EXPERIMENTS WITH RELEASE AND IGNITION OF HYDROGEN GAS IN A 3 M LONG CHANNEL

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ABSTRACT

This paper presents results from laboratory experiments with hydrogen dispersions and explosions in a 3 m long channel. Our objective is to get a better understanding of the phenomena and to develop tools that can analyse hydrogen dispersions and explosions. A total of 5 test series were performed with flow rates of hydrogen from 1.8 dm³/min to 75 dm³/min. The propagation of the combustible hydrogen-air cloud in the channel was observed from high-speed video recordings. The hydrogen-air cloud in the channel behaves as a gravity current and the flow appears to be well described by Froude scaling with a length scale corresponding to the height of a layer of 100 % hydrogen. The Froude numbers observed in the experiments are in good agreement with the theory of "light-fluid intrusion" for gravity currents found in the literature. Numerical simulations with the Flacs code correlate well with the experimental results. The flame propagation indicated that approximately half the height of the channel was filled with combustible mixture. We believe that this Froude scaling can be useful as a tool to analyse the consequences of hydrogen release in buildings, channels and tunnels.

NOMENCLATURE

Fr	Froude number, [-]
g	acceleration of gravity [m/s^2]
h	height of cloud, [m]
h_H	the height of 100 % hydrogen, [m]
L	length from end of channel to ignition point, [m]
Q	volume flow rate, [m^3/s]
u	velocity, [m/s]
u_F	frontal velocity, [m/s]
w	channel width, [m]
H	channel height [m]
ρ_1	density of air, [kg/m^3]
ρ_{H}	density of hydrogen, [kg/m^3]
$\Delta\tau$	time of ignition, [s]
Φ	dimensionless height $\Phi = h/H$, [-]

1.0 INTRODUCTION

When we are using hydrogen the possibility of unintended leaks is always present. Such leaks may result in fires and explosions. It is well known that a hydrogen-air cloud can explode violently and thereby cause severe damage [1]. In Norway, there was an explosion in an ammonia plant in July, 1985. The accident was caused by a hydrogen leak inside a building. The result was a severe explosion and fire with massive material damages and two fatalities. A report of this accident was presented at the 1st ICHS conference in Pisa [2]. The use of hydrogen in the transport sector raises questions about the safety for hydrogen vehicles in garages and road tunnels. The hazard, when hydrogen is leaking, is strongly linked to the dispersion of hydrogen. Fortunately hydrogen gas is lighter then air and buoyancy often causes rapid dispersion. This paper presents results from experiments with hydrogen dispersions and explosions in a laboratory scale channel. These experiments are part of a more extensive experiment program where the goal is to perform larger scale tests simulating the accident of 1985. Our objective is to get a better understanding of the phenomena and to develop tools that can analyse hydrogen dispersions and explosions in buildings, channels and tunnels.

2.0 EXPERIMENTAL SETUP

The experimental setup, as shown in Fig. 1 and Fig. 2, consisted of a horizontal square steel channel, 3 m long, 0.1 m wide and 0.1 m high. The sidewalls were transparent and made out of polycarbonate. The channel was open in one end and closed in the other. The volume of the channel was 30.0 dm³.

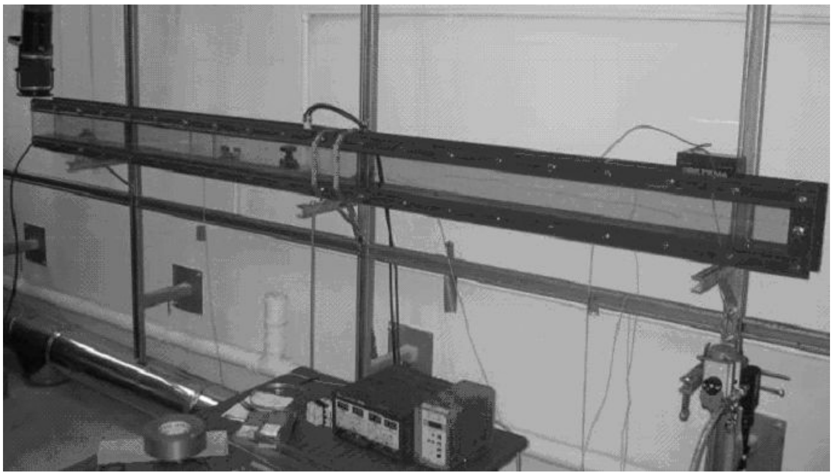

Figure 1. Experimental setup of the 3 m long channel.

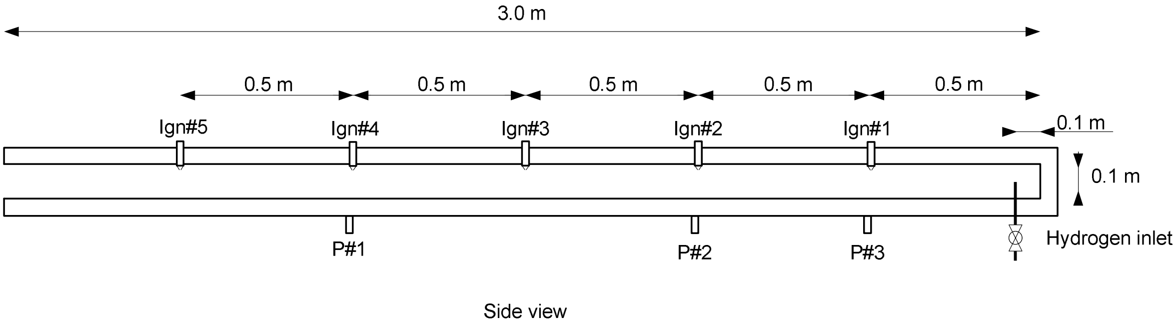

Figure 2. Schematic setup showing the ignition locations and hydrogen inlet.

2.1 Hydrogen gas supply

The hydrogen was supplied from a standard 200 barg gas cylinder. The hydrogen quality was 99.9 %. The volume flow, *Q*, was controlled by a F&P Purgemaster flow meter, which was calibrated prior to the experiments by a Ritter gas meter. By opening a fast acting Asco Joumatic pneumatic ball valve, the hydrogen gas was injected into the channel through a vertical 4 mm ID steel tube. The exit of the 4 mm tube was positioned 50 mm into the channel at the centreline and 0.1 m from the closed end. The release was directed vertically upwards and the flow velocities ranged from 2.4 m/s to 99.2 m/s.

2.2 Ignition

The hydrogen-air mixture was ignited by a Siemens ZM 20/10 high voltage igniter. The ignition source was mounted on the centreline of the channel, 5 mm from the upper wall. The location of the ignition source was varied horizontally according to the 5 test series, 0.5 m, 1 m, 1,5 m, 2 m, and 2,5 m from the closed end of the tube, shown in Fig. 2. The ignition source was switched on and off in a series of short pulses ten times per second.

2.3 Pressure recordings

Three Kistler 7001 pressure transducers measured the explosion pressures and the results were recorded digitally. The three pressure transducers were located 2 m, 1 m and 0.5 m from the closed end of the channel as shown in Fig. 2. They were flush mounted in the lower wall.

2.4 High-speed video

The experiments were recorded with a Photron Ultima APX-RS high-speed digital video camera. Frame rate was typical 2000 fps. The videos were used to observe when the hydrogen release started, the time of ignition of the cloud and the following flame propagation. From the video we could observe when the pneumatic ball valve opened and when the cloud ignited. The high-speed videos were also used to check if the ignition source was on when the gas cloud reached that position.

3.0 FROUDE SCALING

In fluid dynamics, a gravity current is a flow in a gravitational field driven by a density difference [3, 4]. The frontal velocity of gravity currents can typically be expressed by the dimensionless Froude number. The Froude number is the ratio between momentum and gravity forces acting in a fluid flow. The Froude number is often defined as

$$Fr = \frac{u}{\sqrt{gh}} \tag{1}$$

where u is a velocity, g is the acceleration of gravity and h a length scale. In our case the velocity is frontal velocity of the hydrogen-air cloud, u_F. The flow rate of hydrogen gas in to the channel, Q, can be related to the frontal velocity of the cloud by

$$Q = u_F h_H w \tag{2}$$

where h_H is the height of a 100 % hydrogen layer in the channel. If h_H is selected as the length scale in defining the Froude number, we get

$$Fr = \sqrt{\frac{u_F^3 w}{gQ}} \tag{3}$$

The average frontal velocity, u_F, can be expressed by L, the distance from the closed end of the channel to the ignition point and $\Delta\tau$, the time of ignition, i.e. time from the release started to the cloud ignites.

$$u_F = \frac{L}{\Delta\tau} = \sqrt[3]{\frac{Fr^2 gQ}{w}} \tag{4}$$

This yields an expression for the Froude number as follows;

$$Fr = \sqrt{\left(\left(\frac{L}{\Delta\tau}\right)^3 w \middle/ gQ\right)} \tag{5}$$

When the Froude number is known, the time of ignition, $\Delta\tau$ can be estimated from

$$\Delta\tau = \sqrt[3]{\frac{wL^3}{Fr^2 gQ}} \tag{6}$$

4.0 EXPERIMENTAL DISPERSION RESULTS

The test conditions are shown in Table 1. Five test series with hydrogen flow rates ranging from 1.8 dm³/min to 75 dm³/min were carried out. For flow rates less than 1.8 dm³/min no ignition occurred.

Table 1. Flow rates and ignition positions in the channel measured from the closed wall.

Test Series	#1	#2	#3	#4	#5
Length, L [m]	0.5	1.0	1.5	2.0	2.5
$Q_{\min}$ [dm³/min]	1.8	2.7	4.6	10.3	17.5
$Q_{\max}$[dm³/min]	75.0	75.0	75.0	75.0	75.0

4.1 Froude number and time of ignition

Fig. 3 and Fig. 4 show the experimental results expressed in terms of Froude number according to Eq. 5. For the higher flow rates the Froude number approaches a constant value of about 0.65. Some scatter is present at the lowest flow rates, this might be a result of error in the interpretation of time of ignition from the high-speed videos. At low flow rates the initial flame was sometimes difficult to observe. Another factor that might influence the results is that the mixing caused by the low momentum jet can not produce a well mixed layer with a thickness of the upper half the channel for low flow rates.

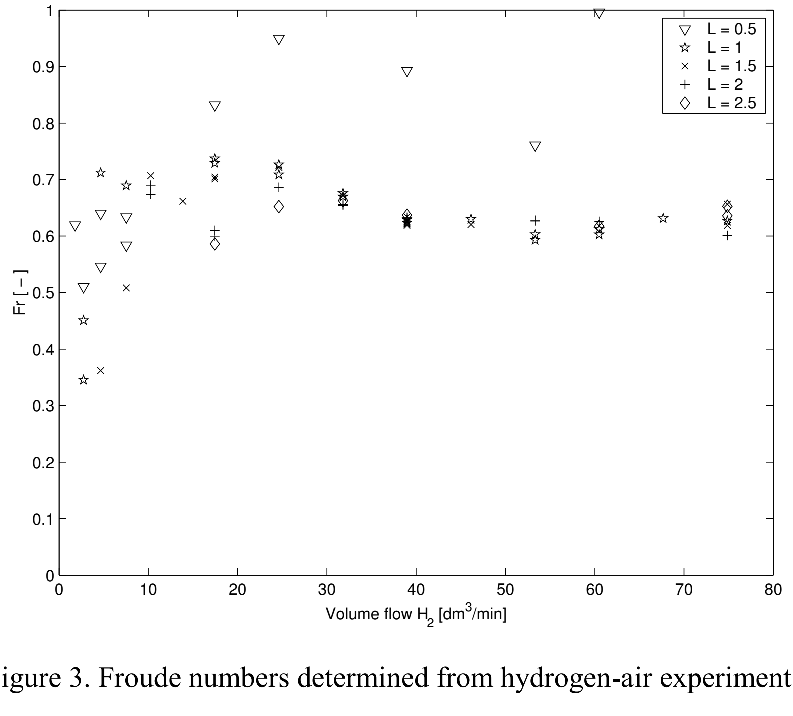

Figure 3. Froude numbers determined from hydrogen-air experiments.

Test series #1 have relatively large deviations from the Froude number found in the other series. In series #1 the distance between the hydrogen inlet and the ignition source is relatively short, and the deviation observed may be explained by the initial non-steady flow caused by the opening of the pneumatic ball valve.

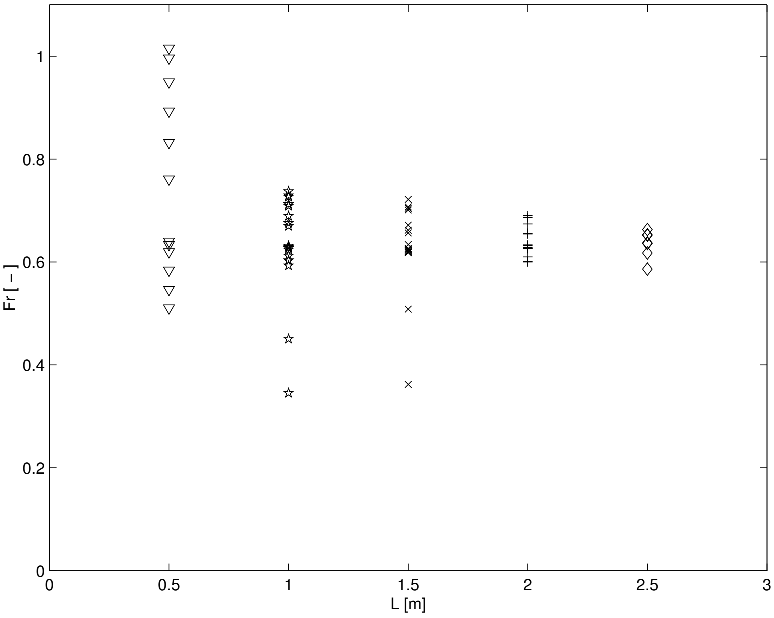

Figure 4. Experimentally obtained Froude number as function of distance between hydrogen jet and ignition source.

The Froude numbers we determined in the experiments are in accord with the theory of "light-fluid intrusion" for gravity currents that can be found in the literature [4, 5, 6]. We have extended the model for "light-fluid intrusion" given by Gröbelbauer et. al. [5] when the Froude number is based on the length scale h_H.

$$Fr = \frac{u_F}{\sqrt{gh_H}} = \frac{H}{H - h_H}\sqrt{\frac{\rho_1 - \rho_H}{\rho_1}\left(\frac{(2-\Phi)(1-\Phi)}{(1+\Phi)}\right)} \tag{7}$$

In this expression $\Phi = h/H$ is an unknown. From our flame propagation experiments we observe that $\Phi \approx 0.5$. If we assume $\Phi = 0.5$ and $h_H << H$ we get $Fr = 0.68$ from Eq.7. When we use this Froude number in Eq.6 we get a reasonable agreement with experimental results as shown in Fig. 5. The solid lines are the calculated values for $\Delta\tau$. A change of 10 % in the value of h yields a Froude number interval between 0.63 and 0.74, when inserted in Eq. 7. The change in h also result in $\Delta\tau = \pm 5.5$ %, obtained from Eq. 6. The deviation from the experimental results becomes significant, and indicating that $\Phi \approx 0.5$. From the video we observe that the combustion products filled the upper half of the channel. From this we also concluded that $\Phi \approx 0.5$. It is likely that the expansion of the combustion products primarily will take place in the longitudinal direction, due to the open end of the channel and the relatively low flame speed (i.e. low Mach number).

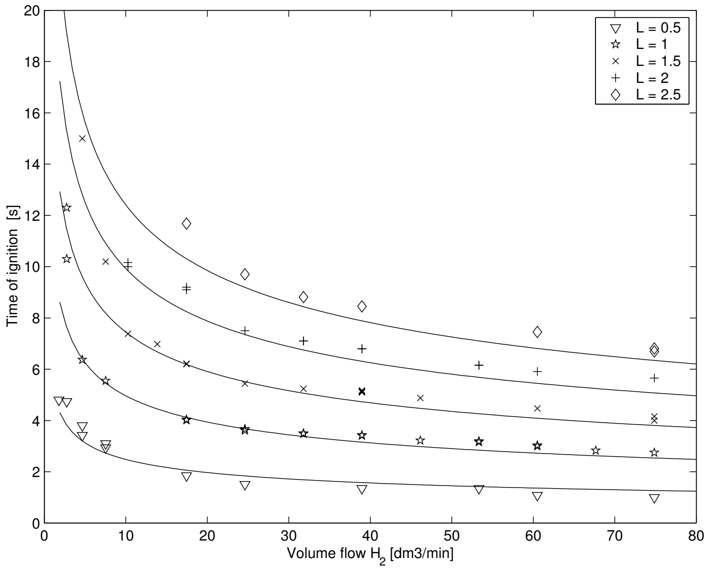

Figure 5. Time of ignition, $\Delta\tau$, as function of volume flow rate, *Q*. The solid lines are calculated from Eq. 6, with $Fr = 0.68$.

It is interesting to note that when *h/H* goes to zero, the Froude number becomes Fr = 2*0.68. This indicates that the frontal velocity will likely be within a factor of about 2 and only dependent on *Q*, *w*, *H* and *h*. Factors influencing the height of the hydrogen-air cloud, *h*, needs to be studied in more detail. We are currently setting up a schlieren system to do such investigations in the 3 m channel. It should be noted that Φ is dependent of the test conditions, and different jet conditions and other geometries will influence the value of Φ.

4.2 Hydrogen concentration

If we assume that $\Phi = h/H = 0.5$ and $Fr = 0.68$, we can estimate an average hydrogen concentration in the combustible cloud. Fig. 6 shows this mole fraction for all the experiments.

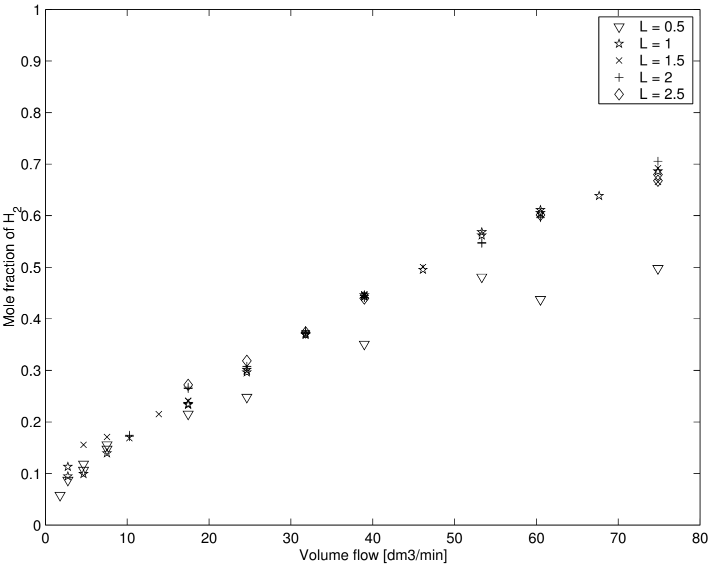

Figure 6. Average hydrogen concentration in the cloud, calculated with $\Phi = 0.5$ and $Fr = 0.68$.

5.0 NUMERICAL DISPERSION SIMULATIONS WITH FLACS

A series of numerical simulations have been performed with Flacs [7]. This programme is a commercial CFD simulation tool for gas dispersion and gas explosions. The modelling was performed with a total of 38200 control volumes. The 3D model grid consisted of grid cells ranging from 5 mm to 50 mm. The jet was modelled with a 5 mm grid refinement with a smooth transition to 10 mm which was used in the rest of the channel. The grid was stretched in the longitudinal direction to 50 mm near the open end wall. The model was used to simulate hydrogen gas dispersions with 3 different mass flow rates, corresponding to 10 dm^3/min, 30 dm^3/min and 60 dm^3/min respectively. The time of ignition criteria was the time when the hydrogen mole fraction reached 8 percent at the ignition location, i.e. the downward flammability limit of hydrogen. Fig. 7 compares the time of ignition from the Flacs simulations with the values from Eq.6, where Fr = 0.68. The Flacs simulations results correlate well with the experimental data. Sensitivity analyses with higher resolution in the Flacs simulations show similar results as with grid size 5 mm.

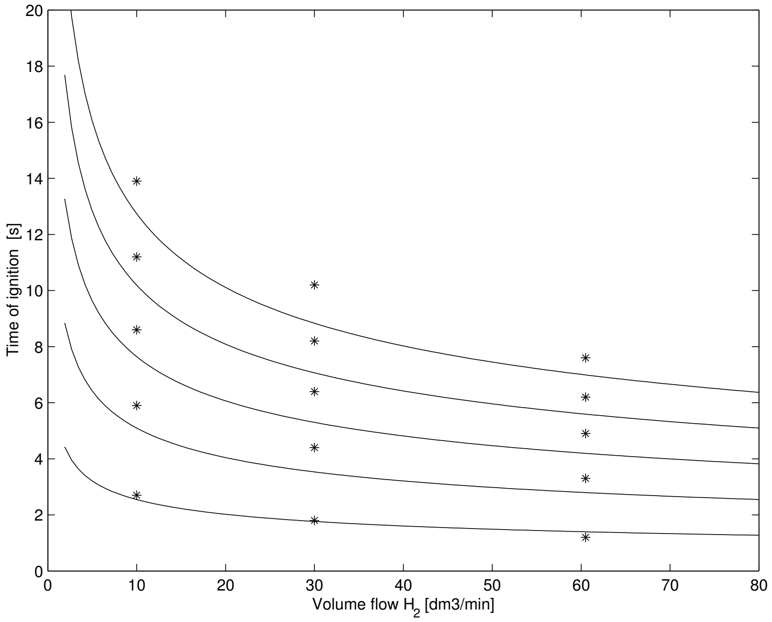

Figure 7. Comparison of numerical and theoretical results. The numerical calculations are performed in Flacs. The lines corresponds to Eq. 6 with Fr = 0.68.

6.0 EXPERIMENTAL FLAME PROPAGATION RESULTS

In this section only a brief presentation of the results from the flame propagation in the channel is given. More details will be published later. Fig. 8 shows a typical development of the combustion process following the ignition of the cloud. In this particular experiment the ignition source was located at L = 2.0 m from the end wall, and the flow rate Q = 17.5 dm^3/min. The time steps between each image are 30 milliseconds. We observe that the combustible gas filled approximately half of the height of the channel.

For small flow rates, the high-speed videos show that the flame speeds were low and the combustion barely visible just below the upper wall. As the flame propagated towards the hydrogen inlet, the visible combustion occurred in the middle of the channel. This phenomenon is shown in Fig. 8. For higher flow rates, the combustion were more turbulent, so the flames expanded over the full height of the channel. For the high flow rate experiments it is possible that the flames were triple flames as discussed by Phillips [8] and Chung [9].

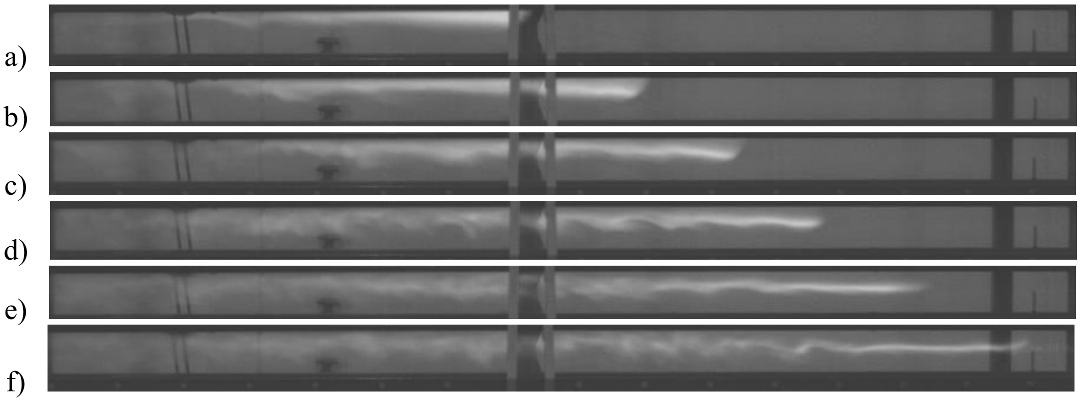

Figure 8. High-speed photos of the combustion of the hydrogen gas cloud at 30 ms time intervals. The ignition source is located at L = 2.0 m and the flow rate is 17.5 dm^3/min.

Explosion pressures were recorded in all the experiments. The maximum pressures versus the volume flow rate are shown in Fig. 9. The explosion pressures in the experiments were less than 32 kPa, except for one experiment. In this particular test with Q = 75 dm^3/min and L = 2.0, the transducer amplifiers were overloaded. As a result, maximum pressure was not recorded, but we know that it was at least 50 kPa and most likely less than 100 kPa.

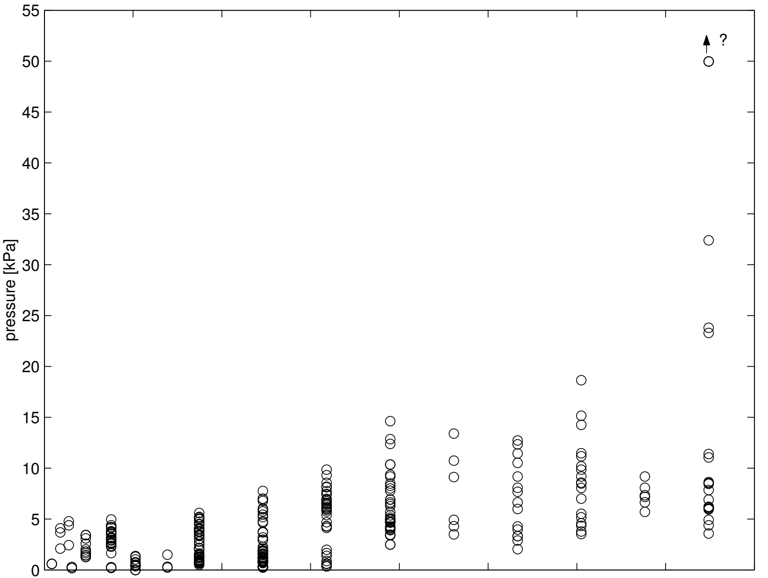

Figure 9. Maximum explosion pressures [kPa] versus the volume flow rate Q .

7.0 CONCLUSIONS

A series of laboratory experiments with release of hydrogen gas inside a 3 m long horizontal channel with a cross section of 0.1 m by 0.1 m have been performed. High-speed videos were used to observe when the hydrogen release started, the time of ignition of the cloud and the following flame propagation. Under the present experimental conditions, the hydrogen-air cloud in the channel behaves as a gravity current. The time of arrival of the gas cloud at the continuous ignition source appear to be well described by Froude scaling with a length scale corresponding to the height of a layer of 100 % hydrogen in the channel. The Froude numbers observed in the experiments are in good agreement with the theory of "light-fluid intrusion" for gravity currents found in the literature. Numerical simulations with the Flacs code correlate well with the experimentally observed frontal velocities. The flame propagation in the channel was also observed on high-speed video. For the rich clouds the flame was possibly a triple flame. The maximum explosion pressures monitored was less than 32 kPa except for one test. The flame propagation indicated that approximately half the height of the channel (i.e. $\Phi = 0.5$) was filled with combustible mixture. We believe that this Froude scaling can be useful as a tool to analyse the consequences of hydrogen release in buildings, channels and tunnels. But it should be pointed out that further work is needed in order to establish the validity of this scaling for other conditions than those of the present small scale tests.

ACKNOWLEDGEMENTS

Financial support from the Norwegian Research Council, Strategiske høgskoleprosjekter, (NFR, SHP) is gratefully acknowledged.

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