Experiments with Flame Propagation in Inhomogeneous Hydrogen–Air Clouds in a Small Vessel

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Introduction

Leaking hydrogen gas represents a significant hazard (Alcock et al., 2001). In Porsgrunn, Norway, there was an explosion in an ammonia plant the 6th of July, 1985. A hydrogen gas leakage resulted in a severe accident, causing massive material damages and killing two people. The factory building confined the gas cloud forming a flammable cloud. The explosion was powerful, due to the degree of confinement and the reactivity of the gas, and was most likely a detonation. Based on this accident this paper describes a small scale approach to hydrogen gas releases and hydrogen gas explosions. A simple model of the factory building has been made in small scale. The experiments performed in this model include various hydrogen gas flows at different constant ignition times as well as experiments with various gas flows using continuous ignition. These experiments are the first phase of a more extensive experiment program where the goal is to perform large scale tests simulating the accident in 1985.

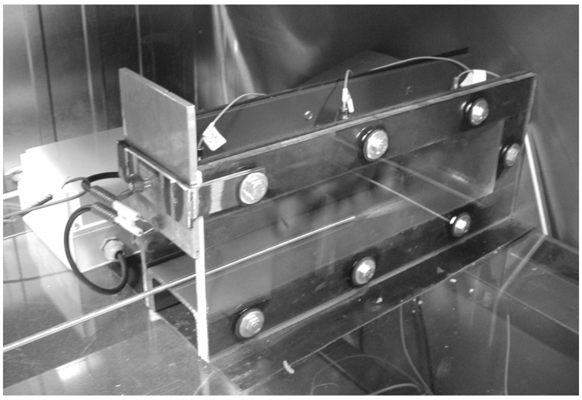

Figure 1. Experimental setup.

Experimental setup

The experimental setup, as shown in Figure 1, consists of a rectangular steel vessel with dimension L = 445 mm, W = 106 mm and H = 100 mm, with polycarbonate sidewalls. The upper part of the open end of the vessel was blocked by an adjustable aluminium wall. All the present experiments were performed with the aluminium wall blocking 20 mm by 106 mm of the open end (i.e. $A/V^{2/3} = 0.075$). In the experiments the vessel was filled with premixed hydrogen-air, or pure hydrogen respectively, using a 3 mm steel tube with the outlet placed on the floor at 250 mm inside the vessel. The flow was controlled by flow meters. The ignition source was a 280 W continuous spark system. The ignition point was 10 mm below the roof of the vessel on the inside of the aluminium wall. Three Kistler 7001 pressure transducers measured the explosion pressures and the results were recorded digitally. The location of the pressure transducer #1, #2 and #3 were respectively 35 mm, 225 mm, and 420 mm from the opening, placed on the roof of the vessel.

Results and Discussion

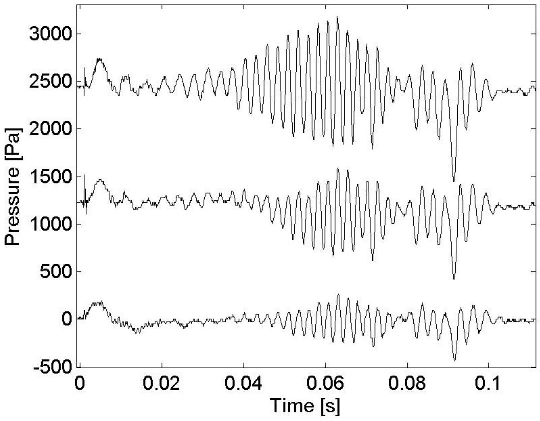

Figure 2. Pressure records for 6.1 l/min hydrogen and ignition after 60 sec.

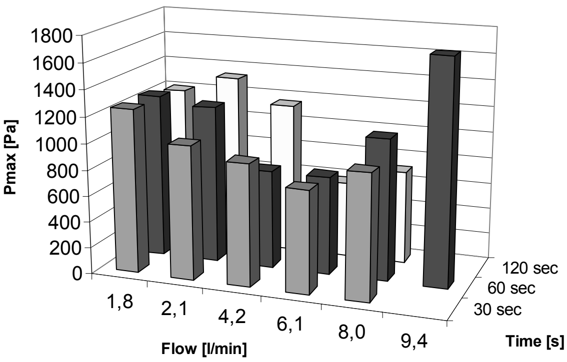

Figure 3. Maximum pressure vs. flow rate and time of ignition .

In the first test series experiments were performed with pure hydrogen, flow rates ranging from 1.0 l/min to 9.4 l/min and with ignition after 30, 60 and 120 sec. Figure 2 shows a typical pressure record. As expected, in this small scale and with $A/V^{2/3} = 0.075$ the explosion pressures were low. Maximum pressure was less then 2 kPa. The pressure records showed in most cases a small initial pressure increase followed by a high frequency oscillating pressure build-up. This type of pressure oscillations are according to Cooper et al. (1986) a result of the coupling of the combustion process and the acoustic modes of the vessel. The oscillating pressure records are highest at the transducer located near the closed end wall (i.e. 420 mm from the opening). Figure 3 shows these maximum pressures for all the experiments with ignition after 30, 60 and 120 sec. The results in the figure indicate that the maximum pressure has minimum for flow rates of 4 to 6 l/min.

In the second test series experiments were performed with pure hydrogen, flow rates ranging from 1.0 l/min to 9.4 l/min and with the ignition system continuously on. Figure 4 shows the time of ignition for the different flow rates. For flow rates more than 4 l/min the time of ignition was approximately 4 sec. For flow rates lower than 4 l/min the time of ignition increased with decreasing flow rates. For flow rates less than 1.8 l/min no ignition occurred. The maximum pressures from these experiments are shown in Figure 5. In contrast to first test series we obtain the highest pressure for flow rates of 4 to 6 l/min. Simulations of the cloud formation may explain this difference in results.

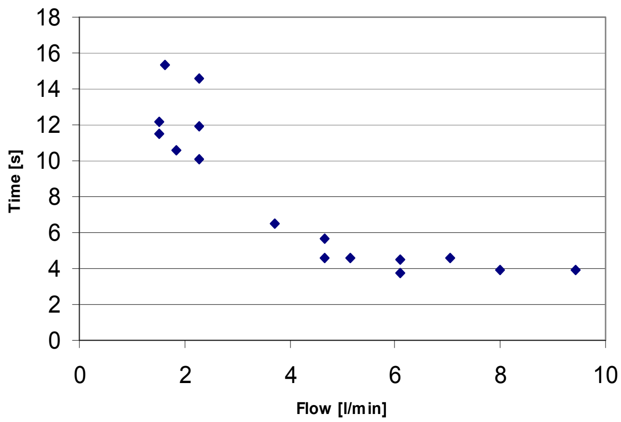

Figure 4. Time of ignition.

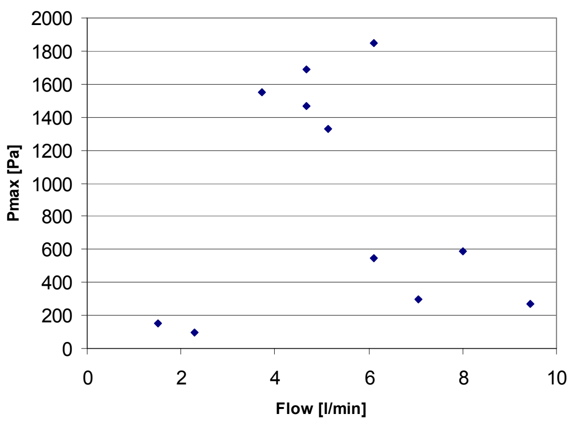

Figure 5. Maximum pressure.

The last test series was performed with homogeneous hydrogen-air clouds. The hydrogen concentration was ranging from 16% to 80%. During gas filling the open end was covered with a thin plastic film. This film was removed immediately before ignition. The maximum pressure obtained is compared with the inhomogeneous tests in Figure 6. The maximum observed pressure was slightly higher for the inhomogeneous case then for the homogeneous case.

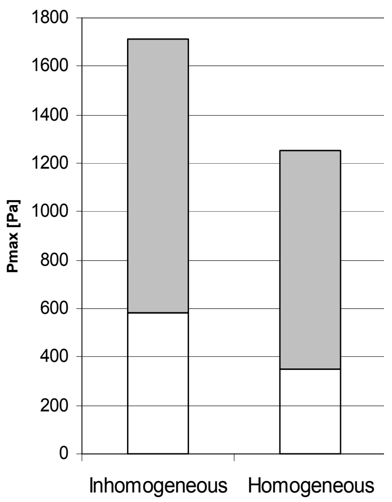

Figure 6. Observed pressures in the homogeneous and inhomogeneous tests.

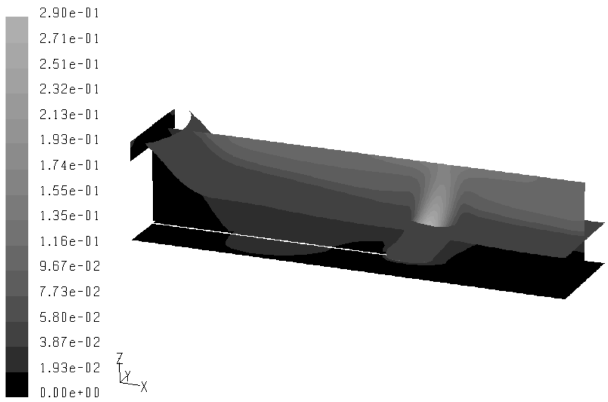

Figure 7. Fluent® simulation 3-dimensional contour plot of the hydrogen mole fraction after 10 seconds, at 8.0 l/min volume flow.

Numerical simulations

The experimental setup was modelled in Fluent® 6.1, using Gambit® as the grid generator. The geometry dimensions were set to x = 445 mm, y = 106 mm and z = 100 mm, based on the inner volume of the physical design. The upper wall at the front was 20 mm, leaving a 80 mm opening in the front wall. The grid consisted of 110419 rectangular cells. The hydrogen-air mixture simulations were segregated and unsteady. Figure 7 represents a 3 dimensional contour plot of the hydrogen mole fraction after 10 seconds, at 8.0 l/min volume flow. The plane in the figure is an iso-surface where the hydrogen mole fraction equals 4.0 percent. These preliminary results indicate ignition (i.e. LFL at the spark) after 10 seconds for the 8.0 l/min case. However, the thermal effect of the ignition source is not included in the simulations, however the thermal effect may be of importance for the results.

Conclusions

Experiments with flame propagation in homogeneous and inhomogeneous hydrogen–air clouds in a small vessel have been carried out. The measured pressures were less then 2kPa. The maximum pressure was slightly higher for the inhomogeneous case than for the homogeneous case. The pressure build-up was controlled by the interaction of the combustion process and the acoustics. As reviewed by Molkov et al. (2000), there exist a lot of experimental results for homogenious fuel-air deflagrations in unobstructed enclosures. However, experiments with inhomogenious deflagrations and detonations are limited (Roy et al., 2004). The process of dispersion, ignition and flame propagation in inhomogeneous hydrogen–air clouds in vessels and buildings is very complex and needs to be investigated further, both in small scale and in larger scale.

References

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