Deflagration to detonation transition in diethyl ether mist/aluminum dust /air mixtures under weak ignition condition

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1. Introduction

Diethyl ether (DEE) is extremely flammable and 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. DEE is highly volatile and has a flash point of -45°C and its flammability limits (volume% in air from 1.9~36.0) [1] are broader than those of many fuels. DEE vapors accumulate in sufficient concentration in a closed space and easily explode with the slightest spark. 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, and even a friction produced by simply unscrewing the cap of a container may cause an explosion. Thus, the key challenges facing the future widespread use of DEE as an energy carrier are safety-related issues that have to be addressed before social acceptance can be achieved. Explosion hazards associated with the production, handling, transportation and storage of DEE must be resolved to a sufficient confidence level.

Although a number of studies have been conducted on the properties and combustion characteristics of DEE [2-8], very limited studies involve experimental investigation into its deflagration to detonation transition (DDT). In particular, investigations have not confirmed whether DEE mist/air can detonate after mix with other solid fuels, like aluminum dust(a common energetic material used in fuel-air explosives). 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 need to be addressed 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 40J. 17 pressure transducers are mounted along the tube to record the histories of pressure wave at different distances to study the DDT process.

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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, a schematic of the experimental setup is given in Fig.1. The experiment system was constructed in our previous studies (see [9-11] for further 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.

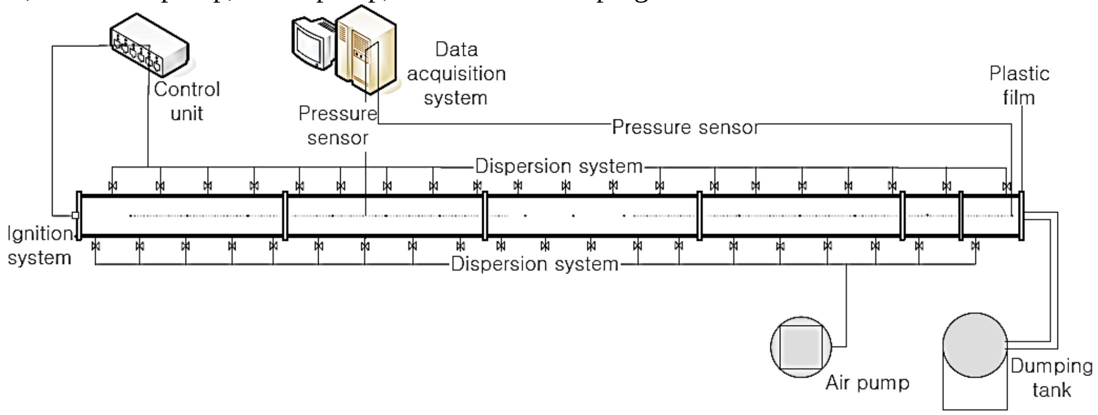


Fig.1 Schematic of experimental setup

The experimental tube includes an experimental 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. In this study, the spark energy ($1/2CV^2$) generated by electric igniter is 40 J, which is used to provide a weak ignition condition for DDT, and the electric igniter is mounted at the beginning of the tube. 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.1. At the end of the tube, a plastic film placed between the experimental tube and the dumping tank to facilitate the establishment of vacuum conditions in the experimental tube and to prevent the cloud of dispersed mixtures from escaping the experimental tube before passage of the explosion wave.

Table 1. Location of pressure transducers

No.	Distance/m	No.	Distance/m	No.	Distance/m
1	1.75	7	10.85	13	21.35
2	3.15	8	12.25	14	23.45
3	4.55	9	13.65	15	25.55
4	6.65	10	15.05	16	26.95
5	8.05	11	17.15	17	29.61
6	9.45	12	19.25		

Each liquid/dust dispersion unit consists of a pressure chamber, a solenoid valve, a directional valve, a sample can, and a spherical nozzle. The dispersion of the dust in the sample cans is controlled by solenoid valves, which are commanded by the control unit. To produce a uniformly dispersed dust cloud in the tube, 164 holes of diameter from 1.2 to 1.8 mm are drilled through each spherical nozzle. The physical state of DEE is aerosol, the diameter of the droplet size is between 0.18~0.45 mm, with the mean value of 0.36 mm.

2.2. Experimental procedure and conditions

In the experiment, DEE mist/air and DEE mist/ aluminum dust /air mixtures are studied. Measured volumes of DEE by means of a syringe and then injected into the sample cans. The aluminum dust used in the experiment is flake aluminum dust with the mean size of the flake particle ~10-16 μm and the thickness of the flake particle ~ 1.5-2 μm. Aluminum dust samples are weighed by means of an electronic balance and transferred to the sample cans. The experimental tube is filled with fresh air. The concentrations of the DEE mist and aluminum dust are calculated from the volume of the tube and the mass of those fuel samples dispersed into it. Over some ignition delay time after the dispersion of the fuels into the tube , a high voltage energy spark igniter is used to initiate the mixtures. After a number of tests, it is shown that the mixtures can be successfully ignited in 350-450 ms after the start of dispersion. After a number of tests, it is found that during the first 50 ms, the dispersion of fuels is slow, between 50 ms~450 ms, most of the fuels are dispersed to the tube, and after 700 ms, the dispersion process is completed. To make sure all the fuels disperse into the tube and to form liquid fuel mist/air mixtures thus, the time between the solenoid valve trigged and the ignition of the spark (i.e., ignition delay time) for DEE mist/air and DEE mist/aluminum dust/air are 400 and 370 ms, respectively. For the dispersing process, the air chamber is pressurized to 0.8 MPa and the duration of the dispersion is 280 ms.

The equilibrium pressure in the tube is 0.14 MPa after the liquid/dust samples has been dispersed into it. The pressure histories of the explosion are recorded by pressure transducers at different locations that are connected to the data acquisition system, which are used to analysis the deflagration to detonation transition process and the detonation structure. After the explosion experiment, the explosion products are drawn to outdoor to decrease the influence of dust release to air pollution and then the experimental tube is filled with fresh air and ready for the next shot.

3. Results and discussion

3.1.DEE mist/air

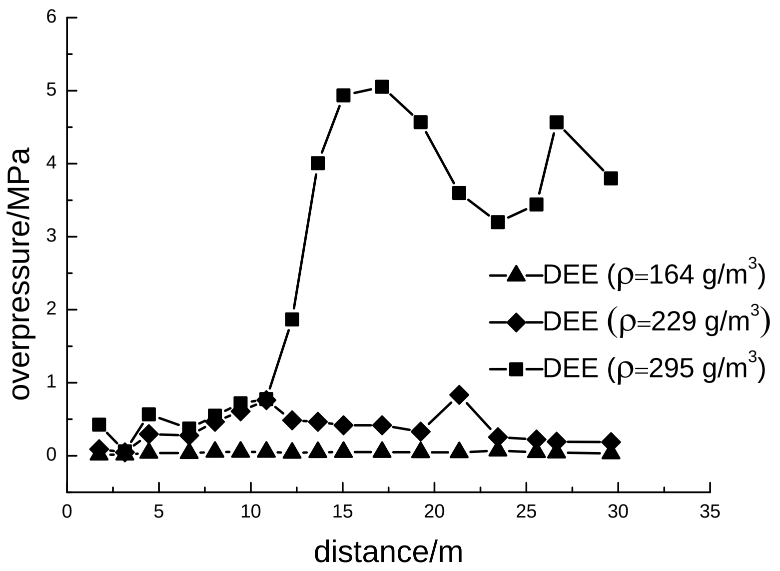


Fig. 2 Overpressure history of the pressure wave along the tube for DEE mist/air mixtures with different concentrations

DDT experiments in DEE mist/air are performed in the experimental setup described above. After DEE dispersed into the tube, DEE mist/air mixture cloud is formed and ignited by the high-voltage spark. The pressure histories from 17 pressure gauges are obtained during the DDT process. It is well known that DDT can not form if the fuel is too lean or rich, it indicates the fuel concentration would affect DDT significantly. Thus, different DEE concentrations, i.e., 164, 229 and 295 g/m^3 are used in the experiment and the pressure profiles are recorded by the data acquisition system, the overpressure profiles of three mixtures are shown in Fig.2.

One can see that, there is no pressure rise happen for DEE concentration is 164 g/m^3 , which means the mixture can not even be initiated. When DEE concentration up to 229 g/m^3, the maximum of the overpressure in the tube is merely 0.8MPa at the distance of 21.35m, the pressure decays to atmospheric pressure at the end of tube. Obviously, detonation is not formed in this case. As DEE concentration is 295 g/m^3, abrupt rise of pressure wave can be seen at the distance of 10.85m, a maximum overpressure 5.052 MPa is found at 17.15 m, it shows the deflagration successfully transits to an overdriven detonation, the overdriven detonation asymptotic decays to the CJ (Chapman-Jouguet) detonation state, the overpressure thus decreases slightly but still keeps the mean value of 3.862MPa.

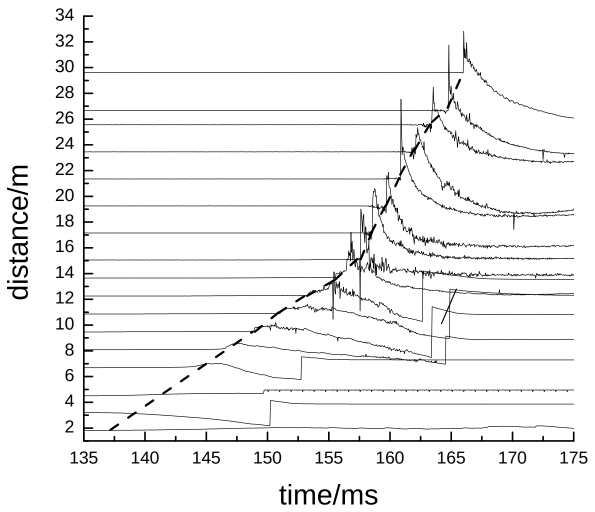


Fig.3 History of pressure wave during DDT process in DEE mist (295 g/m^3) /air mixture

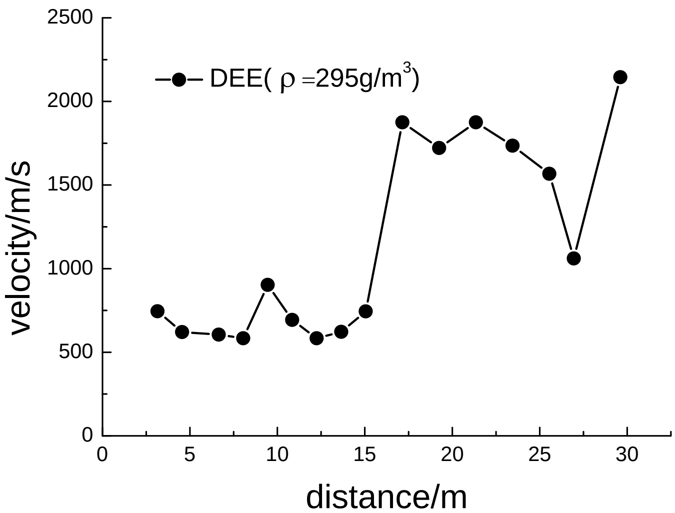
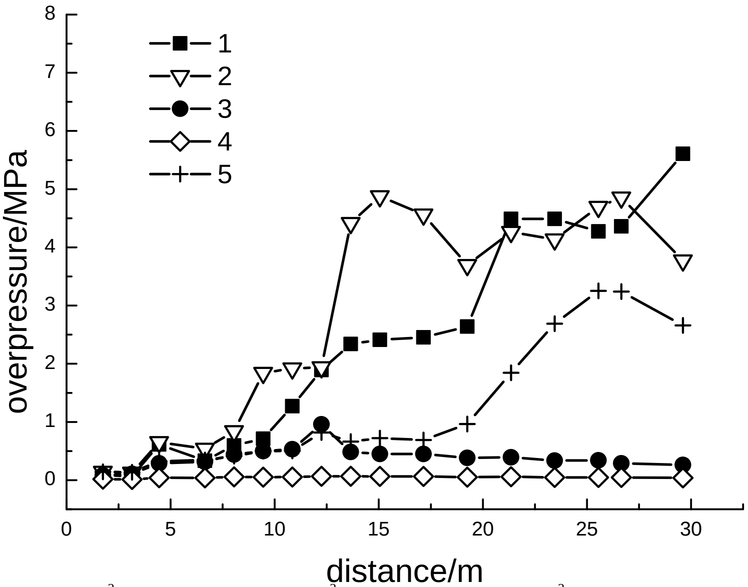


Fig.4 Variation in velocity of the pressure wave with propagation distance in DEE mist (295 g/m^3) /air mixture

The pressure histories of different locations along the tube and the trajectories of pressure wave during the DDT process with the DEE concentration of 295 g/m^3 are shown in Fig.3. The velocity of pressure wave varying with propagation distance is shown in Fig.4. Fig.4 shows that, before the distance 17.15m, flame accelerates during its propagation along the tube after initiation. A critical shock wave forms at 10.85m with a Mach number of 2.66 and overpressure of 0.78MPa, it is thus a slow reaction compress phase within this period of distance. Supported by the chemical reaction energy from the reactant, the shock-reaction complex strengthened and accelerated. A precursor shock of detonation does not form until the distance of 17.15m, the onset detonation subsequently occurs with a Mach number of 5.5 and overpressure of 5.05MPa.

3.2. DEE mist /aluminum dust/air

Mixtures of DEE mist/aluminum dust/air of five different compositions are used in the experiment. The detailed compositions and the overpressure trajectories of mixtures are shown in Fig.5. Critical shock wave can not form in #3 (DEE 262 g/m^3+aluminum dust 127 g/m^3+air) and #4 (DEE 210 g/m^3+aluminum dust 190 g/m^3+air) mixtures, it is thus no DDT phenomenon is observed. For #5 mixture(DEE 157 g/m^3+aluminum dust 386 g/m^3+air), overpressure begins to gradually increase at 19.25m and reaches at its peak of 3.25MPa, it indicates deflagration wave rather than detonation forms in this mixture. However, one can see it is a typical DDT pressure trace in #1 (DEE 367 g/m^3+aluminum dust 184 g/m^3+air) and #2 (DEE 314g/m^3+ aluminum dust 230 g/m^3+air) mixtures. For #1 mixture, the onset of detonation begins at 19.25 m, whereas for #2 mixture, from the variations of overpressure and velocity with propagation distance shown in Fig.6 and Fig.7, it is known that it is a self-sustained detonation after 15.05m, the DDT run-up distance is shorter than in #1 mixture, detailed pressure trajectories at different locations along the tube during the DDT process in #2 mixture are given in Fig.7.



1. DEE mist 367g/m^3+aluminum dust 184 g/m^3+air; 2. DEE mist 314g/m^3+aluminum dust 230 g/m^3+air; 3. DEE mist 262g/m^3+aluminum dust 127 g/m^3+air; 4. DEE mist 210g/m^3+aluminum dust 190 g/m^3+air; 5. DEE mist 157g/m^3+aluminum dust 386g/m^3+air

Fig.5 Distribution of maximun overpressure of the pressure wave along the tube for DEE mist/aluminum dust/air mixtures with different concentrations

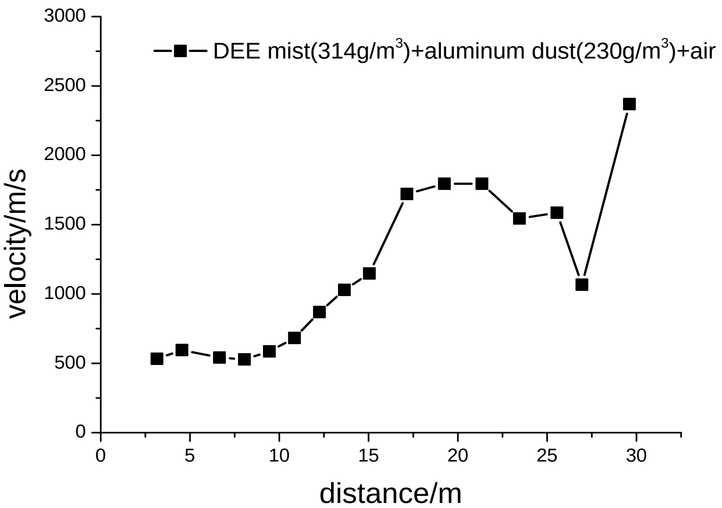


Fig.6 Variation in velocity of the pressure wave with propagation distance in DEE mist (314 g/m^3)/ aluminum dust (230 g/m^3)/air mixture

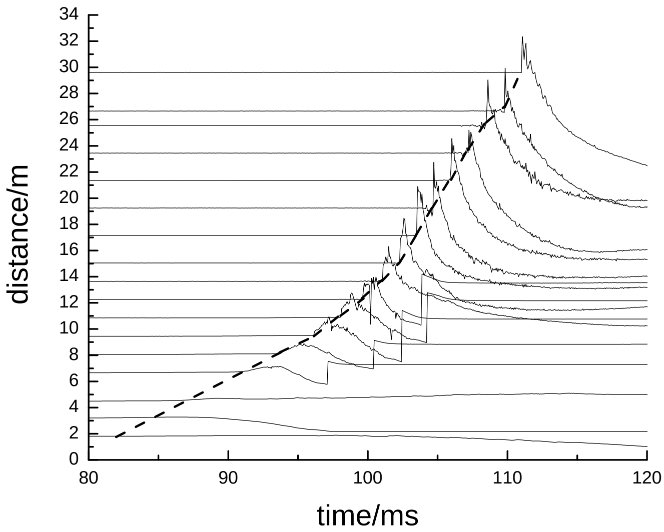


Fig.7 History of pressure wave during DDT process in DEE mist (314 g/m^3)/aluminum dust (230 g/m^3)/ air mixture

4. Concluding remarks

In this study, experiments on the transition from deflagration to detonation (DDT) in DEE mist /air and DEE mist/aluminum dust/air mixtures are carried out in a large scale tube. Different concentrations of DEE mist /air mixtures (i.e., 164, 229 and 295g/m^3) were used and results show that the deflagration can not successfully transmit into a detonation when DEE concentrations are 164 and 229g/m^3. As the DEE concentration in increased up to 295g/m^3, the deflagration accelerates and the onset detonation occurs at distance of 17.15m. Among the five different mixtures composition of DEE mist/aluminum dust/air were investigated, DDT phenomenon is only observed in the mixtures of DEE(367g/m^3)/aluminum dust(184g/m^3)/air and DEE(314g/m^3)/aluminum dust(230g/m^3)/air. The run-up distances of DDT are 19.25 and 15.05m, respectively.

Acknowledgement

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