Experimental research on the infrared gas fire detection system

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Abstract. Open fires and smoldering fires were differentiated using five experiments: wood pyrolysis, polyurethane smoldering, wood fire, polyurethane fire and cotton rope smoldering. At the same time, the distribution of CO₂ and CO concentration in combustion products at different heights was studied. Real fire and environmental interference were distinguished using burning cigarettes and sandalwood. The results showed that open fires and smoldering fires produced significantly different ratios of CO₂ and CO concentrations. By judging the order of magnitudes of the ratio CO₂ and CO concentrations in the combustion products, open fire and smoldering fire could be effectively distinguished. At the same time, the comparison experiment showed that the rate of increase of the concentration of CO in the smoldering fire was higher than that under non-fire conditions. With the criterion of the rate of increase of CO concentration, smoldering fire and non-fire could be distinguished.

1. Introduction
Fire can produce aerosols, smoke, flames and a lot of heat, which are collectively referred to as fire parameters. By measuring these parameters, we can judge if there is a fire. Various fire detectors have been created for the above fire parameters, such as smoke detectors, thermal detectors and flame detectors. Some new fire monitoring methods have also been developed on this basis. For example, researchers tried to use computer video monitoring for fire detection. This method is able to effectively reduce the false alarm rate and shorten the time until an alarm is sounded and has achieved good results [1-4]. In addition, HAI Jun Zhang [5] et al. proposed a new video monitoring method of fire detection and recognition based on the visual attention mechanism, which has improved the accuracy of fire detection. Amin Khatami [6] et al. introduced the particle swarm optimization algorithm to the image processing technology and reduced the fire monitoring response time. Steven Verstockt [7] et al. proposed a new compound multimodal flame detection method which can detect fires in large spaces.

However, the above methods monitor fires essentially based on the change of physical parameters, such as concentration and temperature of smoke. These routine physical parameters will change with different fuel and combustion conditions, which presents a certain difficulty and interference in carrying out detection. In the initial stage of a fire, gas generation occurs earlier than the emergence of smoke and rise of temperature, so the concentration of the characteristic gases generated from the combustion process (mainly CO) can be used to detect fire earlier.

In addition, disturbed by various interference sources in the tested environment, the detector may give a false alarm or fail to give an alarm [8-10]. That is to say, no alarm may be given in a real fire. In the detection process, when there is suddenly a transient signal similar to that of a fire in a non-fire
environment, the detector will provide an alarm signal. Dust, smoke, steam, aerosol and others are all sources of interference [11]. Therefore, it is of great significance to accurately distinguish between real fire and non-fire situations.

Based on the principle of spectrum absorption, this paper achieves fire detection and alarm by using the concentration of CO gas produced in the combustion process, distinguishing between open flame and smoldering fire through the ratio of CO2 and CO concentration, and using the rate of rise of CO concentration as a criterion for judging between smoldering fire and non-fire conditions.

2. Principle of gas concentration measurement

The instrument for measuring gas concentration in the system is a GXH-3010/3011 Infrared Analyzer. It is designed according to the Lambert-Beer law and the principle of selective absorption of infrared rays by gas. Consider a beam of monochromatic parallel light passing through a uniform medium along the X direction, and suppose that the original intensity of the infrared light source is I. When it passes a layer of medium with the thickness of dx, its intensity changes from I to I-dI.

The experiment shows that -dI is proportional to I and dx in a wide range of light intensities, i.e.:

$$-dI = kI dx$$  \hspace{1cm} (1)

Wherein, I is the original light intensity, and k is a proportionality coefficient independent of light intensity, which is called the absorption coefficient.

Assume that the path passed is L, the integral of x is calculated within 0-L, and we can obtain:

$$I_1 = I_0 e^{-kL}$$  \hspace{1cm} (2)

Formula (2) is called Lambert's law. Wherein, I_0 and I_1 are the light intensity when x=0 and x=L, respectively. The dimension of k is the reciprocal of the length, and the physical significance of k^{-1} is the thickness of the medium passed through when the light intensity is reduced to the original e^{1/2}≈36% due to absorption. This formula is a linear differential equation of light intensity I, so Lambert’s law is the linear law of the absorption of light. When the gas chamber contains a gas that absorbs infrared light (such as CO or CO2), the absorption coefficient (k) is proportional to the concentration of gas (C), i.e.:

$$k = AC$$  \hspace{1cm} (3)

After substituting into Formula (2), we can obtain:

$$I_1 = I_0 e^{-ACL}$$  \hspace{1cm} (4)

Formula (4) is called Beer's law [12]. Wherein, A is the infrared light absorption coefficient of the gas, C is the concentration of the gas being tested, and L is the length of the gas chamber. According to Formula (4), when the type of gas and the length of the gas chamber are fixed, A and L in the formula are also fixed. Therefore, as long as the light intensity I is measured, the concentration of the gas is also measured. The infrared gas analyzer works based on these two laws.

3. Experimental study

The whole measuring system consists of the sampling pipeline, pumping unit, infrared gas analyzer, alarm device, fire extinguishing system and computer. The experiment was completed in a 10m×7m×4m standard fire test room. The optical structure of the infrared gas analyzer uses gas filter correlation technology and a high-sensitivity photoconductive detector. The initial infrared energy emitted by the infrared source and the energy passing the reflective chamber several times follow Lambert-Beer’s law. When the instrument was operating, the optical components and the pneumatic system were connected to generate an optical signal. The signal was detected and amplified by the pre-amplifier, further amplified by the signal processing unit, and then controlled by the display and control unit, and data was displayed. The power supply of each component was provided by power supply parts.

At the beginning of the experiment, a gas sampling point was arranged in the measuring chamber. To avoid contamination of smoke particles or other components generated from the combustion process, we designed a filter unit at the front end of the sampling position. The measured gas entered the gas filter through one end of the filter unit, flowed out through the other end, and entered the inlet
of the gas analyzer through the sampling pipeline. The gas analyzer was connected to a computer via a port for data processing.

3.1. Distinguishing between open fire and smoldering fire

3.1.1. Wood smoldering. A 1cm×2cm×3.5cm beech wood block of 150 grams (whose water content was equal to or less than 3%) was radially placed on a heating plate with the heating power of 1.4KW (rated power) and a diameter of 220mm for heating. At the beginning of the experiment, the heating plate was electrified until its temperature reached 500°C and then kept stable. The experimental wood smoldering curve is as shown in figure 1 (a).

3.1.2. Wood fire. Under the same experimental conditions as wood smoldering, wood in the fire plate was ignited with open fire. The experimental curve is as shown in figure 1 (b).

3.1.3. Polyurethane smoldering. 25×25cm² soft polyurethane foamed plastic with a specific density of 40kg/m³ was placed in the heating furnace for heating. Before the experiment, the heating furnace was energized, so as to provide external energy. The experimental curve is shown in figure 2 (a).

3.1.4. Polyurethane fire. The same soft polyurethane foam in Experiment 3.1.3 was used and placed in a 50×50cm² container. A small container 3cm high was placed at the bottom of any corner, filled with alcohol, and then ignited with open fire. The experimental results are shown in figure 2 (b).

Figure 1. The experimental curve of wood smoldering and wood fire.

Compared with figure 1 (a), the main characteristic of figure 1 (b) is that the concentration of CO₂ not only increases quickly, but the content is very high. The maximum value reached 3,390ppm, which is far more than the concentration of CO₂ in the wood smoldering fire, but the concentration of CO shows almost no change. As the combustion is complete, the concentration of CO₂ increases rapidly and reaches its peak within 341s. With the continuous depletion of the wood, the decrease of concentration of CO₂ is much faster than in smoldering.

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3.1.4. Polyurethane fire. The same soft polyurethane foam in Experiment 3.1.3 was used and placed in a 50×50cm² container. A small container 3cm high was placed at the bottom of any corner, filled with alcohol, and then ignited with open fire. The experimental results are shown in figure 2 (b).
According to the results of figure 1 and 2 and the above analysis, it can be concluded that the concentration of CO\(_2\) in the open fire increases faster, which is shown by the obvious wave peak in the figure. The change of CO is relatively small, and it is almost a straight line. From figure 1(b) and figure 2 (b), it can also be seen that the concentration of CO\(_2\) with fireworks is at least more than 1,000ppm; the concentration of CO\(_2\) in the smoldering fire increases smoothly, there is no obvious peak, and the peak concentration is also smaller than that of open fire. From figure 1 (a) and figure 2 (a), it can be seen that the concentration of CO\(_2\) does not exceed 800ppm, while the maximum concentration of CO has reached about 100ppm. This shows that in terms of the concept of "quantity" due to the full combustion of combustible materials the combustion products of open fire (including fireworks) contain almost no carbon monoxide, and all generate carbon dioxide; in smoldering fires, due to incomplete combustion, the concentration of CO\(_2\) will decrease, and the concentration of CO will increase.

From figure 1 and figure 2, we can visually determine the ratio of CO\(_2\) and CO in open fire and smoldering fire, but in order to more conveniently and clearly compare the order of magnitudes of the ratio of CO\(_2\) and CO under the two conditions, we can show the ratios obtained in the above four experiments in the form of curves, respectively, as shown in figure 3 and figure 4.

From figure 3, we can see that the minimum value of the CO\(_2\)/CO ratio curve of wood fire exceeds the maximum value of the CO\(_2\)/CO curve of wood smoldering fire. Obviously, it exceeds that of the wood smoldering fire. Similarly, it can be found from figure 4 that the CO\(_2\)/CO ratio order of
magnitude is far greater than that of the polyurethane smoldering fire. In particular, the maximum value at the wave peak reached about 250.

From the above experiment, we can conclude that the CO$_2$/CO ratio order of magnitude in open fire is much larger than that in the smoldering fire, which shows that CO$_2$/CO ratio order of magnitude is an effective way to distinguish open fire and smoldering fire. The ratio of open fire is generally at least 10 times higher. For example, the ratio of wood fire is about 10-30. Sometimes it can be hundreds of times or even higher. For example, the maximum value of the ratio in the polyurethane experiment reached about 250. The ratio of smoldering fire is very small, generally only below several orders of magnitudes, and sometimes almost close to 1.

3.2. *The distribution of concentration of CO$_2$ and CO in combustion products with height*

Cotton rope was selected as the experimental material. In the experiment, 60 cotton ropes with a diameter of 3mm and a length of 80cm were fixed on a metal ring with a diameter of 10cm, and then hung on the bracket. The lower end of the ropes was ignited, and the flame was immediately extinguished after ignition, so that it continuously smoked.

Three different heights (40cm, 140cm and 240cm) were selected in the experiment, and the curves of the ratio of CO$_2$ and CO measured at the three heights are shown in figure 5. From the experimental results, we can conclude that in the early stage of combustion (0--150s), the difference between the three is relatively large. The closer to the combustion source, the lower the ratio of CO$_2$ and CO, as shown in figure 5. In the middle position (140cm), the ratio of CO$_2$ and CO is relatively large. At the highest position, the order of magnitude of the ratio is generally between the two. This suggests that at the beginning of the experiment the decrease of CO$_2$ is slower than that of CO with the diffusion of gas, so that the ratio of the two increases. At this time, as gas continues to spread upward, the decrease of CO$_2$ begins to accelerate, and the decrease of CO begins to slow.

![Figure 5](image_url)

**Figure 5.** The ratio of concentration of CO$_2$ and CO at different heights.

As the concentration of CO$_2$ and CO does not reach the maximum value in these three states, the concentration of CO$_2$ and CO increases as the experiment goes on. After about 150s, it is in a steady state, which fluctuates around the order of magnitude of 4. The above shows that although the concentration of CO$_2$ and CO decreases in different positions far from the combustion source, the degree of decrease of the two is different. The decrease of CO$_2$ is slow and then fast, while the decrease of CO is fast and then slow.

3.3. *Distinguishing between real fire and non-fire*

The wood smoldering and polyurethane fire experiments were used for fire simulation. Cigarette and sandalwood smoldering were compared as non-fire situations.
3.3.1. Cigarette. 6 cigarettes were placed on the holder and ignited separately. The measured curve is as shown in figure 6. From the experimental results, we can see that the cigarette will also produce a certain amount of CO and CO2 in burning, just like a fire, and the concentration is relatively high. The maximum values of CO2 and CO are 1,550ppm and 190ppm at 240s and 242s, respectively. The concentration ratio of CO2 to CO is shown in figure7.

![Figure 6. Curve of cigarette experiment.](image)

![Figure 7. The ratio of concentration of CO2 and CO in the cigarette experiment.](image)

It can be seen from the picture that the ratio of CO2 and CO for cigarettes is also very small, only about a few orders of magnitude, and basically less than 10 during the whole period of the experiment. When distinguishing between open fire and smoldering fire above, it was noted that the CO2 and CO of smoldering fires are very small, and generally only a few orders of magnitude. This has brought a problem. According to the ratio of CO2 and CO, it is very difficult to distinguish between a smoldering fire and non-fire situation, and the detector is likely to give a false alarm. In order to compare other non-fire situations, we conducted another set of experiments (sandalwood experiment).

3.3.2. Sandalwood. 10 pieces of sandalwood with a length of 10cm were placed on the holder, ignited and extingushed, so that they continuously smoked. Experimental results and the ratio of CO2 and CO are shown in figure 8 and figure 9, respectively.

![Figure 8. Curve of sandalwood experiment.](image)

![Figure 9. The ratio of concentration of CO2 and CO in the sandalwood experiment.](image)

According to results of the experiment, we find that sandalwood can also produce CO and CO2 when burned, but it produces much less CO and CO2 than a cigarette. Between them, the maximum CO2 value is less than half of that of a cigarette, at about 700ppm, but the concentration of CO is
10ppm higher than that of a cigarette. As in the case of cigarette ignition, we obtained the ratio of concentration of CO₂ and CO of sandalwood, as shown in figure 9. From figure 9, it can be seen that the ratio of CO₂ and CO of sandalwood is similar to that of smoldering, and basically is maintained at a low order of magnitudes. At the beginning, it is slightly higher and about 8 orders of magnitude. It drops gradually after about 130s, and fluctuates around 3.

From the above 2 experiments, it can be seen that it is very difficult to distinguish between smoldering fires and non-fire situations by comparing the order of magnitudes of the ratio of CO₂ and CO. In this case, the detector is likely to produce a false alarm, so we must adopt other methods to ascertain the differences between a non-fire source and smoldering fire.

Now we consider identifying the rate of increase of CO concentration. The volume fraction of CO within 750 seconds was measured for the wood, polyurethane, cigarette and sandalwood experiments, and their rate of CO concentration increase was obtained by the least square method (see figure 10). We can see from figure 10 that for sandalwood and cigarettes, the two kinds of non-fire situations, the rate of CO concentration increase was only about 1×10⁻⁵/s, while for wood pyrolysis and polyurethane smoldering, the two kinds of fire, the rate was about 2.5×10⁻⁵/s. This shows that the rate of CO concentration increase in the smoldering fire is higher than that of the non-fire situations, and can be used to distinguish smoldering fires and non-fire situations.

**Figure 10.** The rate of increase of CO in the smoldering fire and non-fire experiments.

### 4. Conclusions

The biggest difference of open fires and smoldering fires is the order of magnitude of the ratio of concentration of CO₂ and CO. The ratio in smoldering is relatively low, generally only a few orders of magnitude, and sometimes close to 1; and the ratio of open fire is at least 10, and sometimes can even reach the order of magnitude of 1,000, which is hundreds of times higher than that of smoldering. The ratio in smoldering basically has no changes, while the ratio of open fire changes a lot and the curve jitter phenomenon is very obvious.

At different heights, in a place nearest to the source of fire, the ratio of concentration of CO₂ and CO changes slightly. At the initial stage of increase, the decrease of CO₂ is slower than that of CO. And then, as the gas further diffuses, the decrease of CO₂ begins to exceed that of CO. That is, the decrease of CO₂ is slow and then fast, while the decrease of CO is fast and then slow.
It is difficult to distinguish between smoldering fire and non-fire situations only from the ratio of \( \text{CO}_2 \) and \( \text{CO} \), but it has been found in the experiments that smoldering fire and non-fire situation can be distinguished with the rate of increase of \( \text{CO} \) concentration.

**Acknowledgment**

This study was sponsored by the Key Project of the Outstanding Young Talent Support Program of Anhui Province University in 2016 (gxyqZD2016392).

**References**

[1] Byoung Chul K, Jung J H, Nam J Y 2014 Fire detection and 3D surface reconstruction based on stereosco-pic pictures and probabilistic fuzzy logic [J]. *Fire Safety Journal* 68 61-70

[2] Kong S G, Jin D L, Li S Z, et al 2016 Fast fire flame detection in surveillance video using logistic regression and temporal smoothing [J] *Fire Safety Journal* 79 37-43

[3] Chiu C W, Lu t, Chao H T, et al 2014 Performance assessment of video-based fire detection system in tunnel environment[J]. *Tunnelling and Underground Space Technology* 40 16-21

[4] Wong A K, Fong N K 2014 Experimental study of video fire detection and its applications[J]. *Procedia Engineering* 71 316-327

[5] Zhang H J, Zhang N, Xiao N F 2015 Fire detection and identification method based on visual attention mechanism[J]. *Optic* 126 5011-5018

[6] Khatami A, Mirghasemi S, Khosravi A, et al 2017 A new PSO-based approach to fire flame detection using K-Medoids clustering[J]. *Expert Systems With Applications* 68 69-80

[7] Verstockt S, Hoecke S V, Beji T, et al 2013 A multi-modal video analysis approach for car park fire detection [J]. *Fire Safety Journal* 57 44-57

[8] William L Grosshandler 1998 Fire Detection for Critical Telecommunications Equipment Nuisance Alarms in Aircraft CargoAreas and Critical Telecommunications Systems, Proceedings of The Third NIST Fire Detector Workshop

[9] Kuklinski D M ,Berger L R and Weaver J R 1996 Smoke Detector Nuisance Alarms: a Field Study in a Native American community. *NFPA Journal* 90(5)

[10] Smithies J N, Burry P E and Spearpoint M J 1991 Background signals from fire detectors. Measurement, analysis, application .*Fire Safety Journal* 17(6) 0379-7112

[11] Smith C L 1994 Smoke detector operability survey report on findings(revised).U.S Consumer Product Safety Commission Washington

[12] Kaihua Zhao and Xihua Zhong 1984 *Optics* (Beijing:Publisher of Beijing University)