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Experimental study of gas deflagration temperature distribution and its measurement

Qi Zhang [a,*,1], Wei Li [a,1], Da-Chao Lin [b,2], Yun Duan [a,1], Hui-Min Liang [a,1]

[a] State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China
[b] Department of Civil Engineering, North China Institute of Science and Technology, Box 206, Yanjiao, Bei Jing Dong, Beijing 101601, China

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ABSTRACT

Explosion temperature is one of the main factors in combustible gas explosion accidents. Despite all this, this problem has not yet received considerable attention, especially few fundamental data related to the temperature distribution of gas explosions in closed vessels in literatures. According to characteristics of gas deflagrations, this work developed a gas explosion temperature measurement system whose response time to temperature is approximate 10 μs. By using this system, an experimental study was carried out which is concerned with the deflagration temperature distribution of premixed methane–air mixtures in the 20 L spherical vessel with a diameter of 168 mm. Experimental results show that temperatures on or near the wall are obviously lower than those in the center part of the vessel and there is a conspicuous gradient from the wall to the center part of the vessel. In the inside of the vessel, the deflagration temperature of premixed methane–air mixtures near the ignition spot at the center of the vessel can approximately reach 1200 °C, while near the wall, only 300 °C. This result throws a light on the specific regularity of gas temperature distribution near the boundary. It is possible to provide an important basis for understanding the general characteristics of gas deflagrations in closed vessels as well as choosing good measurement designs. Otherwise, if the ignition is located in the geometrical center of the spherical vessel, velocity of the flame increases with the distance away from the center inside the vessel, and when the flame arrives at the inner wall, this velocity descend sharply.

1. Introduction

Pressure and temperature are two important parameters to describe characteristics of gas explosions, in which the latter can cause the called temperature effect that is the main form of disaster in explosion accidents. In the closed spherical vessel filled by the premixed methane–air, the flame starts from the ignition point and propagates forward to the wall of the vessel along the direction of radius. The pressure increases gradually during the flame propagation. Values of explosion pressures at various experimental environments have been reported in many publications [1–13]. The experimental study of explosive combustion of LPG was performed, and several explosion characteristics of LPG–air in terms of the transient pressure–time records were determined [14]. Explosion pressure in premixed methane–air mixtures in an elongated explosion vessel is influenced by ignition position and obstacles [15]. Experimental measurement results of explosion pressures in the 40 dm^3 explosion chamber was presented and the rate of explosion pressure rise as a function of molar methane concentration in the mixture with air was found [16]. Explosion and detonation pressure characteristics of dimethyl ether experimentally were investigated by use of a spherical vessel [17].

The temperature measurement of gas explosion is more difficult compared with the pressure measurement of gas explosion. The measured data are hardly available. Ono, et al. [18] measured the gas temperature of capacitance spark discharge, and nevertheless, the used optical method cannot obtain the history of transient local high temperature varying with time. Imamura, et al. [19] investigated the properties of the temperature field of the hot current, the temperature rises in the hydrogen jet flame and hot currents measured were 100–1000 K. The state of jet flame is different from that in quiescent premixed gas. Moreover, temperature–time history was not presented in this literature. Few works have made a contribution to the instantaneous temperature measurement for gas explosion since it is very difficult to operate the measurement of temperature due to complicated temperature response of gas explosions. To the best of the authors knowledge, no publications directly refer to the experimental results of temperature distribution for real gas explosions yet. Ronney et al. [20–22] assessed the requirements for temperature measurements in microgravity combustion experiments. They also studied premixed gas flames

* Corresponding author. Tel./fax: +86 10 68914252.
E-mail address: qzhang@bit.edu.cn (Q. Zhang).
[1] Tel./fax: +86 10 68914252.
[2] Tel.: +86 10 61594883; fax: +86 10 61594887.

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in mixtures numerically using detailed chemical and radiative emission–absorption models, and two heat loss mechanisms that lead to flammability limits were identified.

In view of the environmental particularity in measuring the temperature of gas explosions, we designed a gas explosion temperature measurement system on the basis of virtual instrument technology in this work. And then, by means of this system, we studied the deflagration temperature distribution of premixed methane–air mixtures in the closed vessel.

2. Temperature measurement system of gas explosion

The designed gas explosion measurement system was composed of two parts of hardware and software, in which the hardware included thermocouple temperature sensors, piezoelectric pressure transducer, easy signal conditioning, data acquisition card, PXI mainframe-box and controller, and so on. Thermocouple temperature sensors are the temperature sensing elements, and the measurement system was set-up on the basis of virtual instrument technology. After the temperature signal was modified by the easy signal conditioning and was input into the data acquisition card, it was transformed into digital signal through A/D conversion, realizing signal acquisition, processing and storage.

Fast thermocouple WRe5-WRe26 (type C) made by Nanmac Corporation is very good, having a response time less than 10 μs (this parameter was cited from the manufacture specification), but it is expensive. In general, a thermocouple can be used only once in measurement for high pressure and temperature of explosion. In view of the cost of experiment and the requirement of specific assembly environment, fast naked thermocouples of type K were self-manufactured in this work, and were calibrated by means of the WRe5-WRe26 (type C) taking as the standard thermocouple. In calibrating, the manufactured fast thermocouple of type K was bound together with the standard thermocouple WRe5-WRe26 (type C), aligning the measurement ends of both thermocouples and getting them close as far as possible. And then, the explosion temperature action was exerted on the thermocouples and simultaneously an observation of the voltage signal change was carried out. The results measured with the self-manufactured fast thermocouple of type K and the standard wolfram–rhenium thermocouple WRe5-WRe26 (type C) are presented, as shown in Fig. 1. The *X* axis stands for time interval, and the Y axis is temperature acquired by thermocouples. We can see that both of the self-manufactured thermocouple and the standard wolfram–rhenium thermocouple have similar curves. The self-manufactured thermocouple has almost the same response speed as the standard wolfram–rhenium thermocouple. In Fig. 1, the curve obtained by the self-manufactured thermocouple is over that obtained by the standard wolfram–rhenium thermocouple. This illustrates that the responding time of the self-manufactured thermocouple is less than that of the standard wolfram–rhenium thermocouple (10 μs). From the pressure–time history measured, the time of gas explosion is in an order of milliseconds. The responding time of the self-manufactured thermocouple is in an order of 10^0–10^1 μs. Therefore, the self-manufactured thermocouple can satisfy the requirement of measurement. It should be noted that there are some differences between the measuring results from two thermocouples since the thermoelectric effects produced by different thermocouple types are different in the same temperature condition.

The pressure variation during deflagrations was recorded with a piezoelectric pressure transducer (Kistler 211 M), connected to a Charge Amplifier. The signals of the Easy Signal Condition and the Charge Amplifier were recorded with the data acquisition system, by means of an acquisition card type NI PXI-5922, at 5×10^5 signals/s.

3. Experimental results

The gas in front of the flame or behind the flame was in a state of rest in the experiments, and velocity of the flame was in an order of 10^2–10^0 m/s under the given experiment conditions in this work. For each experiment, a temperature sensor was fixed along radial direction, on which radiation from gas burning was acted directly. Heat transfer coefficients due to convection can be calculated with the help of Nusselt number which depends, among others, on Reynolds number in the combustion gas products. The information available about the combustion gas products is not enough for a calculation of the convection process. Therefore, the convection, not having so large influence on the measurement results presented in this work, was ignored. If the radiation and absorption that exists in the burning gas is not taken into consideration, when the reading of thermocouple remains stable, the radiation heat transfer on unit areas of the thermocouple junction with the wall surface of vessel is equal to the convection heat transfer of the thermocouple from the flame, and consequently a relationship between temperatures of the flame and the thermocouple junction may be given as [23].

$$T_f = T_1 + \frac{\varepsilon C_0}{h}\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_w}{100}\right)^4\right] \tag{1}$$

where T_f is temperature of the flame, T_1 is temperature of the thermocouple junction, T_w is temperature of the wall surface of vessel, ε is radiation rate of the wall surface of vessel, h is convection heat

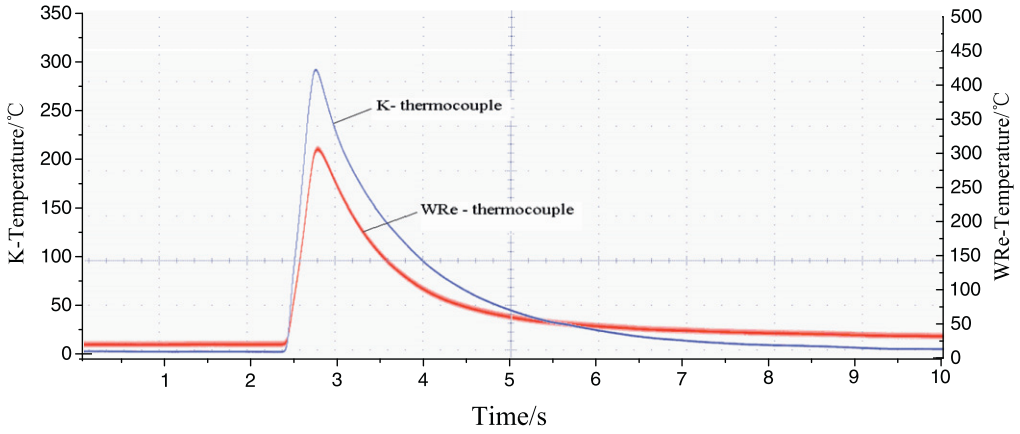

Fig. 1. Calibration of self-manufactured thermocouple.