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Unconfined silane-air explosions

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ABSTRACT

In the present work, field experiments on unconfined explosions of silane-air mixture were performed by utilizing a cubic frame covered with a thin vinyl film for release confinement and a sufficiently high release velocity of silane from a tube to prevent ignition. The silane release was controlled by a mass flow controller such that the amount before the ignition can be accurately controlled. Ignition from the tube exit locating at the center of cubic frame was initiated by shutting off the silane flow. To control precisely the final concentration in the cube, air in the cube was pumped out to the exact amount of silane feed in prior to feeding silane. High-speed video camera and pressure sensors were used to record the blast wave and flame propagation. Experiments on a wide range of silane concentration and total silane mass were performed. Finally, the unconfined gas explosion models by Dorofeev (1996) and the acoustical theory for expanding flame by Thomas and Williams (1966) are used to predict the overpressure from the recorded flame histories. Recommendations are made regarding the worst case modeling of silane release and explosion.

1. Introduction

Silane is an important specialty gas widely used in advanced technology industries as a silicon source. Silane is also a pyrophoric gas with autoignition temperature well below ambient temperature. However, silane may be released into air without prompt ignition by flowing at sufficiently high velocity and later ignited upon flow decay, shutoff or disturbance (Tsai et al., 2010). The delayed ignition may create a significant overpressure and blast effect if the released silane is accumulated (Ngai et al., 2007). The silane release delayed ignition and explosion have contributed to numerous incidents with injuries and fatalities (Chen et al., 2006; Chang et al., 2007).

The destructing effects from silane release and explosion have attracted several investigations aiming at better characterization of the overpressure event. Cruice (1982) was among the first to report the silane release and explosion event. Cruice (1982) performed several tests with silane release into a gas cylinder cabinet from a discharge orifice of 0.38 mm or 1 mm. In one test involving silane source pressure of 3.55 MPa and 1 mm orifice, ignition was not observed during the initial 10.5 s of release but 5 s after flow shutdown the cabinet was completely blown apart. Pressure recorded inside the cabinet showed a pulse of over 0.66 MPa at rise rate above 689.7 MPa/s. Although pressure drop from the silane source was recorded and used for estimating the amount of release, there was no information on the modeling of the overpressure event.

Britton (1990) carried out large-scale silane release tests from a vertical four-inch diameter pipe. Overpressures were measured using two sound level meters. The maximum recorded overpressures were 150 dB (0.63 kPa) at 4.82 m from the pipe exit, and 147 dB (0.45 kPa) at 9.63 m from pipe exit. The cause of the measured overpressure was said to be flame acceleration up the jet as the maximum overpressure did not correspond to the instant of ignition but occurred later during the combustion. The peak flame speed relative to the unburned gas was at least 115 m/s based on high-speed photography. Again, pressure and temperature drop from the silane source were recorded and used for estimating the amount of release. Nevertheless, there was no information on the modeling of the overpressure event.

Chowdhury (1997) reported the large-scale silane release tests under the guidance of the Compressed Gas Association (CGA). The

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results of release tests consisted of four tests with explosions followed by a flame jet, one test with immediate ignition and one test with neither immediate nor delayed ignition. For tests with explosion, a short delay of about 1 s after release was observed followed by an explosion and a subsequent flame jet. The overpressure events were modeled by a TNT equivalency model using a yield factor of 1 and accounting for one reflecting surface. The mass of silane accounting for the bulk autoignition was estimated by using a two dimensional jet dispersion modeling and integrating the jet concentration profile from an upper limit of 96.5%–4.5%. Chowdhury (1997) emphasized that such results were considered preliminary and further detailed analysis was needed.

Recently, Ngai et al. (2015) performed extensive tests on large-scale silane release and explosion. Both unconfined and partially confined, obstructed silane releases were also performed. Unconfined explosion of silane release was only achieved with a jet release and an external ignition source. Without an external source, the unconfined silane jet release was rapidly dispersed in air and the resulting blast was negligible. In most cases with overpressure events, an obstructing plate was placed in front of silane discharge to partially confine the release. Silane mass was estimated from pressure drop in the source cylinder. The blast model by Dorofeev (1996) for a gas detonation was used and compared reasonably well with the measured overpressures. For unconfined tests, silane mass was not estimated and the measured overpressures were not modeled. Although the obstruction added to silane release may help to confine the silane release, it also interfered with the blast wave propagation and complicated the estimation of silane mass during ignition. Thus, there remains lack of consistent and accurate data on unconfined silane release and explosion such that a proper explosion modeling can be verified. This work aims to develop an experimental setup for unconfined silane release and explosion test.

The unconfined explosion for flammable gases have been studied by using, for example, soap bubbles (Kim et al., 2013), latex balloons (Otsuka et al., 2007), and plastic tents (Kim et al., 2015a,b). Both soap bubbles and latex balloons require a premixed gas feed and thus cannot be applied to pyrophoric silane. On the other hand, a large plastic tent may offer sufficient space for silane release into air without prompt ignition. Thus, the plastic tent provides the opportunity for studying unconfined silane explosion and will be utilized in this work. Additional efforts in this work were placed on the precise control of release silane mass and concentration. The results will offer a consistent, reproducible data for unconfined silane-air explosion.

2. Experiments

To achieve unconfined silane cloud explosions in air, it is necessary to confine the silane release without confining the explosion, and also control the ignition to prevent prompt ignition upon mixing with air. Silane release confinement is achieved by a plastic tent made from a cubic frame wrapped with a vinyl film. Pressurization by air in the tent found that the vinyl film ruptured upon pressure exceeded 0.5 kPa. Two different sizes of frame were used: 0.3 m × 0.3 m × 0.3 m and 0.4 m × 0.4 m × 0.4 m. Silane vent tube was inserted into the center of the tent. To avoid the prompt ignition upon silane release into air, it is necessary to release the silane with sufficient velocity to quench the ignition kernel (Tsai et al., 2010). In addition, the vent tube should be free from air to avoid mixing and premature ignition of silane-air in the vent tube. In this work, we adopted the same steady-state release configuration as Tsai et al. (2010) with a four-way switching valve to establish a parallel, steady flow of silane into a burn box and nitrogen into the test tent. A vent tube with an internal diameter of 2 mm was used to ensure a sufficiently high vent flow velocity and prevent premature ignition. Upon switching, silane was flowed steadily at desired flowrate into the tent with nitrogen preceded. To minimize the nitrogen flow into the test box, the nitrogen flow was kept to a minimum and then shutoff upon steady flow of silane was established. The amount of silane in the box can be controlled and calculated from the silane flowrate and release time.

Although the amount silane flowing into the tent was controlled accurately, the silane flowed into the tent will either pressurized the tent if there is no leak or leak out of the tent rendering the amount of silane uncertain. The problem was resolved by placing an additional four-way switching valve before the vent tube. Before silane was released, the air in the tent was pumped out by a vacuum pump to the exact volume of silane feed. The vinyl tent was also sealed to air tight. Upon vacuum suction, the sides of cubic tent formed concave surfaces but recovered to flat after silane feed. With careful switching of air pumping out and silane feed in, the silane mass and averaged concentration in the tent was controlled accurately and reproducibly. Upon the desired amount of silane was released, a pneumatic valve located between the two switching valves was activated to shut off the flow which in turn caused the silane to autoignite at the vent tube exit. The ignition then acted as the ignition source in the center of the tent that triggered the explosion. Fig. 1 shows the release configuration.

There were two other possible sources of uncertainties in the silane concentration: imperfect mixing of silane in air and errors in silane feed. Owing to the pyrophoric nature of silane, external mechanical mixing of silane and air is impossible. The current silane-air mixing was done purely by silane jet momentum and the mixing time was also limited by jet flow time. A simple mixing test with smoke fed into tent at similar flow rate found that at least 20 s was required for the smoke jet and air in the tent to be properly mixed. Thus, the silane flow rate was adjusted such that total silane feed time to be greater than 25 s to ensure well mixing between silane and air. For higher silane concentration, the feed duration was longer and thus uncertainty was also smaller. The imperfect mixing remained near the jet development region where shear flow and entrainment take place. This was further minimized as there was a delay of about 0.5 s between the flow shutoff and ignition occurrence such that the jet flow can be dissipated completely. The 0.5 s delay in silane flow shut off may also gave a maximum of about 2% relative error in silane feed or ±0.3% by volume in silane concentration for 0.4 m cubic frame and ±0.6% by volume in silane concentration for 0.3 m cubic frame.

Overpressures from the explosion were measured on the ground surface with ten Kistler 211B quartz pressure sensors. The layout of the sensors is shown in Fig. 2. Pressure data were acquired though YOKOGAWA DL850E data acquisition recorder at a rate of 200,000 Hz. Two high-speed video cameras, Phantom 711 and 51, were used to acquire the flame propagation at a rate of 2000–10,000 frames per second. Additional color video cameras were placed next to the high speed video cameras. For sake of safety, all flow control and data acquisition were placed at least 30 m away from the test tent. All tests were done in a fire fighting training ground located in suburb of Kaohsiung City which was at least 200 m away from any traffic road. Ambient temperature and relative humidity at time of test varied from 27 to 32 °C and 60–75%, respectively.

3. Results and discussion

3.1. Results of flame propagation

Tests with a wide range of silane concentration were carried out to cover fuel rich and fuel lean range. The maximum amount of

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