Development of Explosion-containment Vessel with 3 kg TNT Equivalent

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Abstract. In this paper, the design theory of explosion-containment vessel is studied, the charge ratio distance, incident overpressure and reflection overpressure acting on the inner wall of the explosion-containment vessel are calculated when 3kg TNT is exploded in it, the transient load generated in the explosion is converted into equivalent static load by the method of dynamic coefficient, and the main wall thickness of 3kg TNT equivalent explosion-containment vessel is determined. A 3kg TNT equivalent capsule explosion-containment vessel is designed and tested the explosion performance, the explosion performance test results show that the design of the 3kg TNT equivalent explosion-containment vessel is reasonable, safe and reliable, and it is of great practical significance to apply it to the transportation and destruction of weapons and ammunition and emergency treatment.

1. Introduction

Explosion-containment vessel is a kind of special sealed pressure container, which can effectively restrain the explosion inside, so that the shock wave and debris generated by the explosion are limited inside the container [1]. It can realize effective close protection for test equipment and personnel, and test and observe the process of explosion.

Since 1945 when Los Alamos laboratory developed the world's first explosive container, many countries have developed explosive containers with TNT equivalent from several kilograms to dozens of kilograms or even hundreds of kilograms [2]. Due to different application purposes, the structure of explosive containers is also diverse, common spherical, cylindrical and composite containers. Such containers are mainly used for explosive tests in scientific research departments, storage and transfer of nuclear and chemical weapons, prevention of environmental pollution caused by radioactive or toxic wastes and other harmful materials, and transportation and destruction of expired weapons and ammunition.

In recent years, explosion emergencies are on the rise all over the world. In order to prevent suspected explosives carried by terrorists from endangering social security, explosion-containment vessel need to be used to deal with suspected explosives. Therefore, it is very important to study explosion-containment vessel to deal with emergencies [3].

2. Design of explosion-containment vessel

Baker et al. [4-10] have done a lot of work on the basic theory of explosion-containment vessel. Explosion-containment vessel requires small volume and light weight, and has a large anti-explosion ability, its size and wall thickness is of great significance. The most fundamental difference between an explosion-containment vessel and a general pressure container is that its internal function is
transient. After the explosion occurred in the center of the explosion-containment vessel, a shock wave propagates in all directions is formed. The shock wave reaches the inner wall of the explosion-containment vessel and forms a reflection shock wave, which is transient load acting on the inner wall of the vessel. Therefore, the strength of the transient load is determined before the design of the explosive container, and then it is converted into the equivalent static load. When the equivalent static load is determined, the main wall thickness of the vessel will be designed based on the equivalent static load.

2.1. selection of explosive container materials

The structural dimensions of the 3kg TNT equivalent explosion-containment vessel are preliminarily determined as shown in figure 1. The explosion-containment vessel designed in this paper is capsule shaped and consists of tank body, hemispherical head, flange and nozzles.

It is mainly used for the transportation of expired weapons and suspicious explosive items. The steel required to be selected has certain strength. In addition, welding and other conditions should be considered.

2.2. Calculation of transient loads

There are many methods to calculate the explosive transient load inside the explosion-containment vessel, but each method has certain preconditions.

The explosion load is the basis of the strength calculation of the explosion-containment vessel. The dynamic response parameters of the explosion-containment vessel under the action of blast wave mainly include: incident overpressure, reflection overpressure and action time of overpressure. These parameters are generally determined by empirical formulas based on a large number of experiments.

The capsule shaped explosion-containment vessel designed in this paper has a radius of 500mm, a length of 2000mm, the charge is 3kg TNT.

2.2.1. Determination of charging ratio distance. The charging ratio distance can be determined by equation (1).

\[ \bar{R} = \frac{R}{\sqrt[3]{W}} \text{ (unit: m)} \] (1)

Where, \( R \) is the radius of the explosion-containment vessel (unit: m), \( W \) is the TNT equivalent (unit: kg). Put \( R = 0.5m \), \( W = 3kg \) into the equation (1), to get \( \bar{R} = 0.35 \).
2.2.2. Determination of incident overpressure. The incident overpressure \( \Delta p_1 \) can be calculated by K-G (Kinney and Graham) formula.

\[
\Delta p_1 = 808 \times p_0 \left[ \frac{1}{1 + (\bar{R} / 0.048)^2} \right]^{1/2} \left[ \frac{1}{1 + (\bar{R} / 0.32)^2} \right]^{1/2} \left[ \frac{1}{1 + (\bar{R} / 1.35)^2} \right]^{1/2}
\]  

Where, \( p_0 \) is the atmospheric pressure. Put \( \bar{R} = 0.35 \), \( p_0 = 1.01325 \times 10^5 \text{ Pa} \) into the equation (2), to get \( \Delta p_1 = 7.22 \text{ Mpa} \).

2.2.3. Determination of reflection overpressure. When the shock wave acts on the container wall, it can be considered as the shock wave acting on the rigid solid wall. Therefore, reflection overpressure \( \Delta p_2 \) is calculated by the equation (3).

\[
\Delta p_2 = 2\Delta p_1 + 6\Delta p_1^2 / (7p_0 + \Delta p_1)
\]  

Where, \( p_0 \) is the atmospheric pressure. Put \( \Delta p_1 = 7.22 \text{ Mpa} \), \( p_0 = 1.01325 \times 10^5 \text{ Pa} \) into the equation (3), to get \( \Delta p_2 = 53.93 \text{ Mpa} \).

2.3. Determination of equivalent static load

The calculation methods of equivalent static load mainly include the empirical formula method, hongdu method and dynamic coefficient method. This paper adopts the dynamic coefficient method.

2.3.1. Determination of dynamic coefficient. According to literature [11], the calculation formula of action time of reflection overpressure is shown below.

\[
t_1 = \eta R / \sqrt{Q_0}
\]

Where, \( R \) is the radius of the container shell (unit: m), \( Q_0 \) is the detonation heat per unit mass (unit: J/kg), and \( \eta \) is the empirical coefficient. When the column is symmetric, \( \eta = 0.5 \); For TNT, \( Q_0 = 4860874.8 \text{ J/kg} \), put \( R = 0.50 \text{ m} \) into the equation (4), to get \( t_1 = 1.134 \times 10^{-4} \).

For a thin shell, if only the extended motion is considered, then the period of natural oscillation:

\[
T = 2\pi R \sqrt{\rho / E}
\]

Where, \( E \) is the elastic modulus, \( \rho \) is the density of shell material (unit: \( \text{kg/m}^3 \)). \( E = 210 \times 10^9 \text{ Pa} \), \( \rho = 7.8 \times 10^3 \text{ kg/m}^3 \), \( R = 0.50 \text{ m} \), \( T = 6.051 \times 10^{-4} \text{ s} \), \( t_1 / T = 0.1874 < 3/8 = 0.375 \). According to literature [1], when \( t_1 / T < 3/8 \), dynamic coefficient \( C_d \) is selected according to the following formula:

\[
C_d = \sqrt{\frac{\omega_1}{2}} \sin^4 \frac{\omega_1}{2} + \left( \frac{\sin\omega_1}{\omega_1} - 1 \right)^2
\]

Where, \( \omega \) is the natural vibration frequency of the explosion-containment vessel, put \( \omega = 2\pi / T = 1.038 \times 10^4 \), \( \omega_1 = 1.1771 \) into the equation (6) to get \( C_d = 0.567 \).
2.3.2. **Determination of equivalent static load.** The calculation method of shell strength is basically the same as that used in the design of anti-explosion protection structure. The calculation formula of equivalent static load is

\[ p_e = \Delta p_2 \times C_d \]  

(7)

Put \( \Delta p_2 = 53.93\text{MPa} \), \( C_d = 0.567 \) into the equation (7) to get \( p_e = 30.58\text{MPa} \). In the structural design, the equivalent static load of 30.58MPa is used for the main structure calculation.

2.4. **determination of wall thickness of container body**

The wall thickness of the vessel under static pressure is

\[ \delta \geq \frac{p_e D}{2[\sigma] \phi - p_e} \]  

(8)

Where, \( p_e \) is the design pressure (unit: MPa), \( D \) is the inner diameter of the container (unit: mm), \([\sigma]\) is the allowable stress of the material under the design temperature, \( \phi \) is the weld coefficient, and is generally taken as 1.

For material used in this paper, the safety coefficient is 2, \([\sigma] = 345\text{MPa}\), put \( p_e = 30.58\text{MPa} \), \( D = 1000\text{mm} \) into equation (8) to get the required wall thickness of the container \( \delta \geq 46.4\text{mm} \).

In actual engineering, from the perspective of safety, the steel plate with a thickness of 60mm is conservatively selected as the plate of the tank body, while the plate with a thickness of 66mm is selected as the upper and lower semicircle head.

3. **Test verification of explosion-containment vessel**

3.1. **test plan**

The 3kg TNT cartridge is bound into an approximate cube with insulating tape and placed in the center of the explosion-containment vessel as shown in figure 2. The cartridge block is fixed by hanging net and placed horizontally as a whole.

![Figure 2. The position of 3kg TNT in the explosion-containment vessel.](image)

After the explosion source in the explosion-containment vessel is detonated, the explosion test of the explosion-containment vessel shall be judged as qualified according to the following standards:
no spatter should be generated outside the explosion-containment vessel
no penetrable holes or cracks shall occur in the explosion-containment vessel
the explosion-containment vessel can be opened and closed normally

3.2. test results
After the explosion test, the appearance of the explosion-containment vessel is detected, the tank body has no penetrable holes or cracks, the external parts are complete, and there is no shedding, damage, deformation or other phenomena, and there is no spatter flying out from the TNT cartridge explosion.

After the explosion-containment vessel is opened, there is no TNT residue and powder in the vessel and the switch mechanism can work normally. In conclusion, the design method of the explosion-containment vessel is safe and reliable.

In addition, this explosion-containment vessel has been carried out more than 10 times of scientific research explosion test so far, and the operation is in good condition. The switch sealing mechanism of this explosion-containment vessel can be fully automatic operation. The successful development of this vessel can be used for reference in the development of similar explosion-containment vessel in the future.

4. Conclusions
The excellent performance of explosion-containment vessel makes it widely used in the national defense industry, scientific research, and public safety. In this paper, the engineering design method of the capsule type explosion-containment vessel is introduced, and it has been verified by experiment. This design method can be briefly summarized as follows:

(1) Determine the shape, inner diameter and material of the explosion-containment vessel according to the working condition;
(2) Calculate the transient load acting on the inner wall of the explosion-containment vessel, including incident overpressure and reflection overpressure;
(3) The dynamic coefficient is determined by the reflection overpressure action time and the natural vibration circular frequency of the explosion-containment vessel, and then the static load is obtained;
(4) The main wall thickness of the explosion-containment vessel is designed based on the static load.

The technical measures that should be given priority in the development of explosion-containment vessel are introduced above. In addition, safety measures should be considered during the long-term operation of explosion-containment vessel. For example, ultrasonic inspection should be carried out regularly for explosion-containment vessel, and detailed archival records of cracks or defects should be established to ensure that no cracking accidents occur during the operation of containers.

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