Gasoline Vapor Explosion Modes in Confined Space under Weak Constraint Conditions

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Abstract: The article focuses on the establishment of the experiment system in confined space with weak constraint surface. It also studies the overpressure variation of gasoline vapor explosion, the mechanism of flame shapes with time, and the coupling relationship between them under different weak constraint conditions. Meantime, the development modes of external flame after the damage of weak constraint are categorized. The results show that: 1. With the increasing area of weak constraint surface, the development modes of external flame can be categorized into: under-expansion jet combustion, jet combustion, external explosion. 2. When an external explosion occurs, the change of internal overpressure in confined space is more complicated, with multiple overpressure peaks as well as strong Helmholtz oscillations. 3. Lower initial gasoline vapor concentration and large area of weak constraint surface are more conducive to external explosion.

1. Introduction
Oil and gas, natural gas and other combustible gas are inflammable, explosive, volatile by nature. In recent years, there have been continuous leakage explosion accidents of oil and gas, natural gas and other combustible gas. The explosion accidents of combustible gas often occur in confined space, such as the oil tank, pump, valve chamber¹⁻³. Compared with the enclosed space, the confined space contains weak-link oil tank top, weak-strength door and window, and plastic diaphragm, all of which are weak constraint surface susceptible to damage under blast load.

When the combustible gas explodes, the weak constraint surface is damaged, and the shock wave and flame rush out from the damage point, forming a release explosion, injuring staff and damaging equipment, or even resulting in more serious secondary accidents⁴⁻⁵.

In this paper, the mixture of 92# gasoline vapor and air is used as the experiment medium to study the characteristics of the external overpressure field and the development modes of flame of gasoline vapor explosion in confined space with weak constraint surface. The corresponding mechanism of experiment laws is analyzed.
2. Experiment system and methods

2.1. Experiment system
As shown in Figure 1, the experiment system consists of an explosion container, a testing system of hydrocarbon volume concentration, a supply system for mixture of gasoline vapor and air, an ignition device, a dynamic data acquisition device, a computer linked with a high-speed camera. The size of explosion container is 0.1*0.1*0.2 m. On the top of the container, the weak confinement structures are set, and the outlets are enclosed with aluminum foil. A pressure sensor P0 is arranged inside the container to test the change of internal explosion pressure with time. Pressure sensors P1 and P2 are arranged in the vertical directions outside the container, and the vertical distances to the outlets are 0.2 m and 0.4 m, respectively. Pressure sensors P3 and P4 are set along the horizontal directions, and the horizontal distances to the outlets are 0.2 m and 0.4 m, respectively. Turn on 1# and 2# valves, turn off 3# and 4# valves, and the high-speed airflow generated by the vacuum pump stirs the gasoline vapor to volatilize, and the gasoline vapor generated is filled into the experiment container through the distribution pipe. Then turn off 1# and 2# valves, and turn on 3# and 4# valves, circulate the mixture in the container. The mixture of gasoline vapor and air would be evenly distributed throughout the container. During the process of the explosion, a high-speed camera is used to capture the change of flame shape.

![Scheme of experiment system](image)

2.2. Experiment condition
In the experiment system shown in Figure 1, the mixture of gasoline vapor and air with initial concentration of 1.17%, 1.43%, 1.75%, 2.07%, 2.46% and 2.68% are used for explosion experiment, and the change characteristics of external pressure in confined space and the change of flame shapes are measured. The initial conditions of the experiment are shown in Table 1.

| Experimental material         | Initial pressure | Initial temperature | Ignition position | Ignition energy |
|------------------------------|------------------|---------------------|-------------------|----------------|
| 92# Gasoline vapor/air mixture | Ordinary pressure | 293 K               | Center of bottom  | 3J             |

3. Experiment result and discussion

3.1. The effect of fracture area on explosion process
To investigate the effect of area of weak constraint surface on the characteristics of gasoline vapor explosion, a dimensionless parameter $K_v$ \cite{6} is defined to measure the relative area of weak constraint
surface. Its expression is as follows.

$$K_v = \frac{V^2}{A_v}$$  \hspace{1cm} (1)

Among them, $K_v$ is the opening coefficient, $V$ is the volume of the confined space ($m^3$), $A_v$ is the area of the weak constraint surface ($m^2$).

3.1.1. Under-expansion jet combustion under the condition of small fracture area ($K_v=6.35$)

Figure 2 shows the relationship between internal explosion pressure and flame shape over time under the condition of $K_v=6.35$. It can be concluded from the figure that, under the condition of small area of weak constraint surface, the development process of gasoline vapor explosion is as follows: constant volume explosion – destruction of discharge -- under-expansion jet combustion -- exhaustion and extinction.

At the initial stage of ignition, the flame is in a state of laminar combustion. The whole flame front is a smooth spherical laminar flame (30ms). At this stage, the pressure rises slowly, and the whole process is in a state of constant volume combustion.

With the combustion of gasoline vapor, the internal pressure gradually increases, and finally the weak constraint surface is damaged, forming the diaphragm-breaking overpressure $P_b$. A large amount of unburned fuel gas is discharged instantaneously. When the discharged gasoline vapor reaches the maximum of mass and flow rate, the discharge overpressure $P_{fv}$ is formed. The combined action of $P_b$ and $P_{fv}$ leads to the maximum value of the internal pressure in confined space, which is 71kPa. Under the extrusion action of internal overpressure and acceleration action of strong discharge effect, the flame is instantly stretched and accelerated, and its shape changes, and it can no longer maintain the shape of smooth ellipsoid(44ms).

The instant the weak constraint surface is damaged, the external condition is the static atmosphere. And the ratio of internal and external pressure is greater than 1, forming a typical under-expansion jet flow. At this point, a diaphragm-breaking shock $P_b$ is generated near the weak constraint position in the outflow field and propagates outward in a divergent manner. The discharged unburned gas expands instantaneously, and Prandtl-Meyer flow comes into being with the edge of the weak constraint position as the vertex. At the same time, the discharged unburned gas forms a tangentially discontinuous jet boundary on the isobaric interface with the stationary atmosphere [7].

With the discharging gasoline vapor, the internal pressure drops to atmospheric pressure (47ms) instantly. When the flame accelerates to the outflow field, the gasoline vapor discharged to the outside is ignited, forming a continuous under-expansion jet combustion flame (47-50ms). The flame shape is mainly in a state of jet combustion, mostly concentrated along the vertical directions. When the discharged gasoline vapor gradually burns out, the flame cannot maintain the state of jet combustion,
and finally weakens and goes out (70-95ms).

Figure 3 shows the relationship between the external pressure in confined space and time. It can be seen from Figure 3 that, under the condition of small area of weak constraint surface, the peak value of external pressure is mainly diaphragm-breaking overpressure $P_b$ and discharge overpressure $P_{fv}$. The overpressure value along the vertical direction is mainly affected by the outflow overpressure $P_{fv}$, that means, when the high-speed moving airflow impinges on the induction surface of the pressure measuring point, the pressure value increases. However, the overpressure peak along the horizontal direction is mainly affected by the overpressure $P_b$, and there is no outflow overpressure $P_{fv}$, and the pressure peak is small, which is nearly one order of magnitude different from the overpressure in the vertical direction. The reason for this difference is that because of the small weak constraint point, the discharged unburned gasoline vapor mainly accelerates along the vertical direction, forming a high-speed airflow along the vertical direction, and then forming a large discharge overpressure $P_{fv}$.

3.1.2. Jet propagation combustion under the condition of medium fracture area ($K_v=3.24$)

Figure 4 shows the relationship between the internal explosion pressure and flame shape over time under the condition of $K_v=3.24$. It can be concluded from the figure that, under the condition of small area of weak constraint surface, the development process of gasoline vapor explosion is as follows: constant volume explosion -- destruction of discharge -- jet-expansion combustion -- exhaustion and extinction.

Just as the condition of small opening ($K_v=6.35$), the development mode of flame at the initial ignition is smooth spherical laminar flame under the condition of medium area of weak constraint surface. The pressure rises slowly, being the state of constant volume explosion (28ms). With the combustion of gasoline vapor, the internal pressure increases, which eventually leads to the damage of the weak constraint surface, forming damage overpressure $P_b$ and discharge overpressure $P_{fv}$. The internal pressure in confined space reaches the maximum value of 40kPa. At the same time, the flame instantly deforms and stretches, and under the extrusion action of pressure wave and the acceleration action of strong discharge, the flame moves towards the damage point at a high speed (47ms).

As can be seen from Figure 5, under the condition of medium opening, the change law of external explosion pressure is just like that under the condition of small opening. The pressure peaks are also mainly diaphragm-breaking overpressure $P_b$ and discharge overpressure $P_{fv}$. In the vertical direction, the pressure is mainly affected by the discharge overpressure $P_{fv}$. But in the near field (Position P1), the influence is relatively obvious, which is reflected in the large discharge overpressure in near field (22kPa). This indicates that the near field outside the confined space has a strong discharge impact intensity, and the flame still maintains a state of jet combustion. The discharge overpressure in far field (Position P2) is relatively small, only 1.2kPa, which is nearly one order of magnitude lower than that.
in near field. The main reason is that although the flame can maintain a state of jet combustion under the condition of medium area of weak constraint surface, its intensity has greatly weakened. It has weakened into diffusion combustion in far field. For the measuring point along the horizontal direction, the overpressure peak is mainly restricted by the diaphragm-breaking overpressure $P_b$ and only a small overpressure peak appears.

3.1.3. External explosion and Helmholtz oscillation under the condition of large fracture area ($K_v=1.59$)

It can be seen from Figure 6 that, under the condition of large area of weak constraint surface, the change of internal overpressure over time is more complicated, with multiple overpressure peaks and strong Helmholtz oscillation. The development process of gasoline vapor explosion is as follows: constant volume explosion -- destruction of flow discharge -- external explosion -- Helmholtz oscillation -- extinction.

Just as the condition of small opening and medium opening, the initial flame shape of gasoline vapor explosion is also smooth spherical laminar flame under the condition of large area of weak constraint surface. The whole process is a constant volume explosion process (19ms). With the increase of internal pressure, the weak constraining diaphragm is damaged, and the diaphragm-breaking overpressure $P_b$ is formed in the size of 30kPa (28ms). The fast-discharging pressure instantaneously reduces the pressure in the pipeline. The compressed gasoline vapor emits quickly from the space. As the emission of gasoline vapor diffuses, the sparse wave is formed near the weak constraint surface because of the dropping pressure. Reflecting on the edge of the cloud cluster, the sparse wave becomes the compression wave. The compression wave gathers inside the cloud cluster, resulting in a preheating zone with high density and high concentration of gasoline vapor. When the gasoline vapor in high-pressure area is ignited by the jet flame, the gasoline vapor in the cloud cluster will burn rapidly, causing a sharp rise in pressure, and an external explosion will occur. The explosion will induce the formation of external explosion overpressure $P_{ext}$ in the size of 20.1 kPa. During the time, the flame will stretch and expand along the lateral direction owing to the influence of barometric effect, forming a typical mushroom-cloud flame (32ms). In the process of explosion, the intense heat loss reduces the temperature of combustion products and forms a negative pressure vacuum area in the confined space, which decreases the pressure. However, because of the suction effect in the vacuum zone and the driving effect of external explosion, the unburned gasoline vapor discharged to outside filed flows back into the pipeline. The returned gasoline vapor collides dramatically with the flame front, resulting in an intense combustion. The flame front expands further, the pressure going up again. The expanding flame front pushes more gasoline vapor out of the container, and the pressure decreases again, forming oscillating flows and inducing oscillating overpressure with decreasing peak value, which is called Helmholtz oscillation [6-7] (32-36ms). When the external explosion is finished, the external fireball dissipates, and the flame flows back into the confined space to form reflux combustion. When the reflux combustion flame dissipates, the air is almost completely consumed at the same time. The pressure drops instantly and forms an obvious negative pressure $P_{neg}$ (58ms). As the combustion proceeds, the residual gasoline vapor reacts completely, and finally the flame is extinguished, and the pressure returns to atmospheric pressure.
Figure 6 Relationship curves of time and flame behaviors and overpressure inside the vessel \( (K_v=1.59) \)

Figure 7 Relationship curves of time and flame behaviors and overpressure outside the vessel \( (K_v=1.59) \)

Figure 7 shows the relationship of the external pressure in confined space and time under the condition of large area of weak constraint surface. It can be seen from Figure 7 that the constraint conditions of external overpressure under the condition of large area of weak constraint surface are significantly different from those under the condition of small and medium area of weak constraint surface. Under the condition of large area of weak constraint surface, the external pressure of confined space is mainly affected by two factors: diaphragm-breaking overpressure \( P_b \) and external explosion overpressure \( P_{ext} \). The pressure variation trend of measuring points along the vertical direction (P1, P2) and that along the horizontal direction (P3, P4) is approximately the same, both of which are "positive diaphragm-breaking overpressure -- negative overpressure -- positive secondary-explosion overpressure". Among them, the overpressure value of the measuring point along the vertical direction is slightly greater than that along the horizontal direction. In view of energy release, the overpressure value reflects the amount of energy release in gasoline vapor explosion. The higher the gasoline vapor concentration near a certain point, the more energy released by gas explosion, and the greater the overpressure value at this point. When the weak constraint structure is damaged, the unburned gasoline vapor will be ejected out of the container rapidly. The ejection will induce strong discharge effect along the vertical direction and drive the unburned gasoline to move at high speed along the vertical direction, which diffuses the unburned gasoline along the vertical direction. However, when the fast-moving gasoline vapor is ejected into the relatively static external atmosphere, the pressure gradient and the density gradient are no longer parallel but intersect because of the action of unstable factors, which results in baroclinic effect. The vortices appear in the flow field. The transverse tensile effect of the vortices drives the horizontal diffusion of gasoline vapor. The driving effect of strong discharge along the vertical direction is much larger than that of stretching vortices along the horizontal direction, so the unburned gasoline vapor is still mainly distributed along the vertical direction, and the gasoline vapor concentration along the horizontal direction is relatively small. Therefore, the energy release rate along the vertical direction after being ignited is larger, resulting in a larger overpressure value.

3.2. Explosion modes under the condition of different fracture area

Under different initial conditions, there are obvious differences in the development process of gasoline vapor explosion in confined space with weak constraint surface. According to different initial conditions, it can be divided into four modes: under-expansion jet combustion, jet expansion combustion, external explosion, and enclosed combustion. Figure 8 shows the development modes of gasoline vapor explosion under the conditions of different initial concentrations and areas of different weak constraint surface.
It can be seen from Figure 8 that when gasoline vapor concentration is small, with the decrease of weak constraint surface area ($K_v$ increases), the development mode of flame is as follows: external explosion--jet expansion combustion--under-expansion jet combustion. Under the condition of large area of weak constraint surface ($K_v < 3$), with the increase of gasoline vapor concentration, the external explosion tends to decrease gradually, and evolves into the mode of jet propagation combustion. Under the condition of medium area of weak constraint surface ($3 < K_v < 5$), external explosions may occur only at low initial concentration, and most of them are in the mode of jet propagation combustion. Under the condition of small area of weak constraint surface ($K_v > 5$), jet propagation combustion occurs only at high concentration, and most of them are under-expansion jet combustion. Under the condition of high initial concentration ($C_{CH} > 2.4\%$), the high initial concentration of gasoline vapor has a small explosion intensity, so the weak constraint structure cannot be damaged. The gasoline vapor cannot be discharged to the outside of the confined space, thus forming the mode of enclosed combustion.

4. Conclusion
This paper constructs the test system of parameters for combustible gas explosion in confined space with the top end containing weak constraint surface. The paper also studies the coupling law of gasoline vapor explosion pressure wave and flame in confined space with the weak constraint surface. The development modes of gasoline vapor explosion under the conditions of different weak constraint surface are categorized. The results show that the pressure wave of gasoline vapor explosion is in a strong coupling relationship to the flame behaviors. With the increasing area of weak constraint structure, the development modes of gasoline vapor explosion are under-expansion jet combustion, jet expansion combustion and external explosion, respectively. Low initial gasoline vapor concentration and large area of weak constraint surface are more favorable to the occurrence of external explosion, which can induce multiple overpressure peaks and strong Helmholtz oscillation.

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