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Experimental study of gasoline vapor deflagration in a duct with an open end

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ABSTRACT

An experimental investigation was conducted on gasoline vapor deflagration in a duct (100 × 100 mm, L/D = 4, 6, 10) with the ignition end closed and the other end open. The tests were focused on the flame behavior and the pressure generation inside and outside the duct. High-speed flame images, schlieren images, and the instantaneous pressure at different test points were recorded. The experimental results verified Bychkov's model [Combust. Flame 150 (2007) 263] in predicting the flame propagation at the early stages. Moreover, a new model was proposed to predict the axial flame moving distance when the flame front moved out of the tube. This model predicts the experimental data precisely when L/D = 4–10, and the deviation increases with larger L/D ratio. Effusive gas mixture gave rise to a vortex ring at the edge of the opening and leads to the formation of a mushroom-shaped gas cloud. A distortion of the flame skirt was observed several milliseconds after the flame ejection at about 10–40 mm away from the opening. The entire external flame was enveloped by the flammable gas cloud. Three peak pressures were obtained for each test point inside the vessel. The first peak was observed when the flame shirt touched the side walls. The second peak appeared when the flame front reached the opening. The third peak pressure was a result of the external explosion. For external test points, the pressure-time curves reached their peaks when the combustion reactions ended, and then dropped below zero due to the dissipation of energy and the low density of the burned gas.

1. Introduction

Deflagration of flammable gases in a confined space is a phenomenon that received a wide range of concerns, especially in the area of safety engineering. 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 [1,2,3]. Oftentimes 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. The flames and pressure waves initially occur in a confined zone that is relatively narrow, and it is followed by the propagation into larger spaces through different types of openings. Deflagration in a duct with an open end may be considered as a model for these structures that enables the pressure generation and flame behavior to be conveniently studied.

Mallard and Le Chatelier were the first to notice that if a flame was ignited at the closed end of a duct with the other end open, the progression of the flame front would be irregular with reversed propagation direction. This observation was then confirmed by the photographs of flame propagation [4]. Since then, experimental investigations of this issue have been mostly image-based. High-speed photography, schlieren method, PIV (particle image velocimetry) and PLIF (planar laser induced fluorescence) are frequently used to analyze the flame shape and dynamics. Based on experimental observations, four essential phases are identified during a premixed flame propagation in a half-open duct [5,6,7]. (a) First, a small hemispherical flame starts to expand at the speed of gas production as a result of ignition. (b) Then, an axial expansion of an elongated finger-shaped laminar flame front emerges with growing surface area. (c) In the third phase, a reduction in the surface area of the flame (when the flame skirt reaches the side walls) along with the deceleration of the flame front followed by the inversion of its curvature. (d) Finally, the tulip flame propagates in an oscillatory fashion all the way to the end of the chamber. During the entire process of propagation, the tulip flame is likely the most perplexing phenomenon whose mechanism of formation and evolution remain elusive even after decades of researches [8–13].

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Also, the notion of "tulip" might be somewhat misleading because it encompassed too many combustion phenomena of different origins [7]. Besides these, flame acceleration inside half opened channels have also been investigated through theoretical and numerical means that focus on the effects of wall friction, thermal expansion, aspect ratio, heat release, and Lewis number [14–19]. Fast turbulent flame may lead to the onset of detonation and retonation waves inside a long tube, or more complex geometries of the ignition section [20–23].

Though a continuous interest is on the dynamics of premixed flame in tubes or ducts with open ends, the consideration of researchers is mainly concentrated in the propagation process within the vessel. As for the interaction between internal and external deflagration, most of the investigations focus on gas explosions that happen in a confined vessel and ventilation through relief pipes [24–29]. These vessel-duct structures would lead to more complex flame behaviors in comparison with a single duct. A generalized quantifiable conclusion is difficult to obtain under these conditions because multiple geometrical parameters need to be defined individually. In addition, vortical structures might form during flame effluxes, and their interactions with the flame could give rise to a variety of combustion instabilities [30].

Overpressure produced by premixed deflagration in a half-open tube was in the order of 10 kpa [5,6], which is relatively low compared to the atmospheric pressure. Therefore, the pressure variations are neglected and the flammable gas is considered incompressible in some model equations [5,7]. However, gas compression could reduce the acceleration rate and the maximum velocity of the flame tip, and thereby greatly moderates the movement of the finger flame [31]. Furthermore, fluctuations in overpressure, a factor that could enhance either the flame acceleration or deceleration depending on the specific condition, are likely related to the displacement of the flame tip [6]. Researches in the field of vented explosion, which is sometimes similar to the premixed deflagration in a half-open duct, have attracted lots of attentions, especially to its pressure changes. Investigations have shown [32,33] that a number of pressure transients emerged as a result of the venting process, and each peak pressure is controlled by a different physical mechanism.

In this study, gasoline vapor explosion is experimentally investigated in a duct with an open end. The flame behaviors and pressure changes inside and outside the duct are both analyzed. This study will likely help with the understanding of premixed flame propagation and pressure generation inside and outside a half-open duct. Meanwhile, the results of this study could provide basic references for protective measures against explosion and safety design during gasoline storage and transportation.

2. Experimental setup

Figure 1 shows the experimental system used in this study. A square duct (100 × 100 mm, L/D = 4, 6, 10) was used with the ignition end closed and the other end open. The duct was made of strengthened glass and was pressure rated at 2.5 MPa. According to [5], the half-open configuration has the advantage of maintaining a consistent pressure, and it could eliminate the complications due to the motion of the flame front associated with compression of the unburned mixture. Even so, it is necessary to explain that the effect of gas compression becomes significant when flame propagation speed increases (e.g., Ma > 0.3) [31].

The initial mixture was prepared by circulating air through liquid gasoline within confined pipes and the vessel [34]. The gasoline vapor was then sampled, and the concentration of which was monitored by a GXH-1050 infrared analyzer (Junfang Physicochemical Science and Technology Institution of Beijing). After a certain period of time (depending on the required vapor concentration), valves located on both sides of the oil bottle were closed, and the pump continued to work for 3 min to create a uniform mixture. The equivalence ratio (ϕ) was set between 0.7 and 2.1, and the detailed analysis was performed at $\phi = 1.2$. Prior to ignition, the unburned mixture was contained within the duct by an aluminum foil covering the vent opening, which will be removed right before ignition.

A high-speed digital video (JVC GC-P100BAC) with frame rate set at 500 Hz was used to capture a full-view including the internal and external flame images in sequence. The schlieren images of the external flame were simultaneously recorded by another video camera (Photron, FASTCAM-Ultima512) with a resolution of 512 × 512 pixels, and the frame frequency of the camera was set at 2000 Hz.

Six pressure transducers (P_a to P_f) were used to measure the instantaneous pressures both on the interior and the exterior of the duct during deflagration. P_a and P_b were located at the bottom of the duct 0.2 m and 0.45 m away from the closed end respectively. P_c and P_d were arranged along the axis of the duct 0.2 m and 0.6 m away from the opening (0.8 m and 1.2 m to the closed end) respectively. P_e and P_f are positioned right below the opening 0.2 m and 0.6 m away from the center of the opening. All experiments were conducted at room temperature (294–301 K) and 1 atm. Each test was repeated three times for repeatability.

3. Results and discussion

3.1. Flame propagation

Figure 2 illustrates the sequence of flame propagation observed with a high-speed camera. When a flammable gas mixture in a duct was ignited at the close end with the other end remaining open to the ambient, a premixed flame would initially form around the ignition point and then propagated to the opening of the duct. As the burning process went on, gases produced from this reaction were trapped between the flame and the closed end. The burnt gas expanded due to the heat of combustion, pushing the unburned gas out of the duct through the opening. Then, the flame propagated out of the duct, spreading into the escaped flammable gas cloud and forming a mushroom-shaped external flame until extinguishment.

When the gas mixture was ignited, a spherical flame first formed and expended freely around the electrode. Bychkov [7] proposed an approximate duration of this phase,

$$\tau_{sph} \approx 1/2\alpha, \tag{1}$$

where

$$\alpha = \sqrt{\Theta(\Theta - 1)}, \tag{2}$$

$\tau = U_f t/R$ $\tau = U_f t/R$is the dimensionless time, where U_f is the laminar burning velocity, R is the radius of the duct, and Θ is the expansion factor, defined as the density ratio of the fuel mixture and the burnt matter. In this study, $t_{sph} = 11.7$ms was derived by setting $U_f = 0.32$ m/s [35] (T = 298 K, p = 1 atm, $\phi = 1.2$), $\Theta \approx T_b/T_u = 7.63$ [36,37], and R = 0.0564 m (an equivalent radius which guarantees the same area).

After that, the flame evolved into a "finger"-shape configuration (Fig. 2(b) and (c)). The surface area of the flame grew faster than the previous stage. The propagation of the flame tip is expressed as [7]

$$\xi_f = \frac{\Theta}{4\alpha}[\exp(2\alpha\tau) - \exp(-2\alpha\tau)] = \frac{\Theta}{2\alpha}\sinh(2\alpha\tau), \tag{3}$$

where $\xi_f = z_{tip}/R$ is the dimensionless coordinate and z_{tip} is the axial flame propagating distance with $z_{tip} = 0$ at the ignition point. The experimental value and the calculated value by Eq. (3) are