Dynamic analysis of flame propagation velocity at the initial stage of gasoline-air explosion in a tube with an open end

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Abstract. Gasoline-air explosion in confined space is a process involving complex fluid mechanics and explosion mechanics. The flame behavior of gasoline-air explosion in a tube with an open end is mainly discussed in this paper. Firstly, on the basis of experimental observation and theoretical analysis, the axial position of the flame front, the flame velocity and the duration of the spherical flame are deduced and calculated. Then, the validity of the theoretical analysis is verified by comparing the theoretical calculation with the experimental data. The results show that the flame velocity is about 2.29 m/s at the initial stage of gasoline-air explosion in the tube. The duration of the spherical flame is about 11.7 ms. The conclusions of this paper can not only provide valuable data reference for combustible gas explosion safety engineering, fire protection design and evaluation, but also lay a foundation for further research on the flame behavior of gasoline-air explosion in the tubes with an open end.

1. Introduction
The process of gasoline explosion propagation in confined space involves complex hydrodynamics and explosion mechanics principles. However, gasoline is a commonly utilized fuel with a high volatility and low flash point. Vaporized gasoline could easily develop into explosive gas once mixed with air. In fact, explosions caused by gasoline vapors, as well as other flammable gases, have frequently led to fatal accidents that have caused serious losses in recent years[1-3]. Offentimes the accidents are triggered by an uncontrolled ignition in the areas where gasoline is stored or has been leaked into, such as oil transmission pipelines, underground storages, cave depots, and municipal pipes[4]. Flame propagation of combustible gas deflagration is not only a typical combustion process of internal combustion engine, but also an important control process of the transition from deflagration to detonation. The research on its propagation law and mechanism has important research value in engineering combustion and fire and explosion protection fields. It is of great significance to study the flame propagation process of oil and gas explosion in confined space to reduce or avoid the economic loss and human casualties caused by the above accidents.

The tube with an open end is one of the typical conditions for the study of premixed combustible gas deflagration flame. Its basic characteristics are as follows: one end of the tube is open, the other end is closed, the tube is filled with combustible mixture gas, the gas is ignited at the center of the closed end of the tube, and the flame spreads to the open end. Clanet[5] divided this deflagration process into four stages: (1) spherical flame stage; (2) The finger-shaped flame stage of axial stretching; (3) the deceleration and propagation stage after the flame side touches the wall; (4) Tulip flame stage. At the same time, Clanet[5] gave a theoretical model for calculating the flame propagation in the second stage, and the calculated results of the flame propagation speed and the contact time were in good agreement.
with the experiment. Bychkov[6] refined the model, supplemented the flame propagation model of the first stage, and compared the theoretical calculation results with the results of direct numerical simulation (DNS). Valiev[7] further considered the compressibility of gas and carried out theoretical, and experimental and numerical simulation studies on the finger-type flame were carried out.

The full development process of the flame in a tube may be affected by the wall conditions, pressure wave superposition and reflection, fluid mechanics and thermodynamic instability, etc., resulting in the state of the deflagration outflow field becoming complex and difficult to describe[8]. However, if the tube length and diameter are relatively small, the flame propagates in the form of laminar flow as a sphere at the initial stage of explosion, and its position and velocity can be theoretically analysed based on the existing models and reasonable simplified assumptions. In this present paper, based on the experimental observation, the axial position of the flame front and the velocity of the flame will be calculated and compared with the experimental results. The validity of the theoretical analysis will also be verified.

2. Experimental equipments and methods

The experimental system used in this article is mainly composed of a glass tube with an open end, a high-speed photography/schlieren system, a gas distribution system, an ignition system, a synchronous control system, etc., as shown schematically in Fig. 1.

![Figure 1. Gasoline-air mixture deflagration experimental system](image)

The sectional size of the glass tube is 100×100 mm, the length is 600 mm, and the length to diameter ratio is 6. The gas distribution system is mainly composed of a vacuum pump and oil and gasoline evaporation apparatus. The gasoline evaporation apparatus and a vacuum circulating pump were used to form a uniform gasoline-air mixture in the test tunnel. Details of structure and working principle of the gasoline evaporation apparatus can be found in reference[9].

Before the experiment, the opening of the tube was sealed with aluminum foil, and the gasoline vapor was filled into the glass pipeline by circulating pump and distribution pipe. The mixture component was detected by GXH-1050 infrared gas analyzer, and the combustion equivalent concentration of the mixture was maintained. Then, the aluminum foil is removed and the combustible mixture was ignited by an electric spark igniter (2J) at the middle of the closed end of the tube. High-speed DV (JVC GC-P100BAC, 500Hz) was used to record the flame characteristics in the whole process of the internal and external field from ignition to extinguishing. High-speed schlieren system (512×512 pixels, 2000Hz) was used to record the flow of uncombustible mixture and flame propagation in the external field of the tube. All experiments were carried out at room temperature (282-288 K) and atmospheric pressure.
3. Experimental results and analysis

3.1. Flame propagation characteristics
Typical flame propagation process of gasoline-air deflagration in the tube with an end opening is shown in Fig. 2. The experiment was carried out in a transparent tube with a length to diameter ratio of 6:1, and the volume concentration of gasoline vapor was 1.74%.

It can be seen from Fig. 2 that, after the gasoline-air mixture in the narrow and long space are ignited, the light blue spherical flame envelope (10 ms) is formed at the ignition position, and then the flame is axially stretched, and the flame front propagates towards the open end (30-50 ms). When the flame front reaches the narrow space opening, it forms a circular vortex (60 ms) near the opening, and then forms an ellipsoidal flame surface (70 ms) in the outfield. The color of the flame is initially blue-green and changes to orange (80 ms) after the ellipsoidal flame surface is formed in the outfield. Finally, the infield flame is extinguished, and the size, shape and position of the outfield flame are basically stable and gradually burned out (90-180 ms).

If the flame front to the opening time is marked, the whole deflagration process can be divided into two stages of diamond flame propagation and flame propagation outfield. During the former stage, the flame is stretched in axial direction result from constraint effect of the long and narrow space, and the unburned gas have been pushed to the outfield due to the expansion of the burned gas, then forms combustible gas cloud, which will provide conditions for the development of the outfield flame. During the latter stage, the flame propagates in the combustible gas cloud without constraint, and the burned zone is reflected as isotropic expansion. Meanwhile, the air outflow at the opening has a significant influence on the external field flame, making the flame produce eddy current structure.

3.2. Flame propagation characteristics and dynamics analysis at the initial stage of explosion
Figure 3 shows the hemispherical flame formed near the ignition electrode at the beginning of explosion (4~8 ms). The premixed combustible mixture is ignited by the electric spark released from the ignition electrode, and the flame zone develops from the ignition point to the periphery. In this stage, the flame range is very small, the influence of the wall can be ignored, and the flame can be approximately considered to expand freely in an infinite space. The flame front divides the flow field into two parts, the burned zone and the unburned zone, as shown in figure 4.

![Figure 2. Typical flame images of gasoline-air mixture deflagration in a narrow space with an open end](image-url)
Since this moment is in the initial stage of deflagration, the pressure generated from flame can be ignored, and the state equation of ideal gas can be simplified into the form of equation (1).

\[ \rho_b T_b = \rho_u T_u \]  

(1)

Where, \( \rho_b \) is the density of the burned gas, \( T_b \) is the temperature of the burned gas, \( \rho_u \) is the density of the unburned gas, \( T_u \) is the temperature of the unburned gas.

Due to the rapid development of the explosion process, the influence of heat transfer and convection can be ignored, and the temperature of the burned zone is taken as the adiabatic flame temperature of gasoline combustion (about 2274 K[10-11]), then the expansion rate can be calculated by equation (2).

\[ \Theta \approx \frac{T_b}{T_u} = 7.63 \]  

(2)

The influence of turbulence at the initial stage of explosion can be ignored, that is, the change in the volume of the burned zone is completely due to the gas expansion in the burned zone caused by laminar combustion, as described by equation (3).

\[ \frac{dV}{dt} = S_w U_f \Theta \]  

(3)

Where, \( V \) is the volume of the burned zone, \( S_w \) is the area of the flame front, and \( U_f \) is the laminar flame velocity. It is noted that, \( \frac{dV}{dt} = 4 \pi r^2 \frac{dr}{dt} \) and \( S_w = 4 \pi r^2 \) the motion equation of the flame front can be expressed in the form of equation (4).

\[ \frac{dr}{dt} = U_f \Theta \]  

(4)

It can be seen from equation (4) that the radius of the burnt zone varies with time as a constant, the magnitude of which is the product of laminar flame velocity and expansion ratio. For the gasoline vapour with volume concentration of 1.74% under normal temperature and pressure, \( U_f \) is about 0.30 m/s[12], so we can get \( \frac{dr}{dt} = 2.29 \text{ m/s} \).

Due to the constraints of the narrow and long space wall, the free expansion process of the hemispherical flame can only last for a very short time. According to the reference value given by Bychkov[6], the duration of the spherical flame can be acquired by equation (5).
\[ \tau_{\text{sph}} \approx \frac{1}{2\alpha} \]  

(5)

Where, \( \tau = \frac{U_t t}{R} \) is the dimensionless time, \( \alpha = \sqrt{\Theta(\Theta - 1)} \). Therefore, the duration of the spherical flame stage is 11.7 ms. Figure 5 shows the ratios of the axial flame propagation distance to the radial and axial propagation distance at the initial stage of ignition, all the data are obtained from the high-speed camera image. The ratio of the radial propagation distance to the axial propagation distance reflects the change of the flame shape. At the beginning of the explosion, \( r / x_f \approx 1 \), it means that the flame is roughly hemispherical, after 10 ms, \( r / x_f \) increases continuously. In this period, the axial tensile velocity of the flame is significantly greater than the radial propagation velocity, and it increases to about 1.8 when time reaches 25 ms. This indicates that the flame have undergone obvious axial stretching and gradually formed a finger-shaped flame front. The dotted line in Figure 5 represents \( t_{\text{sph}} = 11.7 \) ms, which is the theoretical value of the critical time for the evolution of hemispherical flame to a finger-shaped flame obtained by equation (4). It can be seen that the calculated value is in good agreement with the experiment. In fact, the flame shape change process is a continuous, and there is no definite boundary between the spherical flame and the finger-shaped flame, and the estimate of equation (4) is also rough. However, from the perspective of quantitatively definition of such two flame forms, this critical value still has reference significance.

![Figure 5. \( x_f \) and \( r / x_f \) during the initial stage of ignition](image)

4. Conclusions
The flame behaviours at the initial stage of gasoline-air mixture explosion in a tube with an open end were mainly discussed and analysed in this present paper. The propagation velocity of the flame and the duration of the spherical flame at the initial stage of gasoline vapour explosion are deduced and calculated by theoretical analysis, and then, the validity of the theoretical analysis is verified by comparing the theoretical calculation value with the experimental data. The results show that the flame velocity is about 2.29 m/s at the initial stage of gasoline vapor explosion in the pipe with an open end. The duration of the spherical flame is about 11.7 ms. The research results of this paper can not only provide valuable data reference for combustible gas explosion safety engineering, fire protection design and evaluation, but also lay a foundation for further research on the flame behavior of gasoline-air explosion in the tubes with an open end.
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