The effects of pre-ignition turbulence by gas jets on the explosion behavior of methane-oxygen mixtures

Xinyu Chang[1], Bo Zhang[2†], Hoi Dick Ng[3], Chunhua Bai[1]

[1]Beijing Institute of Technology
State Key Laboratory of Explosion Science and Technology, Beijing 100081, China

[2]Shanghai Jiao Tong University
School of Aeronautics and Astronautics, Shanghai, 200240, China

[3] Concordia University
Department of Mechanical, Industrial and Aerospace Engineering
Montréal, QC, H3G 1M8, Canada

[†]Corresponding Author
Shanghai Jiao Tong University
School of Aeronautics and Astronautics, Shanghai, 200240, China
E-mail: bozhang@sjtu.edu.cn

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Abstract

Most of the previous studies investigating explosion characteristics of combustible mixtures were performed at quiescent state. However, in realistic accidental explosion scenarios, the ignition of the combustible mixture usually occurs under a turbulent environment. In this study, we examine the maximum explosion pressure p_{max} and explosion time τ_e of CH_4-$2O_2$ mixtures under the pre-ignition turbulence condition in a spherical closed chamber at a room temperature of 298 K. Turbulence is generated using fluidic jet of three different gases (O_2, CO_2 and N_2) and its intensity is controlled by changing the initial pressure of the gas jet p_{J0} (i.e., 200 and 500 kPa) and the explosion chamber pressure p_0 (i.e., 40 and 60 kPa). The dual effects of turbulence and gas dilution on the explosion behavior of CH_4-$2O_2$ mixtures are investigated in detail. The results indicate that by adding O_2 into CH_4-$2O_2$ mixture at quiescent condition, p_{max} increases but the rate of overpressure rise is reduced. By introducing turbulence through gas jets into the combustible mixture, the explosion behavior is affected by both the turbulence and gas dilution. With O_2 injection, turbulence overall enhances the explosion, but the amount of O_2 dilution increases at higher p_{J0}/p_0 and longer jet duration time (t_{J0}), rendering the mixture to tend toward fuel-lean side and slow down the explosion rate. The present results also demonstrate that the turbulence effect of CO_2 is more profound than that of N_2 jet. Both p_{max} and τ_e are enhanced by CO_2 jet turbulence when t_{J0} is relative short ($t_{J0} < 400$ ms). However, for longer t_{J0}, the dominance of CO_2 dilution becomes more noticeably than N_2 dilution with a longer explosion time τ_e.

Keywords: Turbulence; Fluidic jet; Gas dilution; Explosion; Methane

1. Introduction

Methane (CH_4) is a hydrocarbon fuel widely used in multitudinous fields. Its use in power generation has long been considered as a "cleaner' alternative to other fossil fuels or coal [1]. Not only is the main component of natural gas, methane can also be produced from biomass providing a renewable source of energy. As a combustible fuel source, the flammability and explosion hazards of methane are of great concern concerning its transportation and storage. As such, numerous investigations have been performed on the combustion and explosion characteristics of methane-based mixtures, e.g.,[2-14]. Recently, the detonation propagation and its limits [15-24] have been widely investigated regarding methane mixtures due to their possible applications in detonation-based engines.

In research, the 20-L explosion spherical vessel has become the standard apparatus to evaluate explosion properties of gases/vapors [25], dusts [26], hybrid dust-gas/vapor mixtures [27]. Measurement includes the flammability limits, limiting oxygen concentration, minimum ignition energy, maximum explosion pressure p_{max}, maximum rate of pressure rise $(dp/dt)_{max}$, explosion time τ_e and laminar burning velocity S_L [28-36].

To either enhance the combustion efficiency or mitigate explosion hazards, different fuels or inert gases can be blended into methane-based mixtures. For instance, Wang *et al.* [37] suggested that hydrogen addition can improve the flame speed and decrease the combustion duration notably, while p_{max} is not significantly affected. Ma *et al.* [38] and Wierzba *et al.* [39] showed that the explosion intensity can be enhanced by hydrogen addition; parameters such as p_{max}, $(dp/dt)_{max}$ and temperature increase with increasing hydrogen content in the methane-hydrogen-air mixture. Sarli *et al.* [40, 41] discussed the scenario that hydrogen addition to methane can lead to a more vigorous flame/turbulence interaction, which was the underlying factor being responsible for the explosion

process of hydrogen-methane/air mixtures. Mitu *et al.* [42] investigated the ignition temperatures of flammable substances in (N_2 + O_2) mixtures with different concentrations of oxygen. On the other hand, the explosion behavior can be suppressed by inert gas dilution. Zhang *et al.* [31] showed that addition of argon Ar or nitrogen N_2 into dimethyl ether-air mixture can result in a decrease of $p_{max.}$ Compared with Ar dilution, the decrease of S_L is faster when the mixture is diluted with N_2. Shen *et al.* [43] examined explosion hazards of C_2H_4-N_2O mixtures with N_2 or CO_2 addition. They found that dilutions by N_2 and CO_2 restrict the decomposition of N_2O by enhancing tri-molecular reaction. Zhou *et al.* [44] argued that N_2 and CO_2 dilutions also have an important impact on S_L and flame instability in H_2/CO/CH_4/air mixtures. Their studies showed that the thermal and chemical effects of CO_2 dilution is greater than those of N_2. Mitu *et al.* [45] investigated the effectiveness of diluent gases on explosion characteristics. The experimental results showed that CO_2 was the most effective gas, followed by H_2O, exhaust gas, and N_2. Benedetto *et al.* [46] analyzed the effects induced by the additionally introduced inert gases (CO_2, N_2, He, and Ar) on the explosion behavior of CH_4/O_2/N_2 mixtures, they found that the inhibition effects of those inert gases on the explosion parameters in combustible mixtures were in the order of CO_2, N_2, He and Ar.

Despite a wealth of studies on the explosion behavior of methane-related mixtures, the majority has obtained results with mixtures initially at quiescent state. In real explosion scenarios, the combustible is usually subject to a turbulent flow environment caused by wind or obstacles. In recent years, research has focused on the important role of turbulence on the explosion process [47, 48]. Benedetto *et al.* [49] demonstrated the influence of turbulence on the explosion characteristics of hybrid mixtures of methane and nicotinic acid, such as the maximum pressure, deflagration index, and minimum ignition energy. Sun & Li [50] investigated the effects of initial turbulence on the explosion of hydrogen-air mixtures by comparing the explosion parameters under both laminar and

turbulent ambiences. Bauwens & Dorofeev [51] carefully examined the initial turbulence on vented explosion overpressures. Kundu *et al.* [52] investigated the effect of turbulence and explosive powders in a confined explosion using a 1-m^3 large-scale spherical apparatus.

In most experimental settings, turbulence is typically generated by injecting a gas into the combustible. Hence, turbulence intensity and the nature of the turbulence-generating gas could both affect the explosion process. Up-to-date, no extensive investigation has yet taken into account the combined effect of turbulence and gas dilution. Hence, in this work, this combined effect of pre-ignition turbulence generated by three different gases on the explosion characteristics, i.e., p_{max}, and τ_e, are systematically determined.

2. Experimental setup

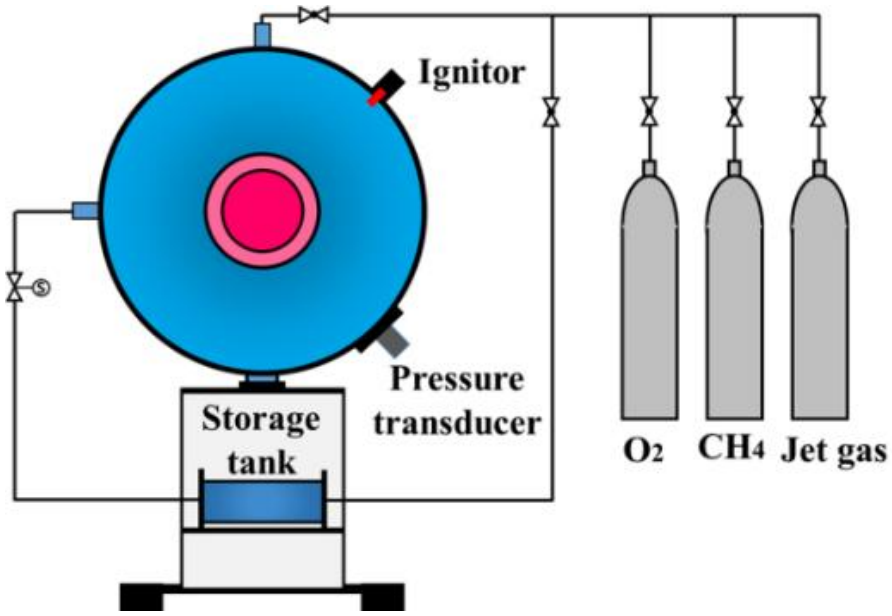


Fig.1 A sketch of the experimental setup.

The experimental setup consisted of a standard 20-L explosion spherical vessel, high-voltage ignition system, fluidic jet generation device, time-delay control and data acquisition system (Fig. 1). The vessel has a 33.68-cm inner diameter and 10-mm thickness. For turbulence generation, high

pressure gas from a 3.1-L tank was promptly injected into the chamber via a solenoid valve. Omega pressure gauges (PXM309, 0-0.7 MPa range and accuracy ±0.25 % of full scale) were used to monitor the initial pressure. The CH_4-$2O_2$ mixture was ignited by an ignitor mounted at the upper part of the spherical vessel, and two electrodes extended into the chamber with a depth of 1 cm.

For each experiment, the explosion vessel was first evacuated below 100 Pa. Afterwards, methane and oxygen were filled into the vessel to the desired condition by the method of partial pressures and left intact for at least 10 minutes to ensure a quiescent well-mixed mixture. The methane volume fraction χ_{CH4} is defined as $\chi_{CH4} = V_{CH4}/ (V_{O2}+V_{CH4})$ where V_{CH4} the methane volume and V_{O2} the oxygen volume. Another tank was filled with a specific gas (O_2, CO_2 or N_2) to a high pressure for injection (200 or 500 kPa). The delay control system arranged the time sequence of fluidic jet generation and ignition. As shown in Fig. 2, when the system was triggered, it sent pulse signals to activate the solenoid valve producing a gas jet from the high-pressure tank, and the jet duration time t_{J0} can be adjusted accordingly, ranging from 20 to 800 ms. After a delay time t_d of 100 ms, the combustible mixture under the turbulent condition was ignited by a spark plug with low energy in order to avoid additional turbulence induced by ignition energy. In this study, t_d was defined as the time period starting from the end of the jet flow to the beginning of the ignition. The pressure evolution inside the explosion chamber was recorded by a PCB transducer (113B21), from which two explosion parameters (p_{max} and τ_e) were determined. Here, τ_e was defined as the period from ignition to the time when the explosion pressure reaches its peak. The initial temperature was 298 K for all experiments. Figure 3 shows a sample explosion pressure data obtained from the experiment. To extract p_{max} and τ_e, the raw trajectory was first processed by a smoothing technique using a Gaussian-weighted moving average filter [21].

Experimental errors in this study can be summarized to two major categories: the random error

and the systematic error. In this study, the random error mainly originated from the measurement of the explosion trajectory, which is due to the transient nature of explosion process. At least three shots were repeated for each condition, and the explosion overpressure trajectories were reproducible because the results fluctuated within 5 %. In order to guarantee the accuracy of the experimental results, the explosion parameters (i.e., p_{max}, τ_e) presented in this work were calculated from the average values of three shots. Systematic error mainly resulted from Omega pressure gauge (PXM309) used to measure the initial pressure, which ranged from 0 to 0.7 MPa with an accuracy of ±0.25 % of full scale, and hence the maximum error of initial pressure measurement was to be approximately ±1.75 kPa.

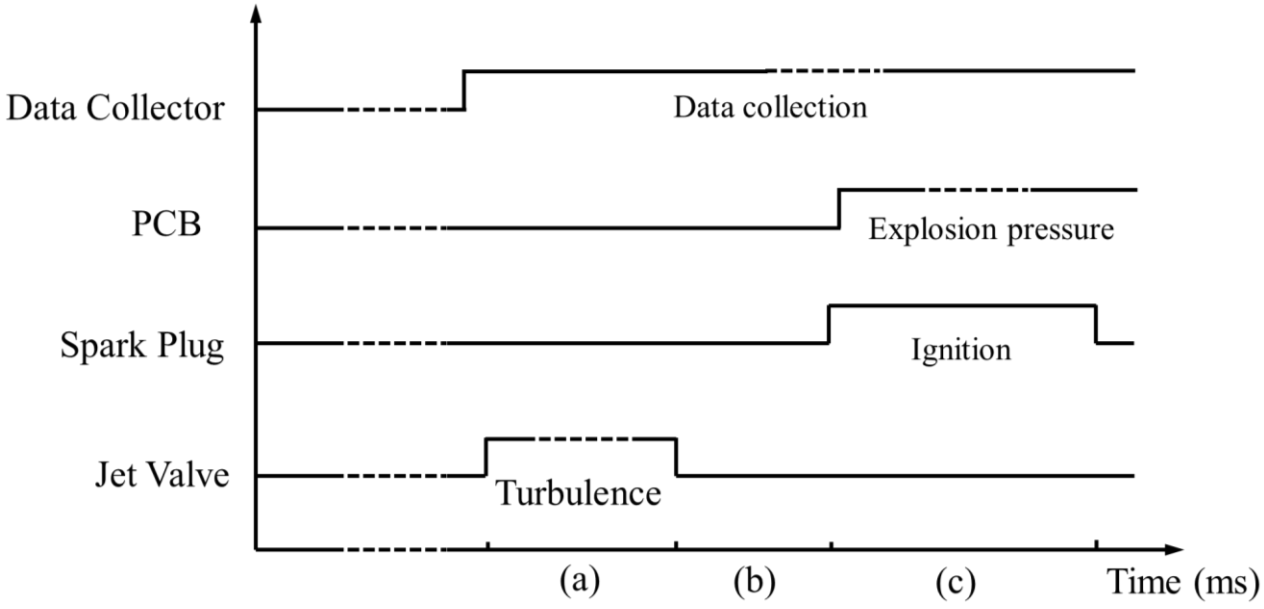


Fig. 2 An illustration of timing for system components.

a) t_{J0} (ranging from 20~800 ms), b) t_d (100 ms), c) ignition time t_i (200 ms).

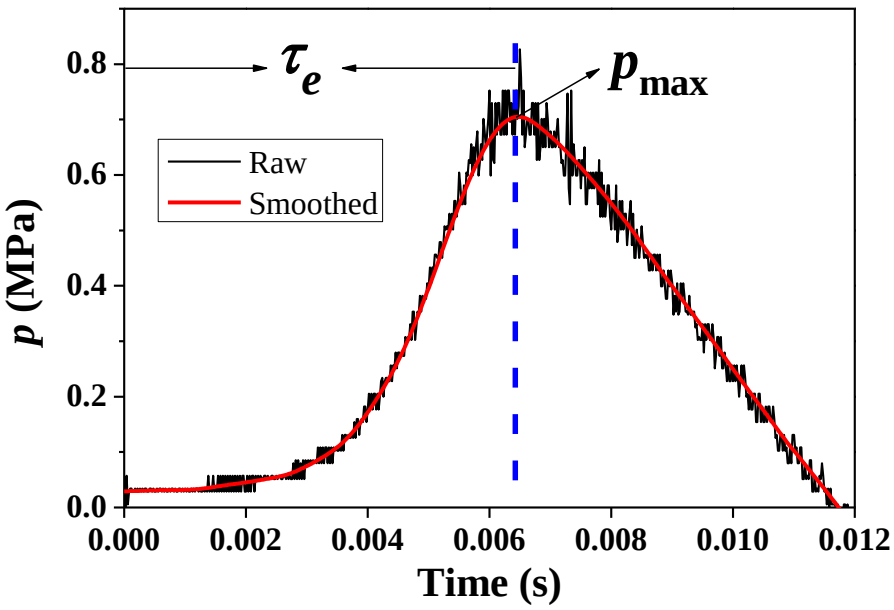
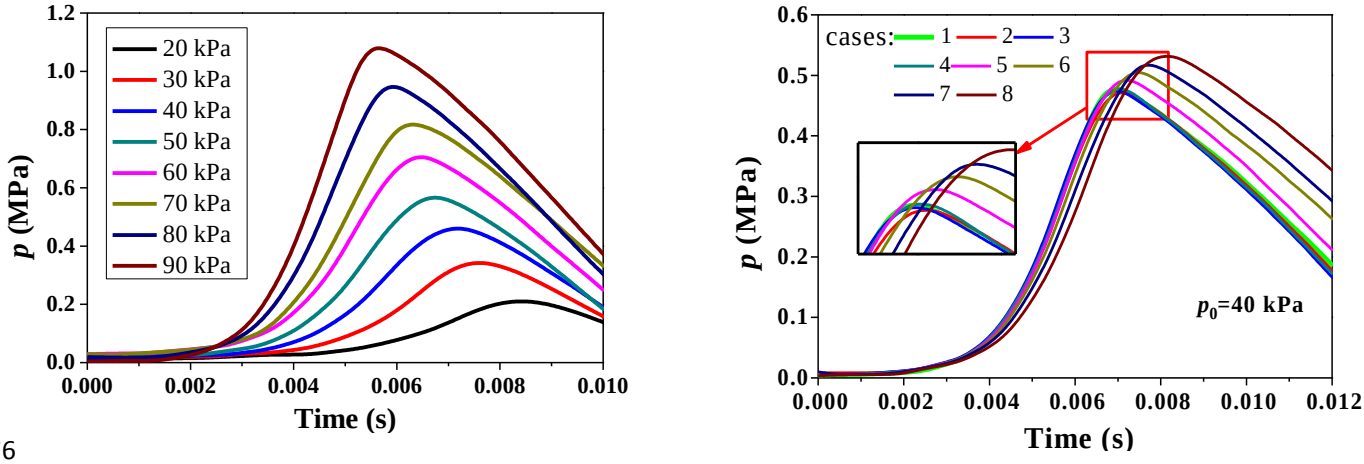


Fig. 3 Comparison of the raw pressure data and curve after smoothing (φ = 1.0, p_0 = 60 kPa, quiescent state).

3. Results and Discussion

3.1 Experiments without initial turbulence

Figure 4a shows the explosion pressure trajectories of CH_4-$2O_2$ under quiescent condition with p_0 from 20 to 90 kPa. For p_0 = 20 kPa, p_{max} is 0.21 MPa and τ_e is 8.5 ms. When p_0 increases to 50 kPa, p_{max} increases but τ_e decreases. The corresponding values are 0.58 MPa and 6.7 ms, respectively. As p_0 increases further to 90 kPa, p_{max} reaches 1.08 MPa with τ_e equal to 5.7 ms. Both the maximum pressure and the rate of pressure rise can be observed to increase with p_0.



(a) (b)

Fig. 4 Explosion pressure evolution for CH_4-$2O_2$ mixture initially at quiescent state. a) with various p_0 and b) diluting with different O_2 amount at p_0= 40 kPa.

Table 1 O_2 dilution for cases with p_0 = 40 kPa and p_{J0} = 500 kPa

Case No.	1	2	3	4	5	6	7	8
t_{J0} (ms)	0	20	50	100	200	400	600	800
p_1 (kPa)	40	40.40	40.89	41.67	43.57	46.46	49.57	52.29
V_{O2} (L)	0	0.08	0.18	0.33	0.71	1.28	1.90	2.43
χ_{CH4}(%)	33.3	33.0	32.6	32.0	30.6	28.7	26.9	25.5
φ	1	0.99	0.97	0.94	0.88	0.81	0.74	0.68

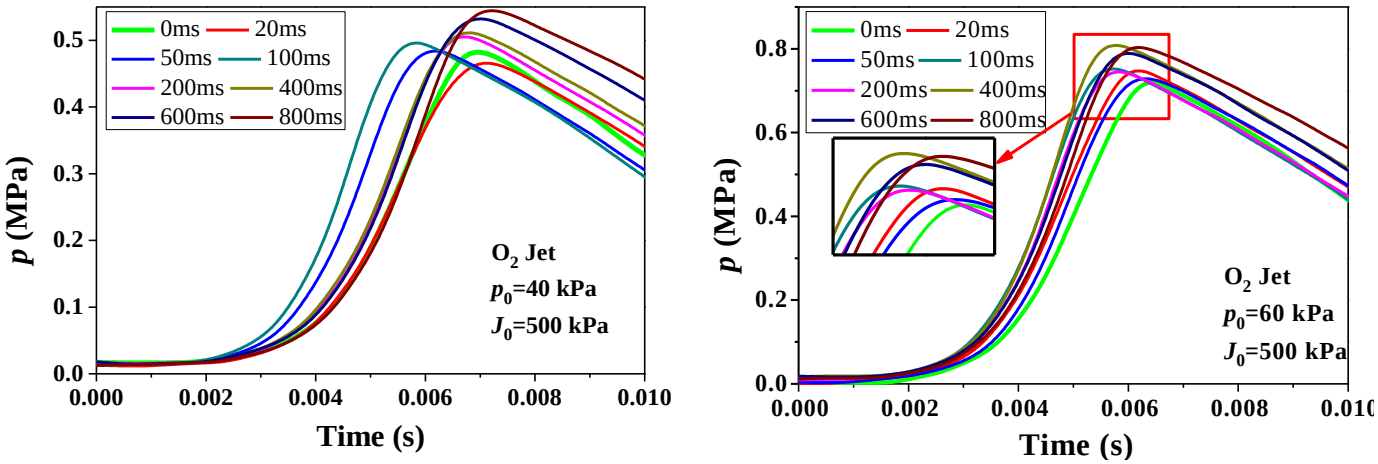
After the fluidic jet emerges into the chamber, the explosion characteristics of the tested mixture are affected by two factors: turbulence and the injected gas. For the latter, it is equivalent to adding a certain O_2 amount into the CH_4-$2O_2$ mixture. Hence, the effective mixture φ tends to the fuel-lean side if the added O_2 is considered. For jet duration t_{J0} ranging from 0 to 800 ms, the initial chamber pressure increases while both χ_{CH4} and φ decrease, which can be determined by calculating the remaining O_2 volume in the storage tank. Table 1 summarizes the parameters after O_2 injection, including the initial chamber pressure p_0 and high-pressure tank for the jet generation p_{J0}, the chamber pressure after the O_2 injection p_1, the volume of oxygen dilution V_{O2}, the mole fraction of CH_4 after injection χ_{CH4}, and the equivalent ratio φ.

The explosion pressure data for different cases of O_2 addition are shown in Fig. 4b. For these shots, O_2 was added into the chamber and the mixture was ignited after 10 minutes. Therefore, the results are considered to be measured at quiescent state without any turbulence effect to investigate only the O_2 dilution on the explosion behavior of methane-oxygen mixtures.

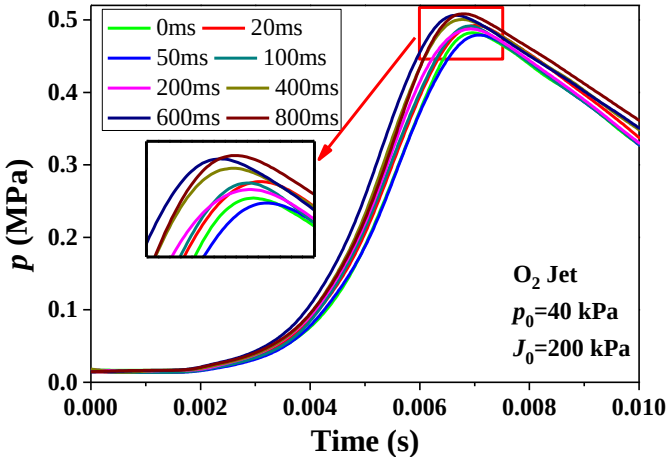
In Fig. 4b, the values of p_{max} and τ_e hold on for cases 1 to 4 (for t_{J0} from 0 to 100 ms). It thus indicates that adding small amount of O_2 plays little impact on the explosion behavior. As t_{J0} increases from 200 to 800 ms (cases 5 to 8), p_{max} increases from 0.48 to 0.53 MPa, and τ_e increases from 7.0 to 8.1 ms, accordingly. Hence, a relatively large amount of O_2 dilution can increase both

p_{max} and τ_e. In other words, the added oxygen increases the overpressure, but it slows down the rate of pressure rise. It is noteworthy that, by adding the amount of O_2 into the mixture, the initial pressure insider the chamber is also increased, e.g., when the jet duration time (t_{J0}) increases from 0 to 800 ms, the initial pressure increases from 40 kPa to 52.3 kPa (shown in Table 1), Fig.4a shows an increase in the initial pressure results in an increase of overpressure and pressure rise rate. Zhang et al. [53] suggested that an increase in the initial pressure could result in a decrease in the distance between molecules, increasing the incidence of collision of molecules, thereby accelerating the chemical reaction rate, and p_{max} accordingly increases. The above analysis suggests that there is a combination effect induced by adding certain amount of O_2 into the mixture (viz. the dilution accompanied by the decrease of equivalence ratio and the increase of total initial pressure), eventually resulting in increasing the overpressure but slowing down the rate of pressure rise.

3.2 Effect of turbulence generated by O_2 jet



(a) (b)



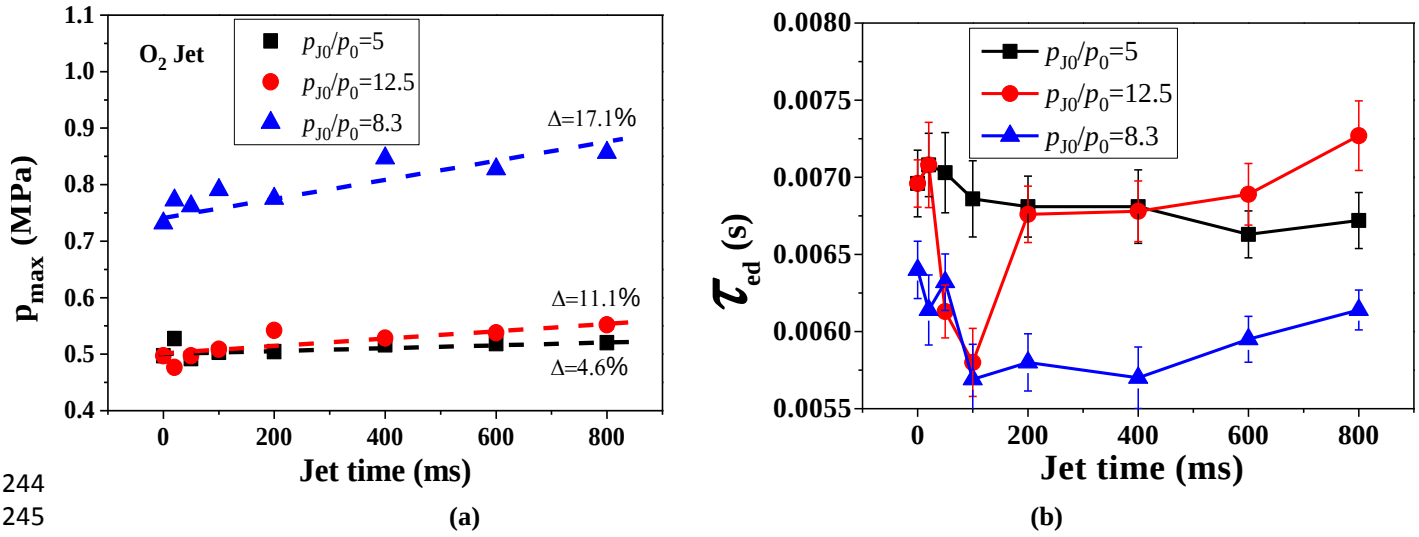
(c)

Fig. 5 Explosion pressure evolution with O_2 jet turbulence.

In this study, the pressure difference between high-pressure storage tank and the explosion chamber is the primary factor that influences the turbulence intensity, i.e., p_{J0}/p_0, the higher p_{J0}/p_0 is, the higher the turbulence intensity will be. Figure 5 shows the pressure trajectories with turbulence effect generated by an O_2 jet. For Fig. 5a, p_0 = 40 kPa and p_{J0} = 500 kPa (hence, p_{J0}/p_0 = 12.5), while t_{J0} varies from 0 to 800 ms. When t_{J0} increases from 0 to 100 ms, p_{max} varies slightly from 0.47 to 0.50 MPa, while the value of τ_e is greatly reduced (i.e., from 7.0 to 5.9 ms). As illustrated in Fig. 4b, adding the same amount of O_2 but without the turbulence has little impact on p_{max} and τ_e. While with turbulence (Fig. 5a), although p_{max} does not change significantly, τ_e is greatly reduced by 15.7 %. When t_{J0} increases from 200 to 800 ms, p_{max} consistently increases (from 0.51 to 0.54 MPa). However, in contrast to the small volume injection (t_{J0} equal to 0 to 100 ms), τ_e also increases from 6.7 to 7.2 ms, indicating the explosion pressure rise rate is lowered. This behavior is similar as that without turbulence (Fig. 4b). From Table 1 and Fig. 4b, as t_{J0} increases from 200 to 800 ms, the volume of O_2 added into the chamber increases from 0.71 to 2.43 L and φ changes from 0.88 to 0.68. Although the explosion characteristics are promoted by the turbulence, the influence of high O_2 dilution is more significant, which reduces the explosion reaction rate, thus increasing τ_e.

Figure 5b shows results for p_0 = 60 kPa and p_{J0} = 500 kPa (p_{J0}/p_0 = 8.3). In this case, the turbulence intensity is reduced. It is observed that, when t_{J0} goes up to 800 ms, the value of p_{max} also increases from 0.72 to 0.81 MPa, and τ_e persistently decreases from 7.0 to 6.2 ms. This suggests that both the effects of turbulence and O_2 dilution promote the explosion characteristics with increasing p_{max} and decreasing τ_e.

Results for p_0 = 40 kPa and p_{J0} = 200 kPa (p_{J0}/p_0 = 5) are shown in Fig. 5c. Note that the turbulence intensity for this case is relatively weak compared to the previous two cases. There is no obvious variation for both p_{max} and τ_e, indicating a competing effect between turbulence and O_2 dilution and hence, results in little impact on the explosion behavior.



(a) (b)

Fig. 6 Explosion parameters a) p_{max} and b) τ_e as a function of t_{J0} with O_2 jet turbulence.

Figure 6 summaries p_{max} and τ_e results with varying t_{J0} for p_{J0}/p_0 = 12.5, 8.3 and 5. For each individual case, there exists a linear increase between p_{max} and t_{J0}. As t_{J0} goes from 0 to 800 ms, p_{max} increases by 11.1% for p_{J0}/p_0 = 12.5, and 17.1% and 4.6% for p_{J0}/p_0 = 8.3 and 5, respectively. At high turbulence conditions (p_{J0}/p_0 = 12.5 and 8.3) and short injection time t_{J0}, the explosion time τ_e is reduced (especial for p_{J0}/p_0 = 12.5). Hence, the combustion rate is promoted at those conditions.

However, for higher t_{J0}, the resulting increase of O_2 dilution into the mixture becomes prominent and this effect suppresses the explosion rate, hence resulting in an increasing τ_e. These results illustrate that there is an opposite effect between turbulence and O_2 dilution, both affecting the explosion behavior in a confined chamber. For higher the p_{J0}/p_0, the stronger the turbulence intensity is, which promotes the chemical reaction, burning velocities and the explosion overpressure via distorting and expanding the flame surface area [54]. In contrast, with increasing jet duration time, hence, O_2 addition amount, the mixture tends to the fuel-lean side which suppresses the explosion rate to some extent.

3.3 Effect of turbulence generated by inert gases

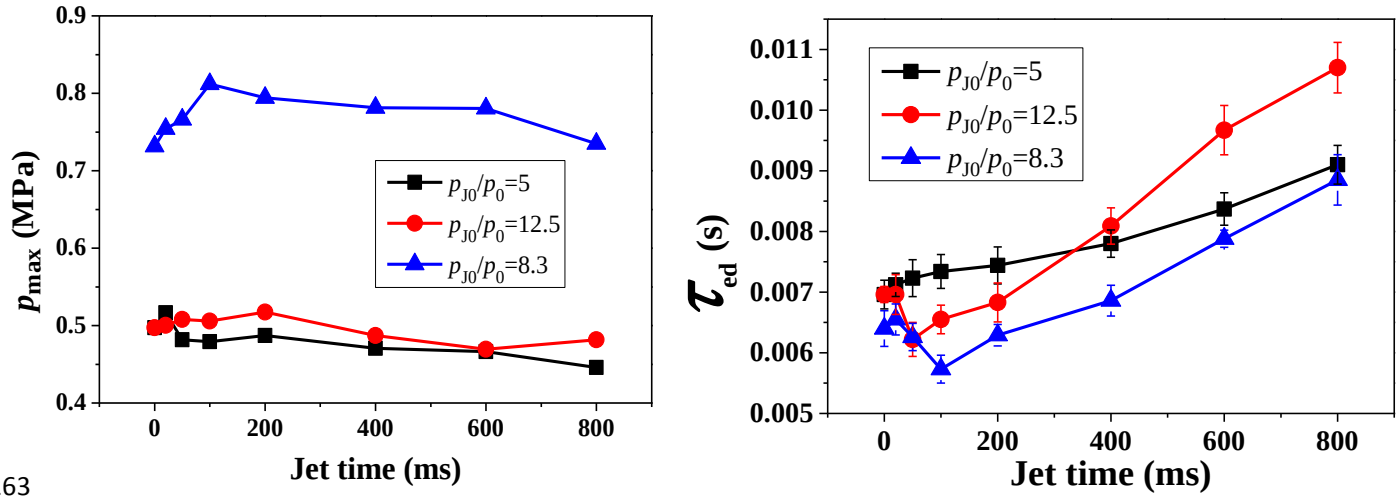


Fig. 7 Explosion parameters a) p_{max} and b) τ_e as a function of t_{J0} with CO_2 jet turbulence.

For the O_2 injection, besides the generated turbulence affecting the explosion behavior, the increased χ_{O2} also influences the chemical reaction rate and the explosion process. Here we further investigate the turbulence effect by inert gases on the CH_4-$2O_2$ explosion behavior. Previous investigations [32, 55-57] illustrated that unreactive gases have significant suppression effects on the explosion process. Figure 7 shows that for p_{J0}/p_0 = 5, with increasing t_{J0} from 0 to 800 ms the explo-

sion hazard is relaxed, i.e., p_{max} decreases and τ_e increases. For $p_{J0}/p_0 = 12.5$, p_{max} generally keeps constant and τ_e first decreases and afterwards it quickly goes up, indicating the explosion hazard is in turn inhibited. Lastly, for the case of $p_{J0}/p_0 = 8.3$, p_{max} first increases to 0.81 MPa and then decays to the state equivalent to that without turbulence ($p_{max} = 0.73$ MPa). Similar to the $p_{J0}/p_0 = 12.5$ case, τ_e decays and then increases. For this last case, the turbulence first promotes the explosion but the CO_2 dilution quickly balances this positive effect as t_{J0} is increasing to 800 ms. The reason that the results from $p_{J0}/p_0 = 8.3$ are different from the cases of $p_{J0}/p_0 = 5$ and 12.5 is mainly because the initial pressure for test is different, i.e., for the cases of $p_{J0}/p_0 = 5$ and 12.5, the p_0 is 40 kPa, while for $p_{J0}/p_0 = 8.3$, the corresponding p_0 is 60 kPa. Results have clarified that the increase in the initial pressure could accelerate the chemical reaction rate and increase in explosion pressure. Therefore, the baseline of p_{max} is much higher for $p_{J0}/p_0 = 8.3$ than other cases.

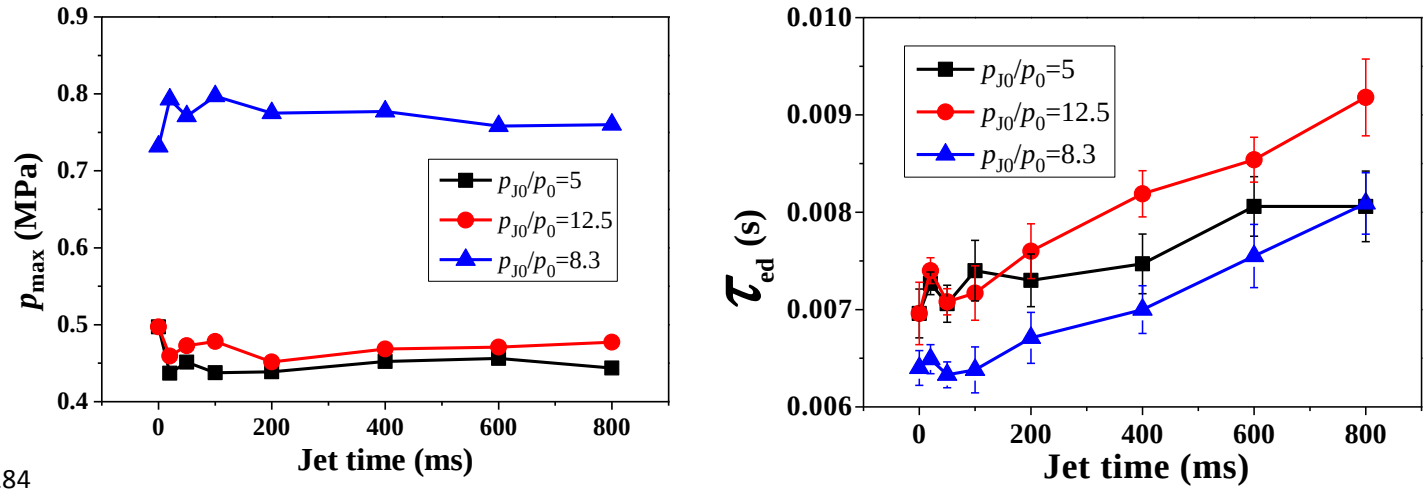


Fig. 8 Explosion parameters a) p_{max} and b) τ_e as a function of t_{J0} with N_2 jet turbulence.

Similarly, Fig. 8 presents the results with N_2 turbulence. With increasing t_{J0} from 0 to 800 ms, p_{max} is generally decreased for cases of $p_{J0}/p_0 = 5$ and 12.5. Only a slightly increase of p_{max} is observed for $p_{J0}/p_0 = 8.3$. Figure 8b also indicates that, although τ_e experiences fluctuation with the

increase of t_{J0} (0 to 50 ms), an increasing behavior of τ_e is generally observed. These results thus show that the suppression effect of N_2 jet on p_{max} and τ_e is more apparent than that by using CO_2.

3.4 Comparison between CO_2 and N_2 injections

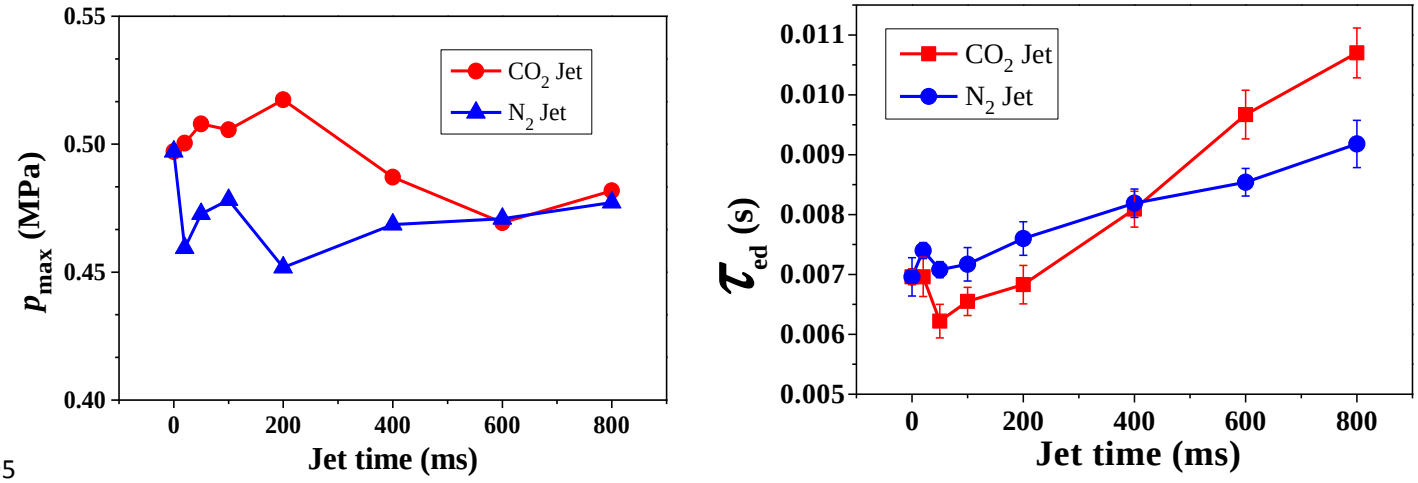


Fig. 9 p_{max} and τ_e as a function of t_{J0} for the case of p_0 = 40 kPa and p_{J0} = 500 kPa.

Figure 9 compares the explosion parameters with t_{J0} variation between the CO_2 and N_2 jet turbulence. The initial condition is kept the same (i.e., p_0 = 40 kPa and p_{J0} = 500 kPa). The results indicate that p_{max} is lower while τ_e is longer under the effect of N_2 turbulence when t_{J0} is less than 400 ms. As t_{J0} increases above 400 ms, τ_e is shorter and p_{max} is approaching that of the CO_2.

Previous investigation [56] suggested that, at quiescent state with no turbulence, the effect of CO_2 dilution is more profound than N_2 dilution in reducing the values of combustion/explosion parameters (including burning velocity, p_{max}, etc). However, the results obtained in this study is the opposite for t_{J0} ＜400 ms, which illustrates the promoting effect by turbulence on the explosion is more profound that the suppression effect by gas dilution at shorter t_{J0} condition.

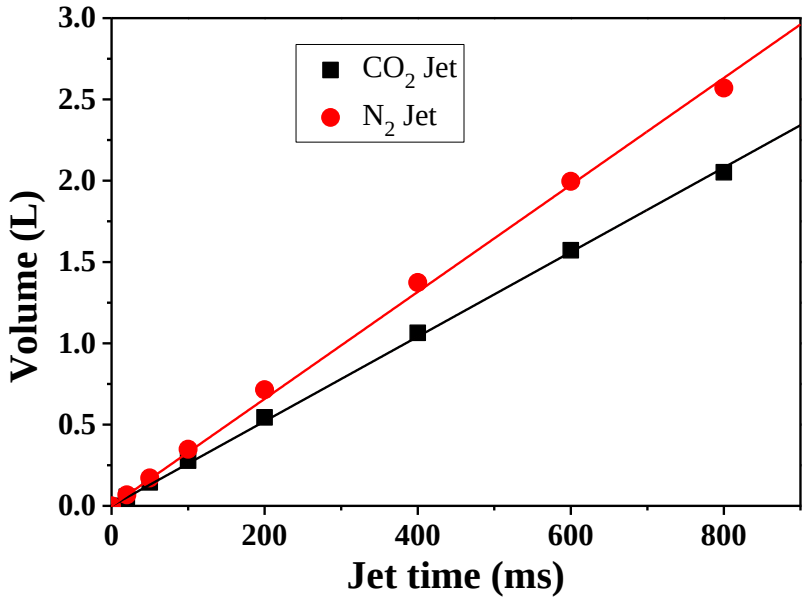
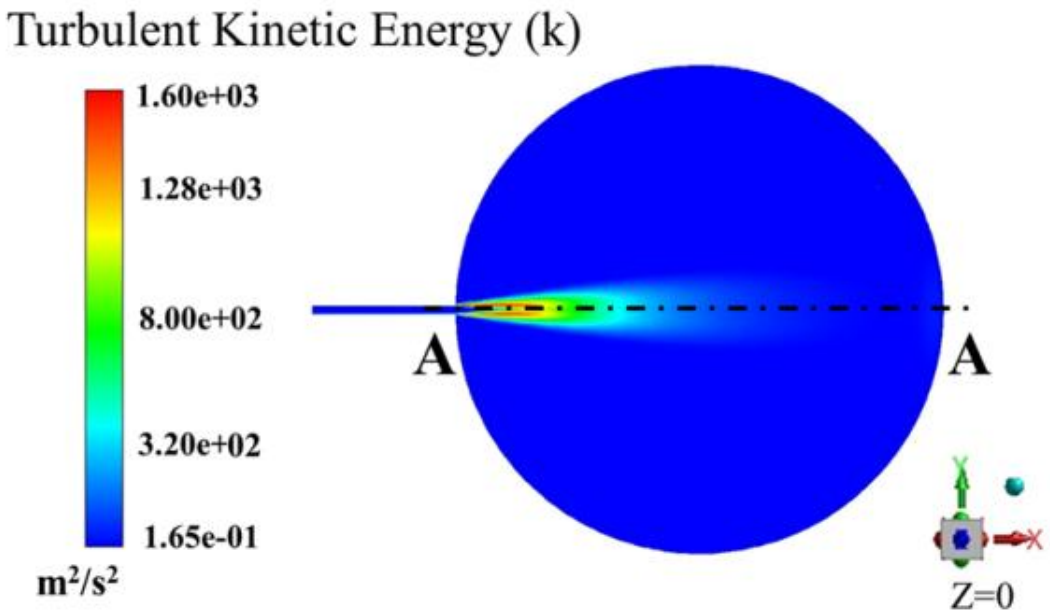
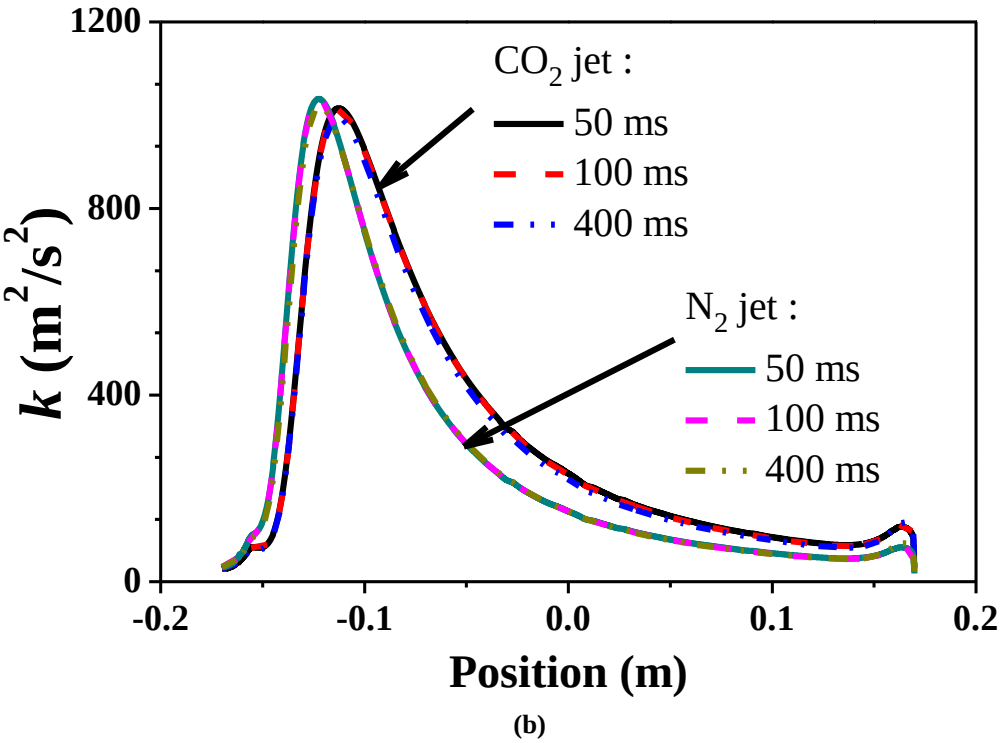


Fig.10 CO_2 and N_2 dilution as a function of t_{J0} for the case of p_0 = 40 kPa and p_{J0} = 500 kPa.

To clarify turbulence effects of CO_2 and N_2 jets on the explosion, numerical simulation using CFD package ANSYS Fluent 3D is performed. Reynolds averaged Navier-Stokes equations with the standard *k*-ε turbulence model are used and solved using the SIMPLE algorithm. The domain is equivalent to the experiment, i.e., V = 20 L. The total number of elements is 1,055,928; increasing above this number of elements has no noticeable influence on the results. Figure 10 exhibits the volumes of CO_2 and N_2 injection at different t_{J0} from 0 to 800 ms for the case of p_{J0}/p_0 = 12.5 in experiment. The relationship between CO_2 or N_2 dilution and t_{J0} can be described as $V_{CO_2}(\mathrm{L}) = 0.0026 t_{J0}(\mathrm{ms})$ and $V_{N_2}(\mathrm{L}) = 0.0033 t_{J0}(\mathrm{ms})$, and the values of linearly dependent coefficient R^2 are calculated as 0.999 and 0.998, accordingly. An approximately linear relation between the inject flow and t_{J0} is assumed and hence, the jet entrance applies velocity-inlet boundary. To ensure the amount of gas injection in simulation is consistent with that in experiment, the jet entrance velocity is set as 162 m/s and 172 m/s for CO_2 and N_2 jet, respectively. The difference is due to the molecular weight of those gases under the same p_{J0}/p_0.



(a)



(b)

Fig. 11 Turbulent kinetic energy for CO_2 and N_2 jet with p_0 = 40 kPa and p_{J0} = 500 kPa. a) The turbulent kinetic energy field of CO_2 jet for t_{J0} = 50 ms; b) Turbulent kinetic energy along centerline for different t_{J0}.

Figure 11a shows the turbulent kinetic energy (k) contour using CO_2 jet with t_{J0} = 50 ms. The axial distributions along the horizontal centerline (A-A) are shown in Fig. 11b for different t_{J0}. "0"

refers to the center of the 20-L spherical chamber. From the simulations, the turbulent kinetic energy plots for each corresponding CO_2 or N_2 jets coincide almost with each other regardless of t_{J0}. Besides, it is indeed found that the k only depends on p_{J0}/p_0. The turbulent kinetic energy is about 35 % greater for CO_2 jet than that of N_2 for the most places in the chamber particularly near the jet entrance. Therefore, for t_{J0} ＜400 ms, the CO_2 turbulence effect is more prominent than that of N_2 turbulence, enhancing explosion over the dilution effect. In contrast, the unreactive gas dilution increases notably when t_{J0} ＞ 400 ms and the prohibiting effect becomes more significant than the turbulence promoting effect on the explosion behavior. This result helps to explain trends in Fig. 9.

This work presents experimental and numerical results of the turbulence effect on the explosion behavior in methane-oxygen mixtures, the competing mechanism between turbulence-enhanced effect and explosion-prohibited effect by added gases is clarified, those results may contribute towards forming a more in-depth understanding of the real explosion process considering turbulent condition.

4 Conclusion

In this study, two explosion characteristics, namely the maximum explosion pressure p_{max} and the explosion time τ_e, are measured experimentally using a standard 20-L spherical explosion vessel for methane-oxygen mixtures at quiescent state and under the influence of initial turbulence. The latter is generated by the injection of different gases (O_2, CO_2 and N_2) into the spherical chamber. Turbulence intensity is controlled by changing the ratio of initial gas jet and chamber pressures p_{J0}/p_0. The following summarizes the findings:

(1) At quiescent state, adding the amount of O_2 into CH_4-$2O_2$ mixture increases the maximum of overpressure but it reduces the pressure rise rate.

(2) There is a competition between explosion enhancing effect by turbulence and explosion prohibiting effect by the injected gas dilution, both influencing the explosion behavior of methane-oxygen mixtures in the confined chamber.

(3) By introducing O_2 jet turbulence, p_{max} increases with increasing t_{J0}. τ_e is greatly reduced for t_{J0} varying from 0 to 200 ms for $p_{J0}/p_0 = 12.5$ and 0 to 400 ms for $p_{J0}/p_0 = 8.3$. Longer t_{J0} renders the chemical reaction rate slow.

(4) The turbulence intensity of CO_2 is more profound than that of N_2 jet. Hence, both p_{max} and τ_e are promoted by CO_2 turbulence for cases when t_{J0} is relatively short. At longer t_{J0} (e.g., $t_{J0} > 400$ ms), the effect of CO_2 dilution dominating the explosion behavior becomes more apparent than N_2 dilution.

Future research will focus on the interaction between turbulence and leading shock of the explosion and its effect on the explosion process by applying high-speed Schlieren camera, laser diagnostic apparatus (e.g., PIV) is to be employed to explore the detailed turbulent flow field on the explosion process.

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The effects of pre-ignition turbulence by gas jets on the explosion behavior of methane-oxygen mixtures

Xinyu Chang[1], Bo Zhang[2†], Hoi Dick Ng[3], Chunhua Bai[1]

[1]Beijing Institute of Technology
State Key Laboratory of Explosion Science and Technology, Beijing 100081, China

[2]Shanghai Jiao Tong University
School of Aeronautics and Astronautics, Shanghai, 200240, China

[3]Concordia University
Department of Mechanical, Industrial and Aerospace Engineering
Montréal, QC, H3G 1M8, Canada

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***Credit Author Statement**

CRediT authorship contribution statement

Xinyu Chang: Investigation

Bo Zhang: Investigation, Validation, Writing - review & editing, Methodology

Hoi Dick Ng：Validation，Writing - review & editing

Chunhua Bai: Investigation, Resources, Funding acquisition, Supervision,