Influence of pre-ignition quasi-isotropic turbulence on burning velocity of diethyl ether /air mixtures

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Abstract. This paper presents a detailed investigation on turbulent burning velocity of diethyl ether (DEE)/air mixtures under different pre-ignition quasi-isotropic turbulence. The concentration of DEE/air mixtures is the equivalence ratio $\phi = 1.1$. The experimental result of the laminar burning velocity ($u_l$) is 0.55 m/s, and the largest data of turbulent burning velocity ($u_f$) are 1.8 m/s at pre-ignition quasi-isotropic turbulence velocity at 6.2 m/s. In this work the model gives the expression on the laminar burning velocity ($u_l$) and turbulent burning velocity ($u_f$) versus the pre-ignition turbulence velocity $U_{rms}$ in accordance with Williams's theoretical model.

1. Introduction

Diethyl ether (DEE) is an excellent compression ignition fuel with a higher-energy density, is also blended with diesel to increase the brake thermal efficiency and reduce emissions in compression ignition engines [1-3]. The low auto-ignition and boiling temperatures of DEE are the principal reasons for selecting it over other fuels as an ignition enhancer [4-5]. In military applications, DEE is a typical fuel used in fuel air explosive (FAE) [6, 7]. Pang et al. [8] and Lee et al. [9] examined the turbulence effect on the explosion and deflagration-to-detonation transition behavior. Therefore, it is of significance to examine the effect of turbulence on the combustible cloud explosions. Some of research effort has been directed towards determining the combustion parameters of DEE in a high pressure or temperature [3, 4]. Recently, Laminar burning velocities of DEE/air mixtures were measured at various equivalence ratios, initial temperatures, and pressures in a spherical bomb by schlieren photography [10, 11]. Unfortunately, few researchers have paid attention to the influence of different pre-ignition quasi-isotropic turbulence on turbulent burning velocity of DEE/air mixtures.

In this paper, a spray test with 275 g/m³ liquid DEE (i.e., the equivalence ratio $\phi = \sim 1.1$) was performed in a 20-L spherical stainless steel vessel to evaluate the influence of different pre-ignition quasi-isotropic turbulence velocity on laminar burning velocity and turbulent burning velocity of DEE/air mixtures.
2. Experimental Apparatus and Procedures

2.1. General
The experiments were carried out in two 20-L spherical vessels, one composed of 5-mm-thick strong Plexiglas for pre-ignition turbulence velocity system, one composed of 10-mm-thick stainless steel for experiments of explosion parameters, respectively. From figure 1, additional details on the experimental set-up can be found in our literature [12-16].

![Experimental Apparatus Diagram](image)

Figure 1. Schematic diagram of experimental set-up.

2.2. Determination of experimental concentration
The chemical reaction of DEE/air mixtures with the stoichiometric mole fraction are

\[ C_4H_{10}O + 6\left(O_2 + \frac{79}{21}N_2\right) = 5H_2O + 4CO_2 + 6 \times \frac{79}{21}N_2 \]

The stoichiometric volume fraction of DEE/air mixtures is

\[ C_{st} = \frac{1}{1 + 6(1 + \frac{79}{21})} \approx 3.4\% \text{(V/V)} \]

The stoichiometric concentration is \(\sim 250\) g/m\(^3\). In actual chemical reactions, the volume fraction at which the peak explosion pressure of a combustible vapor/air mixture reaches its maximum value is always slightly greater than that in the stoichiometric state [17, 18]. So the experimental volume fraction of the DEE/air mixtures is performed in \(\sim 3.7\%\) (V/V), respectively, i.e., the experimental concentration is \(\sim 275\) g/m\(^3\). The equivalence ratio \(\phi\) is \(\sim 1.1\).

2.3. Formation of vapor-phase DEE/air mixtures
In this work, the initial room temperature and atmosphere pressure of the DEE/air mixtures were 21°C and 0.10 MPa, respectively. The spray time was consistently performed for a period of 50ms. And the ignition delay times (IDTs) of 100 ms, 150 ms, 200 ms and 250 ms were performed at pneumatic atomization pressures of 0.4 MPa, 0.6 MPa, and 0.8 MPa, respectively. Whether the DDE completely
vaporized before the IDTs? So the Mie extinction detection system was employed, and it can be found in our literature [12-16]. A spray test with ~275 g/m³ liquid DEE was performed in a strong Plexiglas 20-L spherical vessel for SMD determination experiments. The results of the SMDs assay of DEE at pneumatic atomization pressures of 0.4 MPa, 0.6 MPa, and 0.8 MPa are 19μm, 13μm and 7μm at 50ms, respectively. In this work the lifetime or evaporation time of droplets follows the d² evaporation law. Form the Antoine equation [19], the experimental concentration of ~275 g/m³ is far lower than the saturated vapor pressure concentration (1235.30 g/m³). So the DEE droplets evaporated completely before the IDTs [20, 21].

2.4. Measurement of pre-ignition turbulence velocity
To clearly reveal the motion and velocity distributions of vapor before ignition, the spray process was recorded using PIV at a flow direction. The details on the PIV experimental set-up can be found in our literature [12].

The parameter $U$ of the PIV velocity is calculated using the equation

$$U = \sqrt{\left(\frac{1}{N} \sum_{i=1}^{N} u_i\right)^2 + \left(\frac{1}{N} \sum_{i=1}^{N} v_i\right)^2}$$  \hspace{1cm} (1)$$

where $N$ is the number of recorded velocity fields and $u_i$ and $v_i$ are components of $U$ for field $i$.

For each velocity field, the root mean square (rms) velocity field $U_{rms}$ is determined by

$$U_{rms} = \sqrt{\frac{1}{2} \left(\frac{1}{N} \sum_{i=1}^{N} (u_i - \bar{u})^2 + \frac{1}{N} \sum_{i=1}^{N} (v_i - \bar{v})^2\right)}$$  \hspace{1cm} (2)$$

where $\bar{u} = \frac{1}{N} \sum_{i=1}^{N} u_i$ and $\bar{v} = \frac{1}{N} \sum_{i=1}^{N} v_i$.

Using pneumatic atomization pressures of 0.4 MPa, 0.6 MPa and 0.8 MPa in spray times of 50 ms, the result of the root mean square velocity ($U_{rms}$) and mean turbulence intensity ($U_{rms}/U$) with time is shown in figure 2. In the spherical vessel, the double symmetric spray system can produce larger mean turbulence intensity ($U_{rms}/U$) i.e., the turbulence mean velocity ($U$) is lower, and the root mean square velocity ($U_{rms}$) is higher. At the IDTs of 100ms, 150ms, 200ms 250ms, mean turbulence intensities ($U_{rms}/U$) are no less than 100, $U_{rms}$ are at least two orders of magnitude larger than $U$. It is close to the characteristic of zero-mean velocity turbulent flows and quasi-isotropic turbulence. The pre-ignition quasi-isotropic turbulence velocity $U_{rms}$ and their standard deviation at the IDTs of 100ms, 150ms, 200ms 250ms, are provided in table 1.

![Figure 2. The pre-ignition turbulence velocity $U_{rms}$ with time at pneumatic pressure of 0.4 MPa, 0.6 Mpa, 0.8 MPa.](image)
Table 1. Pre-ignition turbulence velocity and their standard deviation at IDTs.

| Pneumatic atomization pressures (MPa) | Ignition delay time, IDT (ms) | pre-ignition quasi-isotropic turbulence velocity, $U_{rms}$ (m/s) |
|--------------------------------------|-----------------------------|-------------------------------------------------------------|
|                                      | 100                         | 6.2±0.3                                                    |
|                                      | 150                         | 4.0±0.2                                                    |
|                                      | 200                         | 2.5±0.2                                                    |
|                                      | 250                         | 2.0±0.2                                                    |
| 0.6                                  | 100                         | 5.0±0.3                                                    |
|                                      | 150                         | 3.5±0.2                                                    |
|                                      | 200                         | 2.2±0.2                                                    |
|                                      | 250                         | 1.5±0.2                                                    |
| 0.4                                  | 100                         | 4.0±0.3                                                    |
|                                      | 150                         | 3.0±0.2                                                    |
|                                      | 200                         | 2.0±0.2                                                    |
|                                      | 250                         | 1.0±0.1                                                    |

2.5. Experimental ignition procedure

The pneumatic atomization pressure was set to 0.4 MPa, 0.6 MPa, or 0.8 MPa, and the solenoid valve was open for a duration of 50 ms. The air and liquid DEE were dispersed into the explosion vessel, and the igniter was energized after an IDT of 100, 150, 200, or 250 ms. Initiation energy plays an important role in flame propagation processes as well as in avoiding the direct quenching of the DEE/air mixtures. Therefore, the spark ignition was an important factor in our experiments and was sufficient to ensure stable ignition and flame propagation, so the ignition energy ($CU^2/2$) [22, 23] was held at a constant 40 J throughout the experiments. Explosions of the DEE/air mixtures were monitored by means of Kistler pressure gauges mounted on the wall of the experimental vessel.

3. Results and discussion

3.1. Laminar burning velocity

In order to compare the laminar burning velocity ($u_L$) and the turbulent burning velocity ($u_t$) on DEE in air, experiments were first performed in a spherical explosion vessel at an IDT of 1500ms under pneumatic pressure of 0.8 MPa in this work. From figure 2, at 500ms, the pre-ignition turbulence velocity $U_{rms}$ has been lower than 0.2 m/s, so it will be less than 0.1 m/s at an IDT of 1500ms. In this study, the laminar burning velocity is computed through two different methods. The first one uses the FASTCAM SA-6 camera, employed and produced high-quality flame propagation images using an optically ported combustion vessel. The frame rate is 10,000 fps in this work. The second method considers a mathematical model proposed by Dahoe et al. [24, 25], in which the laminar burning velocity depends on $P_{max}$ and $dP/dT$. The model gives the following expression:

$$u_L = \frac{1}{P_{max} - P_0} \frac{4\pi}{3V} \left( \frac{P_0}{P} \right)^{1/\gamma} \left[ 1 - \left( \frac{P_0}{P} \right)^{1/\gamma} \left( \frac{P_{max} - P}{P_{max} - P_0} \left( \frac{P_{max} - P}{P_{max} - P_0} \right)^{\gamma/2} \right) \right] \frac{dP}{dT}$$

(3)

where $V$ is the vessel volume, $P$ and $P_0$ are the actual pressure and initial pressure, $\gamma$ the adiabatic coefficient of the unburned gas. $u_L$ is determined by a fitting method proposed by Dahoe, in which $u_L$ is calculated by fitting the pressure history measurement (i.e., actual pressure $P$ and $dP/dT$).
Under the equivalence ratio $\phi = \sim 1.1$, the experimental results of the laminar burning velocity $u_L$, its value is $\sim 0.55$ m/s. The reported result by Fiona Gillespie et al. [26] is included in the laminar burning velocity of DEE/air mixtures at 298-398 K, and at the equivalence ratio $\phi = \sim 1.1$ the laminar burning velocity is $\sim 0.42$ m/s - $\sim 0.65$ m/s (i.e., the mean value is $\sim 0.54$ m/s). Yage Diet al. [27] is also included at 323 K, and at the equivalence ratio $\phi = \sim 1.2$ the stretched laminar burning velocity is $\sim 0.52$ m/s. These are more close to the result of this study.

3.2. Turbulent burning velocity
In the present work, spherically expanding flames following central ignition of globally homogeneous DEE in air at different pre-ignition quasi-isotropic turbulence velocity was employed to quantify the structure of instabilities in turbulent flames. For instance, from figure 3, an IDT of 150 ms under pneumatic pressure of 0.8 MPa (i.e., the pre-ignition turbulence quasi-isotropic velocity $\sim 4$m/s), Ignition was achieved via an inductive-capacitive spark produced and the spark duration about 3 ms in the DEE/air mixtures. Flame propagation fully occurred in 24ms (i.e., the peak explosion pressures occurred in 24ms). However, under pre-ignition quasi-isotropic turbulence velocity of $\sim 4$m/s, the expanding flame has reached the spherical explosion vessel wall in $\sim 18$ms. Actually, the mean turbulent burning velocities $(u_t)$ is $\sim 1.5$ m/s. The turbulent burning velocity $(u_t)$ of DEE in air at different pre-ignition quasi-isotropic turbulence velocity are shown in figure 4.

Figure 3. Ignition and flame propagation process under pre-ignition quasi-isotropic turbulence velocity $\sim 4$ m/s on DEE/air mixtures.

As shown in figure 4, it appears that the turbulent burning velocities $(u_t)$ of them are increased with the increase of pre-ignition turbulence velocity increased. The largest data of turbulent burning velocity $(u_t)$ is 1.8 m/s at pre-ignition turbulence velocity at 6.2 m/s. Damköhler (1940) [28] was the first to present theoretical expressions for the turbulent burning velocity $(u_t)$ and the laminar burning velocity $(u_L)$. There were many attempts to modify Damköhler’s analysis and to derive expressions that would reproduce on turbulent burning velocities In the following half-century [29]. Expressions of the form have been proposed:

$$\frac{u_t}{u_L} = 1 + C \left( \frac{U_{rms}}{u_L} \right)^n$$  \hspace{0.5cm} (4)

The exponent $n$ is often found to be in the vicinity of 0.7 in Williams (1985) [30, 31]. $C$ is a substance-specific coefficient. The model gives the following expression on the turbulent burning velocity $u_t$ versus the pre-ignition turbulence velocity $U_{rms}$ in this work by Eq. (4)
$u_t = 0.55 + 0.42 \left( \frac{U_{rms}}{0.55} \right)^{0.7} \quad U_{rms} \in [1.0, 6.2]$ \hfill (5)

![Figure 4. Turbulent burning velocity ($u_t$) vs. pre-ignition quasi-isotropic turbulence velocity ($U_{rms}$) for DEE/air mixtures.](image)

4. Conclusions

This paper presents a detailed investigation on the combustion properties (i.e., laminar burning velocity, turbulent burning velocity) of DEE/air mixtures under pre-ignition quasi-isotropic turbulence velocity. The concentration of DEE/air mixtures is the equivalence ratio $\phi = ~1.1$. Experiment is performed by systematically measuring the pressure evolutions in a 20-L explosion spherical vessel.

Detailed conclusions are presented below.

1. The experimental result of the laminar burning velocity ($u_l$) is ~0.55 m/s, and it is close to the result of ~0.54 m/s by Fiona Gillespie et al and ~0.52 m/s by Yage Diet al.

2. The largest data of turbulent burning velocity ($u_t$) are 1.8 m/s at pre-ignition quasi-isotropic turbulence velocity at 6.2 m/s. In this work the model gives the expression on the laminar burning velocity ($u_l$) and turbulent burning velocity ($u_t$) vs the pre-ignition turbulence velocity $U_{rms}$ in accordance with Williams's theoretical model.

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