EXPERIMENTAL STUDY OF HYDROGEN RELEASES COMBUSTION

Aleksandrov A.O., Alekseev V.I, Chernenko E.V., Efimenko A.A., Gavrikov A.I., Mayorov A.S., Matsukov I.D., Schepetov N.G., Velmakin S.M., Zaretskiy N.P.

Russian Research Centre Kurchatov Institute, Kurchatov Sq. 1, Moscow, Russia, gavrikov@iacph.kiae.ru

ABSTRACT

The objectives of the presented experimental work were investigation of hydrogen release distribution and combustion, modeling possible emergency situation at industry scale. Results of large scale experiments on distribution and combustion in an open and congested area are presented. The mass of hydrogen in experiments varied from 50g to 1000g with release rate from 180 to 220 g/s. Qualitative characteristics of high momentum hydrogen jet releases distribution and subsequent combustion were obtained. It is shown that obstacles slow down jet speed, promote combustible mixture formation in a large volume and accelerate combustion process. The maximum overpressure in experiments with additional congested area reached $\Delta P = 0.4$ atm. Using partial confinement of congested area turbulent combustion regime with the maximum overpressure more than 10 atm. was obtained.

1.0 INTRODUCTION

With the increased role of hydrogen as contemporary and future energy carrier the growing demand in understanding of different aspects of industrial safety is coming into light. Intensive development of hydrogen power is substantially restrained by potential danger of hydrogen fuel. Uncontrollable (emergency) releases of hydrogen can have catastrophic consequences [1]. Therefore, hydrogen safety is a very important problem for development of hydrogen power. Hydrogen safety development requires detailed data in such fields as hydrogen distribution processes at releases, explosive mixtures formation, ignition conditions, and possible combustion regimes.

Now there is a set of reviewed publications devoted to safety issues of use of hydrogen as a perspective kind of fuel, capable to replace traditional hydrocarbon ones [2-5]. Most of the known experimental works are laboratory investigations of small hydrogen releases (up to 50 g). It is worth to note works connected with spontaneous ignition of hydrogen at the moment of its release from a vessel under the pressure [5-9]. The authors studied initial conditions for spontaneous hydrogen ignition and conditions for stable combustion of jet numerically and empirically.

However the data on experiments in the open air, modeling hazardous hydrogen releases, are rather limited now. Processes of hydrogen distribution at powerful release or leakage of hydrogen are not studied enough. Possibility of spontaneous hydrogen ignition at powerful jet releases is not evaluated. Explosion processes in nonuniform mixtures formed at powerful jet releases are not explored also.

The objective of the present work is to investigate distribution and combustion of high pressure jet releases under different geometrical conditions.

2.0 EXPERIMENTAL

The present experimental investigation is devoted to hydrogen distribution and combustion at large releases of hydrogen both into free space and into congested area. To perform experiments a new experimental setup was designed and manufactured. Its schematic is shown in Fig. 1. The experimental setup allowed producing high pressure hydrogen releases of (0.05-1.00)-kg mass. Hydrogen concentration and combustion parameters were recorded by the data acquisition system partially modified for these experiments. Hydrogen releases were controlled by the special high speed electromagnetic valve mounted on the pipeline end. Amount of hydrogen ejected was proportional to the time interval between opening and closing of the valve. The welded cubic framework was set on the path of hydrogen jet for mounting wooden obstacles and different types of transducers (pressure, light, hydrogen concentration, heat flux). Ignition system provided two kinds of ignition sources – heated nichrome wire and electric spark. Video filming and BOS photography (Background Oriented Schlieren technique) were used to visualize hydrogen distribution and combustion processes in experiments.

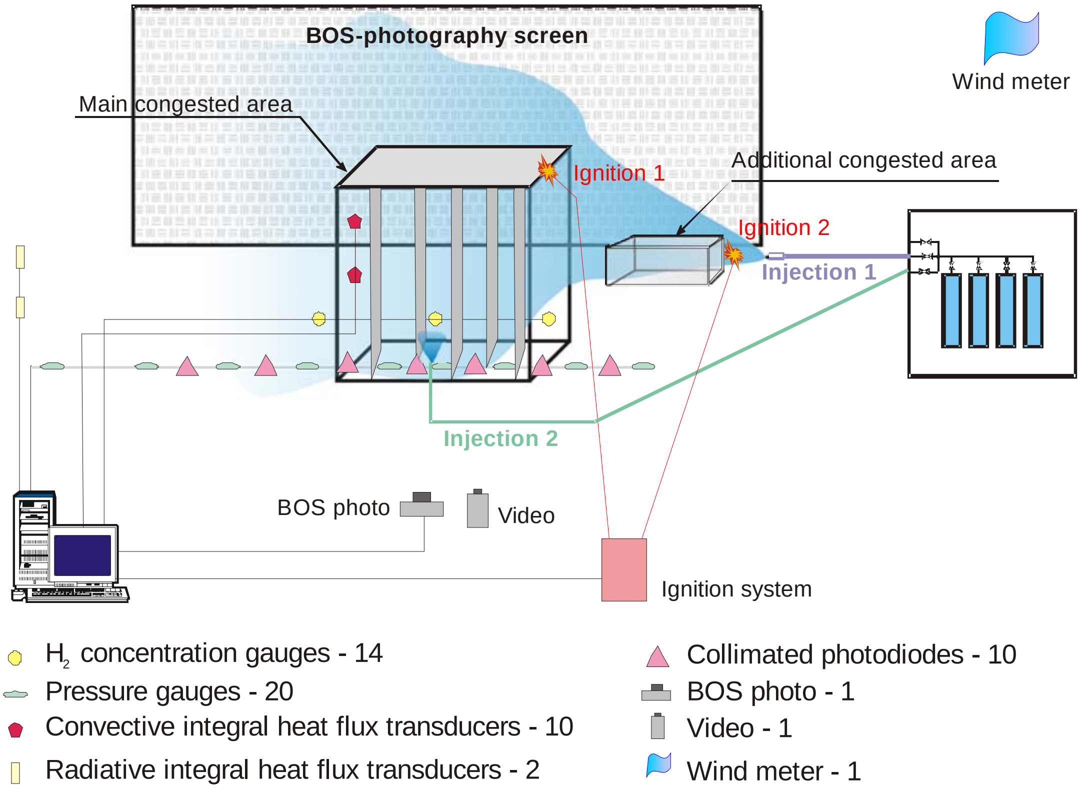

Figure 1. Scheme of experimental facility.

Congested area was created within the welded cubic framework 2×2×2 m, made from steel pipes of 115 mm in outer diameter (see Fig. 2). Congested area was assembled from 5 grids made from boards of 75-mm width and 15-mm thickness. Grids were spaced 0.4 m apart. Two values of blockage ratio (BR) were used in experiments – BR=0.3 and BR=0.54. Roof cover for cube was used in a part of experiments for modelling of worst case scenario.

In some experiments additional small congested area together with main congested area was used. Additional congested area is a part of steel tube (diameter 360mm, length 500mm) filled with a wire (diameter 3mm). Length of the wired part was 350mm and effective BR can be treated as 0.6. Additional small congested area was set up on nozzle axe at 12 cm from the nozzle end.

Figure 2. Main congested area and additional small congested area.

The system of hydrogen supply consisted of gas distribution unit and general pipeline. It is shown in Fig. 3. The system included hydrogen cylinders, connecting pipes, a set of gas valves and manometers, and also the compressor filling cylinders with hydrogen to necessary pressure.

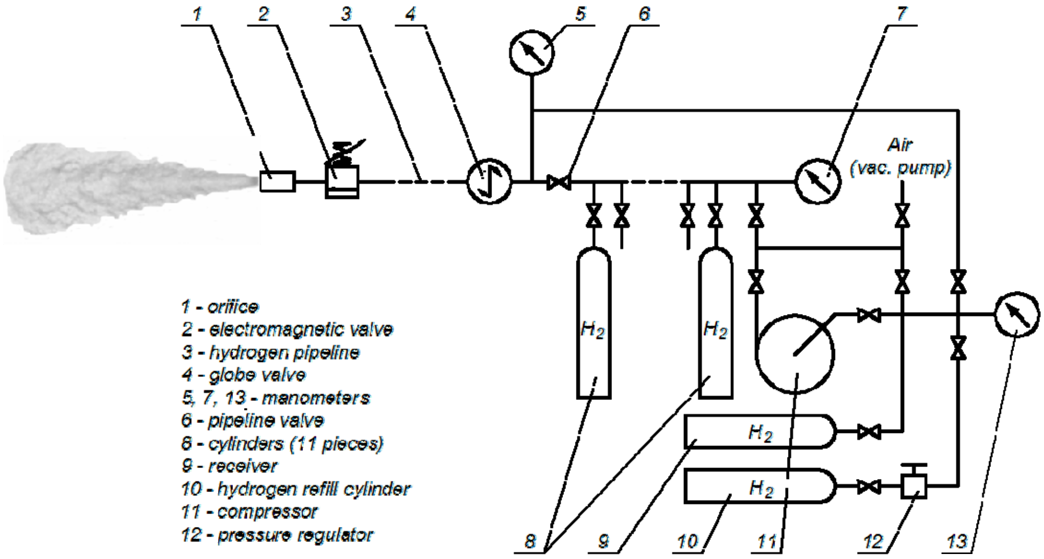

Figure 3. System of hydrogen supply.

The general gas pipeline was used to transport hydrogen from gas distribution unit to a place of release. The total length of general gas pipeline was about 30 m. It was assembled from tubes of 20-mm inner diameter. A special high speed valve was set at the exit of general pipeline. It was servo-assisted solenoid valve for high pressure - BURKERT 2400. Hydrogen was ejected through the orifice mounted at the exit of the valve. Orifice diameter varied from 6.0 to 5.3 mm to provide hydrogen flow rate in the range from 180 to 220 g/s. Most experiments were carried out with the orifice diameter 5.3 mm. It was found out in preliminary experiments that valve opening time was about 20 ms and closing time – about 100 ms.

Gas distribution system was developed according to assigned objectives and provided releases of hydrogen up to 1 kg of H_2. The total number of hydrogen cylinders used for maximum releases (1 kg) was ten. They contained 400 g of hydrogen under 150-bar overpressure. It was enough to provide hydrogen releases with pressure drop less than 20%.

Two kinds of ignition sources were used in experiments. One ignition source was a heated nichrome wire installed on the upper tube of the front cube face. The ignition source was developed in such a way that 10-mm heated nichrome wire fell down through the hydrogen jet at the moment of ignition. The wire was heated by capacitors discharge (total capacity – 30 μF, voltage – 220 V). Another ignition source was an electric spark of approximately 1-J energy. The ignition source was installed on the upper tube of the front cube face.

Data acquisition system was made to get the following data in the experiments on hydrogen distribution and combustion at high pressure releases:

- Schlieren photography of high pressure hydrogen jets.
- Hydrogen concentration in jets.
- Video recording of combustion processes.
- Combustion and explosion parameters (pressure, light, and heat flux data).

<u>BOS (Background Oriented Schlieren) photography.</u> Such optical methods of detection of inhomogeneities in the transparent refractive mediums as Schlieren-method, shadow photography, or interferometry are known for a long time. All of these methods are integrative measurement techniques and are sensitive to changes of the refractive index of the investigated fluid.

To get BOS image one should make two digital photos against the background screen – without and with investigated flow. Computer subtraction of the first image from the second one gives the shadow picture of investigated flow. Generally the screen structure (pattern) can be irregular or regular distribution of black and white stains of different sizes. For the present experiments the pattern with regular distribution of black and white squares 10×10 mm was chosen. Preliminary tests showed that this kind of pattern gave more quality results of the BOS-photos – more detailed and more contrast. The screen with pattern was mounted on the framework made from steel tubes. The screen was 3 m in height and 4.5 m in length. The distance from the photo camera and the BOS-screen was about 40 m.

<u>Hydrogen concentration in jets.</u> Special hydrogen concentration sensors were developed and manufactured in RRC “Kurchatov institute” to provide hydrogen concentration recording in experiments. The view of the sensor and its typical signal are shown in Fig. 6. The sensors were made on the base of matched pair MUP-3 (ultrasonic piezoceramic transducer) developed by OAO ELPA (Russia). The distance between acoustic generator and detector was 100 mm. Each sensor had built-in thermocouple to monitor ambient temperature. Hydrogen concentration sensors location is shown on Fig. 4.

<u>Combustion parameters</u> were recorded by pressure gauges (tensoresistive - DD-2.5, piezoresistive - PCB-113A), integral heat flux gauges, and photodiodes (FD-10 GA). Locations of pressure gauges are shown on Fig. 5.

Ambient temperature varied from 7 to 18°C and atmospheric pressure was around 760 Torr. Wind speed was less than 0.5 m/s during all experiments.

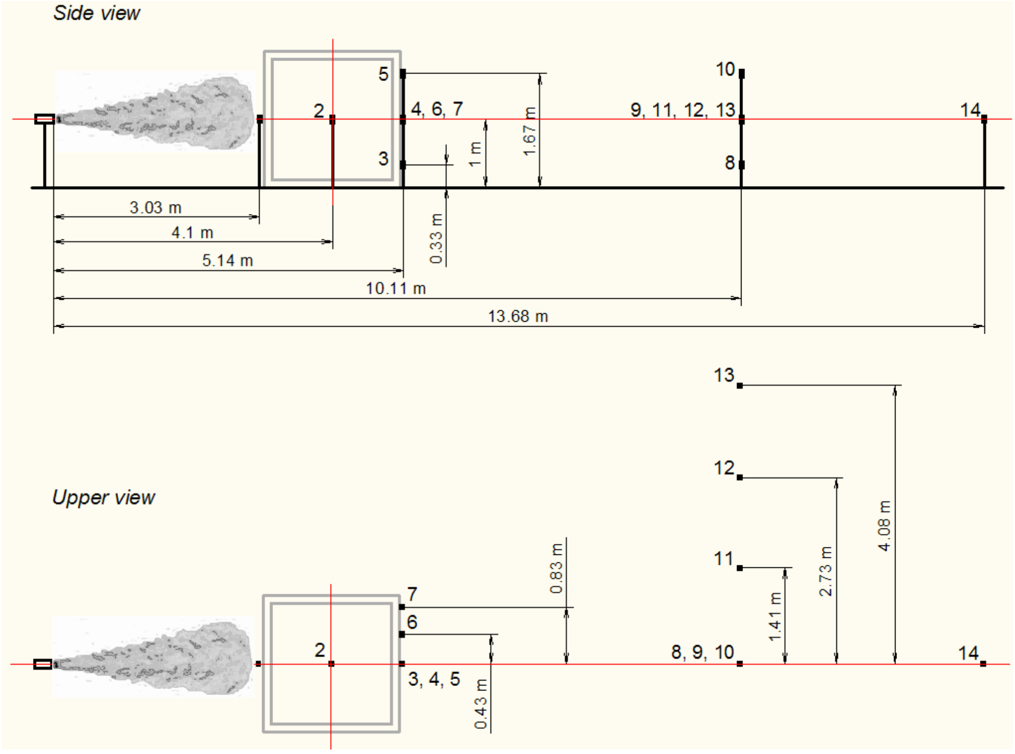

Figure 4. The scheme of hydrogen concentration sensors location in experiments.

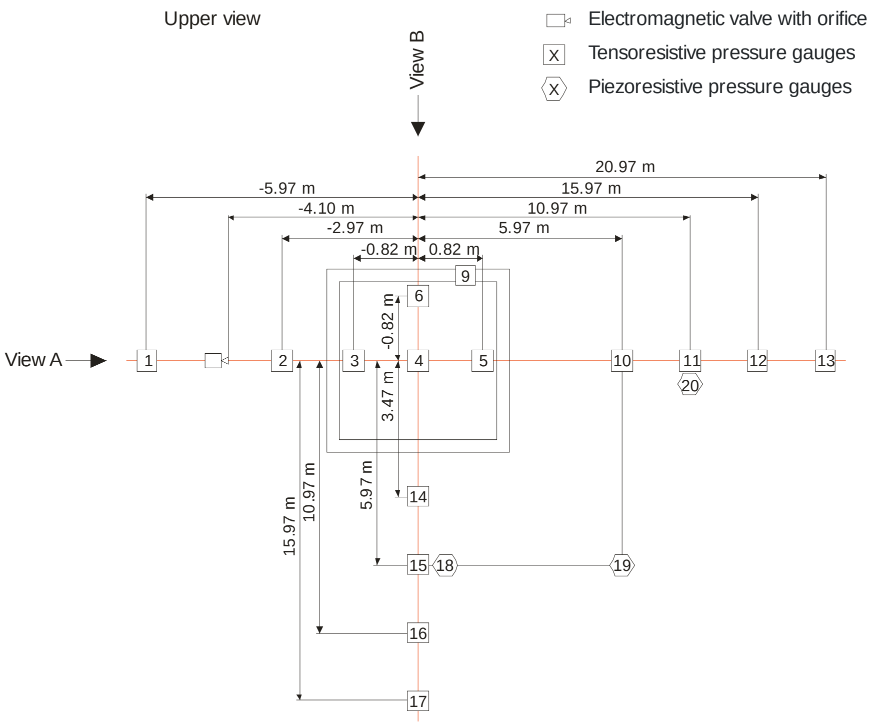

Figure 5. The scheme of locations of pressure gauges in experiments.

3.0 RESULTS AND DISCUSSION

All experiments on distribution and combustion of high pressure hydrogen jet releases were carried out in two stages. The first stage – no ignition experiments on hydrogen content in high pressure jets and their visualisation by means of BOS photography. The second stage – experiments with recording of dynamic parameters of hydrogen jets combustion. In total more than 100 experiments were conducted. Experiments were divided into three parts:

- Experiments on distribution and combustion in open area
- Experiments on distribution and combustion in open congested area
- Experiments on distribution and combustion in open congested area with additional congested area

From all number of experiments 14 experiments were selected as most representative for following detailed analysis. Initial conditions and parameters of representative experiments are presented in Table 1.

Table 1. Conditions of representative experiments.

experiment #	037	064	065	043	071	040	050	051	053	052	055	058	061	101
M_{H2} ejected, g	414	203	402	390	402	402	134	235	579	1031	203	241	222	346
W_{aver}, g/s	199	188	193	187	193	193	231	218	188	185	188	223	205	49
T injection, s	2.0	1.0	2.0	2.0	2.0	2.0	0.5	1.0	3.0	5.5	1.0	1.0	1.0	7.0
t ignition, s	-	1.0	2.0	-	2.0	-	0.5	1.0	3.0	5.5	-	1.4	1.0	7.3
Iginition location		1	1		1		1	1	1	1		1	2	3
BR	0	0	0	0.3	0.3	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.6
Additional BR											√	√	√	√
Roof											√	√		√
Temperature °C	9.0	12.0	12.0	11.5	12.5	11.5	18.0	18.0	13.5	17.0	15.5	11.0	16.0	7.0
P_{max}, bar		0.00	-		0.00		0.00	0.00	0.00	0.06		0.38	0.36	10.9
BOS	√	√	√	√		√	√	√	√	√	√			√
Video		√	√		√		√	√	√	√		√	√	√

P_{max} – final pressure in gas system;
W_{aver} – average H_2 flow rate;
M_{H2} – mass of hydrogen released.

Different modes of combustion of high pressure jet release were realized:

- Quenching mode without combustion of jet release
- Combustion of jet release without overpressure
- Combustion of jet release with small overpressure
- Combustion of jet release with high overpressure

All cases of combustion were subsonic.

3.1 Experiments without combustion of high pressure hydrogen jet release

One the possible scenarios of high pressure jet release ignition are releases without combustion. This scenario is possible only for open area without congestion. As the most representative case of the scenario experiment #65 was selected. Ignition of hydrogen wasn't achieved in the experiment #65. Only quenching mode was realized for this experiment. BOS photos of the experiment #65 are presented in Fig. 6.

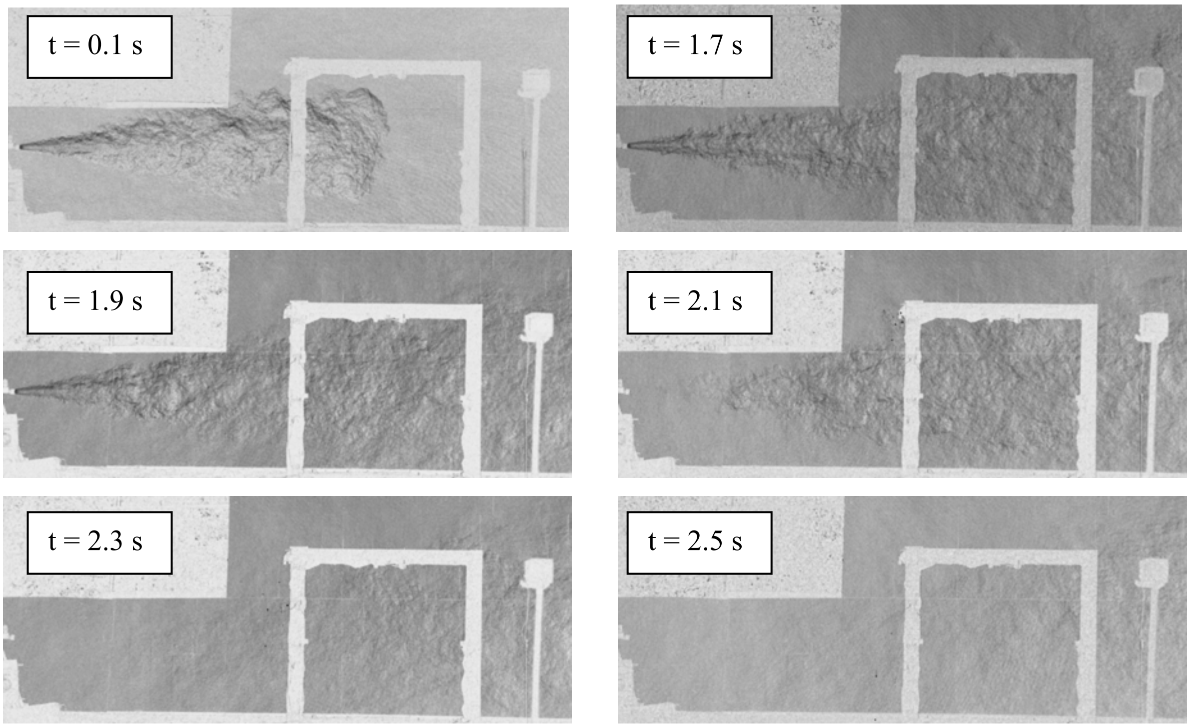

Figure 6. Sequence of BOS-photos of experiment #65 (M_{H2}=402 g, W_{aver}=193 g/s).

3.2 Combustion of jet release without overpressure

Second possible scenario of high pressure jet release ignition cloud is diffusive combustion of release. This scenario is possible only for open area with congestion, but level of congestion may vary. As the most representative case of the scenario experiment #64 was selected. BOS photos of the experiment #64 are presented in Fig. 7. X-t diagram based on light signals from photodiodes is shown in Fig. 8 (x=0 corresponds to horizontal coordinate of ignition point; t=0 corresponds to the moment of ignition source activation). Photodiodes were located on the ground along the jet direction. Average flame velocity along the hydrogen cloud turned out to be 37 m/s. Very weak conductive heat flux was recorded in this experiment. Its value was about 2.6 kJ/m^2. One can estimate an average conductive heat flux density taking into account photodiodes data for length of combustion process. This estimation gives 26 kW/m^2.

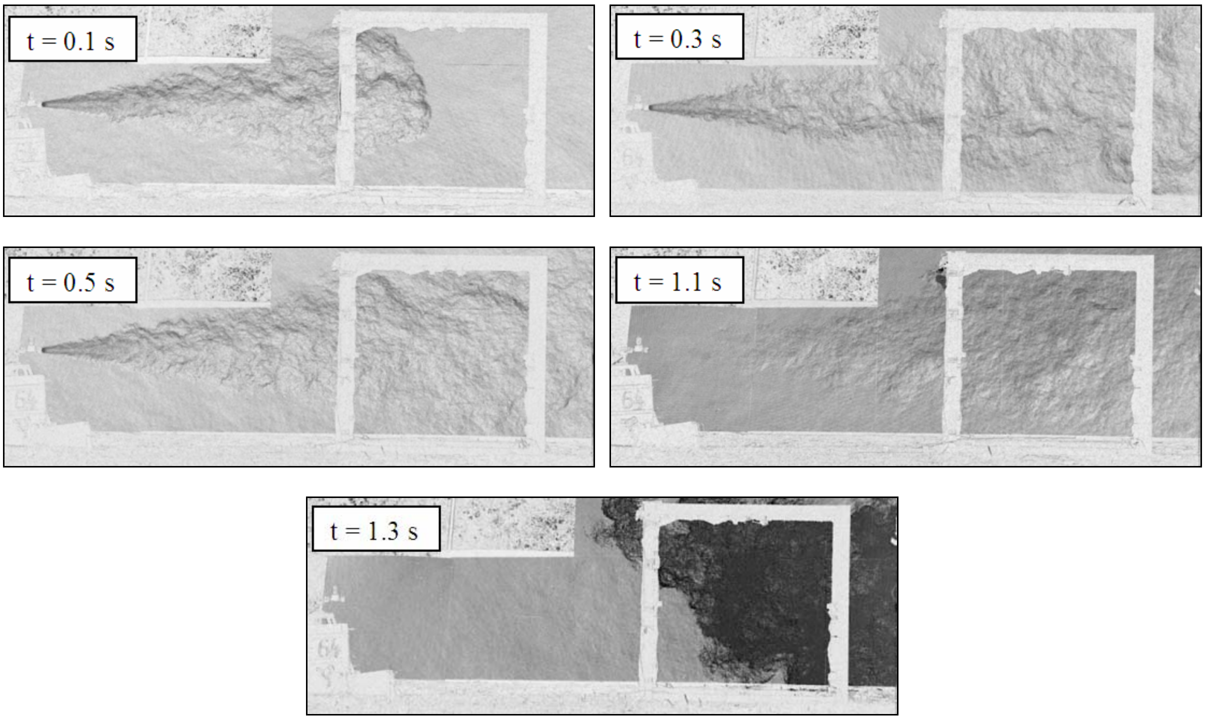

Figure 7. Sequence of BOS-photos of experiment #64 (M_{H2}=203 g, W_{aver}=188 g/s).

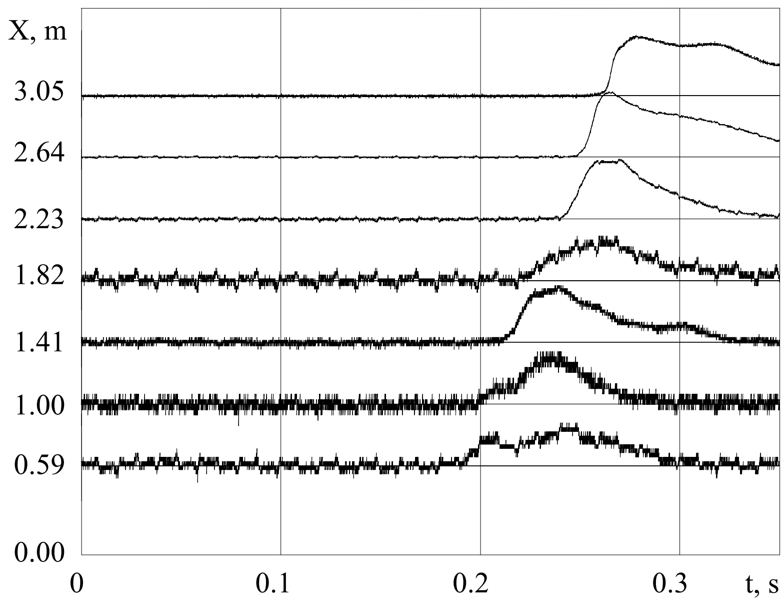

Figure 8. X-t diagram based on light signals from photodiodes, experiment #64.

3.3 Combustion of jet release with small overpressure

Third possible scenario of high pressure jet release ignition cloud is slow combustion of release with small overpressure. This scenario is possible only for open area with high level of congestion or with additional congested area or with cube roof. For this scenario experiment #58 was selected. Pressure records of all gauges of the experiment #58 are presented in Fig. 9. Maximum pressure reaches 0.38 bar in experiment. X-t diagram based on light signals from photodiodes is shown in Fig. 10 (x=0 corresponds to horizontal coordinate of ignition point; t=0). Visible flame speed of combustion process is 160 m/s. Integral heat fluxes records are presented on Fig. 11. Heat flux reached 224 kJ/m^2 (gauge located at the center of the cube) and radiative heat flux was 221 J/m^2 at distance 16.8 m from the center of the cube.

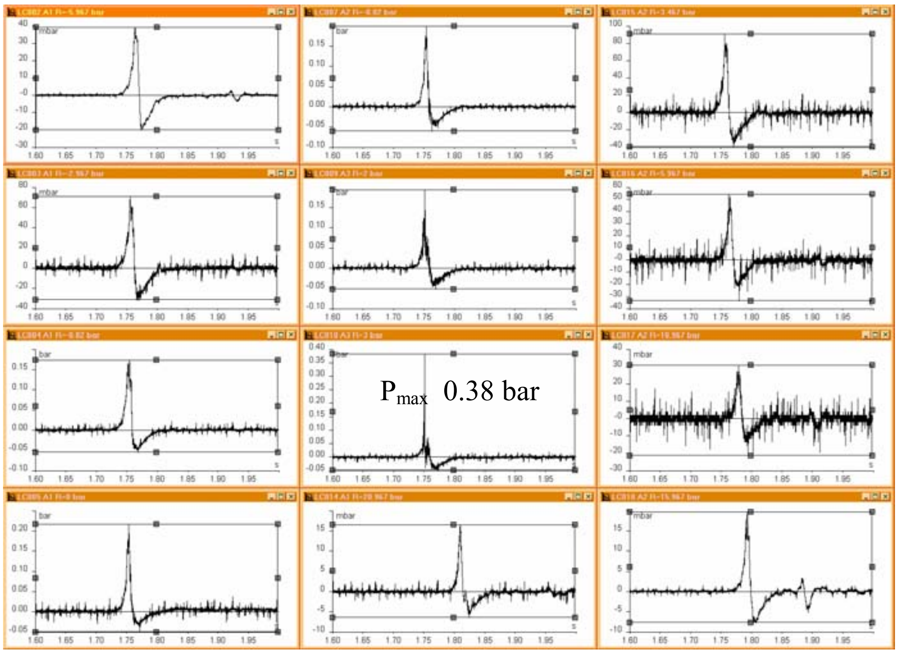

Figure 9. Pressure records of all gauges, experiment #58

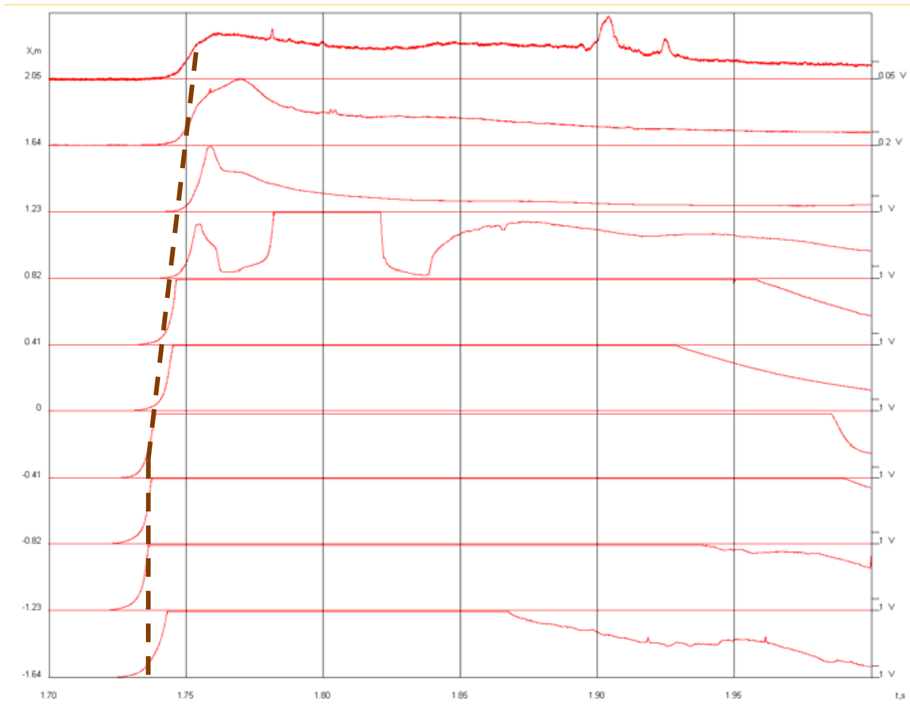

Figure 10. X-t diagram based on light signals from photodiodes, experiment #58.

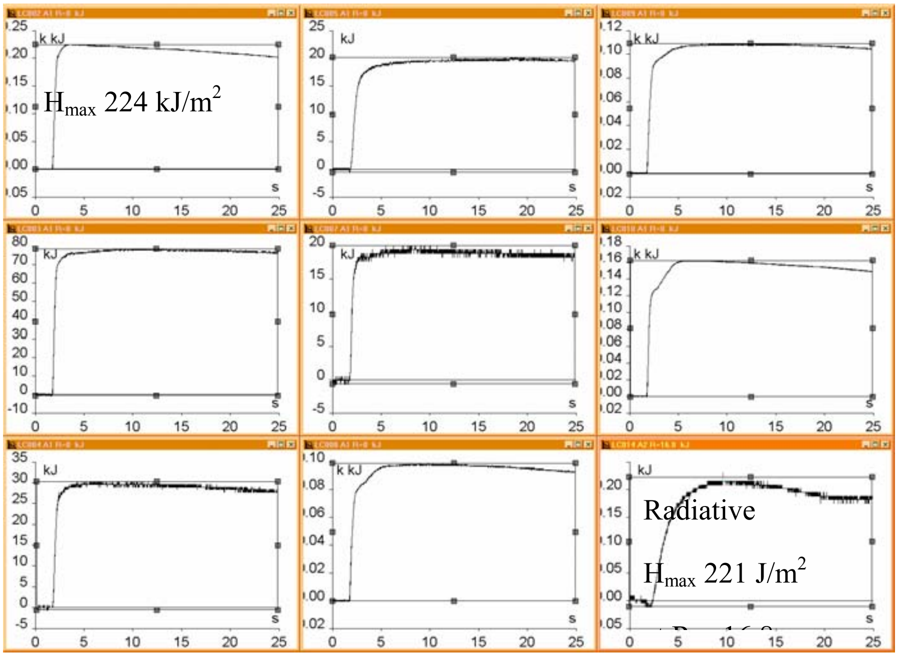

Figure 11. Integral heat flux gauges records, experiment #58.

3.3 Combustion of jet release with high overpressure

For a modeling of possible severe accident scenario of high pressure hydrogen jet release another experimental configuration was chosen. Cube was enclosed with thin polyethylene film and top was covered. The additional small congested area was set up on a top cover and top of that area was open to air (Fig. 12). Effective BR for this configuration was 0.6. Release was performed from the ground at the center into cube. Overall release time was 7 s, mass of hydrogen – 346 g. The resulting mixture was well premixed with the average concentration ≈40% vol. Hot wire ignition source was set up after additional small congested area at 59 cm height from top. Video frames of experiment #101 are presented on Fig. 13. Video camera was destroyed at t=0.22s. Pressure records of all gauges of the experiment #101 are presented on Fig. 14.

Figure 12. Configuration of the tube for severe accident scenario, experiment #101.

Maximum overpressure in experiment reached ΔP=10.9 atm. Combined increase of congestion and confinement results in significant rise of blast parameters (about 30 times overpressure increase).

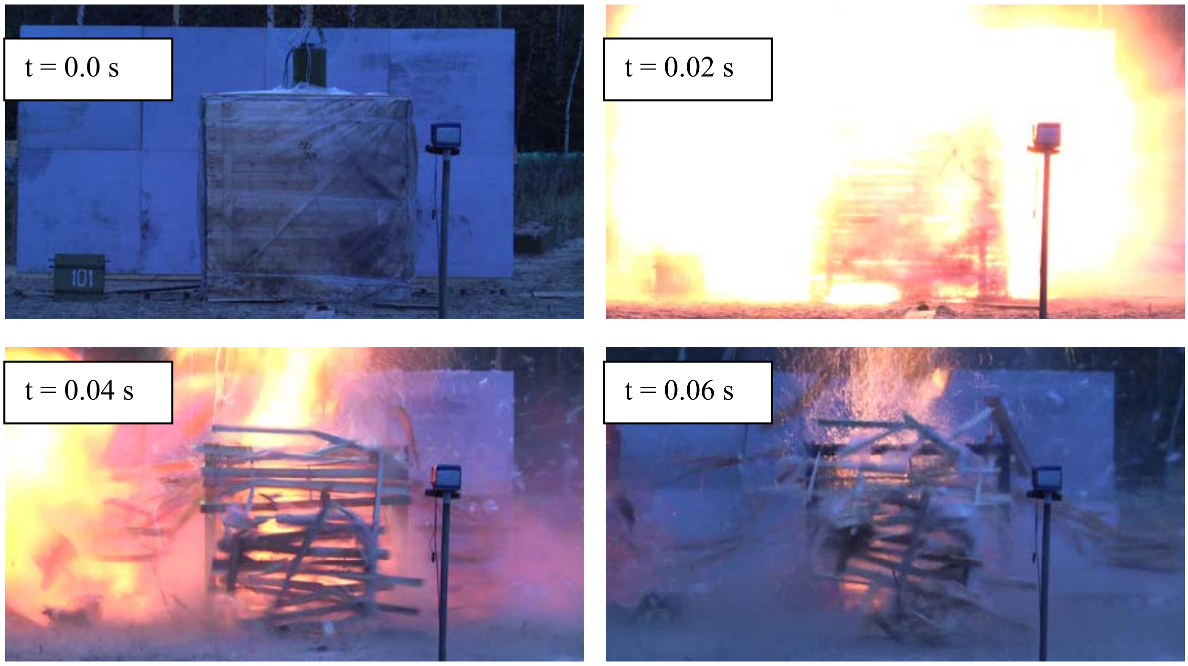

Figure 13. Video frames of experiment #101.

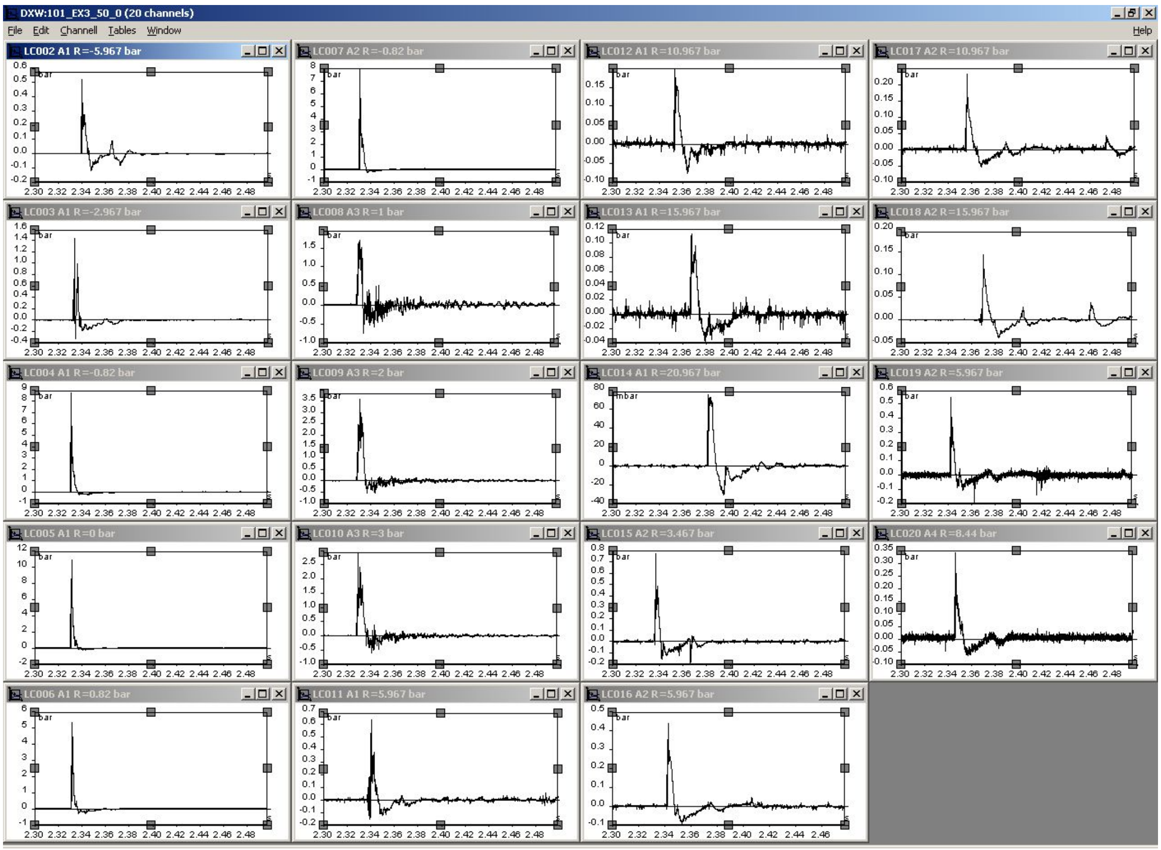

Figure 14. Pressure records of all gauges, experiment #101

3.4 Concentration estimates

Analysis of BOS photographs obtained for distribution experiments was performed. It shows that hydrogen jets became quasistable in about 1 s for a release with approximately constant value of mass flow rate. For larger times the qualitative picture of hydrogen cloud in congested area remains unchanged. For BR=0.3 most mass of hydrogen goes through congested area easily and leaves the congested area in 0.3 s after valve closure. For BR=0.54 the mass of hydrogen that goes ahead through congested area is much smaller than mass of hydrogen going upward.

Some estimates were performed using BOS photos and concentration sensors records. Let's look at typical distribution experiment #55 (Fig. 15). Using two BOS photos below one can obtain jet propagation speed, $V \approx 4.9$m/s. Jet cross section area at the face of the cube is $S \approx 1.5\text{m}^2$.

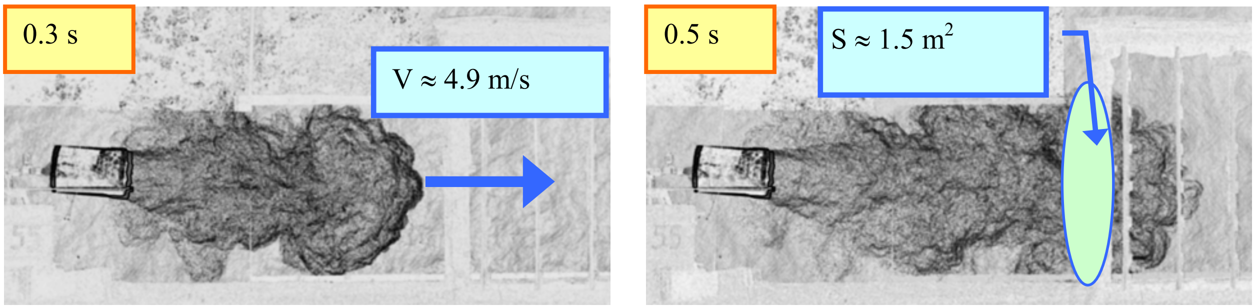

Figure 15. BOS, experiment #55

Estimates of volume average concentration and cross-section average concentration using BOS photo (see Fig. 15) gives the following. For a volume average concentration:

$C_{H2} = W_{aver} \cdot t/\mathbf{V}/\rho_{H2} \approx 34$ % vol, where W_{aver} – average H_2 flow rate; t – time from start of release (0.5 s); **V** – cloud volume $\approx 3\text{m}^3$; ρ_{H2} – hydrogen density; and C_{H2} – hydrogen concentration.

For a mass flow rate of the jet at the face of the cube one will have: $W_{aver} = C_{H2} \cdot \rho_{H2} \cdot V \cdot S$. From this expression follows: $C_{H2} = W_{aver}/\rho_{H2}/V/S \approx 28$ %vol.

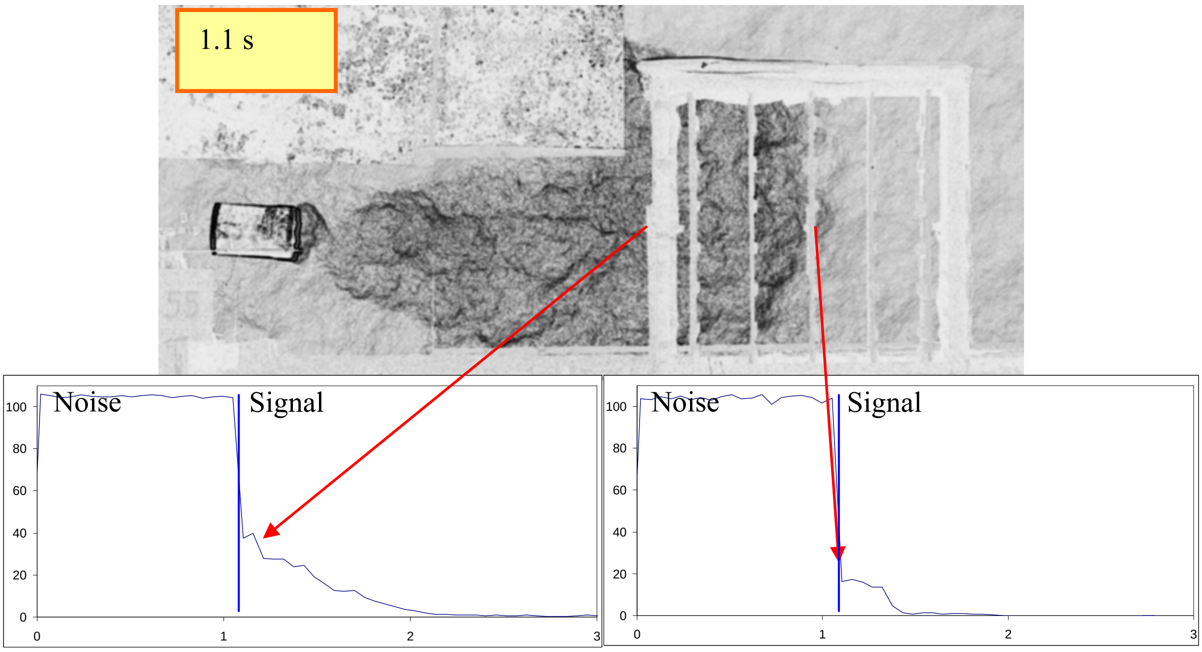

Figure 16. BOS photo after end of injection and concentration gauges records, experiment #55

Results of concentration gauges measurements give us the same order of values as BOS concentration estimates if we exclude initial stage (noise) from concentration gauges records (Fig. 16).

Most of the hydrogen sensors showed more than 100% H_2 concentration during injection. The reason of this effect is high level of sound noise during injection process that influenced on ultrasonic piezoceramic transducer of the hydrogen sensor. The first gauge located at the face of the cube showed C_{H2} = 38 %vol. after end of injection that well correspond with BOS concentration estimates. The sensor located at the center of the cube showed C_{H2} = 17 %vol.

3.4 Combustible mixture volume estimate for a free jet

Using the above presented mathematical technique one can estimate combustible mixture volume for a free jet.

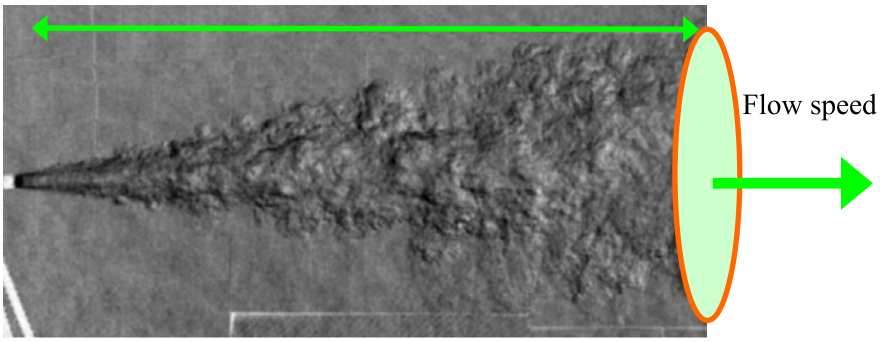

Figure 18. BOS photo of a free jet.

Shape of the free jet is close to the cone (Fig. 18). Let's surface where H_2 concentration falls below lower ignition limit C_L located at distance X from the nozzle and its square is S. Than combustible mixture volume can be estimated as $\mathbf{V} \approx 1/3XS \sim S^{3/2}$ and mass flow rate $W_{aver} = C_L \cdot \rho_{H2} \cdot V \cdot S$. So, $S \sim W_{aver}/V$. Combined with equation for combustible mixture volume it gives $\mathbf{V} \sim (W_{aver}/V)^{3/2}$. One important conclusion can be made from this expression. The higher the jet speed, the lower combustible mixture volume is.

4.0 CONCLUSIONS

Experimental investigation on distributions and combustions of high pressure hydrogen jet releases showed that:

- Free high speed jets produce lean mixtures and weak explosions.
- Deceleration of jet increases the volume of combustible mixture and the mass of hydrogen involved in explosion.
- Obstacles decelerate the flow, promote formation of combustible mixture, and enhance combustion process.
- Combined increase of congestion and confinement results in significant rise of blast parameters (about 30 times overpressure increase).
- Explosion hazard of strong hydrogen release needs further investigation.

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