ОСОБЕННОСТИ ПРОЦЕССОВ ЗАПОЛНЕНИЯ ВОДОРОДОМ ЗАМКНУТЫХ ОБЪЁМОВ – ВЛИЯНИЕ НА БЕЗОПАСНОСТЬ

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PECULIARITIES OF FILLING CONFINED SPACES WITH HYDROGEN - IMPACT ON A SAFETY

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INTRODUCTION

The report summarizes experimental results on the mechanisms and kinetics of hydrogen-air flammable gas cloud formation and evolution due to foreseeable (less than 10^{-3} kg/sec) hydrogen leaks into confined spaces with different shapes, sizes (from 4 to 25 m^3) and boundary conditions. The goals were:

- to obtain qualitative information on the basic gas-dynamic patterns of flammable cloud formation at different leak velocities (between 9,35 and 905 m/sec) for a fixed leak flowrate;
- to collect quantitative data on spatial and temporal characteristics of the revealed patterns.

The experiments have been shown that **two qualitatively different gas-dynamic patterns of flammable gas cloud formation and evolution are realized** (depending on speed of gas) at a hydrogen/helium release into closed space with the constant gas flow rate.

The difference in patterns of the explosive cloud formation in "filling box" and "fading up box" cases is essentially important for hydrogen safety questions and it should be taken into account when special technical or organizational measures of hydrogen safety are developed and implemented.

DESCRIPTION of the EXPERIMENTS

Experiments have been carried out in different experimental chambers - in a metal 4 m^3 unventilated cylindrical barrel, placed, in 25 m^3 experimental “cube” of University of Pisa and in a surrogate “garage” - a parallelepiped with height 2,02 m, length 2,32 m and depth 1,9 m. At the last setup the experiments have been carried out with helium as a hydrogen surrogate. Helium from the gas vessel was supplied into the experimental chamber through a pipe and was released through tubular nozzles of different diameters (from 0,6 to 8 mm) in controlled conditions. The flow rate of helium release was fixed at $8{,}4 \cdot 10^{-5}$ kg/s (or 0,47 l/s) level. Tubular nozzles were placed exactly at the centre of the experimental chamber, the distance between the gas release point and the floor was 0,49 m.

The formation of hydrogen-air cloud has been investigated during short (10 – 20 min) hydrogen/helium release into closed space and during the following free dispersal of flammable gas cloud.

To determine the hydrogen (helium) concentration in the air a spatially distributed, reconfigurable net of 24 hydrogen gauges (thermal conductivity gauges TCG-3880) with a short response time were used.

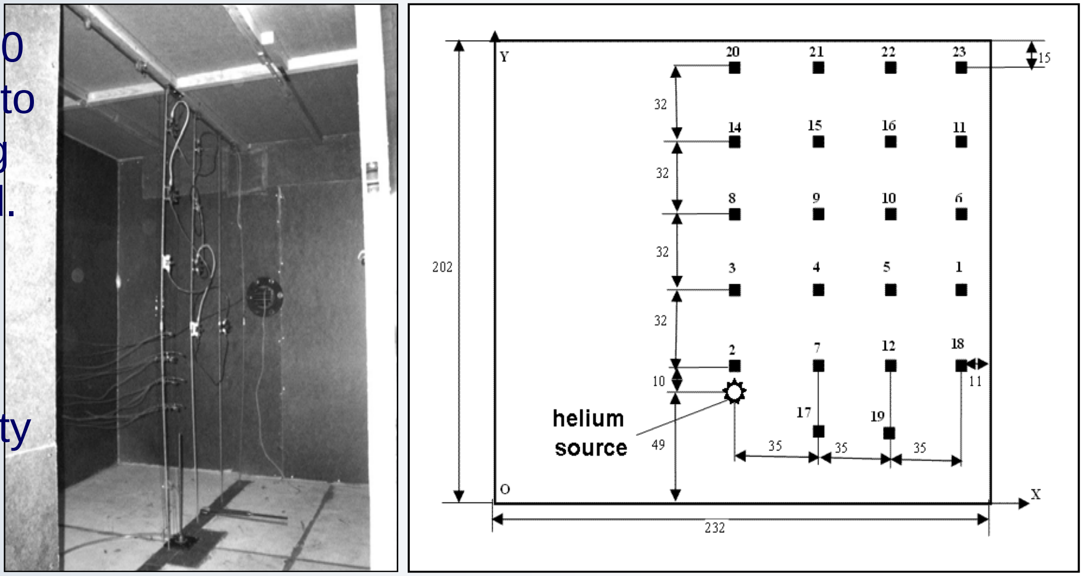


Figure 1. Internal view (left) of the experimental chamber (surrogate “garage”) and the representative schematic of spatial allocation of the sensors (right).

EXPERIMENTAL RESULTS

The experiments have been shown that two qualitatively different gas-dynamic patterns of flammable gas cloud formation and evolution are realized (depending on speed of gas) at a hydrogen/helium release into closed space with the constant gas flow rate.

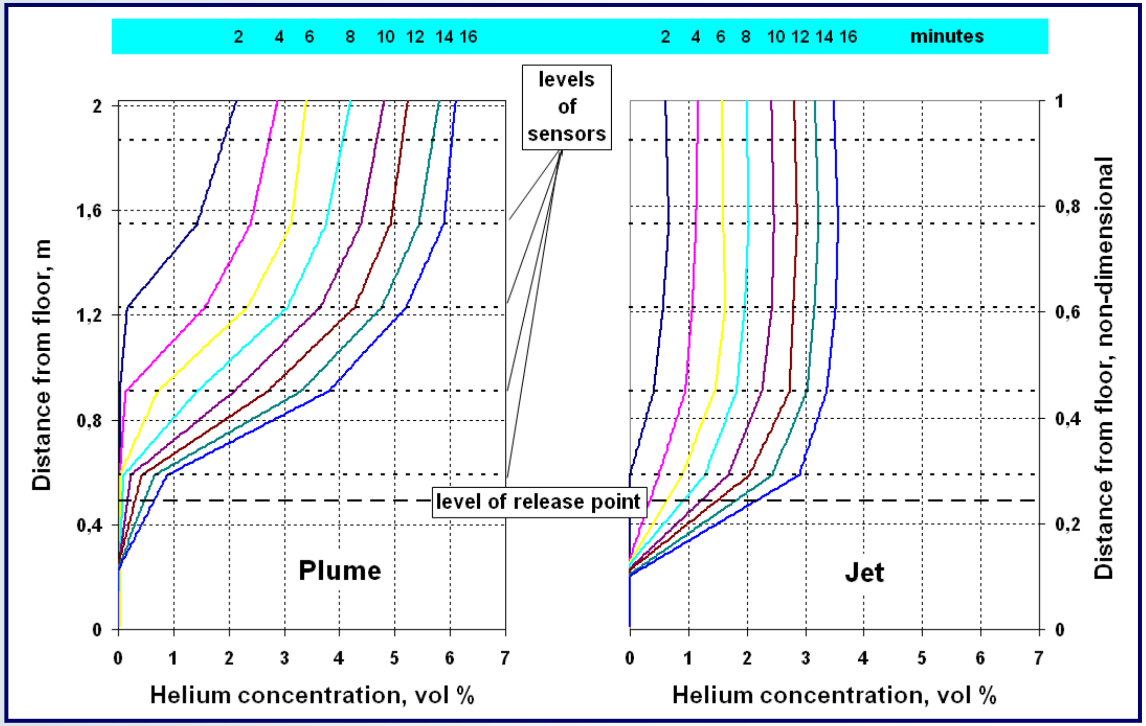


Figure 2. Helium concentration profiles at "filling box" (left) and "fading up box" (right) regimes from consequently 8 mm and 0,6 mm nozzles, data were collected every 2 min.

EXPERIMENTAL RESULTS

- In one limiting case (sufficiently low speed of leak – less than 150 m/s), the overall gas-dynamic pattern can be described by a well-known “filling box” model. Here, hydrogen (helium) jet, released from a nozzle, is transformed into plume before reaching the “garage” ceiling. In this case light gas - hydrogen is first accumulated under the ceiling of the room and then propagates down slowly, and here the main “driver” of hydrogen-air mixing is hydrogen plume.
- In the other limiting case (high velocity of leak), it was proposed to describe the peculiarities of gas-dynamic behavior of flammable cloud as a “fading up box” model. Here the hydrogen (helium) jet, released from a nozzle, “touches” the ceiling without transforming into a plume. In this case hydrogen (helium) concentration increases practically uniformly through the whole free volume above the nozzle, and here the main “driver” of hydrogen-air mixing is hydrogen jet.

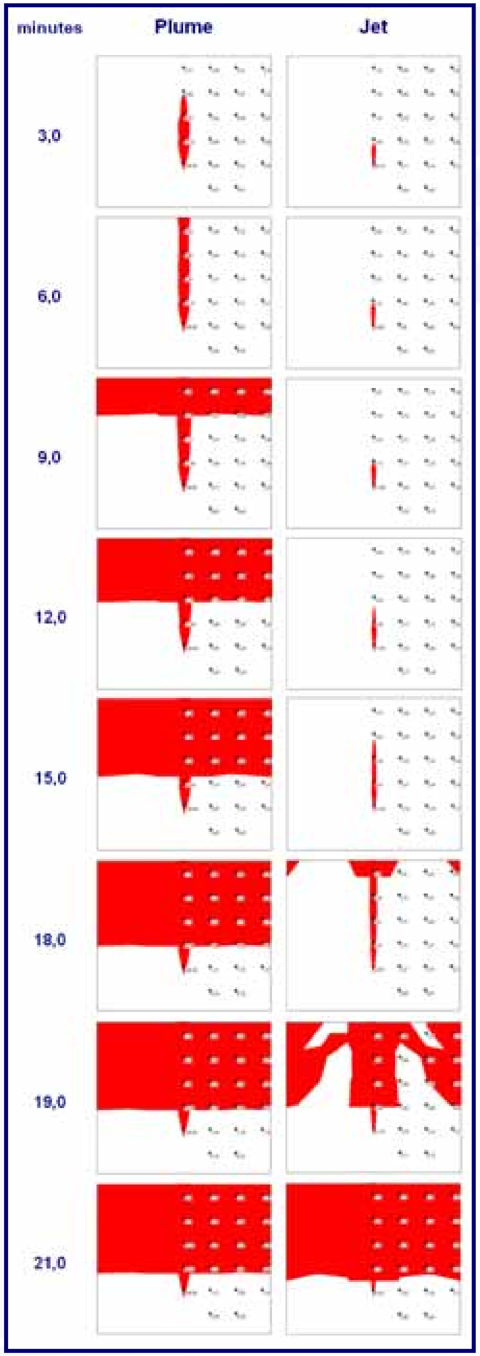
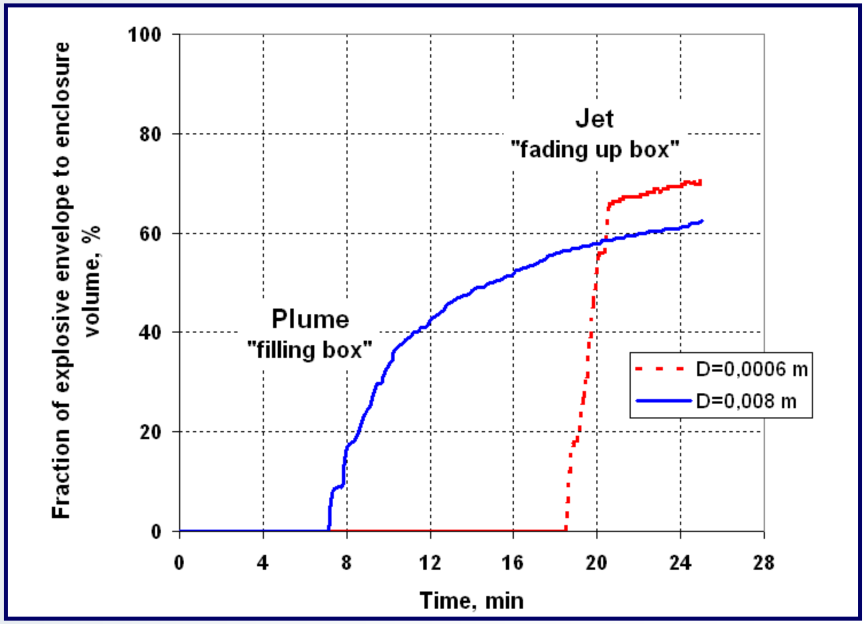


Figure 3. Time evolution of hydrogen explosive envelope (74% > CH2 > 4%), release flow rate is 0,47 l/s.

EXPERIMENTAL RESULTS

Figure 4. Time evolution of "explosive" mixture envelope for two different regimes of gas outflow.



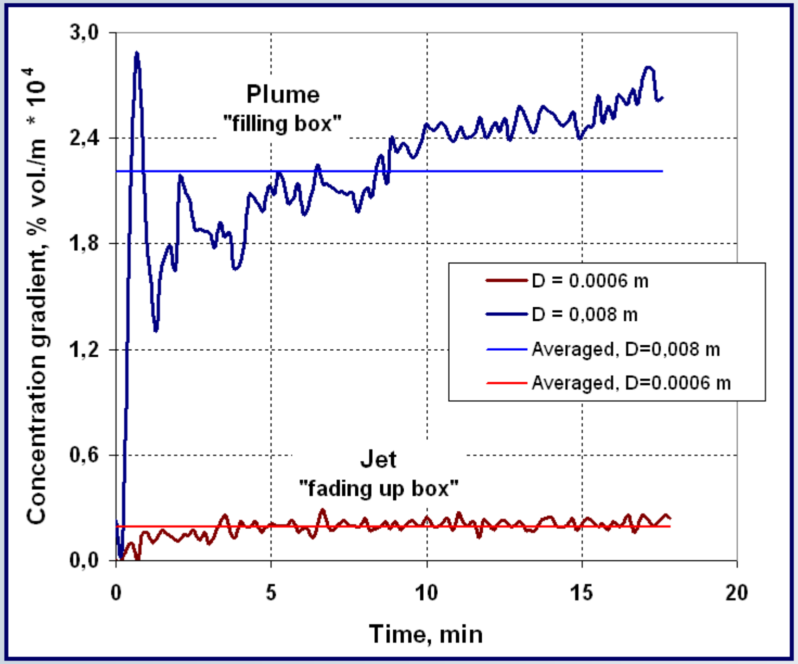


Figure 5. Time dependence of vertical helium concentration gradient of gas propagation from ceiling to floor for different regimes of gas outflow.

EXPERIMENTAL RESULTS

№	Release diameter D_0, m	Release gauge pressure, bar	Initial velocity w_0, m/s	Plume formation distance L_j, m	Morton number $Mo = L_j/Z_r$	Type of release regime
1	0,0006	2,19	905*	7,3	4,8	Jet
2	0,001	0,35	461*	4,8	3,1	Jet
3	0,002	0,020	151	2,23	1,5	Transition
4	0,004	0,0012	37,4	0,78	0,5	Plume
5	0,008	0,00008	9,35	0,28	0,18	Plume

Table 1. Characteristic parameters for different release diameters (initial velocity of gas)

$$L_j = 1.02\frac{M_0^{3/4}}{F^{1/2}} = \frac{0{,}96 w_0\sqrt{D_0}}{\sqrt{\dfrac{g(\rho_a-\rho\ )}{\rho_a}}}$$

We propose to characterize the difference between the two revealed cases by a non-dimensional ratio of plume formation distance (**L_j**) and distance from the release point to the ceiling (**Z_r**). Ratio **$Mo=L_j/Z_r$** can be named as a Morton number.

According to our experimental database, for situations, where Mo < 1, a “filling box” case takes place, for Mo >> 1 a “fading up box” case occurs.

EXPERIMENTAL RESULTS

sensitivity level, %	time delay, min	
	PLUME	*JET*
0,2	6,9	18,1
0,5	6,8	17,3
1	6,3	15,3
2	5	11

Table 2. Time between the first alarm detection of hydrogen and the formation of the explosive cloud for different sensitivity level of hydrogen sensors

The “filling box” case has a relatively short delay time (time before the first detection of hydrogen, i.e. time before the moment when the hydrogen concentration will be more than detection limit of a gas sensor) and a relatively long time for the hydrogen-air cloud to grow to a hazardous scale.

The “fading up box” case has a long delay time and an extremely high development rate of explosive cloud for the same hydrogen release flow rate. It can be said that the explosive volume appears almost at once in the space between the hydrogen release point and the ceiling.

In particular, in our experiments the time between the first alarm detection of hydrogen and the formation of the explosive cloud varies about 3 times for the two cases mentioned, and this difference does not practically depend on the sensitivity level of gas detectors.

CONCLUSIONS

Analysis of the results of the experimental studies results in the following conclusions:

- For a given value of hydrogen release flow rate, two basic patterns of hydrogen explosive envelope evolution inside a confined enclosure have been discriminated experimentally.
  - In a “filling box” case (at a low speed of hydrogen outflow), the explosive cloud initially forms as a thin layer at the ceiling and then expands via concentration front downward.
  - In a “fading up box” case (at a high speed of hydrogen outflow), the explosive cloud forms nearly uniformly throughout the whole volume above the discharge point.
- The difference between the two revealed cases can be characterized by a non-dimensional ratio of plume formation distance (L_j) and distance from the release point to the ceiling (Z_r). Ratio **$Mo=L_j/Z_r$** can be named as a Morton number.
  - when **$Mo < 1$**, a “filling box” case takes place;
  - at **$Mo >> 1$** a “fading up box” case occurs.

PRECAUTION for SAFETY PROVISIONS

- The “filling box” case has a relatively short delay time (time before the first detection of hydrogen, i.e. time before the moment when the hydrogen concentration will be more than detection limit of a gas sensor) and a relatively long time for the hydrogen-air cloud to grow to a hazardous scale.
- Unlike the “filling box” case, the “fading up box” case has a long delay time and an extremely high development rate of explosive cloud for the same hydrogen release flow rate.
- In particular, in our experiments the time between the first alarm detection of hydrogen and the formation of the explosive cloud varies about 3 times for the two cases mentioned, and this difference does not practically depend on the sensitivity level of gas detectors.
- **Due to the principal difference in patterns of the explosive cloud formation in “filling box” and “fading up box” cases, it is essentially important that this difference should be taken into account when special technical or organizational measures of hydrogen safety (ventilation, hydrogen detection system, recombiners allocation and so on) are developed and implemented.**

СПАСИБО !

thank you !

ACNOWLEDGMENTS

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