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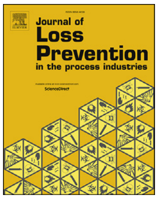

Explosion characteristics of methane-ethane mixtures in air

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ABSTRACT

Experiments were systematically performed in a standard 20-L spherical vessel to measure the explosion parameters of different methane-ethane/air mixtures. Data were scrutinized and carefully compared to elucidate the explosion characteristics. Firstly, it turns out that ethane has higher maximum explosion pressure, P_{max} and maximum rate of pressure rise, $(dP/dt)_{max}$ than methane in air against the equivalence ratio. The Upper Flammability Limit, UFL (in equivalence ratio) of ethane in air is also larger; while the Lower Flammability Limits, LFLs (in equivalence ratio) of both gases in air are almost the same. Then for methane-ethane mixtures, when the ethane content increases, the value of P_{max} versus equivalence ratio and the UFL both rise as well; while the LFL changes little if taking the uncertainty of measurement into account. Similarly, $(dP/dt)_{max}$ increases together with growing ethane content in the fuel mixture at the same equivalence ratio, especially at the fuel-rich side; but at the fuel-lean side the discrepancies are relatively smaller. In general, due to the higher reactivity, exothermicity and laminar flame speed of ethane, it can remarkably raise the explosion pressure, pressure rise rate and flammable range, and ultimately enhance the explosion risk and severity of fuel blend system.

1. Introduction

Methane and ethane are primary components of natural gas (Hu et al., 2015; Liao et al., 2005) which has been widely used in industry and transportation for power generation. However, natural gas is a mixture with varied composition depending on the mining locations and seasons, in which methane content can be as low as around 55% (Lowry et al., 2011). In other word, there might be considerable amount of ethane or other hydrocarbons in NG (Hu et al., 2015; Shen et al., 2016). As a promising alternative fuel, natural gas has still some drawbacks in combustion system, such as local flame extinction, instability and lower power output (Bauer and Forest, 2001). Nevertheless, ethane content variation in the fuel mixture could significantly change the characteristics of ignition and combustion instability in engines (Mitu et al., 2012). Mikulski and Wierzbicki (2016) found that, ethane enrichment could improve the performance of engine with considerable benefits. Therefore, the application of methane-ethane mixtures at various compositions could be expected. Besides, ethane itself is also of great interest in combustion application for engine and material synthesis.

Then in consideration of the practical use of methane, ethane and their mixtures in engines and of great concerns on chemical kinetic modelling, most previous works concentrated on the fundamental combustion parameters, e.g. laminar flame speed (Bosschaart and de Goey, 2004; Halter et al., 2007; Huang et al., 2006; Ravi et al., 2015; Veloo et al., 2010). Usually, the methane and ethane contents varied in a wide range. For example, Lowry et al. (2011) experimentally measured the laminar flame speed of pure methane, pure ethane, 80/20 and 60/40 (methane/ethane) mixtures at elevated pressures. These data could also provide desired targets for validation of chemical kinetics models (Goswami et al., 2016; Naik and Dean, 2006; Pan et al., 2014).

However, the safety issues in applications of natural gas or other methane-ethane mixtures are also outstanding due to the flammability of methane and ethane, which actually deserves much more attention to hazard investigation (Koshiba et al., 2015; Li et al., 2015; Shen et al., 2016; Wang et al., 2016). Unfortunately, at present there have been few works available for assessing the explosion

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risks and consequences of methane-ethane mixtures. Liao et al. (2005) investigated the ethane effect on natural gas-air flammability limits. And they found that with ethane addition the Lower Flammability Limit (LFL) almost remained constant; while the Upper Flammability Limit (UFL) became larger. Another pioneering experimental study was performed by Tang et al. (2014) on explosion characteristics of high methane (95% or more) natural gas (methane/ethane mixtures). They proposed that with increasing methane content in the fuel blend, both the explosion pressure and the maximum rate of pressure rise decreased. But in some situations (in engines as mentioned above, or in unpredictable accidents), ethane content would lie in a much larger range. Therefore, explosion parameters with more ethane are important as well. Nevertheless, relevant works have rarely been reported, which is a shortcoming of global explosion database for hydrocarbons.

In general, flammability limits, maximum explosion pressure, P_{max} and maximum rate of pressure rise $(dP/dt)_{max}$ are most important parameters to characterize the risk and severity of explosion (Zhang and Ng, 2015). The explosion data in a wide range of fuel compositions and equivalence ratios are quite necessary for real accident evaluation, safety design and comprehensive model validation (Faghih et al., 2016; Lowry et al., 2011; Wang et al., 2013). Therefore, given the shortage of the database, this work carried out some experiments in a standard 20-L spherical vessel to systematically determine these parameters for methane-ethane mixtures in air. In the meantime, the explosions of ethane-air mixtures were examined as well for comparison; while for methane-air mixtures, data from our previous works were directly used (Shen et al., 2016; Zhang and Ng, 2015).

2. Experimental methods

The explosion parameters were measured in a 20-L spherical vessel with 16.84 cm inner diameter according to ISO6184-1 (see Fig. 1). The experimental system contains an ignition device, a control unit, a data acquisition system, and a vacuum pump. Experimental details can also be found elsewhere (Shen et al., 2016; Zhang and Ng, 2015).

Here in brief, the experiment was conducted at initial temperature of 298 K and pressure of 0.1 MPa. Firstly, the vessel was vacuumed in the very beginning and then filled with gases by partial pressure method until the desired mixture was obtained. The purity is 99.9% for both methane and ethane gases. The oxidizer was synthetic air with 21% (by volume) oxygen and 79% (by volume) nitrogen.

Afterwards, the quiescent mixture was centrally ignited by a pair of electrodes. The electric spark energy was 10 J, estimated from $1/2\ CU^2$ ("C" and "U" represent the capacitance and voltage, respectively of ignition device, $C = 0.1102 \times 10^{-3}$ F, $U = 426$ V). The subsequent explosion process was monitored by a PCB sensor installed on the vessel wall. Fig. 2 shows a typical pressure trajectory in the vessel during explosion: immediately after ignition (from $t = 0$ s on the Time-axis), the pressure inside the vessel abruptly builds up, which is driven by the drastic heat release from the chemical reaction; after a very short period, the pressure achieves the maximum when the mixture is totally burnt out; then the pressure drops gradually by the cooling effect of the vessel wall. Fig. 2 also illustrates the definition of maximum explosion pressure P_{max}, maximum rate of pressure rise $(dP/dt)_{max}$ and combustion duration t_c.

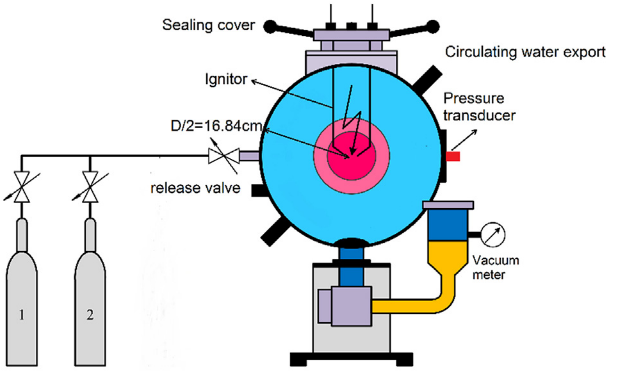

Fig. 1. Experimental apparatus.

The uncertainty of the measurement is mainly from the initial conditions (i.e. temperature, pressure, mixture concentration) and pressure sensor, which was estimated carefully herein. Besides, each case was repeated at least three times to reduce the random error, especially when near the flammability limits (Lower Flammability Limit, LFL and Upper Flammability Limit, UFL).

3. Results and discussion

3.1. Maximum explosion pressure

3.1.1. Methane-air and ethane-air mixtures

The maximum explosion pressure, P_{max} is a widely used parameter which reflects the energy distribution of propagating explosion wave (Li et al., 2012; Nie et al., 2011, 2015). The P_{max} of methane-air mixtures has been well determined in our previous studies (Shen et al., 2016; Zhang and Ng, 2015); while for ethane-air mixtures, except the flammability limits, the explosion data were unexpectedly quite scarce and scattered (Mitu et al., 2012) in the literature and therefore measured in this work.

Fig. 3 compares the P_{max} of different methane-air and ethane-air mixtures in a broad range of equivalence ratios. Generally, the maximum explosion pressures, P_{max} of methane-air and ethane-air mixtures both peak at the rich side (around $\varnothing = 1.1$). And at the same equivalence ratio, P_{max} of ethane-air mixtures is consistently larger than that of methane-air mixtures, which is mainly attributed to the higher exothermicity and flame temperature of ethane (Law, 2006).

The dashed lines in Fig. 3 are chemical equilibrium results obtained from GASEQ (2012) software based on the hypothesis of adiabatic expansion in the vessel. Measured and calculated values qualitatively change in a similar way versus equivalence ratio, but large discrepancies are observed at off-stoichiometric conditions, especially near flammability limits. It could be attributed to the heat loss effect, namely, because the flame speeds are lower at these conditions, the combustion durations in the vessel are therefore extended, which would result in a longer period of cooling effect by the vessel wall and weakened pressure buildup (Mogi and Horiguchi, 2009; Zhang and Ng, 2015). In contrast, around stoichiometric condition (equivalence ratio $\varnothing = 1$, with either 9.5% methane or 5.6% ethane in the mixture), it could be seen that, the experimental data are slightly higher than adiabatic simulations, which is probably due to the transient effect during explosion: near stoichiometric condition, the burning velocity, heat release rate of reaction and generation rate of burnt gas are relatively higher, and thus the pressure equilibrium in the vessel cannot be attained timely. As a result, the unburnt region around the pressure sensor adjacent to the wall confinement would be over-compressed, which makes the peak of the pressure trajectory floated up compared to the simply chemical equilibrium prediction without regard to heat loss. It is noteworthy that, these aforementioned effects (over-compression, incomplete combustion and