

# Effects of humidity, temperature and slow oxidation reactions on the occurrence of gasoline-air explosions

Du Yang, Zhang Pei Li and Ou Yi Hong

Chongqing Key Laboratory of Fire and Explosion Safety, Logistical Engineering University, Chongqing, China

## Abstract

In order to investigate the effects of the humidity, temperature and slow oxidation reactions on the occurrence of explosions in gasoline-air mixtures, experiments are carried out in a cylindrical tunnel with a solid heating device. Experimental results show that whether a gasoline-air explosion occurs or not is determined by a critical relative humidity when the temperature of the heat source is maintained at a specific value. Under the experimental conditions in this study, when the heat source temperature is maintained at 550°C, the critical value of relative humidity is  $32.3\% \pm 0.2\%$ , and when the heat source temperature is maintained at 570°C, the critical value of relative humidity climbs to  $37.7\% \pm 0.2\%$ . The occurrence of gasoline-air explosions is very sensitive to the gas mixture temperature. It is shown that an explosion will not occur if the gas mixture temperature is lower than the critical value of 26°C. Influenced by slow oxidation reactions, concentrations of reactants can decrease below the explosion limit range, resulting sometimes in no observed occurrence of gasoline-air explosions. Experiments show, in this case, that the critical heat source temperature for the gas mixture explosion, defined by a probability of explosion occurrence of 20%, climbs from 510 to 550°C, i.e. it increases 40°C solely due to the influence of slow oxidation reactions.

## Keywords

Explosion limits, gasoline-air mixture, mixture humidity for explosion, mixture temperature for explosion, slow oxidation reactions

---

## Corresponding author:

Zhang Pei Li, Chongqing Key Laboratory of Fire and Explosion Safety, Logistical Engineering University, Chongqing 401311, China.

Email: zpl612323@163.com

## Introduction

Fires and explosions in the process industry are still a common accident scenario, leading to casualties, destruction of equipment and downtime. In order to prevent losses, experimental and theoretical studies have been undertaken to understand the ignition laws, propagation characteristics, chemical reaction process and other mechanisms of flammable gas explosions [1–4]. Among these studies, work has commonly involved hydrogen, methane, propane and other single industrial gases mixed with air or oxygen [5–8] but hybrid or multiple flammable gases (e.g. gasoline vapor) are seldom considered. In fact most fire and explosion accidents in the process industry, especially in the petrochemical industry, have been caused by multiple flammable gas mixtures [9]; for example the super-large fire and explosion accident of Huangdao oil depot in 1989, Buncefield oil depot fire in London, LPG fire of Vishakhapatnam in India, oil transportation pipe fire of Dalian in 2010, etc.

Gasoline, one of the most extensively used fuels, is volatile and can form a flammable gas mixture with air easily. Statistics indicates that more than 55 gasoline-air mixture fire or explosion accidents occurred from 1960 to 2003 [9]. To better prevent losses from fires and explosions, it is important to investigate the influence factors for the occurrence of gasoline-air mixture explosions, such as the composition of the mixture, initial temperature, initial pressure, ignition energy, ignition delay time, humidity, equivalence ratio and even including slow oxidation reactions. It has been shown [10] that thermal radiation can lead to a considerable reduction (up to about 30%) of the total ignition delay time. Zabetakis [11] and Steinle [12] reported that the auto-ignition temperature of a hydrocarbon is significantly affected by the mixture composition and initial pressure. Pre-ignition reactions occurring in the regime of the low-temperature oxidation mechanism can change the mixture composition and result in a different explosion pressure [2]. Edenhofer et al. [13] showed that this slow oxidation can lead to a larger spatial and temporal extension of the reaction zone, which may cause a sharp decrease in reactants. These factors were also investigated in the engine field by undertaking experimental, theoretical and numerical studies of the auto-ignition process [13,14–18]. However, the auto-ignition in engines is mostly triggered by compression or spark rather than temperature elevation caused by a heat source. In addition, humidity also plays an important role in flammable gas explosions and has a great effect on burning velocity [19,20]. Unfortunately, few previously published works focus on the influence of humidity on the occurrence of gasoline-air mixture explosion.

In order to better understand the effects that temperature, humidity and slow oxidation reactions can have on the occurrence of gasoline-air explosions, experiments involving gasoline-air mixtures in a closed tunnel with a solid heating device are reported in this article.

## Experimental apparatus

The experimental apparatus used in this study mainly consisted of a tunnel, solid heating device, gasoline evaporation apparatus, circulating pump, concentration

collection system, temperature measurement system and a computer. Arrangement of the experimental apparatus is shown in Figure 1. For ensuring the safety of the experiments, the tunnel is made of Q235C steel with thickness of 9 mm. The total length of the experimental tunnel is 1700 mm and the diameter of the cross section is 340 mm. Two observation windows with high-temperature and high-pressure tolerance are designed into the tunnel and their distances to the right end of the tunnel, respectively, are 500 mm and 1500 mm.

A solid heating device is set opposite one of observation window in the tunnel (see Figure 1). 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 a thickness of 2 mm. In the experiments, the copper sheet is heated by the heat source (its heating rate is 0–3000 W, adjustable by the transformer) and can achieve a temperature range of 300–800°C.

In order to obtain an atomized stream of gasoline mixed with air uniformly in the tunnel, a gasoline evaporation apparatus is used. This apparatus, shown in Figure 3, works as follows: when gas flows through a decreasing area section, flow velocity increases and pressure decreases, so that a vacuum is generated in the bottle connected below the decreasing area section. As a consequence, liquid gasoline is absorbed into the plastic pipe, atomized by the high-speed flow and

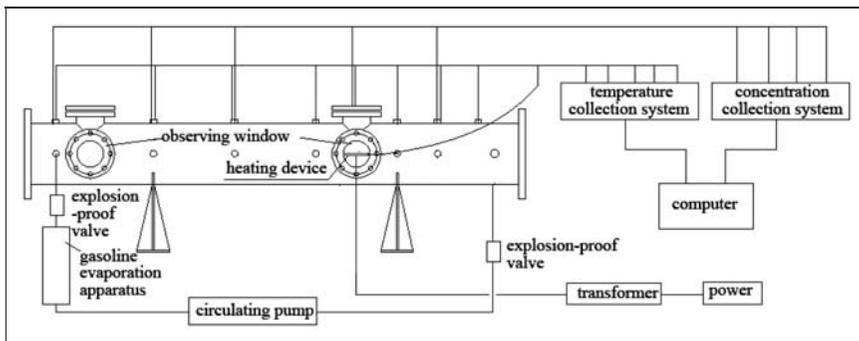


Figure 1. Arrangement of experimental apparatus.

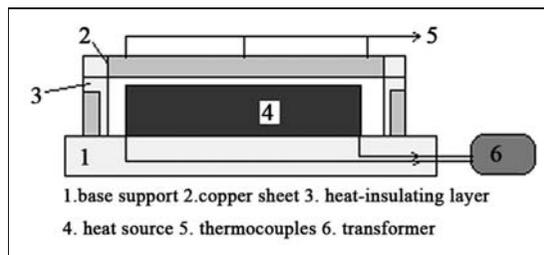
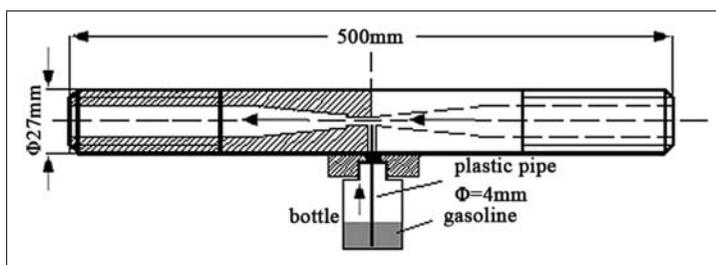


Figure 2. Composition of the heating device.



**Figure 3.** Structure of the gasoline evaporation apparatus.

evaporated by the vacuum in the decreasing area section (the initial Reid vapor pressure of gasoline used in the experiments is about 72 kPa). Because the volumes of gasoline evaporated from the same liquid gasoline are equal at the same pressure and temperature conditions, the concentration of gasoline vapor in the tunnel can be determined from the volume of gasoline in the bottle. In addition, the concentration of the gasoline vapor in the experiments also can be measured and monitored by an infrared analyzer.

A sprayer able to produce a minimum water mist diameter of  $10\ \mu\text{m}$  is used to change the humidity in the experimental tunnel. When a higher humidity is needed, water mist can be added into the test tunnel by the sprayer and transformed to gas form by the heating device mentioned above. While, when a lower humidity is needed, the humidity in the experimental tunnel can be adjusted by discharging humid gas into the atmosphere.

Experimental data needed to be collected mainly includes gaseous concentrations before and after reaction in the tunnel, heat source temperature, gas mixture temperature and humidity etc. The GXH-1050 infrared analyzer (Junfang Physicochemical Science and Technology Institution of Beijing) is used to obtain gasoline vapor concentration, and other gaseous concentrations were acquired by NHA-502 automotive emission analyzer (Nanhua instruments Co. Ltd.). Temperature in the experiments is collected by a Monitor and Control System (Shenzhen Advantech Co. Ltd.). The temperature data in the tunnel were acquired by eight chrome-nickel-silicon thermocouples, which were arranged at intervals of 200 mm 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 source, respectively. Humidity in the experiments is gathered by a TRH-AZ temperature-humidity meter.

## Experimental results and discussion

### *Humidity effects on occurrence of gasoline-air mixture explosions*

In order to investigate the influence of humidity on the occurrence of gasoline-air explosion, with the same gasoline vapor concentration of 1.5% by Vol.,

**Table 1.** Effects of different humidity on the explosion occurrence at a heat source temperature of 550°C (“+” and “-” represent an explosion or no explosion, respectively).

Relative humidity	Experiment number				
	1	2	3	4	5
18.6% ± 0.2%	+	+	+	+	+
20.3% ± 0.2%	+	-	+	+	+
21.8% ± 0.2%	+	+	-	+	-
25.6% ± 0.2%	+	+	+	-	-
29.7% ± 0.2%	+	-	-	-	-
32.3% ± 0.2%	-	-	-	+	-
33.4% ± 0.2%	-	-	-	-	-
34.6% ± 0.2%	-	-	-	-	-
36.1% ± 0.2%	-	-	-	-	-
37.7% ± 0.2%	-	-	-	-	-
39.5% ± 0.2%	-	-	-	-	-
42.3% ± 0.2%	-	-	-	-	-

experiments under two temperature conditions (550°C and 570°C) are systematically carried out at different humidity levels. Heat source temperatures of 550°C or 570°C are used, respectively, as typical for analysis. The effect of different humidity levels on the occurrence of an explosion at a heat source temperature of 550°C is shown in Table 1. Experimental results show that the relative humidity has a great impact on the occurrence of a gasoline-air explosion. The probability of an explosion occurrence is defined here as the number of times an explosion occurs divided by the total number of experiments repeated under the same conditions, the result times 100%. With increasing relative humidity, this explosion probability is reduced; when the relative humidity is  $\geq 32.3\% \pm 0.2\%$ , the probability of explosion occurrence tends to be smaller, less than 20%; however, under a relatively dry condition (the relative humidity is  $\leq 32.3\% \pm 0.2\%$ ), the probability of explosion occurrence is much greater, more than approximately 80%; When the relative humidity is  $\leq 18.6\% \pm 0.2\%$ , the probability of explosion occurrence rises to 100%. This is because added humidity enriches radicals evolved from the water molecule, leading to a reduction of the radical concentration of the reactants in the tunnel. As a consequence, the possibility of collisions of reactant radicals is decreased correspondingly.

In addition, it is found that the lower the humidity in the tunnel, the higher is the observed explosion intensity (greater noise or flame). On the other hand, with increasing of the relative humidity in the tunnel, the intensity of the explosion is reduced, if the explosion occurs at all. This can be explained by the mitigation ability of the water molecule discussed by Acton et al. [21] and Van Wingerden et al. [22].

**Table 2.** Effects of different humidity on the explosion occurrence at a heat source temperature of 570°C (“+” and “-” represent an explosion or no explosion, respectively).

Relative humidity	Experiment number				
	1	2	3	4	5
18.6% ± 0.2%	+	+	+	+	+
20.3% ± 0.2%	+	+	-	+	+
21.8% ± 0.2%	+	+	+	+	-
25.6% ± 0.2%	+	+	+	+	-
29.7% ± 0.2%	+	-	+	-	-
32.3% ± 0.2%	-	+	-	-	-
37.7% ± 0.2%	-	-	-	+	-
38.1% ± 0.2%	-	-	-	-	-
38.5% ± 0.2%	-	-	-	-	-
39.5% ± 0.2%	-	-	-	-	-
42.3% ± 0.2%	-	-	-	-	-

The effect of different humidity levels on the occurrence of an explosion at a heat source temperature of 570°C is shown in Table 2. Here also, the relative humidity has a great impact. With increasing relative humidity, the probability of explosion occurrence is again reduced; when the relative humidity is  $\geq 37.7\% \pm 0.2\%$ , the probability of explosion occurrence tends to be much lower, less than 20%. This critical value is larger than that when the heat source temperature is 550°C. Under a dry condition (the relative humidity  $\leq 37.7\% \pm 0.2\%$ ), the probability of explosion occurrence is much greater, more than approximately 80%. When the relative humidity is  $\leq 18.6\% \pm 0.2\%$ , the probability of explosion occurrence rises to 100%. Similarly to the results for a temperature of 550°C, the lower is the humidity in the tunnel, the higher is the observed explosion intensity (with greater noise or flame) and with increasing relative humidity in the tunnel, the lower is the intensity of the explosion, if the explosion occurs at all.

Another important conclusion can be drawn from the experiments, that is, whether the explosion occurs or not depends on a critical value for the temperature of the heat source. Under the experimental conditions in the present study, when the heat source temperature is maintained at 550°C, the relative humidity critical value is  $32.3\% \pm 0.2\%$ , but when the heat source temperature is maintained at 570°C, the relative humidity critical value is  $37.7\% \pm 0.2\%$ .

### *Effects of gas mixture temperature on occurrence of gasoline-air mixture explosions*

Gas mixture temperature is also an important factor influencing the occurrence of an explosion. Therefore, this influence is studied systematically. In order to ensure

**Table 3.** Experimental results when gas mixture temperature is varied from 20 to 29°C (“+” and “-” represent an explosion or no explosion, respectively).

Gas mixture temperature/°C	Heat source temperature/°C					
	510	520	540	550	570	600
20	-	-	-	-	-	-
22	-	-	-	-	-	-
23.4	-	-	-	-	-	-
24.7	-	-	-	-	-	-
25.8	-	-	-	-	-	-
26.5	-	-	-	-	-	+
28	-	-	-	-	-	+
29	-	-	-	-	-	+

**Table 4.** Experimental results when gas mixture temperature is varied from 30 to 39°C (“+” and “-” represent an explosion or no explosion, respectively).

Gas mixture temperature/°C	Heat source temperature/°C					
	510	520	540	550	570	600
30	-	-	-	+	+	+
33.4	-	-	+	+	+	+
35	-	-	+	+	+	+
36.8	-	-	-	+	+	+
38.5	-	-	+	+	explosive	+
39	-	-	-	+	+	explosive

the stability of the ambient temperature in the tunnel, 20-mm thick insulation material is wrapped over the outer wall of the tunnel. In addition, on the outer surface of this insulation material, an aluminum foil layer is applied to reduce thermal radiation. The gas mixture is heated by the device described previously. In a systematic experimental process, the heating rate is set at a constant 650 W, the gasoline vapor concentration is maintained within the explosive range (during this experiment, it is controlled at about 2.8% by Vol.) and the relative humidity is controlled at 20.3. Then, the temperature of heat source is varied.

The typical experimental results of explosion occurrence under conditions of different heat source temperatures and a gas mixture temperature that varies from 20 to 29°C are shown in Table 3. Table 4 provides the experimental results

**Table 5.** Experimental results when gas mixture temperature is varied from 40 to 49°C (“+” and “-” represent an explosion or no explosion, respectively).

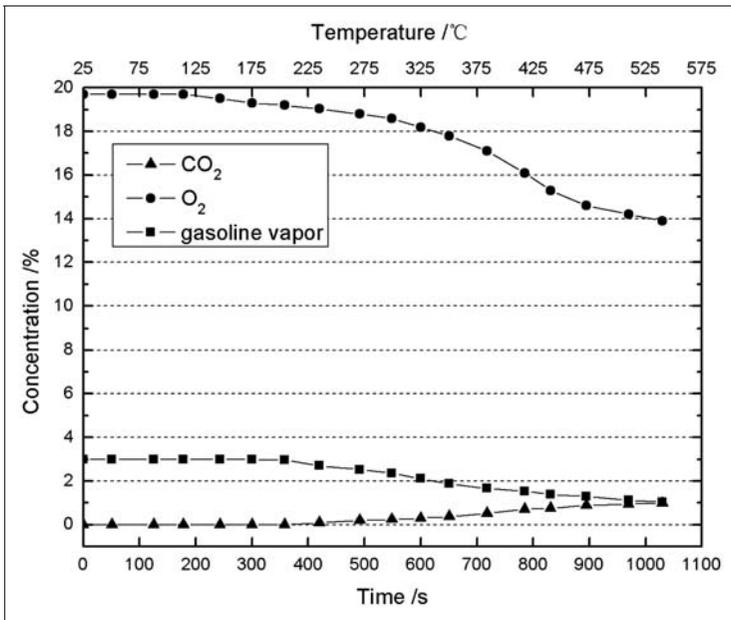
Gas mixture temperature/°C	Heat source temperature/°C					
	510	520	540	550	570	600
40	-	-	+	+	+	+
42	-	-	+	+	+	+
44.7	-	-	+	+	+	+
45.8	-	+	+	Explosive	+	+
47.5	-	+	+	+	Explosive	+
48	+	+	+	+	Explosive	Explosive
49	+	+	+	+	Explosive	Explosive

when gas mixture temperature varies from 30 to 39°C, and Table 5 illustrates the experimental results when environmental temperature varies from 40 to 49°C.

The multiple tests indicate that the occurrence of a gasoline-air explosion is very sensitive to the gas mixture temperature in the tunnel. It is clearly seen from Table 3 that the probability of explosion occurrence is close to zero when the gas mixture temperature is lower than 26°C. When the gas mixture temperature is maintained between 26 and 29°C, an explosion did not occur unless the heat source temperature reaches 600°C. However, when the gas mixture temperature is maintained in the range of 30–39°C (Table 4), the heat source temperature needed for an explosion occurrence decreases to 540°C, with the appearance of explosive deflagrations. When the gas mixture temperature further rises to 40–49°C (Table 5), the probability of the explosion occurrence increases greatly if the gas mixture temperature is more than 45°C, and the minimum temperature of the heat source for the explosion occurrence decreases sharply as well.

In this set of experiments, the heat source can be identified as an ignition source for the explosions. Under the condition of a lower gas mixture temperature, the heat source has the ability to trigger the explosion only when its temperature reaches a certain value. This is because the occurrence of a gasoline-air explosion requires a certain ignition energy provided by the heat source to activate reactions in the mixture.

Through the experiments, it can be concluded that there exists a critical gas mixture temperature when the explosion occurs under the condition of a certain heat source temperature. If the value of gas mixture temperature is less than the critical one, an explosion will not occur. In these experiments, this critical value is 26°C.



**Figure 4.** Variations of gasoline vapor, O<sub>2</sub> and CO<sub>2</sub> concentration at a heating rate of 2000 W.

### *Effects of slow oxidation reactions on occurrence of gasoline-air mixture explosion*

In some experiments, even with a higher heating rate than that used above, it is found that the explosion still did not occur, although the humidity, temperature and concentrations of gasoline vapor and oxygen were maintained in a reasonable range. Through monitoring the concentrations of the mixture composition during the heating process of the experiments, decreases of gasoline vapor and oxygen concentration and an increase of carbon dioxide concentration are detected, indicating that oxidation reactions happen actively within the gasoline-air mixture before the occurrence of the explosion in these cases. Compared to the fast oxidation reactions during the explosion process, the speeds of these reactions are much slower; however, these slow oxidation reactions influence the occurrence of gasoline-air mixture explosion to a great extent. Representative variations of gasoline vapor, oxygen and carbon dioxide concentration during a heating process at a rate of 2000 W are shown in Figure 4. It is clearly seen from this figure that the oxygen decreases from 19.7% to less than 14% and the gasoline vapor concentration drops from 3.0% to 1.0%, while carbon dioxide increases from 0 to near 1.0%. The minimum oxygen concentration for a gasoline explosion is about 14%, and the lower limit of gasoline vapor for a gasoline explosion is about 1.3% [23]. Therefore, the concentrations of oxygen and gasoline vapor have already dropped out of the explosive range, resulting in the absence of a gasoline-air explosion.

In order to investigate the slow oxidation reactions and study their influence on the explosion occurrence, two experimental processes are used in conjunction with an insulated cover over the heating device: (1) during heating of the gas mixture, the insulated cover is removed and the heat source is allowed to be in contact with the gasoline-air mixture during the entire experiment, thus allowing the occurrence of thermal explosion to be influenced by slow oxidation reactions and (2) during heating of the gas mixture, the insulated cover remains in place, i.e., the heat source is not allowed to be in contact with the gasoline-air mixture, until the heat source temperature has reached the desired value. Obviously, in the second set of experiments, the slow oxidation reactions are not active and the influence of the slow oxidation reactions is avoided. For this set of experiments, the gas mixture temperature in the tunnel is set at 35°C, humidity at 25.6% and concentration of gasoline vapor at 2.4%. Tables 6 and 7 show the experimental results when the slow oxidation reactions are not active (experimental process #2) or are important (experimental process #1), respectively. Table 6 indicates that the explosion occurs when the heat source temperature is 510°C and its probability is 20%, while the probability rises to 100% when the heat source temperature increases to 570°C. Table 7, however, demonstrates that the explosion could not be triggered, as a result of the slow oxidation reactions, when the heat source temperature is lower than 550°C, and the probability of the explosion occurrence drops to 20% when

**Table 6.** Experimental results when slow oxidation reactions are not active (“+” and “-” represent an explosion or no explosion, respectively).

Heat source temperature/°C	Experiment number				
	1	2	3	4	5
510	+	-	-	-	-
540	+	+	-	-	+
550	-	+	+	+	+
570	+	+	+	+	+

**Table 7.** Experimental results when slow oxidation reactions are important (“+” and “-” represent an explosion or no explosion, respectively).

Heat source temperature /°C	Experiment number				
	1	2	3	4	5
510	-	-	-	-	-
540	-	-	-	-	-
550	+	-	-	-	-
570	-	-	-	+	-

the heat source temperature is in the range of 550°C to 570°C. The critical heat source temperature, defined by a probability of explosion occurrence of 20%, has climbed from 510 to 550°C, i.e. it increases 40°C due to the influence of the slow oxidation reactions.

It is difficult to determine the exact cause in some experiments why the gas explosion occurred and in others it did not, as there are complicated chemical and physical process involved, such as trigger and termination processes of the chain reactions, interaction process between heat release of the reactions and heat loss in the tunnel wall etc. In fact, the effects of slow oxidation reactions in the present experiments can be explained by a pre-ignition reaction that occurs in the regime of the low-temperature oxidation mechanism and can change the mixture composition [2]. According to a study of Edenhofer et al. [13], slow oxidation can lead to a larger spatial and temporal extension of the reaction zone. As a consequence, the temperature and temperature gradient near the solid heat source is reduced and the concentrations of reactants also quickly decrease out of the explosion range. In the current experiments, due to the influence of slow oxidation reactions, the oxygen concentration in the tunnel might drop to 14% or less and the gasoline vapor concentration in the space could also fall to 1.0% or less. In this situation, the concentrations of oxygen and vapor are below the explosion limit, and as a consequence, an explosion cannot be triggered.

## **Conclusions**

Experiments are carried out to investigate the effects of the humidity, temperature and slow oxidation reactions on the occurrence of gasoline-air mixture explosions. Experimental results show that the relative humidity has an important influence on the occurrence of gasoline-air explosions. Whether gasoline-air mixture explosion occurred or not is determined by a critical relative humidity when the temperature of heat source is maintained at a certain value. Under the experimental conditions for this article, when the heat source temperature is maintained at 550°C, the critical value of relative humidity is  $32.3\% \pm 0.2\%$ ; when the heat source temperature is maintained at 570°C, the critical value of relative humidity is  $37.7\% \pm 0.2\%$ .

The occurrence of gasoline-air explosions is also very sensitive to the gas mixture temperature. There exists a critical gas mixture temperature when the explosion occurs under the condition of a specific heat source temperature. If the value of gas mixture temperature is less than the critical one, an explosion will not occur. In the experiments completed for this article, this critical value is 26°C.

Slow oxidation reactions yield concentrations of reactants that can decrease to below the explosion limit range, resulting in an absence of gasoline-air explosions. Under these conditions, the critical heat source temperature, defined by a probability of explosion occurrence of 20%, climbs from 510 to 550°C, i.e. it increases 40°C due to the influence of the slow oxidation reactions.

## Funding

This research received specific grants from National Natural Science Foundation of China (No. 51276195), Natural Science Foundation of Chongqing (CSTC. 2009BA6019) and Foundation of Chongqing Key Laboratory of Fire and Explosion Safety (CSTC. 2010CA0005).

## References

1. Kindracki J, Kobiera A, Rarata G, et al. Influence of ignition position and obstacles on explosion development in methane–air mixture in closed vessels. *J Loss Prevent Process Indust* 2007; Vol. 20: 551–561.
2. Pekalski AA, Terli E, Zevenbergen JF, et al. Influence of the ignition delay time on the explosion parameters of hydrocarbon–air–oxygen mixtures at elevated pressure and temperature. *Proc Combust Inst* 2005; Vol. 30: 1933–1939.
3. Razus D, Movileanu C, Brinzea V, et al. Explosion pressures of hydrocarbon–air mixtures in closed vessels. *J Hazard Mater* 2006; Vol. 135: 58–65.
4. Hakima AR, Laurent B, Guoying X, et al. On the correlation between kinetic rate constants in the auto-ignition process of some oxygenates and their cetane number: a quantum chemical study. *J Mol Struct (Theochem)* 2003; Vol. 621: 293–304.
5. Dahoe AE. Laminar burning velocities of hydrogen–air mixtures from closed vessel gas explosions. *J Loss Prevent Process Indust* 2005; Vol. 18: 152–166.
6. Gieras M, Klemens R, Rarata G, et al. Determination of explosion parameters of methane–air mixtures in the chamber of 40 dm<sup>3</sup> at normal and elevated temperature. *J Loss Prevent Process Indust* 2006; Vol. 19: 263–270.
7. Razus D, Brinzea V, Mitu M, et al. Temperature and pressure influence on explosion pressures of closed vessel propane–air deflagrations. *J Hazard Mater* 2010; Vol. 174: 548–555.
8. Razus D, Brinzea V, Mitu M, et al. Inerting effect of the combustion products on the confined deflagration of liquefied petroleum gas–air mixtures. *J Loss Prevent Process Indust* 2009; Vol. 22: 463–468.
9. Chang JI and Lin CC. A study of storage tank accidents. *J Loss Prevent Process Indust* 2006; Vol. 19: 51–59.
10. Goldfarb I, Gol'dshtein V, Katz D, et al. Radiation effect on thermal explosion in a gas containing evaporating fuel droplets. *Int J Thermal Sci* 2007; Vol. 46: 358–370.
11. Zabetakis MG. *Flammability characteristics of combustible gasses and vapors*. Bulletin 627, US Department of the Interior, Bureau of Mines, Washington, DC, 1965, p.121.
12. Steinle JU and Franck EU. High pressure combustion–ignition temperatures to 1000 bar. *Ber. Bunsenges. Phys Chem* 1995; Vol. 99: 66–73.
13. Edenhofer R, Lucka K and Köhne H. Low temperature oxidation of diesel–air mixtures at atmospheric pressure. *Proc Combust Inst* 2007; Vol. 31: 2947–2954.
14. Caron M, Goethals M, Smedt GD, et al. Pressure dependence of the auto-ignition temperature of methanair mixtures. *J Hazard Mater* 1999; Vol. 65: 233–244.
15. Bar-Kohany T and Dahan K. Evaluation of the one-step hydrogen–oxygen global reaction rate in a non-premixed mixture to predict auto-ignition limits. *Int J Hydrogen Energy* 2012; Vol. 37: 14669–14675.
16. Goldsborough SS. A chemical kinetically based ignition delay correlation for iso-octane covering a wide range of conditions including the NTC region. *Combustion Flame* 2009; Vol. 156: 1248–1262.

17. Oh CB, Lee EJ and Jung GJ. Unsteady auto-ignition of hydrogen in a perfectly stirred reactor with oscillating residence times. *Chem Eng Sci* 2011; Vol. 66: 4605–4614.
18. Kawahara N and Tomita E. Visualization of auto-ignition and pressure wave during knocking in a hydrogen spark-ignition engine. *Int J Hydrogen Energy* 2009; Vol. 34: 5946–5953.
19. Thomasa G, Oakley G and Bambrey R. An experimental study of flame acceleration and deflagration to detonation transition in representative process piping. *Proc Safety Environmental Protect* 2010; Vol. 88: 75–90.
20. Ou YH, Du Y, Jiang XS, et al. Study on the thermal ignition of gasoline-air mixture in underground oil depots based on experiment and numerical simulation. *J Thermal Sci* 2010; Vol. 19: 173–181.
21. Acton MR, Sutton P and Wickens MJ. An investigation of the mitigation of gas cloud explosions by water sprays. *Instit Chemical Eng* 1990; Vol. 122: 61–76.
22. Van Wingerden K, Wilkins B, Bakken J, et al. The influence of water sprays on gas explosions: 2. Mitigation. *J Loss Prevent Process Indust* 1995; Vol. 8: 61–70.
23. Zhao HY. *Explosion theory of gas and dust*. Beijing: Beijing Institute of Technology Press, 1996.