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Experimental analysis of the flame speed, brightness and zone thickness of gasoline-air explosion in a closed tunnel

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ABSTRACT

With the help of a flame signal sensor and a brightness sensor, the effects of the initial gasoline vapor concentration on the flame speed, brightness and zone thickness of gasoline-air explosion were studied by carrying out experiments in a closed tunnel. Results showed that the flame speed fluctuated in the test tunnel during the explosion propagation process and maximum of flame speed under different initial gasoline concentrations appeared within the anterior 1/3 of the test tunnel. The maximum flame speed first increased and then decreased with the increase of the initial gasoline vapor concentration. Due to the existence of flame oscillation phenomenon in the explosion process, experimental data of the flame zone thickness were greater than their actual values. Based on reasonable simplifications and assumptions of the flame oscillation phenomenon, the data of the flame zone thickness in accordance with the actual situation were calculated. Results also showed that the flame zone thickness first increased and then decreased with the increase of initial gasoline vapor concentration. The flame brightness increased with the increase of the initial gasoline vapor concentration when the initial gasoline vapor concentration was set at a lower level (less than 1.7%), and when the initial gasoline vapor concentration was greater than the stoichiometric concentration, the flame brightness reduced with the increase of initial gasoline vapor concentration. However, when the initial gasoline vapor concentration further increased to a higher level (higher than 2.1%), the flame brightness increased again with increasing of initial gasoline vapor concentration.

1. Introduction

Fires or explosions in the petroleum chemical industry field are still common safety accidents leading to casualties, destruction of equipment and even downtime. Statistics indicate that within the short span from 1960 to 2003, more than 55 cases of serious gasoline-air mixture fire or explosion accidents had occurred worldwide (Chang and Lin, 2006). Despite the advancements in technology in the recent years, gasoline-air mixture explosion accidents are still occurring frequently all over the world. Especially in China, some prominent examples would include the Southwest China oil depot explosion accident in 2007, Qingdao crude oil pipeline explosion accident in November 2013 (Zhu et al., 2015) and Kaohsiung gas explosion accident in Taiwan in July 2014 (http://usa.chinadaily.com.cn/epaper/2014-08/01/content_18231388.htm) etc. Without exception, all these accidents had caused serious casualties and huge property losses. In order to avoid such accidents and reduce casualties and property losses, researches on the mechanism of gasoline-air explosion still need to be developed so that more effective gasoline-air explosion prevention techniques and measures can be proposed.

Flame is always the inner motive power in the development and evolution process of the whole flammable gas explosion. Flame behavior characteristics presented in such explosion process are directly related to explosion overpressure, explosion regime, explosive intensity and destructive power etc. Researchers at home and abroad had done a lot of scientific researches on combustible gas flame behavior characteristics. Especially, the relationships between flame behavior characteristic and explosion overpressure (Yan et al., 2015; Kim et al., 2014), explosion regime (Kelley et al., 2011; Di Sarli et al., 2012; Martz et al., 2011) or explosive intensity (Nishimura et al., 2013) etc. were common targets in these literature. For example, Kelley et al. (2011) had studied combustion regime of the isooctane laminar flame, and analyzed the chemical kinetics of the combustion process. Razus et al. (2011) had experimentally studied the relationship among flame area, flame speed and explosion strength index of the propane explosion and corrected the third power law of the combustible gas explosion intensity index. However, flame behavior and characteristics not only includes the parameters such as flame combustion regime (Nishimura

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et al., 2013; Abraham et al., 1985; Williams, 1986), flame temperature (Nie et al., 2014), flame speed (Cao et al., 2014), flame shape (Ichikawa et al., 2011), flame area (Pang et al., 2014), the flame thickness (Xiao et al., 2014) and flame stability (Kim et al., 2014; Liu et al., 2015) etc., but also includes flame zone thickness and brightness because these two parameters are also important for the flame behavior and characteristics description of a flammable gas explosion process.

From the perspective of the related literature, literature involved flame zone thickness and brightness are common in the studies of premixed or non premixed diffusion flame (Zhang et al., 2013a, 2014; Shin and Lieuwen, 2012), which always belongs to the burning problem in an open space rather than the explosion problem in the confined space. Unfortunately, works involving flame zone thickness and thickness of the flammable gas explosion in confined space are seldom reported. In addition, studies related to flame behavior characteristics and the relationships between flame behavior characteristic and explosion overpressure, explosion regime or explosive intensity etc. mostly focus on the industrial gas with simple composition, such as methane (Di Sarli et al., 2012; Pang et al., 2014), propane (Razus et al., 2010, 2011), hydrogen (Kim et al., 2014) and ethylene (Liebner et al., 2012) etc., but studies focusing on flammable gas with complex composition, for instance, gasoline-air mixture, are still limited so far.

With the help of the flame signal sensor and brightness sensor, flame zone thickness and brightness of gasoline-air mixture explosion were studied by carrying out experiments in a 5.5 m long tunnel in this paper. Based on the experimental data analysis, the effects of initial gasoline vapor concentration on the flame zone thickness and brightness were also discussed in this paper.

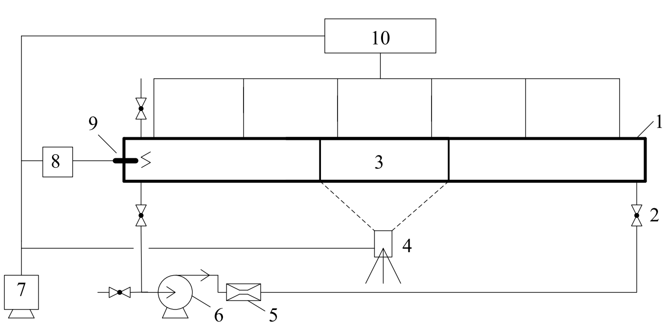
2. Experimental equipments and methods

The experimental equipments used in this article mainly comprised of an experimental tunnel (containing a visualization section), a high speed camera, a gasoline evaporation apparatus, a vacuum circulating pump, a data acquisition system, an ignition system and a computer, as shown schematically in Fig. 1. The data acquisition system mainly consisted of concentration measurement equipment, flame signal sensors and flame brightness sensors etc.

The dimension of the tube is 200 × 200 × 5500 mm, and the length of the observation section is 300 mm. 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 Zhang et al. (2013b) or Yang et al. (2013).

The type of the gasoline used in the experiments was 93# and its main properties were summarized in Table 1.

The concentration measurement equipments mainly included a GXH-1050 infrared analyzer (Junfang physicochemical Science and Technology Institution of Beijing) and a NHA-502 automotive emission



1. Test tunnel; 2.Valve; 3. Visualization section; 4. High speed camera; 5. Gasoline evaporation apparatus; 6.Vacuum circulating pump; 7.Computer; 8. Ignition system; 9. Spark plug; 10. Data acquisition system.

Fig. 1. Arrangement of the experimental equipments.

Table 1
Main properties of the gasoline 93#.

Lower flammable limit (v %)	1.0	Upper flammable limit (v %)	2.6
Octane rating	93	Average molecular formula	$C_{7.9}H_{14.21}$
Specific gravity	0.725	Average heating value (kJ/kg)	44,000

Fig. 2. Photo of the flame signal sensor.

analyzer (Nanhua instruments Co. Ltd.). Concentration of the gasoline vapor was measured by the GXH-1050 infrared analyzer, and other gaseous concentrations were measured by the NHA-502 automotive emission analyzer.

Flame signal sensor was mainly composed of ultraviolet light-sensitive photodiode (Japan Hamamatsu 1753 or 2868 series), flame detection module and optical focusing system. The ultraviolet light-sensitive photodiode could detect flame location in the test tunnel, so the flame speed could be determined by dividing the distance (Δx) between the two adjacent flame signal sensors by the time interval (Δt) that the flame passed through the two adjacent flame signal sensors. In order to conveniently connect to the test tunnel and effectively protect the flame signal sensor, a connection base was also designed. The flame signal sensor and its connection base were shown in Fig. 2. According to the experimental requirement, 13 flame signal sensors were arranged along the test tunnel and 12 time intervals can be recorded.

The flame brightness and duration could be recorded by the flame brightness sensor. The flame brightness sensor mainly comprised of a photodiode, a base and a signal line, as shown in Fig. 3. The photodiode could detect radiations of the flame in ranges of ultraviolet to infrared lights, and transform these light signals into voltage signals. Before the experiments, all flame intensity sensors were calibrated by a UNI-T381 digital luxmeter (Uni-Trend Group Limited, see Fig. 4).

With the help of the flame signal sensor and brightness sensor, the experimental data of flame speed and flame zone thickness could be obtained. Specific methods was shown in Fig. 5. Flame arriving time interval between point A and B were collected by the flame signal sensor A and B. Since length of the AB section was known, average flame speed in the AB section could be determined by dividing the

Fig. 3. Flame intensity sensor.