

# The secondary explosion phenomenon of gasoline-air mixture in a confined tunnel

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**Abstract.** In this article, experimental evidences of the special phenomenon of the secondary explosion of gasoline-air mixture were presented in the first place, and then, the causes for the secondary explosion were discussed. At last, effects of concentration on the secondary explosion were studied in detail through multiple experiments carried out in a cylinder tunnel with a solid heating device. Based on the experimental results analysis, the critical concentration for the secondary explosion of the gasoline-air mixture in the confined tunnel were discussed. Results indicated that main causes for the secondary explosion could be summarized as 4 points. Whether the secondary explosion occurred or not was determined by critical gasoline vapour and oxygen concentration even if the temperature was maintained in a reasonable scope. When the concentration of the gasoline vapour was as low as 0.45% and the oxygen as low as 10.4%, the secondary explosion still could be triggered.

## 1. Introduction

Fires and explosions are extremely dangerous in oil depots and coal mines. In fact, hundreds of these serious accidents have happened in the past ten year [1]. It is found that the special phenomenon of secondary or even multiple deflagrations induced by heat are very common in these accidents. For example, a serious explosion occurred in a southwestern oil depot in 2006 in China and, in that accident, a deflagration (explosion) still emerged many times after the flame of thermal spontaneous combustion was being extinguished. As a result, this occurrence made a common fire accident turn into a serious fire and explosion accident, and the oil depot was destroyed thoroughly by explosions and the resulting fast-spreading fire. In order to prevent and reduce the hazards of fire and explosion, the research on producing condition and influencing factors of the gasoline-air mixture's secondary thermal ignition in a confined tunnel has great importance in science and practice.

For the (first) gas explosion, many experimental and theoretical studies on its ignition laws, propagation characteristics, chemical reaction process and other mechanisms have already been undertaken [2-3], but the studies on secondary or multiple explosions induced by a heat source, however, are seldom reported. Harrison et al. [4], Ponizy et al. [5] Catlin [6] and Forcier et al. [7] have studied the secondary explosions caused by vented explosions in a variety of situations. In addition, experimental and numerical simulation research on the inducing process, influencing factors and

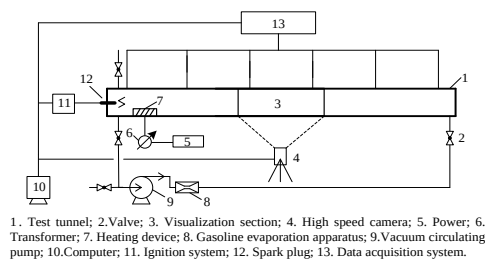


mathematical model of the multiple explosions of combustible gas and dust have also been carried out by Jiang et al.[8], Fan et al. [9], Ou et al. [10] and Du et al. [11] etc. However, due to the differences among flammable materials, the mechanism and influencing factors in multiple ignition processes will vary from one situation to another. From surveying the data we collected, explosive mixtures from flammable gases of simple composition, such as hydrogen, methane, propane and other single industry gases mixed with air or oxygen [12-14], have been studied in detail. However, research on mixtures involving multi-component explosive gases, such as gasoline, diesel oil and other materials, which can trigger spontaneous thermal combustion in the air easily are very rare.

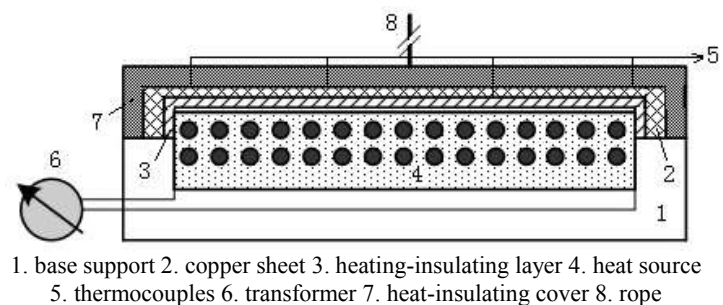
In this study, through experiments carried out in a cylinder tunnel with a solid heating device, the basic experimental data and occurrence laws of the secondary gasoline-air mixture explosion will be obtained, and then, the concentration effects on the secondary explosion of gasoline-air mixture will be explored by means of results analysis.

## 2. Experimental apparatus and methods

Visualization research on the secondary occurrence of gasoline-air explosion in confined tunnel was carried out during the experimental process. The experimental apparatus used in this study mainly consisted of experimental tunnel (containing two visualization windows), high speed camera, gasoline evaporation apparatus, vacuum circulating pump, data acquisition system and computer, as shown schematically in Figure 1.



1. Test tunnel; 2. Valve; 3. Visualization section; 4. High speed camera; 5. Power; 6. Transformer; 7. Heating device; 8. Gasoline evaporation apparatus; 9. Vacuum circulating pump; 10. Computer; 11. Ignition system; 12. Spark plug; 13. Data acquisition system.



1. base support 2. copper sheet 3. heating-insulating layer 4. heat source 5. thermocouples 6. transformer 7. heat-insulating cover 8. rope

**Figure 1.** Schematic of experimental equipments

**Figure 2.** composition of the heating device

The heating device was set horizontally in the tunnel and could be seen from the right observation window. The heating device mainly consists of a transformer, a heat source, a copper sheet, a base support, a heat-insulating layer and five thermocouples, as shown in Figure 2. The copper sheet is square ( $170 \times 170$  mm) with thickness of 2 mm. In the experiments, the copper sheet was heated by the heat source (its heating rate is 0-3000 W and can be adjusted by the transformer) and can get a temperature region of 300-900K. In order to prevent influences of local high temperature on heating device surface on the concentrations of the gas composition during the heating process, the heating rate was set at a lower value of 500 W and the gas mixture in the tunnel was also circulated by the circulation pump, when the gas mixture was heated by the heating device. When the heating device was used as an igniter in the experiments, the heating rate was set at a higher value of 2000 W, which can increase the temperature of copper sheet quickly and ignite the gas mixture.

In order to better prevent influences of heating device on the concentrations of the gas composition during the heating process, a heat-insulating cover was set on the surface of the heat source to separate the heat source and the gasoline-air mixture. The heat-insulating cover also can be lifted easily by a rope when the contact of gasoline-air mixture with the heat source is needed.

Experimental data needed to be collected mainly includes gaseous concentration, temperature and humidity etc. The GXH-1050 infrared analyzer was used to obtain gasoline vapor concentration, and other gaseous concentrations were respectively acquired by NHA-502 automotive emission analyzer.

Temperature in the experiments was collected by a Monitor and Control Generated System. Humidity in this present paper was gathered by a TRH-AZ temperature-humidity meter.

The temperature of gas mixture was measured by eight chrome-nickel-silicon thermocouples, which were arranged at intervals of 200mm along the experimental tunnel, while the heat device temperature is measured by five thermocouples located on the copper sheet (one is arranged at the center of copper sheet and the other four at the four corners of the sheet). Temperature data from these thermocouples were averaged as the final temperatures of gasoline-air mixture and heating device, respectively.

### 3. Results and Analysis

#### 3.1. Phenomenon of the secondary explosion

Multiple experiments indicated that the flame behavior of the gasoline-air explosion in the closed tunnel was affected by various factors, such as the initial concentration, temperature, humidity, etc. The flame in the test tunnel roughly had undergone ignition, development, attenuation and extinguishment process, respectively, and the lasting time was always less than 500 ms. However, both explosion overpressure curve and high speed photos were showed that the secondary explosion was occurred when the initial gasoline vapor concentration was maintained at a higher level (vol. 2.55%). Figure 3 and Figure 4 show the explosion overpressure curve and high speed photos of the secondary gasoline-air explosion process. In this experiment, the sampling frequency of high speed camera was 250 fps and the shutter speed was 1/250 s, so the time interval between the neighbor photos was 4 ms.

Figure 3 shows that the overpressure rose rapidly after the ignition of the mixture at about 1.81 s, and the overpressure peak was appeared at about 2.22 s and then the overpressure curve dropped sharply. However, the overpressure curve increased again at about 2.97 s and climbed sharply to another peak at about 3.09 s, and then attenuated down once again until the end of the explosion. The time interval between these two overpressure peaks was 0.846 s, which was longer than the lasting time of the normal experiment we carried out. This special two-peak phenomenon of the overpressure curve indicated that a secondary explosion might happen in the test tunnel. This conclusion was proved by the followed high speed photos.

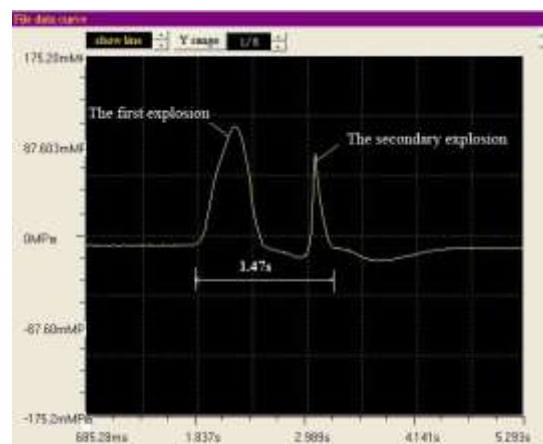


**Figure 3.** Overpressure curve of the secondary explosion

It can be seen from Figure 4 that the flame propagated forward after the ignition of the gasoline/air mixture (1.82 s, ignition delay). The flame area and the brightness were also increased as the flame propagated forward. The color of the flame was orange when the flame entered the observation window and then became bright yellow-white color. The flame brightness reached maximum at about 2.285 s and the visualization window was fully covered by bright yellow flame at this time. Then, the

flame began to decay and quenched at about 2.451 s. After 0.5 s (i. e. at about 2.973 s), however, combustion flame of a secondary explosion was appeared. From Figure4, it can be seen easily that the flame of the secondary explosion had in turn experienced resurgence (2973-2989 ms), development (2989-3053 ms), attenuation (3053-3085 ms) and extinguishing (after the time of 3149 ms) process.

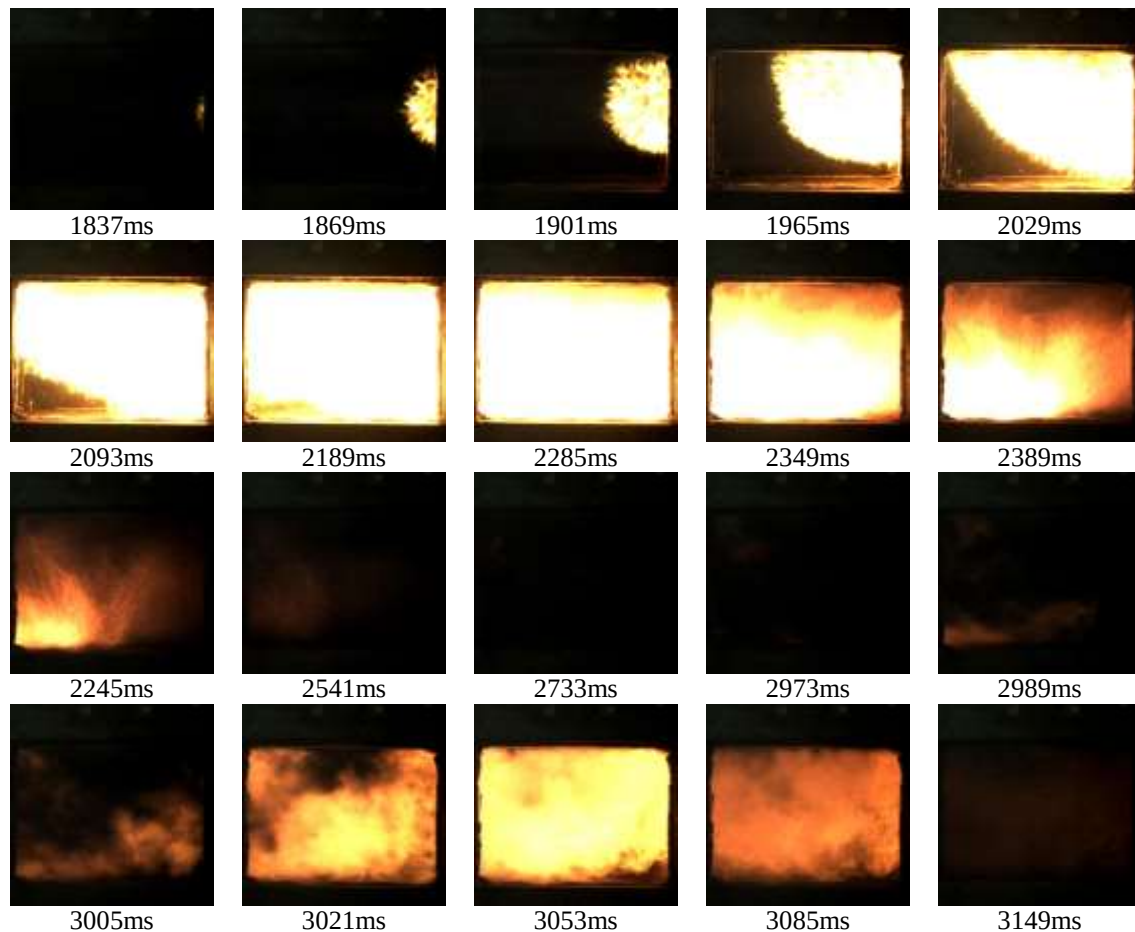


**Figure 4.** High speed photos of the secondary explosion process

Based on the comprehensive analysis of the experimental data before and after the secondary explosions, we realized that the main causes for the secondary explosion could be summarized as follows: (1) the high temperature environment and the existence of a large number of active group formed after the first explosion were the necessary conditions. (2) Due to the high initial gasoline vapor concentration, gasoline-air mixture was still remaining after the first explosion. (3) The experimental tunnel could not be absolutely airtight, part of the fresh air outside the tunnel might enter into the test tunnel so that the oxygen in the tunnel had been added. (4) In addition, it was worth noting that the occurrence of the secondary explosion had undergone a longer induction period (about 1.47 s) after the first explosion. Although no flame was appeared in this induction period, some important pre-ignition chemical reactions [3, 15] might possibly happened in the test tunnel, these pre-ignition chemical reactions produced a lot of intermediate products or active groups, which provided favorable conditions for the secondary explosion of the gasoline-air mixture. Causes (2) and (3) had ensured that the concentration of combustible gas mixture after the first explosion in the test tunnel was maintained in the range of explosion limit, cause (1) had provided ignition conditions for the secondary explosion, while, cause (4) had provided subsidiary condition for the occurrence of secondary explosion.

### 3.2. *Effects of concentration on the secondary explosion of gasoline-air mixture*

Although the influence factors for the secondary explosion maybe included humidity, temperature, concentration, etc. [16, 17]. The most important influence factor is concentration. So multiple experiments were carried out to investigate the critical concentration for the secondary explosion.

Multiple experiments indicated that whether the secondary explosion occurred or not was determined by critical gasoline vapor and oxygen concentration even if the temperature was maintained in a reasonable scope. A comparison of components' concentration before and after ignition is shown in Table 1. From Table 1, it can be seen that the secondary explosion in the confined tunnel would still be triggered even if the gas vapor concentration was as low as 0.45% and the oxygen concentration was as low as 10.4%. This value was much lower than the critical value (1%) of the first explosion reported by some references [18]. The reason behind this observation was that the first explosion of the gasoline-air mixture usually produced incomplete combustion and the chemical reaction was not complete either. As a result, there were a large number of intermediate products and active free radicals in the confined tunnel. It was shown that the highest concentration of CO had reached 6.06% before the secondary explosion, however, after the secondary explosion, this concentration was nearly 0 at some time and the highest CO<sub>2</sub> concentration had increased to 6.32%. This phenomenon indicated that intermediate products continued to react and released heat after encountering a heat source at high temperature, leading to the occurrence of the secondary explosion. In addition, due to the increase of the gas mixture temperature and pressure, the decrease of humidity in the confined tunnel after the first explosion, all components became so active that the chemical reaction would be triggered easily, and then the flame appeared. Based on the analysis mentioned above, the components of gasoline-air mixture after the first explosion became more complex, and the criterion on minimum oxygen and gas vapor concentration used for the first explosion was no longer appropriate to judge whether a secondary explosion would be triggered.

**Table 1.** Comparison of components concentration before and after the secondary explosion in the confined tunnel

| Components concentration after the first explosion (%) |                |      |                 | Components concentration after the secondary explosion (%) |      |                 |                |
|--------------------------------------------------------|----------------|------|-----------------|------------------------------------------------------------|------|-----------------|----------------|
| HC                                                     | O <sub>2</sub> | CO   | CO <sub>2</sub> | HC                                                         | CO   | CO <sub>2</sub> | O <sub>2</sub> |
| 0.60                                                   | 12.9           | 4.21 | 2.51            | 0.19                                                       | 0.01 | 4.01            | 7.80           |
| 0.47                                                   | 10.8           | 2.35 | 3.22            | 0.25                                                       | 0.00 | 5.32            | 8.20           |
| 0.45                                                   | 10.4           | 2.50 | 3.78            | 0.10                                                       | 0.00 | 4.01            | 9.00           |
| 0.57                                                   | 12.8           | 1.35 | 2.78            | 0.18                                                       | 0.00 | 4.03            | 7.10           |
| 0.76                                                   | 11.5           | 5.30 | 2.19            | 0.09                                                       | 0.00 | 4.53            | 6.90           |
| 0.82                                                   | 10.4           | 5.52 | 2.46            | 0.11                                                       | 0.01 | 4.83            | 7.00           |
| 0.99                                                   | 12.3           | 5.43 | 4.55            | 0.05                                                       | 0.02 | 5.80            | 7.09           |
| 0.67                                                   | 14.9           | 3.78 | 5.14            | 0.02                                                       | 0.00 | 6.90            | 7.50           |
| 0.77                                                   | 15.3           | 6.06 | 4.53            | 0.11                                                       | 0.01 | 6.32            | 6.40           |
| 0.86                                                   | 14.4           | 4.78 | 3.10            | 0.14                                                       | 0.01 | 5.81            | 13.00          |
| 0.72                                                   | 15.1           | 2.51 | 4.80            | 0.07                                                       | 0.01 | 6.20            | 11.00          |
| 0.63                                                   | 11.6           | 2.64 | 4.23            | 0.11                                                       | 0.00 | 6.22            | 9.00           |
| 0.57                                                   | 11.9           | 4.12 | 3.93            | 0.16                                                       | 0.01 | 5.46            | 8.70           |

## 4. Conclusions

The main causes for the secondary explosion could be summarized as follows: (1) the high temperature environment and the existence of a large number of active group formed after the first explosion were the necessary conditions. (2) The oxygen in the tunnel had been added. (4) Some important pre-ignition chemical reactions might possibly happened in the test tunnel,

these pre-ignition chemical reactions produced a lot of intermediate products or active groups, which provided favorable conditions for the secondary explosion of the gasoline-air mixture. Causes (2) and (3) had ensured that the concentration of combustible gas mixture after the first explosion in the test tunnel was maintained in the range of explosion limit, cause (1) had provided ignition conditions for the secondary explosion, while, cause (4) had provided subsidiary condition for the occurrence of secondary explosion.

The secondary explosion could still be triggered even if the gas vapor concentration was as low as 0.45% and the oxygen concentration was as low as 10.04%. After the first explosion, due to the increase in the gas mixture temperature and pressure, all components became more active and they could participate in the chemical reactions more easily, which was the main reason for the secondary occurrence of the gasoline-air explosion.

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