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Explosions and deflagration-to-detonation transitions in epoxy propane/air mixtures

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ABSTRACT

The explosion and deflagration-to-detonation transition (DDT) in epoxy propane (E.P.) vapor/air mixture clouds under weak ignition conditions has been studied in an experimental tube of diameter 199 mm and length 29.6 m. E.P. vapor clouds were formed by injecting liquid E.P. into the experimental tube and evaporating of the fine E.P. droplets. The dimension and the evaporating process of the E.P. droplet were measured and analyzed. The E.P. vapor/air mixture clouds were ignited by an electric spark with an ignition energy of 40 J. The characteristics and the stages of the DDT process in the E.P. vapor/air mixtures have been studied and analyzed. A self-sustained detonation wave formed, as was evident from the existence of a transverse wave and a cellular structure. Moreover, a retonation wave formed during the DDT process in the E.P. vapor/air mixture. The influence of the E.P. vapor concentration on the DDT process has been studied. The minimum E.P. vapor concentration for the occurrence of the DDT in the E.P. vapor/air mixture has been evaluated and the variation of DDT distance with E.P. vapor concentration has been analyzed.

1. Introduction

Epoxy propane is an important raw material in chemical industries and an energetic material in power industries. It has a wide variety of applications, which include its use as an important raw material in the production of many organic compounds (polyether polyols, propylene glycol), and as a fuel for racing engines, a fuel for thermobaric weapons, and a high-performance fuel additive for internal combustion engines, aero jet engines, and pulsed detonation engines.

The dominant species in the DDT process of E.P. vapor/oxygen mixtures have been studied by means of instantaneous spectroscopic techniques by Li et al. (2004, 2005, 2006), Xiao et al. (2005) and Hu et al. (2006). In their studies, E.P. vapor/oxygen mixtures were introduced into a 0.1 m diameter and 4 m long shock tube, and combustion was initiated by a high-voltage electric spark (Li et al., 2004, 2005, 2006; Xiao et al., 2005) or a hydrogen/oxygen detonation (Hu et al., 2006). The species O, OH, CH, C_2, C_3, CO, CO_2, CHO, CH_2O, CH_3O, and H_2O were detected during the DDT process of the E.P. vapor/oxygen mixtures, among which CO, CHO, and OH were recognized as the dominant species and O was invariably formed first as an intermediate species after the leading shock (Hu et al., 2006).

Flame propagation in fuel mist/air mixtures has been studied both theoretically and experimentally by Chan and Jou (1988, 1989). The burning velocities of tetralin mist/air mixtures with different droplet sizes were determined. It was found that the burning velocity of the tetralin fuel mist/air mixtures varied with the diameter of the fuel droplets. The burning velocity reached its peak value of 150 cm/s in tetralin mist/air mixtures with a fuel equivalence ratio of 0.5. The DDT process in *n*-hexane mist/air mixtures was studied by Frolov et al. using a 51 mm diameter tube (Frolov and Basevich, 2005; Frolov et al., 2005). Their experiments demonstrated that the detonation velocity and peak overpressure in *n*-hexane mist/air mixtures were 1700–1800 m/s and 30–50 bar, respectively. The DDT process in diesel mist/air mixtures was studied using an 80 mm diameter and 2000 mm long tube connected to a 150 mm diameter and 150 mm long chamber by Smirnov and co-workers (2007). Their experiments showed that there was no onset of detonation in the diesel mist/air mixtures, and that the maximum velocity of the shock-flame complex was in the range 950–1150 m/s. Our experimental research on the DDT process in nitromethane mist/air mixture shown that the onset of detonation did not occurred with the mist concentration ranged from 360 g/m^3 to 772 g/m^3 and the corresponding equivalent ratio from 0.83 to 1.82. And the maximum velocity of the shock reaction complex ranged from 730 m/s to 1080 m/s (Liu et al., 2010).

With regard to the safe operation of industrial process and the potential usage of E.P. (propylene oxide) as a fuel or fuel additive for pulsed detonation engines (PDEs), we have studied the explosion

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and deflagration-to-detonation transition (DDT) process in E.P. vapor/air mixtures. In the DDT process, the run-up distance, defined as the distance from the ignition point to the detonation onset, is a key parameter. For the safety of industrial processes, the run-up distance has been used to characterize the detonability of mixtures. In PDEs, the detonation run-up distance provides a rough estimate of the shortest possible combustor length for a PDE operating with the flame and DDT mode of initiation. Detonation parameters, such as the detonation velocity and the detonation overpressure of the E.P. vapor/air mixture, have been measured. These data should prove valuable for the safe design of industrial processes and the performance evaluation of PDEs.

2. Experimental details

2.1. Experimental set-up

The experimental set-up used in this study was similar to that used in Liu et al. (2009, 2010). Only the main features of the experimental set-up are given here. It mainly consisted of an experimental tube, an electric ignition system, a control unit, a data acquisition system, a venting system, and a 10 m^3 dumping tank, as shown in Fig. 1.

The experimental tube was 29.6 m in length and was composed of an experimental section and a transition section. The experimental section was a 199 mm diameter 28 m long tube with 40 sets of liquid dispersion systems on both sides. Each unit of the liquid dispersion system consisted of a pressure chamber, a solenoid valve, a directional valve, a sample can, and a spherical nozzle. The dispersion of the liquid E.P., the ignition of the fuel/air mixture cloud, and the triggering of the data acquisition system were all controlled by the control unit. The transition section was 1.6 m long and had the same diameter as the experimental section.

2.2. Experimental procedure and conditions

Measured volumes of liquid E.P. were drawn-up by means of a syringe and then injected into the sample cans. The E.P. vapor cloud was formed by the evaporation of the E.P. droplets at room temperature. The concentration of the E.P. vapor was evaluated from the volume of the tube and the mass of the E.P. vapor samples dispersed into it. The E.P. vapor/air mixture was ignited by an electric spark. Experimental study showed that the E.P. vapor/air mixture could be ignited 330–530 ms after the start of dispersion. In the work described in this paper, the ignition delay time was chosen as 430 ms. For the dispersal process, the air chamber was pressurized to 8 bar and the duration of the dispersion was 280 ms. The equilibrium pressure in the tube was 1.4 bar after the liquid samples had been dispersed into it. After each explosion experiment, the explosion products were drawn-up a flue and released at a height of 40 m and the experimental tube was filled with fresh air in readiness for the next experiment.

3. Explosion and DDT process in E.P. vapor/air mixture clouds

After the liquid E.P. sample had been dispersed in the experimental tube, the vapor cloud formed by the evaporating of epoxopropane droplets was initiated by an electric spark. The pressure histories at different points along the tube and the trajectory of the pressure wave during the DDT process with an E.P. concentration of 355 g/m^3 are shown in Fig. 2. The variations in the velocity and the maximum overpressure of the pressure wave with propagation distance are shown in Fig. 3. From Figs. 2 and 3, we can see that, under the weak ignition conditions, the E.P. vapor/air mixture cloud was ignited and the flame accelerated with the propagation along the experimental tube. And sonic wave resulting from the combustion formed and propagated as a leading wave. Due to the positive feedback coupling of flame acceleration, turbulence, and chemical reaction rate, a compression wave formed, which was strengthened with the propagation distance. The compression wave developed into a shock wave at 8.05 m. A shock-reaction complex formed and propagated along the tube. At the same time, a retonation wave propagating with a velocity of 1330–1500 m/s towards the burned side of the shock-reaction complex formed at 8.05 m. Supported by the energy release from the chemical reaction, the shock-reaction complex accelerated and was strengthened. The critical shock wave leading to detonation formed at 12.25 m with a Mach number of 5.1 and an overpressure of 1.82 MPa, whereupon the maximum overpressure oscillation with the propagation distance commenced. The critical shock wave marks the transition from the slow reaction compression stage to the fast reaction shock stage. Here, the reaction shock wave propagated rapidly and detonation occurred at 15.05 m with a peak overpressure of 4.64 MPa and a velocity of 1840 m/s. It then propagated as a self-sustained detonation wave characterized by a transverse nature and a cellular structure. Thus, the DDT process of E.P. vapor/air mixtures can be divided into a slow reaction compression and a fast reaction shock stage marked by the formation of a critical shock wave that can lead to the onset of detonation.

3.1. Epoxy propane droplet diameter evaluation and vapor cloud formation

3.1.1. The formation of epoxy propane mist clouds

In the present study, the diameters of the holes in the spherical nozzle ranged from 1.2 to 1.8 mm. The initial pressure of the pressure chamber was 8 bar, and the atomizing gas-to-liquid ratio was 1.4. From the droplet diameter evaluation method given in Sovani et al. (2001), the initial diameters of the liquid droplets in mist clouds were roughly in the range 20–30 μm. The diameters of the droplets were measured by the smoke foil technique. The droplet's mean diameter of the E.P. mist clouds was 25 μm.

3.1.2. Droplet evaporation and vapor cloud formation

E.P. has a high vapor pressure and the fine E.P. droplets suspended in tube air evaporate quickly. The lifetime or evaporation

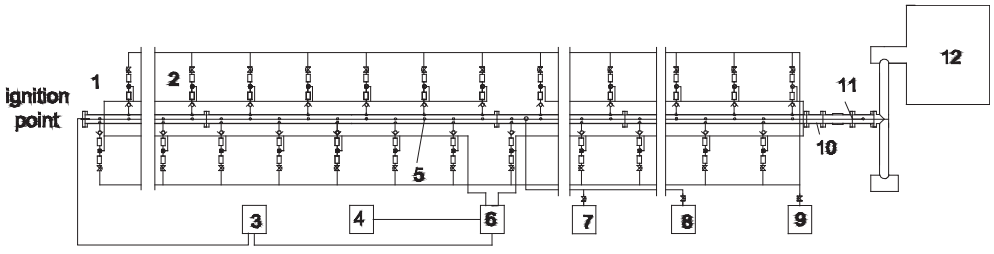

Fig. 1. Schematic diagram of the experimental set-up. 1 – experimental tube 2 – dispersion system 3 – ignition system 4 – data acquisition system 5 – pressure sensor 6 – control unit 7 – vacuum pump 8 – venting system 9 – air pump 10 – transion section 11 – plastic film 12 – dumping tank.