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Blast wave parameters at diminished ambient pressure

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ABSTRACT

Relation between blast wave parameters resulted from a condensed high explosive (HE) charge detonation and a surrounding gas (air) pressure has been studied. Blast wave pressure and impulse differences at compression and rarefaction phases, which traditionally determine damage explosive effect, has been analyzed. An initial pressure effect on a post-explosion quasi-static component of the blast load has been investigated. The analysis is based on empirical relations between blast parameters and non-dimensional similarity criteria. The results can be directly applied to flying vehicle (aircraft or spacecraft) blast safety analysis.

1. Goals of study

Currently reported acts of terrorism on board of aircrafts draw great attention to a problem of suppression of damage effects caused by blast shock waves and following co-current flows (explosive effect).

The presence of improvised HEs onboard spacecraft (the elastic HE charges based on PETN can be used for undocking and so they should be kept inside a spaceship, for example) requires us to consider the application of this problem to space flight safety as well.

A physical nature of a condensed HE charge explosion inside a civil flying vehicle is an impulse energy release inside a closed pressurized space heavily encumbered by objects including survival systems and constructive elements and bounded by a thin-wall shell. Interaction of blast wave and co-current flows with those systems and elements [1] becomes more complicated due to the waves multiple amplification caused by reflections or refraction on porous and multi-layer surfaces [2,3]and the waves propagation through pre-perturbed non-uniform flows.

Normally, a civil flying vehicle construction is not designed to resist inner impulse mechanical loads. For instance, the experience of terrorist explosions and results of full-scale testing [4] have revealed that an explosion of a charge about 100 g in TNT equivalent (100 g TNT) results in the aircraft cabin depressurizing, control units failure, hull cracks growth and its fast destruction, loss of the aircraft flight capability, death of passengers and crew, sometimes people on the ground. For example, the notorious explosion over Lockerbie (Scotland) on board the Boeing 747 aircraft was caused by detonation of a 440 g HE charge.

The International Civil Aviation Organization (ICAO) and the Russian Federation government require to equip all newly designed aircrafts of seating capacity for more than 60 people with special means of bomb protection (blast inhibitors) that are capable to mitigate a potential damage explosive effects of a suspicious object found on board. The analogous blast protection devices can be applied onboard the spaceships to store the necessary HE charges [5].

G.V. Novohzilov, academician of RAS, initiated a project involving some institutions ("Ilyushin" aerospace company, "Special Materials, Corp.", 294 Center of the Russian Federation Emergency Ministry and CIS International Aviation

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Committee). The project included a cycle of theoretical and experimental studies completed by designing, development and production of special bomb inhibitors “Fountain” family for flying vehicles. A mitigating effect of the destructible blast inhibitors “Fountain” is based on pressure amplitude and impulse reduction and blast wave head front transformation from a gas-dynamic discontinuity into Riemann-type compression wave resulted from its interaction with a multi-phase system [6–8]. Theoretical analysis, numerical simulation data, data obtained in laboratory, field tests and full-scale testing have revealed that application of developed “Fountain” blast inhibitors “Fountain 3MK-2000” allows to preserve an wide-body aircraft (or a space vehicle of analogous size) flight capability after onboard explosion of a HE charge up to 2 kg in TNT equivalent; “Fountain 4M-500” and “Fountain 4MK-500” do this job in case of up to 500 g TNT charge explosion on board of a narrow-body aircraft or analogous space vehicle [5].

The conclusive stage of the aforementioned investigation project was multiple full-scale testing of the developed blast inhibitors on board of wide- and narrow-body passenger aircrafts (“IL-96”, “IL-114”). Based on those test results the blast inhibitors were formally accepted as a part of those aircrafts onboard equipment. The testing was performed on an airfield at normal atmospheric pressure inside the aircrafts cabins.

However, ICAO recommends an aircraft to descend to about 3000 m altitude and to equalize onboard and overboard pressure if a potentially dangerous object is found on its board [9]. Pressure difference acting on the aircraft hull is absent then, and it is not necessary to increase the cabin pressure above the atmospheric level (approximately 1.4–1.5 atm [4,10] for its physical simulation during the airfield testing. It is also evident that the ambient pressure inside a space vehicle can also differ from the normal atmospheric meaning.

Overpressures and pressure impulses of blast waves propagating along the cabin and affecting the structural elements at lower pressure ($p_0 \approx 0.64$ atmospheres according [9]) differ from similar values under normal atmospheric conditions. For full-scale testing data verification pressures and impulses of blast waves generated as recommended by ICAO conditions, and quasi-static gas pressure in the closed space should not exceed the similar values of those parameters resulted from the same power charge explosion at normal initial conditions.

Pressure reduction in the surroundings could result in decrease of generating blast wave amplitude Δp_1 (thus, in some cases, Δp_1 value is in proportion to $p_0^{1/3}$ [11], that is proven by the theory of similarity). However, solution of the pressure discontinuity disintegration problem has revealed that increase in relation ratio between the detonation pressure and the surrounding pressure leads to the blast wave strength (i.e. pressure ratio $J_1 = p/p_0 = (p_0 + \Delta p_1)/p_0$ at its head front [12]) sufficient growth.

2. Empirical relations for blast wave parameters

Overpressures and blast wave impulses at voluntary surrounding pressure have been evaluated using dimensionless Sachs variables [11,13]. In practically important dimensionless distance range $0.27 \le \overline{R} \le 10$ where $\overline{R} = R \cdot (p_0/E)^{1/3}$, R is dimensional distance to the blast epicenter, E is blast energy, blast wave amplitude Δp_1 at the compression phase is defined from [14]:

$$\overline{p} = \frac{0.46}{\overline{R}^{4/3}} + \frac{0.099}{\overline{R}^2} + \frac{0.065}{\overline{R}^3}, \tag{1}$$

where $\overline{p} = \Delta p_1/p_0$ is dimensionless overpressure. Rarefaction wave amplitude $\Delta p_- = |p_- - p_0|$ following the N-blast wave compression phase is evaluated at the distance $0.45 \le \overline{R} \le 10$ from the blast epicenter,

$$\overline{p}_- = \Delta p_-/p_0 = 0.113/\overline{R}^{1.1} \tag{2}$$

Here p_- is minimal pressure at the blast wave negative phase, Δp_- is negative phase dimensionless amplitude.

Dimensionless compression phase impulse $\bar{I} = c_0 I/(Ep_0^2)^{1/3}$ or rarefaction phase impulse $\bar{I}_- = c_0 I_-/(Ep_0^2)^{1/3}$ of the blast wave are calculated as it follows:

$$\bar{I} = 0.055/\overline{R}^{0.97}, \; \bar{I}_- = 0.052/\overline{R}^{0.85} \tag{3}$$

at $0.27 \le \overline{R} \le 10$ and $0.45 \le \overline{R} \le 10$, respectively. Here, as it is admitted in physics of explosion, I and I_- are dimensional pressure impulses (pressure integrals on the time spans of the positive blast wave phase and negative one, correspondingly), c_0 is sound speed in undisturbed ambient media.

Since a damage blast shock wave effect is determined by dimensional amplitude (Δp_1) and impulse (I) of its compression phase, then the following relations (1)–(3) are written in dimensional form:

$$\Delta p_1 = \frac{0.46E^{4/9}p_0^{5/9}}{R^{4/3}} + \frac{0.099E^{2/3}p_0^{1/3}}{R^2} + \frac{0.065E}{R^3},$$

$$I = \frac{0.055E^{0.657}p_0^{0.343}}{c_0 R^{0.97}}, \tag{4}$$

$$\Delta p_- = \frac{0.113E^{0.367}p_0^{0.633}}{R^{1.1}}, \; I_- = \frac{0.052E^{0.617}p_0^{0.383}}{c_0 R^{0.85}}, \tag{5}$$

reveal attenuation of a blast shock wave explosive effect both at compression and rarefaction phases.

Effect of p_0 value on the quasi-static pressure growth amplitude $\overline{\Delta p}_{qs} = (p_{qs} - p_0)/p_0$ resulted from a HE charge explosion of energy $E = GE_1$ inside a volume V can be estimated from [15,16],

$$\overline{\Delta p}_{qs} = 1.047\left(\frac{E}{p_0 V}\right)^{0.64}, \tag{6}$$

Here p_{qs} is dimensional quasi-static overpressure remaining in closed space after all dynamic shock-wave processes, Δp_{qs} is dimensionless quasi-static overpressure, G is TNT charge equivalent, kg; E_1 is blast specific energy, J/kg; pressures are given in Pa, volume are given in m^3. Relation (6) shows that pressure fall in a certain volume confinement (for example, $V = 706$ m^3 is over-deck space in “IL-96” aircraft cabin) leads to unambiguous reduction of quasi-static component Δp_{qs}.