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Short communication

Explosion behaviors of mixtures of methane and air with saturated water vapor

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HIGHLIGHTS

- Saturated water vapor effect on explosion of methane/air mixtures was evaluated.
- Explosion and combustion parameters of methane/air mixtures were measured.
- The dual role of water vapor in the explosion was revealed and interpreted.

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ABSTRACT

The explosion and combustion parameters of mixtures of methane and air with saturated water vapor were experimentally measured in a standard 20-L spherical explosion vessel at room temperature and atmospheric pressure. The experimental data were carefully scrutinized and compared to elucidate the effect of saturated water vapor in air. When the methane content is below 10%, the maximum explosion pressure, maximum rate of pressure rise and laminar flame speed during explosion are slightly affected, which is attributed to the dual role of water vapor: on one hand, the water vapor suppresses the explosion by thermal and chemical effects; on the other hand, the addition of water vapor makes the equivalence ratio higher than that at dry condition with the same methane content. Then when the methane content is relatively higher, the discrepancies between parameters are quite pronounced for the same reason. The flammability limits of methane in the mixture become narrower (6–14%) compared to dry methane/air mixtures (5–15%). Additionally, the measured laminar flame speeds and computed ones by HP-Mech agree well with each other in this work.

1. Introduction

The crisis of upcoming fossil fuel exhaustion and environmental degradation necessitates the use of alternative fuels with high efficiency and low pollutant emission [1,2]. Natural gas is well recognized as a promising energy carrier due to its large reserves and favorable properties, such as high H/C ratio, large octane number and low CO_2 emission [3]. In China, as part of a long term green energy strategy, in some situations natural gas has substituted the petroleum or coal based fuels in industry and transportation.

However, natural gas (mainly consists of methane) is flammable and explosive [4,5], which increases the risk and hazard in its exploitation, storage and powertrain. Therefore, the safety issues accompanied should be fully exposed and carefully evaluated before further promotion of natural gas. Up to now, there have been extensive works carried out on the explosion characteristics [6–9] and inhibition technique of natural gas (methane) [10–18]. However, usually in the literature only the dry mixtures were prepared for tests; while the wet condition which is also familiar, especially in a rainy day, was rarely considered. The explosion hazard of natural gas mixed with wet air at room temperature is not well estimated, which becomes the defect of relevant explosion database.

Hence, in this study, the explosion and combustion parameters, i.e. maximum explosion pressure, maximum rate of pressure rise and laminar flame speed were explored and analyzed for mixtures of methane and air with saturated water vapor (i.e. 100% relative humidity, analogous to rainy situation) in a standard 20-L spherical

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vessel. The data obtained can give additions to the database and contribute to a comprehensive view of explosion behaviors of natural gas.

2. Experimental method

The experiments were performed in a standard 20-L spherical explosion vessel [17,19] with PCB pressure sensor according to ISO6184-1. The experimental system also includes an ignition device, a control unit, a data acquisition system, a vacuum pump and most importantly a humidity controller.

There could be two experimental designs to assess the saturated water vapor effect on explosion: (1) the air was first stored in a humidity controlled atmosphere and then blown into the 20-L vessel mixing with dry methane; (2) the dry methane/air mixture was wetted in a container at constant relative humidity during a sufficient period of time and then blown into the vessel. In this work, from the view of safety, only the first, (1) was conducted in the experiment but simulation was done for both. One would find out later that there is little difference between them because air has large volume in the mixture (approximately 85–95%). Mole fractions of water vapor in the mixtures are provided in Table S1 in Supplementary file I.

The initial temperature and pressure were 298 K and 101,325 Pa, respectively. Thus the saturated water vapor pressure was calculated as 3.159 kPa at 298 K from NIST Chemistry Webbook [20].

Generally, the vessel was vacuumed first and then filled with gases by partial pressure method. The purity of methane was 99.9%. Afterwards, the quiescent mixture was centrally ignited by a pair of electrodes. A PCB sensor recorded the pressure trajectories for analysis. The uncertainty of the measurement is mainly from the initial conditions (i.e. temperature, pressure, mixture concentration) and pressure sensor, which was carefully estimated. Each case was repeated at least three times. More details of the experimental system and procedure can be found elsewhere [18,21].

3. Results and discussion

3.1. Maximum explosion pressure and maximum rate of pressure rise

The maximum explosion pressure, P_{max} is an important parameter which could reflect the energy distribution of explosion wave during propagation [22,23]. And the maximum rate of pressure rise $(dP/dt)_{max}$ is commonly used to determine the explosion index [24]. Fig. 1 presents and compares the P_{max} and $(dP/dt)_{max}$, respectively of different methane/air mixtures. Apparently, when the methane content is more than 10%, the saturated water vapor prominently inhibits the explosion process by decreasing both parameters. Nevertheless, when the methane content is relatively low (<10%), the differences between the explosion parameters become quite small. This is attributed to the dual role of water vapor in the explosion: on one hand, the water vapor would definitely suppress the explosion by thermal and chemical effect as well discussed in previous studies [12,13,25,26]; whereas on the other hand, the addition of water vapor would increase the equivalence ratio Φ of mixture, which posts a positive effect to increase the P_{max} at the lean side and a negative effect at the rich side. For instance, $\Phi = 0.80$ for dry mixture with 7.8% methane, but $\Phi = 0.83$ for methane (still 7.8% in the mixture) mixing with wet air (with saturated water vapor, i.e. 100% relative humidity). In a word, the competing roles of water vapor dominate the variations of explosion parameters in this work. Further, to eliminate the water vapor effect on equivalence ratio, the measured data are also plotted versus equivalence ratio instead of methane content in Supplementary file I, in which

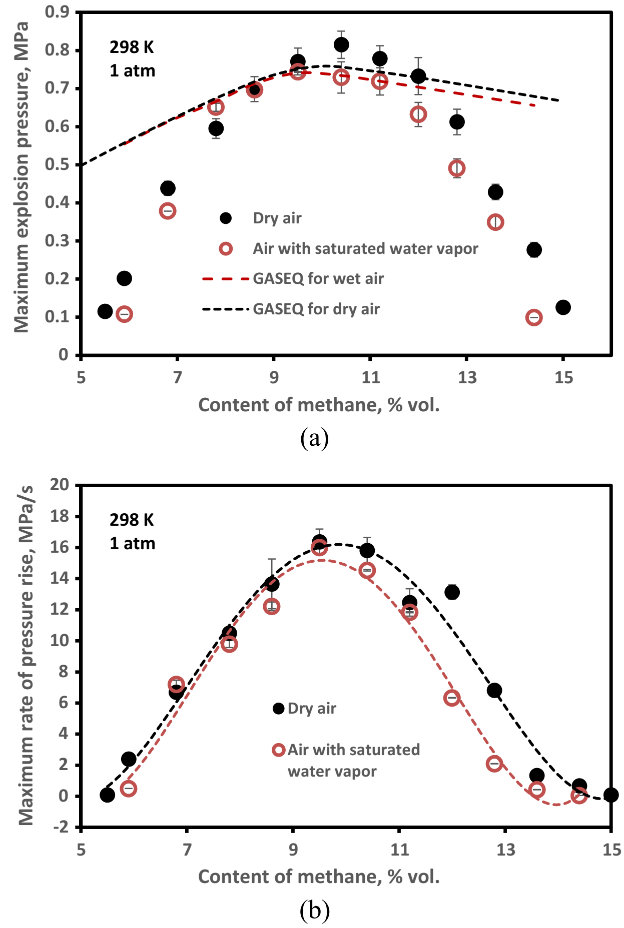

Fig. 1. Explosion parameters of different methane/air mixtures: (a) maximum explosion pressure; (b) maximum rate of pressure rise.

only the inhibition effect of water vapor on the parameters at both lean and rich sides is observed. Curves in Fig. 1(a) are calculated P_{max} by chemical equilibrium method using GASEQ software [27] which is based on the hypothesis of adiabatic expansion in the vessel for methane/air mixtures with/without water vapor. Large discrepancies are expected at off-stoichiometric conditions between simulation and measurement due to the possible heat loss and non-equilibrium reaction in the experiment.

Table 1 summarizes the calculated P_{max} by GASEQ for methane/air mixtures with water vapor using different experimental designs. Obviously, as the mixture deviates much from stoichiometric condition (about 9.5% methane), the measured P_{max} differs significantly as well from the ideal value. It is also noteworthy from the calculation that, the ideal P_{max} is almost the same for both experimental designs mentioned above in Section 2.

Additionally, the flammability limits of methane in the mixture are 6% and 14%, respectively for wet mixture herein, which have a narrower range than that at dry condition (5–15%).

3.2. Laminar flame speed

Laminar flame speed is not only a fundamental combustion property, but also an indispensable parameter in the assessment of explosion hazard [18]. However, the flame speeds of mixtures of methane and air with water vapor at room temperature are rarely reported.

In this study, the laminar flame speed is determined by a theoretical model from Dahoe et al. [28,29] in which only the pressure