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Enhanced ignition behavior of reactive material projectiles impacting fuel-filled tank

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ABSTRACT

Reactive material projectiles can be an extremely efficient lethality enhancement technology that incorporates the defeat mechanisms of chemical energy and kinetic energy. This paper presents such a research on the enhanced ignition behavior of reactive material projectiles impacting a fuel-filled tank. Firstly, the ignition process description of the fuel-filled tank impacted by inert metal and reactive material projectiles is presented. Secondly, ballistic impact experiments are performed to investigate the ignition effects of the fuel-filled tank impacted by reactive material versus tungsten alloy projectiles with mass matched. The fuel tank used for the experiments is a cylindrical steel casing structure filled with aviation kerosene and sealed with aluminum cover plates on both ends using screw bolts. The experimental results indicate that, compared with impacts from tungsten alloy projectiles, there is dramatically enhanced structural damage to the fuel-filled tank and an enhanced ignition effect caused by reactive material projectile impacts. Finally, an analytical model is developed, by which the effects of the aluminum cover plate thickness on critical structural failure energy of the fuel-filled tank and the total energy of the reactive material projectile deposited into the fuel-filled tank are discussed. The analysis shows a good agreement with the experiments.

1. Introduction

Reactive materials are a class of energetic materials with both sufficient insensitivity and strength. In general, these reactive materials are formed by introducing active metal powders into a polymer binder and consolidating via a pressing/sintering process, typically such as Al/W/PTFE (aluminum/tungsten/polytetrafluoroethylene) or Al/PTFE [1–3]. Different from the traditional kinetic energy projectile that produces perforation damage to the impacted targets by penetration-only mechanism, the reactive materials, under highly dynamic loads, release large amounts of chemical energy into target structures, creating dramatic overpressures, considerable amount of heat and incendiary effects, thereby significantly enhancing the damage to the targets by the combined defeat mechanisms of kinetic energy and chemical energy.

Due to their unique performances, reactive materials have received extensive attention and are actively developed for military applications. Over the past few decades, much progress in these reactive materials has been achieved, such as in their components and fabrications [4], mechanical properties under quasi-static [5] or dynamic loads [6,7], and energy release characteristics [8,9]. In addition, the enhanced lethality of the reactive material projectile impacting a variety of targets has been researched, namely: Ref. [10,11] studied the damage effects on a single aluminum plate and double-spaced aluminum plates impacted by reactive material projectile, respectively. Ref. [12] studied the enhanced initiation behavior of reactive material projectile impacting an explosive covered with a metal (aluminum and steel) plate.

Although the lethality enhancement of the reactive material projectile has been studied extensively, little research has been done on the enhanced ignition effect of fuel-filled tank by a reactive material projectile impact, consequently, the enhanced fuel ignition mechanism is not well understood. The current study focuses on this enhanced ignition behavior of the reactive material projectile. Firstly, the structural damage to the fuel-filled tank and the ignition effect caused by reactive material projectile and tungsten alloy projectile impacts are studied experimentally. Secondly, the enhanced ignition mechanism of the reactive material projectile is

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analyzed and discussed.

2. Problem description

Compared with inert metal projectile, the interaction process of a reactive material projectile (hereafter called reactive projectile) impacting a fuel-filled tank is more complicated due to its additional chemical energy release inside the fuel tank structure. To understand the enhanced ignition behavior of reactive material projectile impacting a fuel-filled tank, a simple comparison between inert metal projectile and reactive projectile is presented below.

Fig. 1 shows the fuel ignition process when the tank is impacted by an inert metal projectile. When penetrating the fuel, the inert metal projectile generates shock waves to compress the fuel, resulting in a rapid pressure and temperature rise across the shock wave front (see Fig. 1(a)). As the fuel is compressed, a growing cavity is formed followed by the projectile (see Fig. 1(b)). Then the shock waves reach the tank walls and result in a rapid loading of the structure, commonly known as the hydraulic ram (HR) effect [13–15]. Finally, the tank is cracked starting from the penetration hole or is evenly deformed, and the fuel ejected from the damaged sites is ignited.

In general, the fuel ignition requires at least two essential conditions: high temperature (beyond the ignition point) and the presence of oxygen gas. During the impact process, the fuel is penetrated by a high velocity projectile which generates compression shock waves in the fuel, providing enough high temperature for the fuel ignition [16], however, due to little air in the penetration channel, the heated and atomized fuel has little chance to mix with the atmospheric air and might not be ignited. In general, the key to ignite the fuel is how to mix the fuel with the atmospheric air, where one of the means to achieve efficient mixing is to produce a catastrophic structural damage to the fuel-filled tank. With sufficiently high impact velocity, the inert metal projectile could produce a dramatic HR effect, transferring the kinetic energy of the projectile to the fuel-filled tank structure and “opening” the structure beginning from its perforation site, from which the heated and atomized fuel would have a greater chance to mix with the atmospheric air outside the fuel tank and hence to be ignited.

In the case of a reactive projectile impact, the fuel ignition process and mechanism are different from that of the inert metal projectile impact, as shown in Fig. 2. When the reactive projectile impacts the fuel-filled tank, owing to a relatively low mass density of the reactive materials, relatively weaker shock waves are produced and propagate into the fuel, causing a relatively smaller rise in pressure and temperature and a relatively weaker HR effect. However, the impact upon the cover plate induces the fracture and initiation of the reactive materials, resulting in a large amount of chemical energy release into the fuel tank. The chemical energy release of the reactive materials creates a dramatic temperature rise (usually reaching up to thousands of degrees Kelvin [17]) and, more importantly, it provides an additional overpressure inside the fuel-filled tank, due to which the catastrophic structural damage of the tank can take place. By the combined mechanisms of kinetic energy and chemical energy, the fuel tank structure is more readily “opened”, so the heated and atomized fuel splashes outside the tank and is allowed to mix with the atmospheric air more efficiently, such that the enhanced ignition of the fuel can be achieved.

3. Experiments

3.1. Experimental setup

In order to investigate the enhanced ignition performance of the reactive projectile impacting the fuel-filled tank, a series of ballistic impact tests have been conducted. The schematic of the experimental setup is shown in Fig. 3. The projectile was fired from a powder gun and impacted the front aluminum cover plate of the fuel-filled tank at 0-degree obliquity. By adjusting the black powder mass in the powder gun, the impact velocity of the reactive projectile and the inert metal projectile were controlled at about 900 m/s and 1150 m/s, respectively. The impact velocity was recorded by the velocity probes set at 0.5 m in front of the fuel-filled tank. The impact process is recorded by high speed video.

Fig. 4 shows the reactive projectile and the bullet sample. The cylindrically pressed/sintered PTFE/Al/W (polytetrafluoroethylene/aluminum/tungsten) reactive projectiles were prepared with a mass of 8 g and a dimension of 10.7 mm high and 11 mm in diameter. The reactive projectiles were all made with the identical formulation, namely: 11.3 wt% PTFE, 7.5 wt% Al, and 81.2 wt% W. The powder grains of the individual ingredients had the following average size: Al: 44 μm; W: 44 μm; PTFE: 100 nm. The tungsten alloy projectile was designed with the same mass as that of the reactive projectile. The size-matched nylon sabot was used to guarantee the trajectory stabilization.

Both schematic and photographs of the fuel-filled tank structure are shown in Fig. 5. The cylindrical fuel-filled tank comprised a 10 mm thick steel casing and two aluminum cover plates on both

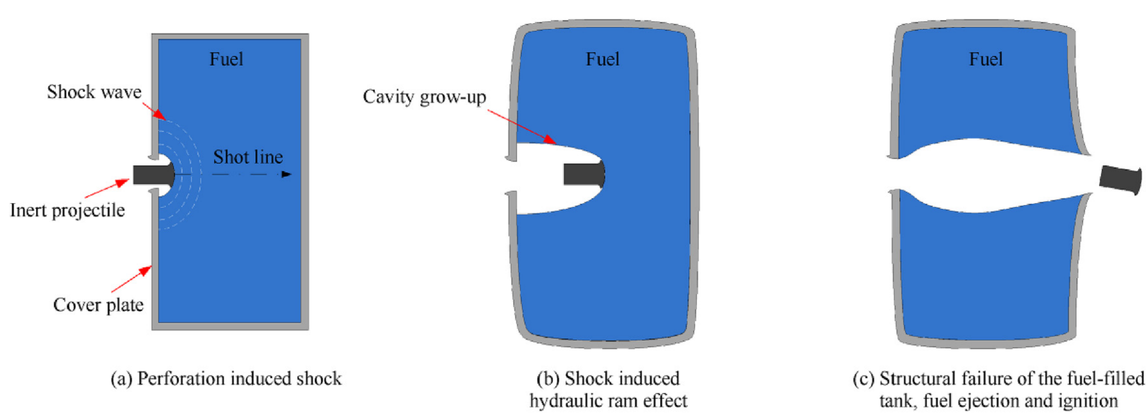

Fig. 1. Fuel ignition process by inert metal projectile impact.

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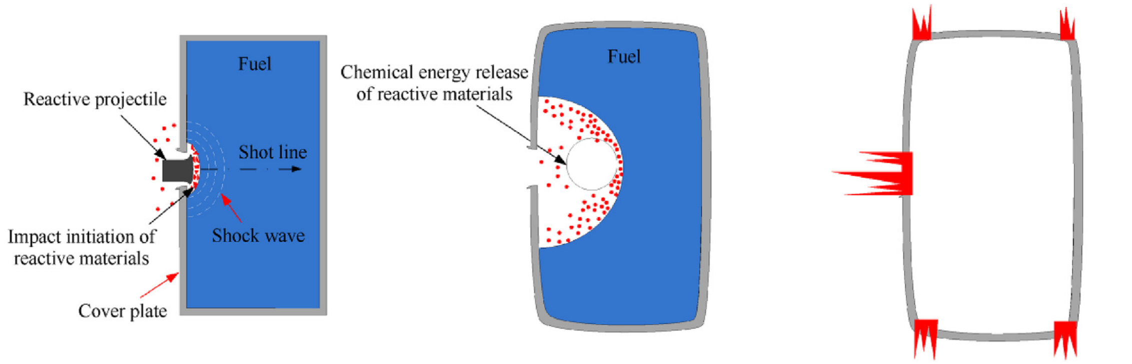


(a) Perforation induced shock and initiation
(b) Initiation induced overpressure effect
(c) Enhanced tank structural failure, fuel splash and enhanced fuel ignition

Fig. 2. Fuel ignition process by reactive material projectile impact.

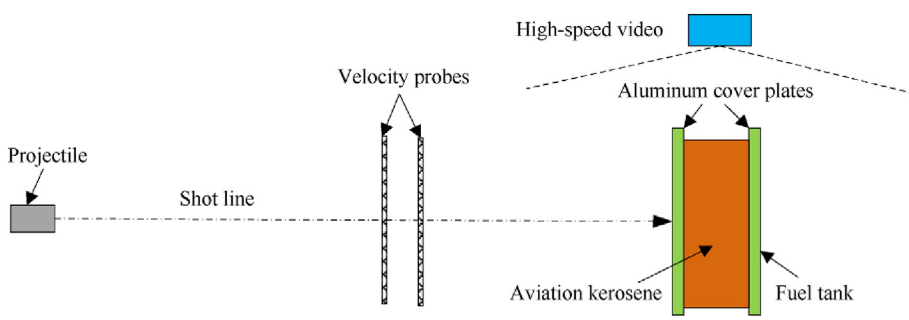
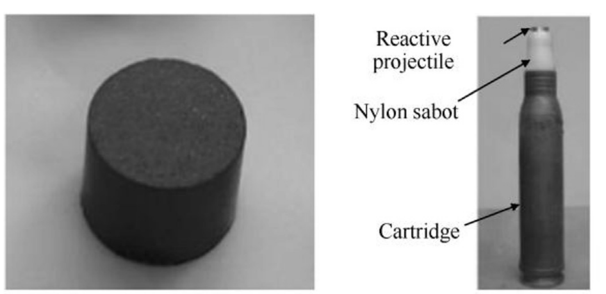


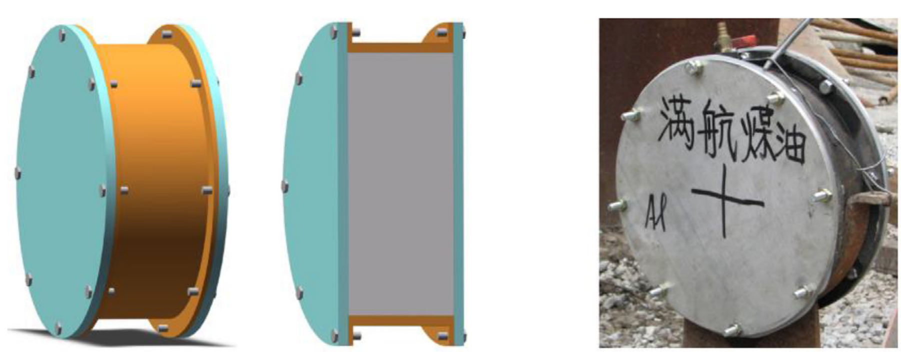
Fig. 3. Schematic of experimental setup.

ends with the same thickness. Three thicknesses of aluminum cover plates were tested, namely: 3 mm, 6 mm and 10 mm. The fuel tank was 100 mm wide inside and 290 mm in internal diameter. Eight screw bolts were used to fix each aluminum cover plate to the tank body, and rubber washers were used at the connections to ensure a liquid seal. The nominal diameter of each bolt was 18 mm, where the tensile and yield strengths of a single bolt was 800 MPa and 640 MPa, respectively. In experiments, the tank was filled with RP-3 aviation kerosene. To guarantee the impact point was beneath the fuel surface so as to produce the HR effect upon the fuel tank structure, the aviation kerosene was filled to approximately the top of the tank.



(a) Cylindrical reactive projectile
(b) Bullet sample

Fig. 4. Reactive projectile and bullet sample.



(a) Schematic of fuel-filled tank
(b) Photograph of the fuel-filled tank

Fig. 5. Schematic and photograph of the fuel-filled tank structure.

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3.2. Results

The experiments investigated the enhanced ignition behavior of reactive projectile impacting the fuel-filled tank with different thick aluminum cover plates. The experimental results are listed in Table 1. As can be seen, all the reactive projectiles ignited the fuel but the experimental phenomena were significantly different for varying cover plates thicknesses. With the decreasing thickness of the aluminum cover plates, the damage effect of the fuel-filled tank structure and the ignition effect of the fuel tank are enhanced. Compared with reactive projectile, the tungsten projectiles could not ignite the fuel during the impact process, even at a higher impact velocity.

Typical high-speed photography frames of both reactive projectile (shot 1# and shot 2#) and tungsten projectile (shot 4#) impacting fuel-filled tank are shown in Fig. 6, respectively. The projectile is moving from left to right and $T = 0$ ms is the impact time. As shown in Fig. 6 (a), at the time of 9 ms after impact, the front cover plate can be observed to depart from the tank body. Deflagration within the reactive materials was initiated and the fuel splashed from the tank was ignited completely. 22 ms after impact, it is clearly observed that both the front cover plate and the rear cover plate were separated from the tank body. The fuel, splashed far away from the tank on the ground, burnt continuously 27 ms after impact. Fig. 6 (b) shows the ignition process of reactive projectile impacting the fuel-filled tank with 6 mm thick aluminum cover plates. As can be seen in Fig. 6 (b), most of the fuel splashed from the back of the fuel tank because the front cover plate was not separated from the tank. The rear cover plate departed from the tank body (shown later in Fig. 7) and lends support to explain this mode of fuel ignition. Compared with reactive projectiles, the tungsten projectiles did not cause the structural failure of the tank at the impact velocity of 1143 m/s and the fuel ejected from both the entrance and the exit penetration holes did not result in fuel ignition.

The progressive development of damage to the fuel-filled tank with increasing aluminum cover plate thickness is illustrated in Fig. 7. In Fig. 7(a), the front and rear aluminum cover plates were separated from the tank body, indicating that the initiation of the reactive projectile produced sufficiently high overpressure inside the fuel tank to cause the structural failure of both 3 mm aluminum plates. When the thickness of the cover plate was increased to 6 mm, the energy deposited into the fuel-filled tank by the reactive projectile was not enough for damaging both aluminum cover plates and only the rear cover plate separated from the tank body. The rear cover plate was recovered and it is clear that there was no perforation hole in it, however, there is evidence of shear at the location of the 8 screw bolts (see Fig. 7 (b)). By further increasing the thickness of cover plates, the fuel-filled tank could not be totally opened and the damage effect of the tank decreased significantly. The rear aluminum cover plate did not depart but three connecting points failed, causing the fuel to leak out of the fuel tank from the damaged sites and to ignite. In the first three cases involving reactive projectile impact, as can be observed, all the screw bolts were not fractured and were still fixed to the tank body after the impact, indicating that the prominent damage mode of the fuel-filled tank structure was failure in the connecting points between the screw bolts and the aluminum cover plates, suggesting these connections are the weak links behind this type of fuel tank structure. The experiments reveal that the structural failure of the fuel-filled tank by reactive projectile impact depends on the results of competition between the overpressure inside the fuel tank produced by the projectile and the connecting strength of the fuel tank itself. Compared with the reactive projectile, Fig. 7 (d) shows the impact of a tungsten projectile causing entrance and exit holes in both front and rear cover plate of the fuel-filled tank, respectively. In this case, the aluminum cover plates remained fixed on the tank body without showing signs of failure.

4. Discussion

4.1. Analytical model for structural failure of the fuel-filled tank

As mentioned above, when the reactive projectile impacts the fuel-filled tank, the initiation of the reactive materials produces a dramatic temperature rise that is much higher than the ignition point of the fuel, therefore, to mix with the atmospheric air outside the tank is key for the fuel to ignite. The experiments also show that after impact, the structure of the fuel tank was first damaged and then the fuel splashed or leaked outside the tank before finally igniting. Therefore, the occurrence of ignition strongly depends upon the structural failure of the fuel-filled tank. To understand the enhanced ignition effect of the fuel-filled tank by reactive projectile impact, the structural damage to the tank should be first considered. In this section, a structural failure model of the fuel-filled tank is developed to evaluate the structural failure energy of the fuel-filled tank.

In the experiments, the structure failure of the fuel-filled tank takes place at the connections between the fixed screw bolts and the aluminum cover plate, which is shown in Fig. 8 (a). As can be seen, due to the overpressure inside the fuel-filled tank, the aluminum plate is first deflected outward and then sheared and plugged by the screw bolts. This failure process can be simply described as a number of fixed screw bolts “penetrating” the aluminum cover plate, schematically shown in Fig. 8 (b). The aluminum cover plate is subjected to the force F_s by the fuel, which originated from the overpressure inside the fuel-filled tank, and to the shear stress by the head of screw bolt. The critical structure failure condition is defined by the “penetration depth” by the screw bolt being equal to the thickness of the aluminum cover plate and the cover plate has no velocity when it separated from the tank body.

The force supplied by the overpressure inside the fuel-filled tank F_s is described as:

$$F_s = \sigma_c \pi D \int_0^h dx \tag{1}$$

Where, D is the diameter of screw bolt's head, for the M18 bolt,

Table 1
Experimental results.

No.	Projectile materials	Impact velocity/$(\mathrm{m \cdot s^{-1}})$	Aluminum cover plates thickness/mm	Phenomenon
1#	Reactive	903	3	Both cover plates departed, fuel splash and ignition
2#	Reactive	895	6	Rear cover plate departed, fuel splash and ignition
3#	Reactive	898	10	Cover plates deflection, fuel leak and ignition
4#	Tungsten	1143	6	Fuel tank perforated only
5#	Tungsten	1148	3	Fuel tank perforated only

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Fig. 6. Typical high-speed video frames of reactive and tungsten projectiles impacting the fuel-filled tank.

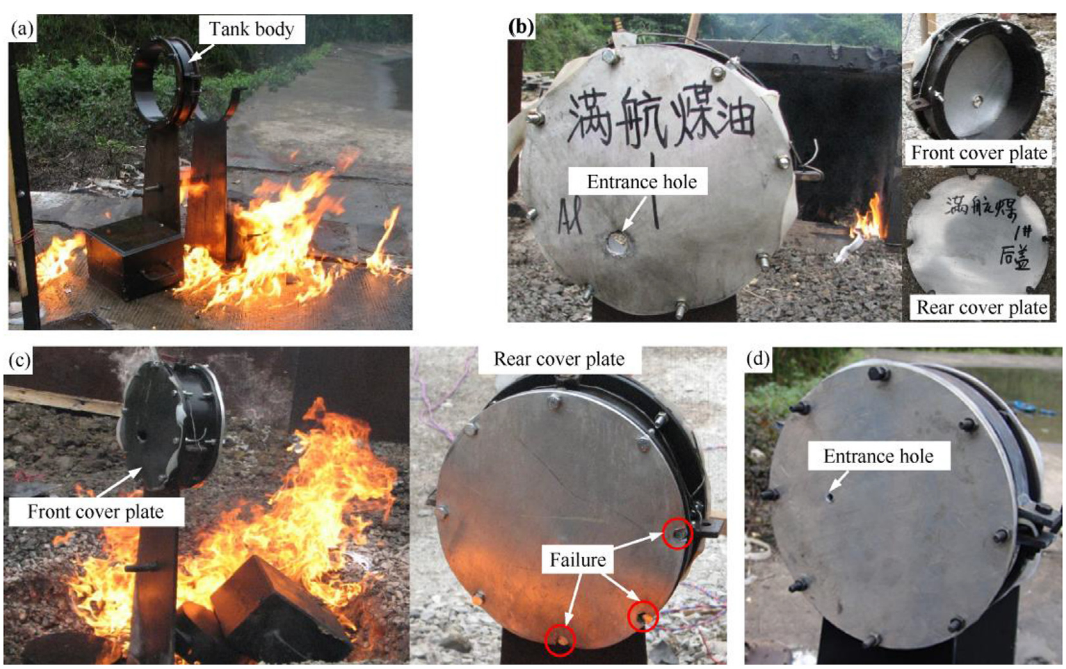

Fig. 7. Damage to the fuel-filled tank structure: (a) the tank body after shot 1#; (b) the tank body with the fixed front cover plate and the separated rear cover plate after shot 2#; (c) the tank body with the fixed front cover plate and the partial damaged rear cover plate after shot 3#; (d) No structural damage to fuel tank occurs after shot 4#.

$D = 27$ mm dx is penetration depth, and σ_c is the ultimate shear stress of the aluminum material.

The critical structural failure energy for the fuel-filled tank E_{failure} can be described as the aluminum cover plate doing work for a number of fixed screw bolts:

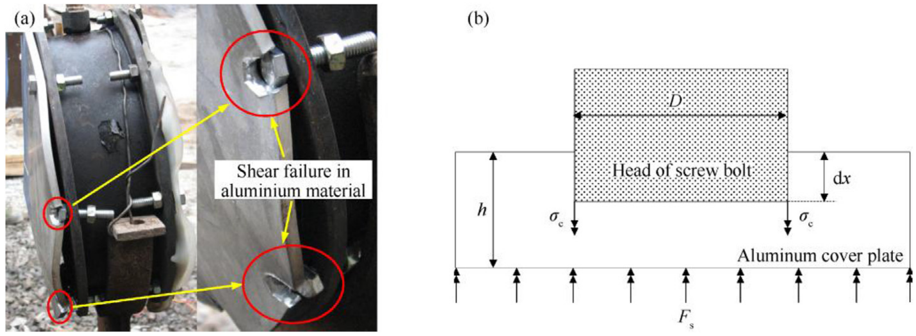

Fig. 8. Structure failure model of the fuel-filled tank: (a) Photograph of the damaged tank, the aluminum cover plate is sheared by the head of screw bolts (b) Schematic of the aluminum cover plate/screw bolt interaction process.

$$E_{\text{failure}} = nW_{\text{i}} = n\int_0^h F_{\text{s}}dx \tag{2}$$

Where n is the screw bolts number, W_{i} is the work for a single screw bolt.

4.2. Enhanced ignition mechanism of reactive projectile

To create the ignition effect, the total energy deposited into the fuel-filled tank by reactive projectile should be high enough to produce the structural damage to the fuel-filled tank. In this section, based on the energy balance, the total energy of the reactive projectile and the critical failure energy of the fuel-filled tank are compared and the enhanced ignition mechanism is analyzed.

In general, the energy balance of this tank/projectile interaction process is well known [18], however, for reactive projectile, the chemical energy carried by it should be considered. The adapted energy balance can be described as follow: during the interaction process, neglecting the internal heating and the internal energy due to compression, the reactive projectile mainly transfers its energy (including kinetic energy and chemical energy) to the structural failure energy of the fuel-filled tank and the ejection energy of the fuel. As the fuel tank structure is already damaged before the fuel ejects or splashes, the fuel ejection energy can be neglected in this issue. Therefore, the critical condition for the structural failure of the fuel-filled tank can be given as:

$$\varDelta E_{\text{k}} + \varDelta E_{\text{c}} \geq E_{\text{failure}} \tag{3}$$

Where, $\varDelta E_{\text{k}}$ is the kinetic energy deposited into the fuel tank by the reactive projectile, $\varDelta E_{\text{c}}$ is the chemical energy released into the fuel tank by reactive projectile.

According to a simple momentum balance and assuming that the fuel is incompressible and the cross-sectional area of the projectile is constant, the kinetic energy deposited into the fuel tank by the reactive projectile is due to the drag force by the fuel and can be expressed as [19]:

$$\varDelta E_{\text{k}} = \frac{m_{\text{p}}}{2}\left(v_{t=0}^2 - v_{\text{exit}}^2\right) = \frac{1}{2}C_{\text{d}}\rho_{\text{f}}A_{\text{p}}v(t)^2\varDelta L \tag{4}$$

Where m_{p} is the mass of reactive projectile, $v_{t=0}$ is the velocity of reactive projectile when it just perforated the front aluminum cover plate, v_{exit} is the velocity of reactive projectile immediately before impacting the rear aluminum cover plate. ρ_{f} is the density of the RP-3 aviation kerosene, and A_{p} is the cross-sectional area of the projectile. C_{d} is the drag coefficient of the reactive projectile and it can be safely assumed to be a constant [13]. For cylindrical projectile, $C_{\text{d}} \approx 1.17$. $\varDelta L$ is the width of the fuel tank along the shot line. $v(t)$ is the reactive projectile velocity after perforating the front aluminum cover plate, and it is a function of time which can be given by:

$$v(t) = v_{t=0}\Big/\left[1 + 0.75C_{\text{d}}\left(\rho_{\text{f}}v_{t=0}\Big/\rho_{\text{p}}d_{\text{p}}\right)t\right] \tag{5}$$

Here, ρ_{p} and d_{p} are the density and diameter of the reactive projectile, respectively. $v_{t=0}$ can be calculated according to Ref. [20]:

$$v_{t=0} = v_0 - 1855.7\left(hA_{\text{p}}\right)^{0.4143}m_{\text{p}}^{-0.5549} \tag{6}$$

In equation (6), v_0 [m/s] is the impact velocity of reactive projectile, h [cm] is the thickness of the front aluminum cover plate, and the unit of A_{p} here is [cm^2].

The chemical energy released by reactive projectile can be assessed by the sealed chamber test which was first presented by Ames [21]. Our research team has improved and standardized the experimental method and apparatus. A series of experimental data has been obtained and published in Ref. [22]. In the current paper, the reactive projectile is of the same type and mass as the one studied in Ref. [22]. Based on the database obtained, the chemical energy released by the reactive projectile can be calculated by:

$$\varDelta E_{\text{c}} = \varDelta PV/(\gamma - 1) \tag{7}$$

Where, $\varDelta E_{\text{c}}$ is the chemical energy deposited into the sealed chamber, $\varDelta P$ is the peak overpressure in database, the volume of the test chamber in our standardized experiments V is 27 L, and γ is the ratio of specific heats of the gas. For an ideal gas assumption, $\gamma = 1.4$. Part of our experimental database is listed in Table 2.

Fig. 9 shows the comparison among the kinetic energy of reactive projectile, the chemical energy released by reactive projectile and the critical structural failure energy for different tank structure. The critical structural failure energy for the fuel-filled tank with different thickness cover plates can be obtained by Eq. (2). The kinetic energy deposited into the fuel tank by the reactive projectile is calculated by combining Eq. (4) to Eq. (6). The chemical energy released by reactive projectile is evaluated by Eq. (7) based on our published experimental data listed in Table 2. In this figure, the critical failure energy for 3 mm and 6 mm aluminum cover plate are calculated by considering the structural failure of one single cover plate, whereas the critical failure energy for 10 mm aluminum cover plate is obtained by considering the structural failure in three screw bolts (three failed bolts could be observed in experiments, see Fig. 7 (c)). The corresponding critical structural failure energy for the fuel-filled tank with 3 mm, 6 mm and 10 mm thick aluminum cover plates are 3.91 kJ, 7.81 kJ and 8.14 kJ,

Table 2
The sealed chamber experimental results to evaluate the overpressure by reactive projectile impact.

No.	Impact velocity/($m \cdot s^{-1}$)	Aluminum cover plates thickness/mm	Peak overpressure/MPa
257#	898	3	0.15
280#	905	6	0.21
362#	910	10	0.12

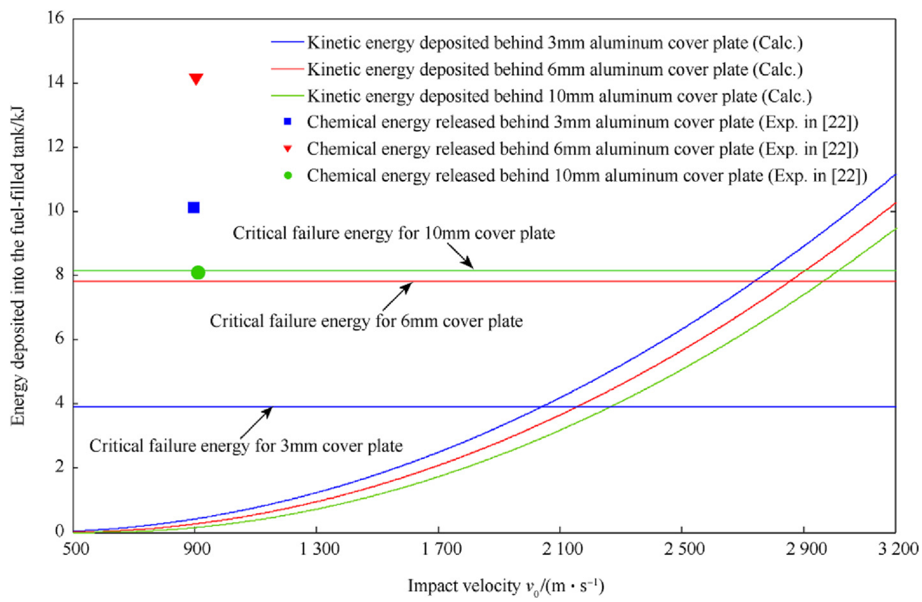

Fig. 9. Energy deposited into fuel-filled tank by reactive projectile vs impact velocity.

respectively. The kinetic energy of the reactive projectile deposited into the fuel-filled tank at the impact velocity in experiments are 0.41 kJ, 0.26 kJ and 0.14 kJ, respectively. The corresponding chemical energy released by reactive projectile deposited into the fuel-filled tank are 10.13 kJ, 14.18 kJ and 8.1 kJ, respectively. Apparently, for the reactive projectiles, at about 900 m/s impact velocity, the kinetic energy deposited into the fuel-filled tank is far less than the critical structural failure energy of the fuel-filled tank and is not enough for causing a catastrophic structural failure of the fuel-filled tank. However, after perforating the cover plate, the reactive projectile released a large amount of chemical energy which is much higher than the critical structural failure energy of the fuel-filled tank. In the case of the 3 mm aluminum cover plate, the total energy of the reactive projectile deposited into the fuel-filled tank was much higher than the critical failure energy for both of the aluminum cover plates. In the case of the 6 mm aluminum cover plate, the total energy was higher than the failure energy for one single aluminum cover plate but not enough to damage both aluminum cover plates. The total energy deposited into the fuel-filled tank of the reactive projectile after perforating the 10 mm aluminum cover plate was slightly higher than the corresponding calculated critical structural failure energy, which explains the experimental phenomenon in the case of the 10 mm aluminum cover plate. Unlike an inert metal projectile, the reactive projectile provides a defeat mechanism which combines both kinetic and chemical energies. The additional chemical energy release significantly enhances the structural failure of the fuel-filled tank and the ignition effect.

5. Conclusions

The enhanced ignition behavior of reactive material projectile impacting the fuel-filled tank was studied by experiments and theoretical analysis combined. Several conclusions can be drawn as follows:

- The experiments show that there are dramatically enhanced structural damage to the fuel-filled tank and enhanced ignition effect due to the reactive material projectile impact. By decreasing the thickness of the aluminum cover plate, the enhanced effects are improved significantly.
- An analytical model considering the failure mechanism of the tank structure was developed, by which the kinetic energy and chemical energy deposited into the fuel-filled tank by reactive projectile impact are discussed. The model prediction of the enhanced damage to the fuel-filled tank shows a good agreement with the experiments.
- Though the chemical energy release induced pressure rise inside the fuel-filled tank by reactive material projectile impact is the prominent mechanism to enhance the structural damage and ignition effect, the connecting strength between the cover plates and the tank body is also important.

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