UNCONFINED SILANE VAPOR CLOUD EXPLOSIONS

Hsiao-Yun Tsai, Yu-Jhen Lin, Yan-Cheng Chang, Jyun-Sian Lin, Jenq-Renn Chen

Department of Safety, Health and Environmental Engineering, National Kaohsiung First University of Science and Technology, Yenchau, Kaohsiung, Taiwan

Introduction. Silane is an important specialty gas widely used in advanced technology industries. Silane is also a pyrophoric gas that normally ignites upon release into air. Under certain condition, however, silane may be released at high velocity without prompt ignition and later ignited upon flow decay, shutoff or disturbance [1]. The delayed ignition may create a significant blast effect if the released silane is accumulated [2]. The silane delayed ignition and explosion have contributed to numerous incidents with injuries and fatalities [3,4]. Despite the destructing effect, there remains lack a systematic and quantitative studies on the silane explosion blast which requires the simultaneous control of silane ignition as well as silane accumulation in air. For example, Ngai et al. [2] used a gas cabinet while Ngai et al. [5] used a vertical plate to confine the silane release. Although the obstruction added to silane release may help to confine the silane release, it also interfered with the blast wave propagation and conplicated 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 vapor explosion modeling can be verified.

The unconfined vapor explosion for flammable gases have been studied by using, for example, soap bubbles [6,7], latex balloons [8], and plastic tents [9]. Both soap bubbles and latex balloons require a premixed gas feed and thus cannot be applied to pyrophoric silane. On the other hand, a sufficiently large plastic tents may offer 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.

In the present work, unconfined explosions of silane-air mixture are studied by utilizing a cubic frame covered with a thin vinyl film for release confinement and a sufficiently high release velocity 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 in the center od cubix frame was actuated by shutting off the silane flow. High-speed video camera and pressure sensors were used to record the blast wave and flame propagation. It is found that the flame acceleration and overpressure are strongly affected by silane concentration and total silane mass. The results are also compared with the large scale, partially obstructed CGA tests. The comparison stressed again the important role of silane concentration in the silane combustion and explosion.

Experimental setup. To achieve unconfined silane/air explosions, it is necessary to confine the silane release, but not silane explosion, and also control the ignition to prevent prompt ignition upon mixing with air. Silane release confinement is achieved by a cubic frame wrapped by a vinyl film. Three different sizes of frame were used: 0.3m×0.3m×0.3m, 0.4m×0.4m×0.4m and 0.5m×0.5m×0.5m. Silane vent tube was inserted into the center of the box. 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 [1]. In addition, the vent tube should be free from air to avoid premature mixing and ignition of silane/air in the vent tube. In this work, we adopted the same steady-state release configuration as Tsai et al.[1] with a four-way switch valve to establish a parallel, steady flow of silane into a burn box and nitrogen into the test box. Upon switching, silane was flowed steadily at desired flowrate into the box with nitrogen preceded. The nitrogen flow was kept to a minimum and then shutoff upon steady flow of silane was established to minimize the nitrogen flow into the test box. The amount of silane in the box can be controlled and calculated from the silane flowrate and release time. Upon the desired amount of silane was released, a pneumatic valve located near the box was activated to shut off the flow which in turn caused the silane to autoignite at the vent stub. The ignition then acted as the ignition source in the center of the test box that triggered the explosion. Figure 1 shows the release configuration.

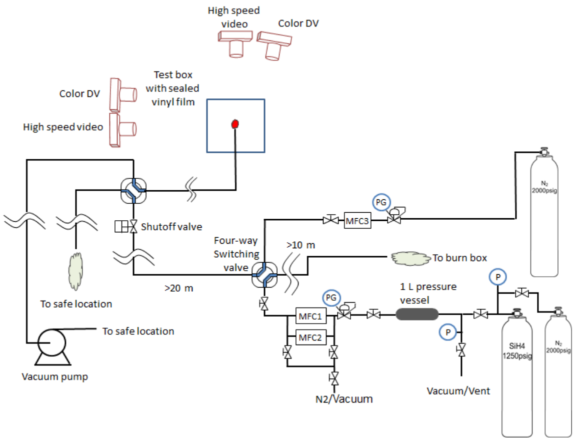

Figure 1. Release configuration.

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 Figure 2. Pressure data were acquired though Ypkogawa DL850E data acquisition system 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 1000~2000 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 box. 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.

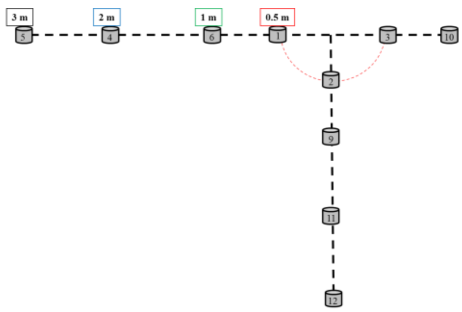

Figure 2. Layout of pressure sensor.

Results. Figure 3 shows the typical results of flame propagation for silane concentration 15.59 % in a 0.4 m cubic frame. It is clear that the ignition at the vent tube created a flame ball which expanded spherically until it reached the box frame where the flame become aspherical and turbulent. Figure 4 show its overpressure histories at different locations. The pressure and shock waves were roughly symmetric as seen from the high-speed videos and the pressure transients in different directions. These measured peak overpressures and blast wave trajectory for the test are generally consistent with the ideal relationship between the overpressure and shock velocity [10].

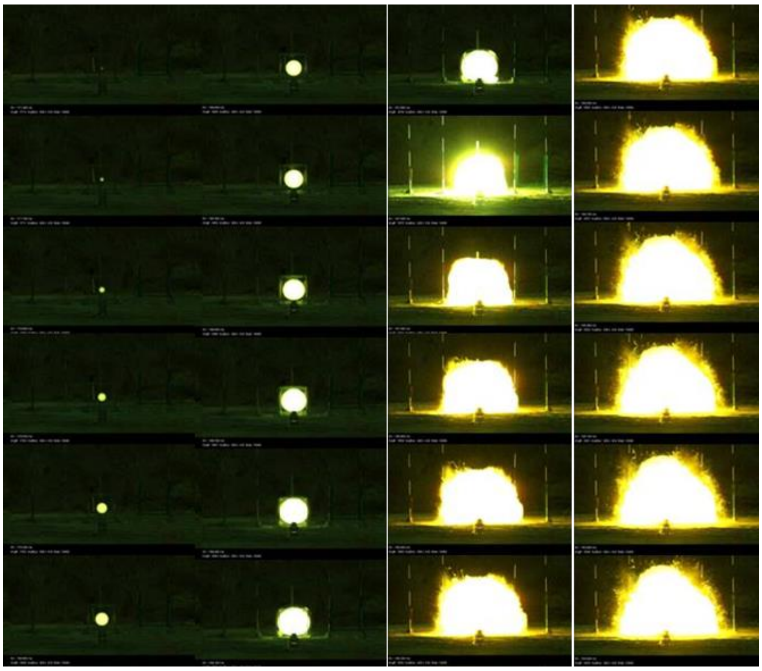

Figure 3. Typical results for flame propagation for different silane concentration 15.59 % in a 0.4 m cubic frame. Each frame differs by 0.3 ms.

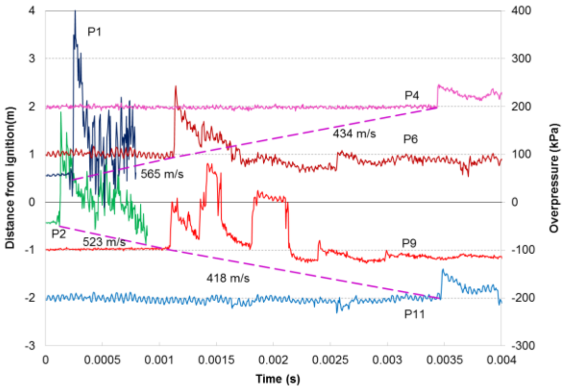

Figure 4. Overpressure histories of vapor explosion from silane concentration of 15.59 % in a 0.4 m cubic frame.

Figure 5 summarized the peak overpressures for different silane concentrations at different locations for the two different sizes frame. It can be seen that the overpressure is a strong function of silane concentration. For explosions with a certain range of silane concentration, the fast acceleration developed into a shock with a strong overpressure greater than 200 kPa. In addition to the silane concentration, the overpressure is also affected by the total amount of silane in the cloud as seen in comparison of different frame sizes. Figure 6 summarized the recorded flame radius for different silane concentrations for the two different sizes frame. It is clear that the tests with strong overpressures were a result of sharp increase in flame radius and thus flame acceleration.

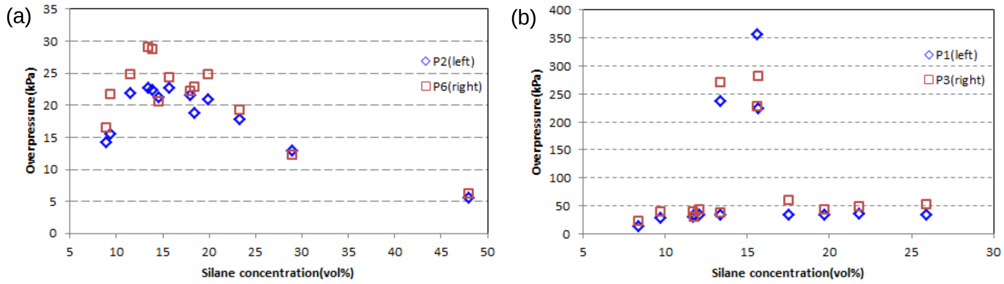

Figure 5. Summary of peak overpressures for different silane concentrations at different locations for (a) 0.3 m frame (b) 0.4 m frame.

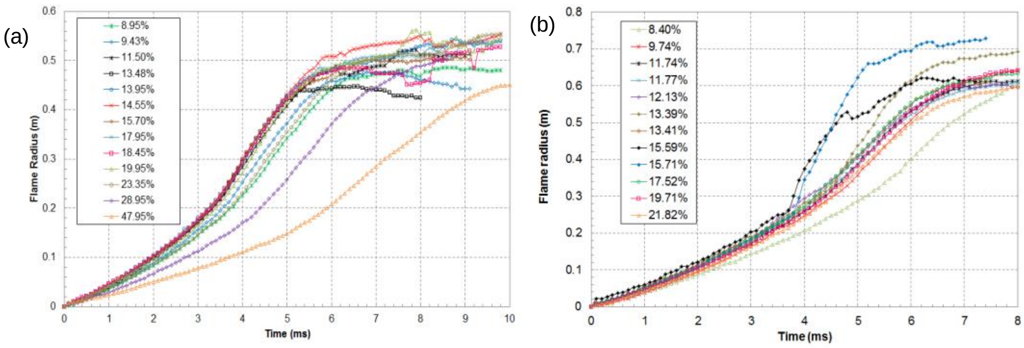

Figure 6. Summary of flame radius for different silane concentrations for (a) 0.3 m frame (b) 0.4 m frame.

Thomas and Williams [11] proposed an acoustical theory for predicting overpressure generation with an propagating flame:

$$p = \frac{\rho}{d}\frac{E-1}{E}\left\{2r\left(\frac{dr}{dt}\right)^2 + r^2\frac{d^2r}{dt^2}\right\}, \tag{1}$$

where p is the overpressure (Pa), ρ is the density (kg/m^3), E is the volumetric expansion coefficient of burnt and unburnt gases, d is the distance from explosion center to overpressure measurement (m), r isthe flame radius (m), dr/dt is the flame speed (m/s), and d^2r/dt^2 is the flame acceleration (m/s^2). For silane combustion, the volumetric expansion coefficient depends on the silane combustion stoichiometry. For $SiH_4 + 2\ O_2 \rightarrow SiO_2 + 2\ H_2O$ and $SiH_4 + O_2 \rightarrow SiO_2 + 2\ H_2$, E is 1 and 1.5, respectively. As the overpressure depends strongly on non-unity E, we assumed a constant 1.5 for E. The results are shown in Figure 7. The results showed reasonably well agreement between the current overpressure measurement and the acoustical theory model, which confirmed again the validity of the current tests and overpressure measurements. Work is currently underway to develop a predictive model for predicting silane ovepressure based on size of vapor cloud and silane concentration. The results will greatly benefit the reliability of risk assessment of silane accidental release and explosion.

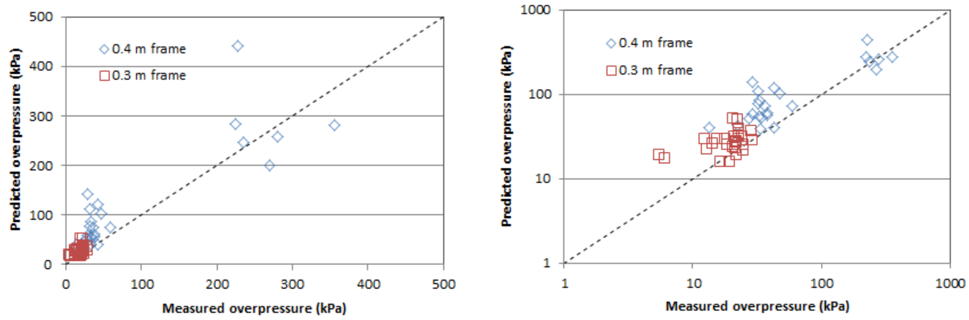

Figure 7. Results of overpressure prediction with the acoustical theory of Thomas and Williams.

Conclusions. Unconfined explosions of silane-air mixture are studied by utilizing a cubic frame covered with a thin vinyl film for release confinement and a sufficiently high release velocity from a vent tube to prevent prompt ignition. A mass flow controller was used to control the amount of release. Ignition is actuated by shutting off the silane flow. High-speed video camera and pressure sensors were used to record the blast wave and flame propagation. It is found that the overpressure and mode of explosion are dictated mainly by silane concentration. The overpressure is also found to relate to flame propagation and can be predicted by acoustical theory for flame propagation. The results are expected to benefit the modeling of silane combustion and explosion.

LITERATURE

1. **Tsai H.Y., Wang S.W., Wu S.Y., Chen J.R., Ngai E.Y., Huang K.P.P.** Experimental studies on the ignition behavior of pure silane released into air // J. Loss Prev. Process Industries. 2010. Vol. 23, P.170-177.
2. **Ngai, E.Y., Huang K.P.P., Chen J.R., Shen C.C., Tsai H.Y., Chen S.K., Hu S.C., Yeh P.H., Liu C.D., Chang Y.Y., Peng D.J., Wu, H.C.** Field tests of release, ignition and explosion from silane cylinder valves // Process Saf. Prog. 2007. Vol. 26, P.265-282.
3. **Chen J.R., Tsai H.Y., Chen S.K., Pan H.R., Hu S.C., Shen C.C., Kuan C.M., Lee Y.C., Wu C.C.** Analysis of a silane explosion in a photovoltaic fabrication plant // Process Safety Prog. 2006. Vol. 25, P.237-244.
4. **Chang Y.Y., Peng D.J., Wu H.C., Tsaur C.C., Shen C.C., Tsai H.Y., Chen J.R.** Revisiting of a silane explosion in a photovoltaic fabrication plant // Process Safety Prog. 2007. Vol. 26, P.155-157.
5. **Ngai E.Y., Fuhrhop R., Chen J.R., Chao J., Bauwens C.R., Mjelde C., Miller G., Sameth J., Borzio J., Telgenhoff M., Wilson B.** CGA G-13 Large-Scale Silane Release Tests – Part II. Unconfined Silane-Air Explosion // J. Loss Prev. Process Ind. 2015. Vol. 36, P. 488-496.
6. **Kim W.K., Mogi T., Dobashi R.** Fundamental study on accidental explosion behavior of hydrogen-air mixtures in an open space // Int. J. Hydrogen Energy 2013. Vol.3, P.88024-8029.
7. **Kim W.K., Mogi T., Dobashi R.** Effect of propagation behaviour of expanding spherical flames on the blast wave generated during unconfined gas explosions // Fuel 2014. Vol. 128, P. 396–403
8. **Otsuka T., Saitoh H., Mizutani T., Morimoto K., Yoshikawa N.** Hazard evaluation of hydrogen–air deflagration with flame propagation velocity measurement by image velocimetry using brightness subtraction // J. Loss Prev. Process Ind. 2007. Vol. 20, P. 427–432.
9. **Kim W.K., Mogi T., Kuwana K., Dobashi R.** Self-similar propagation of expanding spherical flames in large scale gas explosions // Proc. Combust. Inst. 2015. Vol. 35, P. 2051–2058.
10. **Kinney G.F., Graham. K.J.** Explosive Shocks in Air, Second Ed., Springer-Verlag, New York Inc., 1985.
11. **Thomas A., Williams G.T.** Flame noise: sound emission from spark-ignited bubbles of combustible gas // Proc. Royal Soc. London. A, Math. Phys. Sci. 1966. Vol, 294, P.449-466.