal of the diaphragm separating the high and low pressure chambers. To interpret the revealed effect, we analyzed the results of numerical modeling, taking into account the effect of diaphragm fragments on the formation and propagation of a shock wave.

1. Introduction

The rupture of a gas-filled high-pressure vessel (HPV) is one of the most common types of accidents in modern energy-intensive industrial sector. The potential damaging effect of HPV is associated with air shock waves that form in the surrounding space, as well as with the high-speed fragments.

It was shown in [1,2] that a conical shock tube (CST) with a bursting diaphragm separating the conical high-pressure chamber from its extension — the conical low-pressure chamber — is an effective tool for reproducing dynamic loads during spherical explosion of the HPV. In [3], based on the analysis of the results of 3D numerical simulation, it was found that the difference between the flow in conical geometry and the spherical case is associated with a change in the shape of the front of the secondary shock wave and the flow parameters behind it due to interaction with the bounding surface (wall of the cone). Friction and heat transfer processes do not significantly affect the amplitude and impulse of the compression phase and generate certain distortions of the pressure profile only in the rarefaction phase. Nevertheless, it turned out that even taking into account the above factors, the calculations [3] predict an overestimated shock wave intensity in comparison with the experimentally measured one. In the case when the driver gas is nitrogen [1-3], this difference is about 30%. It was suggested in [1-3] that the reason for this discrepancy may be that the calculations do not take into account the dynamics of diaphragm opening. In addition, the fragments of the diaphragm formed during rupture can affect the flow pattern in CST. Thus, for a more complete description of the CST operating conditions, it is necessary to take into account these phenomena.

The problem of the influence of the finite time of diaphragm opening on the formation of a shock wave was considered in detail for shock tubes of constant cross-section [4]. It was found that a complex flow pattern arises near the membrane, including a series of transverse compression and rarefaction waves. Only at a distance of 10 - 20 tube diameters the flow becomes quasi-one-dimensional and the parameters of the shock wave practically coincide with the theoretical predictions. Thus, in a traditional shock tube, the problem of the influence of the dynamics of diaphragm rupture on the flow can be solved by simultaneously increasing the length of the high and low pressure
chambers. The situation is different in the case of a conical shock tube. Compression waves that arise during the
diaphragm opening process are attenuated along the path of propagation in the expanding low-pressure chamber. As
a result, the generated shock wave has a significantly lower intensity than that calculated on the assumption of
instantaneous diaphragm removal.

It is noted in [4] that typically when copper or aluminum foil is used as a bursting diaphragm, fragments are
formed. In CST, these fragments are entrained by the expanding flow and accelerated to a certain maximum
velocity \(v_m\). This process is similar to the problem of the fragment effects at the rupture of an HPV described in
detail in [5]. Analysis of literature data [4, 5] shows that the processes of shock wave formation and acceleration of
diaphragm fragments depend on the properties of the driver gas.

The purpose of this work is to reveal, on the basis of experimental data and numerical modeling, the features of
the flow in a conical shock tube, caused by the presence of diaphragm fragments in the expanding flow. The results
collected in the CST experiments could be useful for validation of numerical calculations of blast waves from
fuel-air explosions [6-8]. The dynamics of the HPV envelope rupture should be taken into account in the modelling
of gas release from pipelines [9].

2. Materials and methods

The experiments were carried out in a CST-38 conical shock tube with an opening angle of 38° and an open conical
low-pressure chamber up to 1 m long. The experimental procedure and a description of the main elements of the
setup are presented in [1,2]. The distance from the apex of the conical high pressure chamber to the ruptured
diaphragm is \(r_0 = 67\) mm. Thus, CST-38 reproduces the parameters of the blast waves that form when a spherical
volume of radius \(r_0\) is expanded. Unlike [1-3], the high-pressure conical chamber was filled with helium.

Preliminary experiments have shown that both the burst pressure of the diaphragm and the parameters of the blast
waves depend significantly on the diaphragm material. For comparative tests, we used three types of copper foil and
aluminum foil, the characteristics of which are given in Table 1.

| Notation | Foil material       | \(h, \text{ mm}\) | \(P_1, \text{ bar}\) | Fragmentation | \(M, \text{ g}\) |
|----------|---------------------|------------------|----------------------|---------------|----------------|
| Cu_0.3u  | unannealed copper   | 0.3              | 23±1                 | 1 fragment    | 5.2            |
| Cu_0.15a | annealed copper     | 0.15             | 23±1                 | no fragments  | -              |
| Cu_0.1u  | unannealed copper   | 0.1              | 6.7±0.5              | 1 fragment    | 1.7            |
| Al_0.1   | aluminum            | 0.1              | 6.7±0.5              | 1 fragments   | 0.5            |

\(h\) – foil thickness; \(P_1\) – rupture pressure; \(M\) – mass of fragment

As can be seen from Table 1, it was possible to select two pairs of diaphragms with the same burst pressure, but
differing from the point of view of the formation of fragments. In CST-38, thanks to the use of special gaskets,
aluminum or unannealed copper foil is torn along the contour of the clamp with a diameter of 50 mm, forming a
single fragment.

To reveal the specific features of the flow in the CST in the presence of a single fragment of the diaphragm, the
results of numerical simulation were analyzed using the gas dynamic calculation package GAS DYNAMICS
TOOL (GDT) [10]. GDT has demonstrated its efficiency in solving problems of pressure wave propagation in a
conical shock tube during the expansion of a gas mixture [3] and the explosion of a charge of a condensed explosive
[11]. To simulate the flow process with a fragment, the GDT built-in procedure for calculating the motion of a solid
body under the action of external forces was used. Numerical modeling was performed in a three-dimensional
setting. The size of the computational domain 260x270x270 mm\(^3\) covered the initial part of the CST-38. The size of
the computational cell is 1 mm. A nonreflecting boundary condition was set on the tube exit. In the calculations, the
diaphragm was represented as a solid thin disk of mass \(M\) (see Table 1), which started to move under the action of
the value of pressure rupture \(P_1\) (see Table 1). The simulation results for a CST with a diaphragm were compared
with the calculated flow field in its absence, which corresponded to the idealized case of instantaneous removal of
the diaphragm. Calculated dependences were compared with experimental data.
3. Results and discussion

The analysis of the results of numerical 3D modeling reveals the features of the flow pattern in the CST in the presence of a fragment of the diaphragm moving in the flow. Figure 1 shows the flow pattern in form of the spatial distribution of pressure at different times after the start of the diaphragm movement. As can be seen, at the initial stage of the process (frame 1), gas flows out of the high-pressure chamber through the gap along the periphery of the diaphragm. A compression wave is formed, which propagates along the tube wall and towards the axis. On the CST axis, these waves collapse (frame 2). Subsequently, the pressure over the cross-section of the CST is equalized, and by the time instant of about 300 $\mu$s, a spherical shock wave is formed. Simultaneously with the formation of compression waves, rarefaction waves propagate into the high-pressure chamber. The pressure on the back of the fragment decreases and eventually equalizes with the external pressure. The fragment moves with acceleration as long as the pressure difference is applied. The maximum speed of about $v_m = 70$ m/s is reached in 0.35 ms. At this moment of time, the fragment has traveled a distance of about 20 mm from its original position. Subsequently, the speed of the fragment smoothly decreases due to air drag.

![Figure 1. The flow field (spatial distribution of pressure, bar) at different times after the start of the diaphragm movement. The time between frames is 30 $\mu$s. $P_1 = 23$ bar, $M = 5.2$ g. The axis of the CST is in the right of each frame](image_url)

In calculations without taking into account the diaphragm, the spherical shock wave is formed...
immediately after the start of calculation. A detailed description of the flow pattern for this case is presented in [3]. The influence of the diaphragm on the parameters of the shock wave is illustrated in Fig. 2. As can be seen, despite the same burst pressure $P_1 = 23$ bar, the calculated shock wave amplitude in the absence of a diaphragm (Fig. 2a) is significantly higher than when its motion is taken into account (Fig. 2b). At the same time, in both cases, for a given distance, there is good agreement between calculated and experimental results.

**Figure 2.** Calculated and experimental pressure profiles at a distance of $r/r_0 = 2.91$ from cone apex. (a) experiment Cu$_{0.15}a$, calculation without diaphragm; (b) experiment Cu$_{0.3}u$, calculation with moving diaphragm ($M=5.2$ g). The time is counted from the beginning of the calculation.

The influence of the initial pressure is shown in Fig. 3. It can be seen that the results of experiments at $P_1 = 23$ bar (Fig. 3a) are well described by numerical simulation. A different case is observed for reduced initial pressure $P_1 = 6.7$ bar (Fig. 3b). Calculation for the experimental conditions of Cu$_{0.1}u$ gives overestimated values of the shock wave overpressure. The results of the Al$_{0.1}$ experiment are close to curve 3, but the mass of the fragment in this case is much less ($M = 0.5$ g). The revealed discrepancy may be due to the fact that in the calculations, the separation of the diaphragm occurs instantly. In the experiment, the diaphragm ruptures along the periphery in a finite time and a significant portion of the driver gas flows out until the moment of complete separation. Thus, a set of pressure wave are generated instead of a shock wave. This effect is more pronounced in the case of a lower initial pressure.

4. Concluding remarks
Experimental and numerical modeling revealed the features of the flow in a conical shock tube associated with the entrainment of diaphragm fragments into the flow. It is shown that the shock wave amplitude in the presence of fragments is significantly lower than when the diaphragm is opened without the formation of fragments. In the case of an increased initial pressure, agreement between the experimental and calculated values is obtained. For a more complete description of the process, it is necessary to take into account the finite time of opening (detachment) of the diaphragm or its fragment. It has been demonstrated that a conical shock tube is an effective tool for simulating both blast and fragmentation effects of a spherical explosion.
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Figure 3. Dependences of over-pressure at the shock front on the relative distance at different initial pressure. (a) $P_1 = 23$ bar, 1 - calculation without a diaphragm, 2 - experiment Cu_0.15u, 3 - calculation at $M = 5.2$ g, 4 - experiment Cu_0.3u; (b) $P_1 = 6.7$ bar, 1 - calculation without a diaphragm, 2 - experiment Al_0.1, 3 - calculation at $M = 1.6$ g, 4 - experiment Cu_0.1u.

References
[1] Medvedev S P, Polenov A N and Gelfand B E 1995 Shock Waves @ Marseille IV eds Brun R and Dumitrescu L Z (Berlin, Heidelberg: Springer) pp 381–6
[2] Medvedev S P, Polenov A N, Gel’fand B E and Khomik S V 1997 Fluid dynamics 32 (5) 724
[3] Medvedev S P, Ivantsov A N, Mikhailin A I, Silnikov M V, Tereza A M and Khomik S V 2020 Russ. J. Phys. Chem. B 14 (4) 601
[4] Gaydon A G and Hurle I R 1963 The shock tube in high-temperature chemical physics (London: Chapman & Hall)
[5] Baker W E, Cox P A, Westine P S, et al. 1983 Explosion hazards and evaluation (Amsterdam-Oxford-New York: Elsevier)
[6] Sumskoi S I, Sof'yn A S, Agapov A A, Zaintdinov S Kh 2020 J. Phys. Con. Ser. 1686 012085
[7] Sumskoi, S.I., Sof‘in, A.S., Zaintdinov, S.K., Agapov, A A 2020 Russ. J. Phys. Chem. B 14 (4) 625
[8] Agapov A A, Safonov V S, Sumskoy S I, Shvyrvaev A A 2020 Bezopasnost' Truda v Promyshlennosti, 2020 (5), 36
[9] Shargatov V A, Sumskoi S I, Pecherkin A S 2019 J. Phys. Conf. Ser. 1205 (1) 012050
[10] Zibarov A V 1999 ASME, PVP 397-1 117
[11] Medvedev S P, Khomik S V, Ivantsov A N, Anderzhanov E K, Tereza A M, Mikhailin A I and Silnikov M V 2020 J. Phys. Conf. Ser. 1686 012084