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## Flame Behavior of Gasoline-Air Explosion Suppression by Non-Premixed Nitrogen in a Closed Tube

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### ABSTRACT

Flame behavior of the gasoline-air explosion suppression by non-premixed nitrogen was studied by carrying out experiments in a closed tube through a visualization experimental bench and high speed photos of the flame front for the suppression process were acquired by a high speed camera. Based on the analysis of these high speed camera photos, flame behavior and flame velocity of the suppression process were discussed. Results showed that the whole suppression process can be divided into inertia maintenance stage, suppression attenuation stage and diffusion extinguishment stage. The dominant mechanism for the nitrogen non-premixed suppression is that the energy of the high-energy radicals of the chemical reaction could be taken away by the nitrogen molecule in the suppression section, resulting in the main reaction chains which were changed into termination chains.

**Key words:** Gasoline-air mixture, explosion suppression, nitrogen, flame behavior, flame velocity

### INTRODUCTION

Gasoline, one of the most extensively used fuels, is volatile and can form a flammable gas mixture with air easily. Statistics shows that more than 55 serious explosion accidents which involved gasoline-air mixture occurred from 1960-2003 (Chang and Lin, 2006). What is more, in the past decades, gasoline-air explosions were still common safety accidents leading to serious casualties and huge economic losses. Such as the Buncefield oil depot explosion accident in London in 2005 (Johnson, 2010), Indian Oil Corporation Ltd. explosion accident in 2009 (Sharma *et al.*, 2013), Qingdao oil pipeline explosion accident in China in 2013 ([http://www.chinadaily.com.cn/china/2013-11/23/content\\_17125977.htm](http://www.chinadaily.com.cn/china/2013-11/23/content_17125977.htm)) and Gaoxiong gas pipeline explosion accident in Taiwan in 2014 ([http://202.39.176.53/etn/news\\_content.php?id=2540315](http://202.39.176.53/etn/news_content.php?id=2540315)), etc. As a consequence, studies on suppression mechanisms of the gasoline-air mixture explosion still need to be strengthened so that more effective gasoline-air explosion suppression techniques and equipments can be put forward.

Nitrogen is inert, stable and non-reactive and widely used to provide an inert atmosphere and prevent explosions or fires in many cases. Works on its dilute effect (Molnarne *et al.*, 2005; Dong *et al.*, 2005; Razus *et al.*, 2006) and inert characteristic (Su and Liu, 2001; Li, 2001; Razus *et al.*, 2009) when it is premixed with flammable gas for the purpose of preventing fires or explosions have been reported commonly. In these studies, usually nitrogen was used as a premixed dilute agent rather than a non-premixed suppressant. Actually, premixed nitrogen was always used as a prevention agent for preventing fires or explosions before a fire or explosion occurred, while, non-premixed nitrogen could be used as a suppression agent for the purpose of suppressing explosions when a fire or explosion occurred. However, the suppression performances of nitrogen when it is used as a non-premixed suppression agent for preventing flammable gas explosion are seldom reported.

In addition, from the perspective of the previously published literature, works involving methane (Parra *et al.*, 2004; Ye *et al.*, 2005), propane (Razus *et al.*, 2011; Liu *et al.*,

2015) and other flammable gas or dust (Zalosh, 2007; Nie *et al.*, 2011; Deng *et al.*, 2012; Liu *et al.*, 2013) are common but research works involving gasoline-air mixture have seldom been considered (Zhang *et al.*, 2014; Du *et al.*, 2014).

The main purpose of this study is to study the mitigation performances of the non-premixed nitrogen for a gasoline-air explosion in a closed tube through visualization experiments and provide data of the flame behavior of the suppression process from such experiments.

### MATERIALS AND METHODS

The experimental equipments mainly consisted of a tube, a gasoline evaporation apparatus, a vacuum circulating pump, a concentration collection system, an ignition system, a high speed camera and a computer, as shown in Fig. 1. The total length of the tube was 6100 mm and the cross section dimension was 200×200 mm. In order to acquire the flame behavior photos of the suppression process, a visualization section was installed in the test tube. The structure, dimension and the real picture of the visualization section are shown in Fig. 2.

The gasoline evaporation apparatus and vacuum circulating pump were used to form a uniform gasoline-air mixture in the test tube. Details of structure and working principle of the gasoline evaporation apparatus can be found in the work of Zhang *et al.* (2013) or Yang *et al.* (2013).

The concentration collection system was mainly composed of a GXH-1050 infrared analyzer (Junfang physicochemical Science and Technology Institution of Beijing) and a NHA-502 automotive emission analyzer (Nanhua instruments Co. Ltd.). Concentration of the gasoline vapor was obtained by the GXH-1050 infrared analyzer and other gaseous concentrations were collected by the NHA-502 automotive emission analyzer.

The pictures of flame behavior in the visualization section were recorded by a FASTCAM-Ultima 512 high speed camera (Photron Co. Ltd. of Japan) and Fig. 3 is the image of the high speed camera. Through these pictures and the camera's speed (frame per second), flame front speed can be calculated by the flame front differential position ( $\Delta x$ ) and time interval ( $\Delta t$ ) of the neighboring photos.

The ignition system consisted of spark plug, power and high voltage which could give a maximum ignition energy about 20 J. The ignition energy and position of the ignition source had a significant effect on the initial propagation of the flame and the resulting flame speeds and overpressures, so it was set at a constant ignition energy of 5 J and kept at a constant position flush at the center of one of the blind flanges. The nitrogen and oxygen used in the experiments were separated from air and generated by a nitrogen production system (Shanghai Rich gas equipment Co. Ltd.). The purities of the nitrogen and oxygen were about 95-99%. During the course of the experiment, the tube was divided into three parts by two plastic films: Igniting section, nitrogen suppression

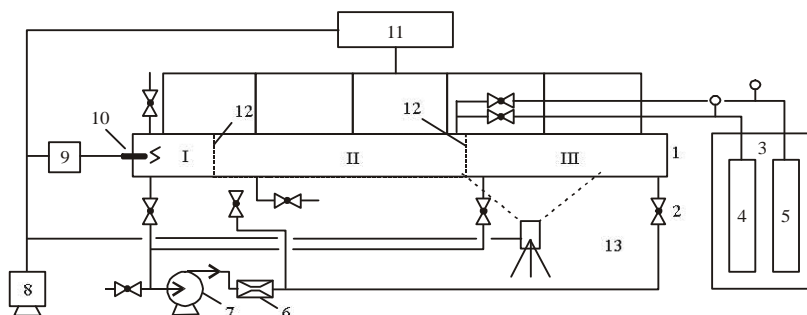


Fig. 1: Schematic of experimental apparatus, 1: Test tube, 2: Valve, 3: N<sub>2</sub> production system, 4: N<sub>2</sub> container, 5: O<sub>2</sub> container, 6: Gasoline evaporation apparatus, 7: Vacuum circulating pump, 8: Computer, 9: Ignition system, 10: Spark plug, 11: Concentration collection system, 12: Plastic film, 13: High speed camera, I: Ignition section, II: N<sub>2</sub> Suppression section, III: Gasoline-air mixture section

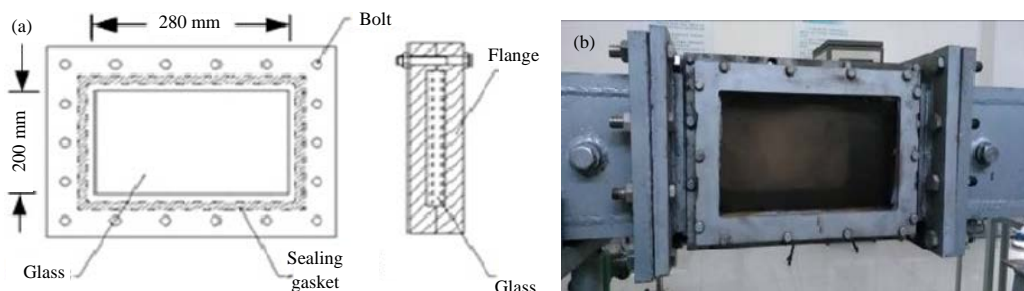


Fig. 2(a-b): Structure, dimension and real image of the visualization section, (a) Structure and dimension and (b) Real image



Fig. 3: Image of the FASTCAM-Ultima 512 high speed photography

Table 1: Initial condition set of the nitrogen non-premixed suppression experiment

Parameters	Value
Length of the nitrogen section (cm)	226
Length of the ignition section (cm)	55
N <sub>2</sub> concentration in nitrogen section/vol. (%)	95
O <sub>2</sub> concentration in nitrogen section/vol. (%)	5
Initial gasoline vapor concentration/vol. (%)	1.61
Initial O <sub>2</sub> concentration/vol. (%)	20.6
Ignition energy (J)	5
Initial temperature (K)	300
Initial relative pressure (Pa)	0

section and gasoline-air mixture section, as shown in Fig. 1. Both the two plastic films were held by the flange of the test tube. The lengths of the ignition section and nitrogen suppression section were 55 and 226 cm, respectively.

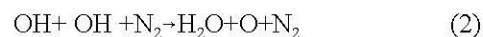
In order to obtain representative results, the initial equivalence ratio of the gasoline vapor (considerate the gasoline vapor as isoctane) was set at about 1 and the corresponding initial volume concentration of gasoline vapor was about 1.61%. Other initial conditions are presented in Table 1.

## RESULTS AND DISCUSSION

### Flame development process in the nitrogen suppression section:

Figure 4 shows the high speed photos of flame development process of the suppression in the nitrogen suppression section. It can be seen from Fig. 4 that, after entering the nitrogen suppression section, the flame front still kept propagation trend from the upstream. At this time, the outline of the flame front was still, relatively clear and the shape was a parabolic (228-234 msec). This is mainly due to the effects of the upstream expansion pressure wave on the flame front resulting in flow velocity was greater than the flame burning velocity when the flame front entered nitrogen section from upstream at this time. As a consequence, the flame still had certain degree of "Inertia" and still combusted and released heat continuously, leading to the flame front boundary was still supported by energy and showed a clear outline. The main characteristic of the flame front in this stage was inertia maintenance.

The shape of the flame front began to gradually change from a parabolic to a rectangle (234 msec). The color of the peripheral flame was also gradually changed from light yellow to dark red and the outline was not distinct any more (234-244 msec). This is mainly because the influence of the nitrogen on the flame of the explosion began to emerge from 234 msec, resulting in nitrogen molecules diffused from peripheral to internal of the flame under the convection mechanism resulted from flame heat release. Due to the inert characteristic of the nitrogen molecules, nitrogen began to participate in the chemical reactions of the gasoline-air explosion as a third body (Turns, 2000) under the high temperature of the flame. The main reaction process in this period can be expressed by the following chemical reactions:



Energy of the nitrogen molecules on the left side of the reaction in Eq. 1-3 is lower, while, on the right side is higher. Therefore, the main influences of these nitrogen molecules in the reactions were that they can take the energy away from these high-energy radicals, such as HC, O, OH and CO on the left side of the reaction in Eq. 1-3. In the process of these collision reactions, these high-energy radicals delivered internal energy from the high-energy radicals to the nitrogen molecules leading to most chemical reaction chain became termination chain. As a consequence, the flame temperature was gradually decreased with the change of the chemical reaction path which resulted in the decrease of radiation intensity of the carbon smoke particles in excited state and the color change from light yellow to dark red, correspondingly. The main characteristic of the flame in this stage was suppression attenuation.

During 246-276 msec, the flame front attenuated gradually. In this stage, the flame front color was gradually changed from yellow red to dark red and the shape of the flame region could not self-sustain any more. At the end of this stage, the flame diffused and disappeared gradually. This is mainly because the chemical reaction rate was so weak in this stage that the heat released from reactions could not provide enough energy for the continuous propagation of flame and the flame region also could not maintain its shape and spread to all around gradually which led to a further intensification of heat loss and the flame temperature and thickness dropped rapidly. Finally, the flame extinguished completely in the nitrogen section. The main characteristic of the flame in this stage was diffusion extinguishment.

From the analysis mentioned above, the whole suppression process can be divided into three periods, i.e., inertia maintenance stage, suppression attenuation stage and diffusion extinguishment stage. Each period of these three stages had lasted about 6, 12 and 32 msec, respectively.

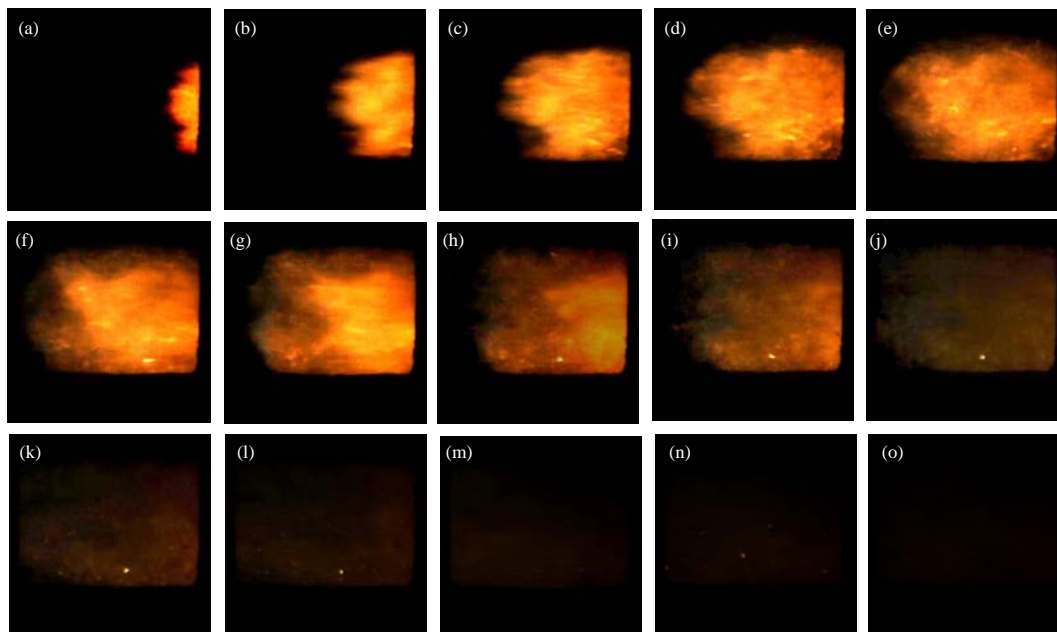


Fig. 4(a-o): High speed photos of the flame development process in the nitrogen suppression section, (a) 228, (b) 230, (c) 232, (d) 234, (e) 236, (f) 238, (g) 240, (h) 242, (i) 244, (j) 246, (k) 248, (l) 250, (m) 258, (n) 267 and (o) 276 msec

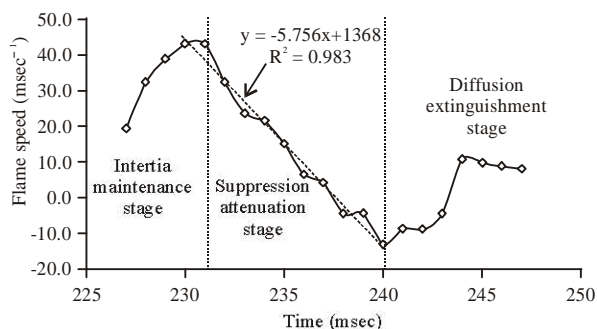


Fig. 5: Variation curve of the flame velocity of the suppression process

**Flame velocity in the nitrogen suppression section:**

Figure 5 shows the variation curve of the flame velocity of the suppression process. It can be seen from Fig. 5 that: (a) The velocity of the flame front was fluctuating with time in the explosion suppression process. This is mainly due to the complicated interactions among heat release and loss, the flow field velocity of the mixture gas, boundary conditions (such as open or closed) and the explosion pressure wave etc., in the process of the flame propagation. All these interaction processes together caused the fluctuation. (b) The flame velocity was about 20 msec<sup>-1</sup> when the flame reached the nitrogen section and climbed to 43 msec<sup>-1</sup> soon under the inertia influence of upstream flow, then, the inhibitory effect of the nitrogen began to work and the flame velocity began to drop. The flame velocity decreased to 0 at 238 msec, so the flame stagnated at this time. However, the reduction of the

flame velocity did not stop after this time and the flame began to move inversely. As a result, negative flame velocity appeared. The minimum flame velocity (about 12.92 msec<sup>-1</sup>) appeared at about 240 msec. The period after 240 msec was diffusion extinguishment stage and the flame velocity increased to 10.77 msec<sup>-1</sup> at 244 msec under the impact of flow field oscillation (Zhang *et al.*, 2013). However, after 244 msec, the flame began to diffuse and the flame heat release, temperature and area reduced rapidly, the flame extinguished completely at last. (c) During the suppression attenuation stage, the flame velocity decreased linearly with the increase of the time and the relationship between the flame velocity and time can be summarized by a linear equation:

$$y = -5.756x + 1368, R^2 = 0.983 \quad (4)$$

where, y represents flame speed, m/s and x represents time, ms. From the Eq. 4, It can be see that the attenuation intensity of the flame velocity during the suppression attenuation stage was about 576 msec<sup>-1</sup> and the suppression influence of the nitrogen on the flame was very significant.

Based on Eq. 4, the minimum length of the nitrogen suppression section will be estimated if this linear formula is applied to another experiment. For example, if the flame speed is 40 msec<sup>-1</sup> and the suppression attenuation stage lasts 10 msec, the minimum length of the nitrogen suppression section can be estimated by multiplying the flame speed and the time of the suppression attenuation stage. This means that the minimum length of the nitrogen suppression section should reach 0.4 m at least in this assumed situation.

## CONCLUSION

During the suppression process, energy of the high-energy radicals of the chemical reaction could be taken away by the nitrogen molecules in the suppression section which took part in the reaction as the third body, leading to that the main reaction chains were changed into termination chains. This was the dominant mechanism for the nitrogen non-premixed suppression process. During the suppression attenuation stage, relationship between the flame speed and time can be summarized by a linear formula. The findings mentioned in this study may provide some useful references to the nitrogen application in flammable gas explosion suppression field.

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