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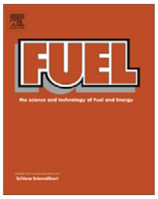

Deflagration to detonation transition and detonation structure in diethyl ether mist/aluminum dust/air mixtures

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HIGHLIGHTS

- ▶ New insights into the DDT and detonation structure in DEE mist/aluminum dust/air mixtures.
- ▶ The detailed run-up distances of DDT in DEE mist/aluminum dust/air mixtures are obtained.
- ▶ Detonation in DEE (295 g/m^3)/air mixture has a double-headed spinning structure.
- ▶ Detonation in DEE (314 g/m^3)/aluminum dust (230 g/m^3)/air mixture has a single-headed spinning structure.

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ABSTRACT

Although diethyl ether (DEE) is an excellent compression-ignition fuel, it is extremely flammable and presents a serious fire and explosion hazard. Therefore, before widespread use of DEE as an energy carrier, its safety-related issues must first be addressed. In this study, experiments of transition from deflagration to detonation (DDT) and detonation structure in DEE mist/air and DEE mist/aluminum dust/air mixtures are carried out in a horizontal tube of inner diameter 19.9 cm and length 32.4 m. The mixtures are initiated by a high-voltage electric spark and the histories of pressure wave are recorded by 17 Kistler pressure transducers in the axial direction along the tube to study the DDT process. To study the detonation structure, 4 cross-sections are chosen during the self-sustained propagation phase of the detonation where, 8 pressure transducers are arranged with the same interval angle of 45° on the same tube circumference to obtain the pressure profiles. The experimental results indicate that, deflagration cannot successfully transmit to detonation in DEE mist/air mixtures when DEE concentrations are 164 and 229 g/m^3. Deflagration is observed to continuous accelerate and the onset detonation occurs at distance of 17.15 m as DEE concentration is increased up to 295 g/m^3, in which a double-headed spinning detonation structure is observed. Among the 5 different mixture composition of DEE mist/aluminum dust/air, DDT phenomenon is only observed in the mixtures of DEE mist (367 g/m^3)/aluminum dust (184 g/m^3)/air and DEE mist (314 g/m^3)/aluminum dust (230 g/m^3)/air, the run-up distances of DDT are 19.25 and 15.05 m, respectively. A single-headed spinning detonation structure is observed in DEE mist (314 g/m^3)/aluminum dust (230 g/m^3)/air mixture.

1. Introduction

Diethyl ether (DEE), which is easily converted through a dehydration process from ethanol, is an excellent compression-ignition fuel with higher energy density than ethanol [1]. DEE is also blended with diesel for improving the brake thermal efficiency and reducing emissions in compression-ignition engines [2,3]. DEE has a high cetane number and is used as a starting fluid, in combination with petroleum distillates for gasoline and diesel engines because of its high-volatility and low flash point. DEE's low autoignition and boiling temperature are the principal reasons for selecting it over other fuels as an ignition improver along with lethargic fuels like biogas. DEE's physical properties of interest are given in Table 1.

Diethyl ether is extremely flammable and therefore presents a serious fire and explosion hazard. For example, the autoignition temperature of diethyl ether is 160 °C. It can be ignited by a hot surface without a flame or spark. Table 1 also shows that DEE is highly volatile and has a flash point of −45 °C. Table 2 shows that

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Table 1
Physical properties of diethyl ether.

Formula	$C_2H_5OC_2H_5$
Calorific value	33.9 MJ/kg
Density	713 kg/m^3
Boiling point	34.4 °C
Flash point	−45 °C
Stoichiometric air fuel ratio (mass basis)	11.1
Autoignition temperature	160 °C
Cetane number	>125

DEE's flammability limits [1] (vol.% in air from 1.9 to 36.0) are broader than those of many diesel fuels. DEE's vapors can accumulate in sufficient concentration in a closed space and can easily explode with the slightest spark (the minimum ignition energy is 0.33 mJ at the standard conditions). Furthermore, upon exposure to air and light, DEE tends to form unstable peroxides which will concentrate by evaporation or distillation of the DEE and may detonate with a violent explosion when disturbed by shock or friction. In addition, friction produced by simply unscrewing the cap of a container may cause an explosion. Thus, the key challenges facing the possible future widespread use of DEE as an energy carrier are safety-related issues that must be addressed before social acceptance of this fuel can be achieved. Explosion hazards associated with the production, handling, transportation and storage of DEE must be resolved with sufficient confidence level.

Although a number of studies have been conducted on the properties and combustion characteristics of DEE [4–12], very limited studies involve experimental investigation into its deflagration to detonation transition (DDT) and its detonation structure. In particular, investigations have not confirmed whether DEE mist/air can detonate after mixing with passive and energetic materials, such as fire extinguisher powder or aluminum dust, since previous studies performed by Amyotte [13], Liu et al. [14,15], Zhang et al. [16–18] have confirmed that the detonation parameters (e.g. velocity, overpressure, and temperature) would be highly affected by the addition of passive and energetic dust in the mixtures. For instance, methane/coal dust/air explosions can be effectively suppressed by suppression agents (ABC fire extinguisher powder, SiO_2 powder, and $CaCO_3$ powder) characterized by the rapid decrease in overpressure and propagating velocity of the explosion waves [19]. However, with the addition of aluminum dust in nitromethane mist/air, detonation waves form with a velocity and peak overpressure of 1710–1730 m/s and 39–47.5 bar, respectively. In comparison, a quasi-detonation wave propagating in nitromethane mist/air mixtures without aluminum dust addition, has a velocity and peak overpressure of only 730–1080 m/s and 10–55 bar, respectively [14].

Hence, for the potential usage of DEE as a fuel for compression-ignition engines and to assure its safe operation in industrial processes, the deflagration to detonation process and its detonation structure need to be investigated properly. In this study, experiments of transition from deflagration to detonation in DEE mist/air and DEE mist/aluminum dust/air mixtures are conducted in a horizontal tube with a diameter of 19.9 cm and a length of 32.4 m. The mixtures are initiated by high-voltage electric spark with initiation energy of 40 J. To study the DDT process, 17 pressure transducers are mounted along the tube to record pressure wave histories at different distances. To investigate the detonation structure, the pressure profiles from 4 cross sections during the detonation self-sustained propagation phase are obtained. The objective of this study is to investigate the transition from deflagration to detonation in DEE mist/air and DEE mist/aluminum dust/air mixtures and to study the detonation structure in those mixtures.

2. Experimental details

2.1. Experimental setup

The experiments were carried out in a horizontal tube with a diameter of 19.9 cm and a length of 32.4 m, as shown in Fig. 1. The experimental setup was constructed in previous studies (see [20–22] for full details). It essentially consists of an experimental tube, an electric ignition system, a control unit, a data acquisition system, a venting system, a vacuum pump, an air pump, and a 10 m^3 dumping tank.

The experimental tube includes a test section, 44 sets of liquid/dust dispersion system, and a connecting section. The dispersion systems are mounted horizontally on both sides of the tube, regularly spaced at intervals of 0.7 m in the axial direction of the tube. High-voltage electric spark has been used to supply powerful initiation energy, as in previous direct detonation initiation studies [23–27]. To ignite all the DEE mist/air and DEE mist/aluminum dust/air mixtures, and form a self-sustained propagated explosion wave, a spark energy of 40 J, estimated from $1/2CV^2$ ('C' and 'V' refer the capacitance and voltage, respectively), is generated by an electric igniter. The igniter is mounted at the beginning of the tube and it also used to provide a weak ignition condition for deflagration. It should be noted that, once initiated the detonation propagates downstream in a planar geometry. The pressure measurement system comprises of two parts: (a) 17 Kistler pressure transducers are mounted on the wall of the experimental tube in order to study deflagration to detonation transition process, the location of each transducer is shown in Table 3; (b) To study the structure of the detonation wave 4 cross-sections are chosen in the axial direction of the tube, as shown in Fig. 2. Eight pressure gauges are arranged with an interval angle of 45° on the tube circumference during self-sustained propagation phase at 29.96 m from the ignition point. A left-view of the cross-section is given in Fig. 2. At the end of the tube, a plastic film is placed between the experimental tube and the dumping tank to help achieve vacuum conditions in the experimental tube and to prevent the cloud of dispersed mixtures from escaping the experimental tube before the passage of the explosion wave.

Table 2
Flammability limits for diesel fuels [1].

Fuel	Formula	Flammability limits, lean vol.%	Flammability limits, rich vol.%
Diethyl ether	$C_2H_5OC_2H_5$	1.9	36.0
Dimethyl ether	CH_3OCH_3	3.4	27.0
DF-2 diesel	$\sim C_{10}–C_{21}$	1.4	7.6
Gasoline	$C_4–C_9$	1.0	6.0
CNG	CH_4	5.0	13.9
Propane	C_3H_8	2.4	9.5
Methanol	CH_3OH	7.3	36.9
Ethanol	C_2H_5OH	4.3	19.0
Methylal	$CH_3OCH_3OCH_3$	3.3	14.9