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Coke oven gas explosion suppression

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ABSTRACT

Coke oven gas explosions are a 'killer' both in production and in the daily life of urban dwellers. It is important for the safe production of coke oven gas and the safety of urban dwellers in daily life to understand the processes governing coke oven gas detonation and to prevent or control explosions. Using N_2 as an example, the mechanism by which inert gas suppresses the characteristics of coke oven gas explosions, such as the explosion limit, maximum explosion pressure, maximum rate of pressure rise, deflagration index and combustion flame, has been systematically examined and determined. The relevant theories have been investigated, and conclusions have been drawn. It was found that in explosions of turbulent mixtures, the maximum rate of pressure rise and maximum explosion pressure for coke oven gas–air mixtures decrease inversely with the increasing volume of N_2 added. The influence of N_2 on coke oven gas–air mixtures can also be observed from the variations in their flame with the addition of N_2.

1. Introduction

With the development of the coal chemical industry, the by-product coke oven gas has been widely used in the chemical industry, power production, and even in the lives of thousands of families. However, coke oven gas is a flammable and explosive substance. Improper operation in the process of production, usage, transportation and storage can easily lead to combustion and explosion, posing a serious threat to lives and property. Therefore, how to safely and effectively utilise or dispose of coke oven gas has become an urgent task. We should thoroughly explore its burning and explosion characteristics and take appropriate safety measures, such as explosion suppression by inert gas, which can effectively control coke oven gas explosion accidents.

A large number of investigations on preventing the explosion of flammable and explosive gas using inert gases have been performed. In particular, a 1994 ban on the use of halons, an extremely effective suppressant series, has led to the introduction of a variety of alternative inert gases, and many studies on their characteristics and suppressive effectiveness have been performed.

Previously, the investigation of the suppression effect on combustible fuel–air mixtures was mostly focused on the explosion limit, a fundamental property of combustible fuel–air mixtures. Yang et al. (2004) experimentally studied the inert effect of R134a and R227ea on the explosion limits of six flammable refrigerants and determined their explosive ranges. Liao et al. (2005) tested the influence of diluents (CO_2, N_2) on the explosion limits of natural gas–air mixtures and employed LeChatelier's rule and Sheboke's analytical method to predict their flammability characteristics. Shebeko et al. (2002) proposed new analytical methods for the calculation of explosion limits in mixtures of combustible–oxidiser–diluent, using some peculiarities of the chemical kinetics of the combustion of gaseous organic substances in air. The minimum extinguishing concentration is the critical value between the lower limit and the upper limit of the fuel-oxidiser-diluent mixture. Katta et al. (2006) numerically investigated the minimum extinguishing concentration of CF_3H on methane–air mixtures, and Senecal (2005) developed an explicit relation for the inert gas (CO_2) extinguishing concentration in terms of heat capacity and fuel (n-heptane) properties. Zhang and Soteriou (2011) established an analytical model for the determination of the cup-burner minimum extinguishing concentration of (CO_2), which can also predict the minimum extinguishing concentration of inert fire suppression agents. Vahdat et al. (2003) used a method based on adiabatic flame temperature calculations and the dependence of the rate of fire suppression of chemical agents on temperature to estimate the extinguishing concentration of binary mixtures, and the predicted values are very close to experimental data. Saito et al. (1996) investigated the fire-extinguishing efficiency of inert gas (N_2, Ar, CO_2) mixtures by measuring the flame-extinguishing concentrations and peak concentrations for hydrocarbon fuels.

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Limiting oxygen concentration as the other fundamental characteristic has also attracted considerable attention. Razus et al. (2004) described a new procedure (algorithm) to estimate the limiting oxygen concentration of fuel–air–inert premixed systems, using the values of the lower explosion limit of the fuel–air mixture and the calculated adiabatic flame temperature both at the limiting oxygen concentration and at the lower explosion limit when nitrogen is used as an inert gas. Wan and Wang (1999) obtained the values of the limiting oxygen concentration for nine gases by experimental and computational methods.

Later on, many researchers also considered the effect of inert gas on many other factors, such as explosive temperature, pressure and the time to peak pressure. Razus et al. (2009) determined several flammability parameters for liquefied petroleum gas (LPG)/air gaseous mixtures in the presence of their own exhaust gas: the maximum (peak) explosion pressure, p_{max}, the time to peak pressure, q_{max}, the maximum rate of pressure rise, $(dp/dt)_{max}$ and the explosion index, K_G. In another experiment (Razus et al. 2007), they also studied the influence of inert gases (exhaust gas, Ar and CO_2) on the rate of pressure rise of gaseous propylene–air explosions. Dong et al. (2003) experimentally studied the effect of N_2 on the explosive temperature and pressure of combustible gases (e.g., gasoline vapor).

As the research progressed, many people began to explore the underlying mechanism of inert gas on combustible gas based on chemical reaction principles and flame structure. Kishore et al. (2009) employed a combination of experiments and computational simulations to study the effects of diluents (CO_2, N_2, and Ar) on the laminar burning velocity of premixed hydrogen/oxygen flames using the heat flux method. They found that lean and stoichiometric $H_2/O_2/CO_2$ flames with 65% CO_2 dilution exhibited cellular flame structures in an experimental study of the inhibition effect of CO_2 on an H_2/O_2 mixture. Su and Liu (2002) experimentally investigated impinging diffusion flames mixing with inert gas. The results showed that a conical flame was changed by the addition of inert gas to the pure methane fuel. Aggarwal (2009) numerically and experimentally studied the extinction of partially premixed flames, which represent a broad family of flames, including double, triple (tribrachial), and edge flames, in coflow and counterflow configurations. Korobeinichev et al. (2009) experimentally and numerically researched the effect of the equivalence ratio (in the range 1.3–3) and dilution of unburnt gases by nitrogen on the burning velocity of premixed atmospheric-pressure $H_2/O_2/N_2$ flames, both without additive and doped with 0.04% trimethylphosphate ($(CH_3O)_3PO$, TMP). Yu and Chen (2008) numerically studied the influences of inert gases (helium and nitrogen) on the quenching of high-speed deflagration flame in tubes under different combustible gas activity and tube diameter. Zhang et al. (2012) computationally studied the thermal and flame-dynamic effects of dilution in terms of the adiabatic flame temperature, the Markstein length and the minimum ignition energy.

In this work, a series of experiments was employed to study the effects of N_2 on the explosion limit, maximum explosion pressure, maximum rate of pressure rise and deflagration index of coke oven gas/air mixture. The effect of inert gas on the flame was also shown by images taken with high-speed phototropic vision and analysed.

2. Experimental

2.1. Experimental device

The experiments were performed in a stainless steel cylinder (volume = 20 L) that can withstand an internal pressure of 40 atm and is equipped with a mixing nozzle (which consists of many small helical pipes to mix the adding gases thoroughly). The ignition source is located in the geometrical centre of the cylinder. In the experiment, ignition was performed with inductive–capacitive sparks produced between stainless steel electrodes (the optimum gap is 4 mm).

A diagram of the experimental set-up is shown in Fig. 1.

In addition, a TST6300 data dynamic collection analyser and high-speed phototropic vision were used in the experiment.

Coke oven gas–air and coke oven gas–air–inert mixtures were obtained by the partial pressure method in gas cylinders and were ignited at once after mixing the components (from which it can be observed that the reaction of the mixture is performed in the turbulent state).

The experimental procedure was as follows: (a) the air in the explosion vessel was evacuated to a vacuum of 0.1 mbar; (b) mixing gases were added into the vessel at different ratios; (c) the mixture was admitted at the desired pressure, then ignited at once; (d) after ignition and the capture of the signals by the acquisition system, the burned gas was completely evacuated. Then, a new cycle was repeated.

As reported in many literatures, measurements of explosion parameters were performed in various vessels, such as 0.5 L, 40 L or 1 m^3 spheres or cylinders (Harris, 1967; Huzayyin et al., 2008), which provided a lot of important safety data for their application. Compared with these vessels, the installation of fittings for the reported 20 L cylinder-vessel in this paper is more reliable, and easier to operate due to moderate vessel volume.

2.2. Coke oven gas used in the experiment

The gases used in the experiment included coke oven gas (main components given in Table 1), air, and N_2. The experiment was con-

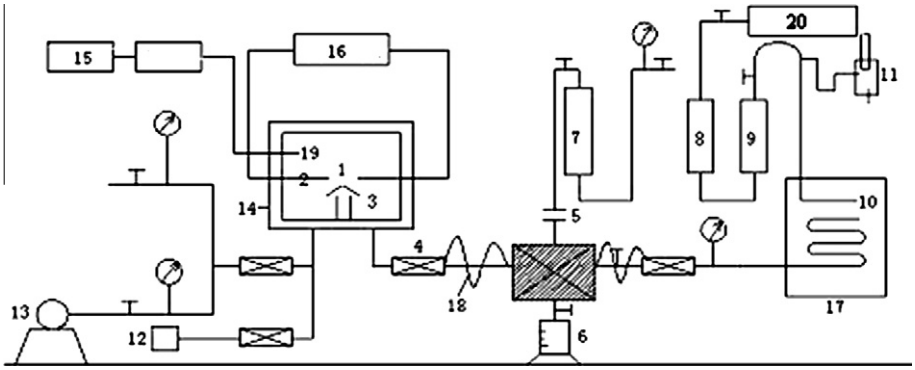

Fig. 1. General layout diagram of the testing system, 1 explosion cylinder, 2 discharging pole needles, 3 mixing nozzles, 4 electromagnetic valve, 5 ejection device, 6 flammable liquid metering device, 7 flammable gas metre, 8 air drier, 9 air flow metre, 10 air heating snake-like duct, 11 air humidity metre, 12 oxygen analyser, 13 vacuum pump, 14 temperature sensor, 15 computer, 16 high-voltage power, 17 electrical heater, 18 electrothermal coil, 19 pressure-electric crystal sensor, 20 air compression pump.