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Temperature measurement of gas explosion flame based on the radiation thermometry

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ABSTRACT

In order to obtain more detailed temperature information from images photographed with a high speed camera located at the transparent window of explosion pipeline, a method of calculating the two-dimensional temperature distribution field of premixed gas explosion flame is put forward based on the radiation thermometry. Also, the calculation results of the upside and downside flame temperature are modified according to the different emissivity of gases at the upside and downside zone and the temperature isotherms of gas explosion flame are depicted. The calculated average temperature of explosion flame is compared with the experimental results measured by thermocouples and both are close, which can testify that the method of calculating temperature is correct and feasible. The results show that there is a sharp increase of the temperature at the flame front, then the increase rate of the flame temperature slows down gradually until the maximum temperature and then the temperature declines. The results also indicate that chemical reaction is the most intense at the flame front, but the time of maximum temperature reached lags behind the front. This phenomenon may be attributed to that reactants fail to react completely and aggregate in groups at the flame front due to large numbers of ions. By this method the temperature field of gas explosion can be attained from flame images. So the retrospective study can be done by this method and more information can be obtained. This method can be used widely in the field of explosion flame propagation and provide the theoretical foundation for investigating the rules of gas explosion.

1. Introduction

Gas explosion is one of the main disasters threatening production safety in coal mines. In recent years, gas emission tends to increase with the increase of mining depth of coal mines, which enhances the possibility and severity of gas explosion. 25 coal mine accidents causing more than 100 deaths each occurred in China since 1949, which are shown in Table 1 [1].

Researches on flame temperature field and pressure field of the gas explosion propagation, which are helpful in the design and layout of gas explosion suppression system in coal mine, can play an important role in preventing gas explosion or alleviating the consequences. Many scholars have studied the flame temperature rules of premixed gas explosion. Yokomori et al. [2] measured the temperature of premixed propane/air explosion with a non-uniform stretch rate by thermocouple and the results show that the effects of flame stretch and preferential diffusion along the flame surface are related to non-uniform stretch rate and cause a temperature gradient along the surface. Kumar et al. [3] investigated multiple Pelton-like rotating flame structures in radial micro-channels with lean methane/air mixtures and the maximal temperature measured by thermocouple occurs at the flame front. Ergut et al. [4] studied the effect of temperature on the soot onset chemistry in one-dimensional premixed laminar ethyl benzene flames at atmospheric-pressure and used thermocouples to measure flame temperature. Their researches indicated that the coolest flame was slightly sooting, the intermediate temperature flame was at the visible onset of soot, and the hottest flame was not sooting. Alfe et al. [5]studied the effect of flame temperature on soot properties in premixed methane/oxygen flames burning at a constant mixture composition(C/O = 0.60, $\Phi = 2.4$) and different cold-gas flow velocities (4 and 5 cm/s) and measured flame temperature along the flame axis with a fast-response thermocouple. Charles S. Mcenally

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Table 1
Coal mine accidents with more than 100 deaths in China since 1949.

No.	Date	Location	Accident type	Death toll
1	1950.2.27	Yiluo Coal Mine in Henan Province	Gas explosion	187
2	1954.12.6	Dafa Coal Mine in Neimenggu Province	Gas and coal dust explosion	104
3	1960.5.9	Laobaidong Coal Mine in Shanxi Province	Coal dust explosion	684
4	1960.5.14	Songzao Coal Mine in Chongqing	Coal and gas outburst	125
5	1960.11.28	Longshanmiao Coal Mine in Henan Province	Gas and coal dust explosion	187
6	1960.12.15	Zhongliangshan Coal Mine in Chongqing	Gas and coal dust explosion	124
7	1961.3.16	Shengli Coal Mine in Liaoning Province	Electric fire	110
8	1968.10.24	Huafeng Coal Mine in Shandong Province	Coal dust explosion	108
9	1969.4.4	Panxi Coal Mine in Shandong Province	Gas and coal dust explosion	115
10	1975.5.11	Jiaoping Coal Mine in Shanxi Province	Gas and coal dust explosion	101
11	1977.2.24	Pinghu Coal Mine in Jiangxi Province	Gas explosion	114
12	1981.12.24	Wu Coal Mine in Henan Province	Gas and coal dust explosion	133
13	1991.4.21	Sanhe Coal Mine in Shanxi Province	Gas and coal dust explosion	147
14	1996.11.27	Dongcun Coal Mine in Shanxi Province	Gas and coal dust explosion	114
15	2000.9.27	Muchonggou Coal Mine in Guizhou Province	Gas explosion	162
16	2002.6.20	Chengzihe Coal Mine in Heilongjiang Province	Gas explosion	124
17	2004.10.20	Daping Coal Mine in Henan Province	Gas explosion	148
18	2004.11.28	Chenjiashan Coal Mine in Shanxi Province	Gas explosion	166
19	2005.2.14	Sunjiawan Coal Mine in Liaoning Province	Gas explosion	214
20	2005.8.7	Daxing Coal Mine in Guangdong Province	Water accident	121
21	2005.11.27	Dongfeng Coal Mine in Heilongjiang Province	Gas explosion	171
22	2005.12.7	Liuguanzhuang Coal Mine in Hebei Province	Gas explosion	108
23	2007.8.17	Huayuan Coal Mine in Shandong Province	Water bursting	172
24	2007.12.5	Yuanxinyao Coal Mine in Shanxi Province	Gas explosion	105
25	2009.11.21	Xinxing Coal Mine in Heilongjiang Province	Gas explosion	108

et al. [6] studied nonfuel hydrocarbon concentrations in coflowing partially premixed methane/air flames and measured centerline gas temperature with thermocouple. The results indicated that partial premixing reduces radial heat and mass transfer in the lower part of the flames and causes an inner rich premixed flame front to form at one-half of the height of the outer flame front. Nogenmyr et al. [7] researched the temperature field of unsteady partially premixed methane/air flames with OH-PLIF and demonstrated the difference of flame propagation under normal gravity conditions and zero gravity conditions. Ayoola [8] investigated premixed turbulent flame temperature with OH and CH_2O-PLIF and computed heat release rates and the results show that heat release rate rises with negative curvature increasing. Thomas Eeeger et al. [9] used combined vibrational coherent anti-Ctokes Raman spectroscopy and dual-broadband rotational CARS simultaneous measurements of temperature and relative concentrations of O_2/N_2 and CH_4/N_2 have been conducted in a fuel-rich partially premixed laminar methane/air flame. Knaus et al. [10] demonstrated a new technique for obtaining instantaneous, high-resolution, three-dimensional thermal structure data from turbulent flames, crossed-plane Rayleigh imaging and used the technique to measure temperature gradient data for a lean, premixed, methane-air turbulent V-flame and a laminar Bunsen flame for comparison. Wang and He [11] investigated methane/air explosion flame propagation and temperature in the rectangle pipe with thermocouple and pointed out that flame distribution along the pipe cross section is heterogeneous and the luminophor in the main chemical reaction zone propagates along the bottom of the pipe. Chen et al. [12] researched fine flame structure of premixed propane-air and reaction characteristics of combustion reaction zone in the process of laminar to turbulence flow transition with Schlieren photography technology and thermocouples. The results showed reaction characteristics and temperature distribution law of combustion reaction zone. However, because the temperature can be measured by a single thermocouple at only one position, the temperature distribution of other sections in the pipe cannot be described distinctly.

In recent years, digital imaging technology is used to measure flame temperature and other flame parameters. Currently this method is mainly used in the flame temperature measurement in boiler, combustion chamber, diesel engine and so on. Hottel and Broughton [13] pioneered in the two-color technique and applied it to determine the flame temperature in utility furnaces. Kurihara et al. [14] used colorimetric method to compute flame temperature and soot concentration in combustion chamber. Terumi Inagaki et al. [15] integrated three-color technique with three kinds of infrared radiometers that have different detection wavelength bands to measure the temperature quantitatively under near-ambient conditions. Brown et al. [16] reported a method to determine combustion flame temperature for premixed lean burn conditions using ultraviolet emission. Bheemul et al. [17] measured three-dimensional flame temperature with colorimetric method and obtained flame signals from flame detection equipments, realizing online coal species recognition. Teri Snow Draper et al. [18] measured flame temperature of 150 KWh boiler by colorimetric method and revealed that average temperature decreases from 2183 K to 2022 K when O_2/CO_2 concentration changes from 0.59 to 0.13. Wu et al. [19] investigated the temperature distribution of miniature emitting flame. They derived the relationship between image brightness and temperature and attained polynomial regression model by calibrating with blackbody furnace. Zhou et al. [20–22] developed a calculation method of monochrome image temperature field based on the reference point by means of radiation law and attained temperature field by comparing monochrome images with radiation strength of one reference point in images. Jeffrey J. Murphy and Christopher R. Shaddix [23] used an optical particle-sizing pyrometry diagnostic on the study of combustion kinetics of coal chars which can simultaneously measure the velocity, diameter and temperature of individual burning char particles at selected heights within the reactor. However, these methods are weak in studying the flame temperature field of premixed gas explosion flame. Especially, when the experiments were finished and lots of flame images photographed by high-speed camera were obtained from the experiments of gas explosion, how to get more information of gas explosion from these images is in question. The information may include flame propagation speed, flame temperature field and