EXPERIMENTAL STUDY OF THE MITIGATION OF HYDROGEN-AIR EXPLOSIONS BY AQUEOUS FOAM

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ABSTRACT

The development of hydrogen production technologies, as well as new uses, represents an opportunity both to accelerate the ecological transition and to create an industrial sector. However, the risks associated with the use of hydrogen must not be overlooked. The mitigation of a hydrogen explosion in an enclosure is partly based on prevention strategies such as detection and ventilation, but also on protection strategies such as explosion venting. However, in several situations, such as in highly constrained urban environments, the discharge of the explosion through blast walls could generate significant overpressure effects outside the containment which are unacceptable. Thus, having alternative mitigation solutions can make the effects of the explosion acceptable by reducing the flame speed and the overpressure loading, or suppressing the secondary explosion. The objective of this paper is to present the experimental study of the mitigation of hydrogen-air deflagration in a 4 m^3 vented enclosure by injection of aqueous foam. After a description of the experimental set-up, the main experimental results are presented showing the influence of aqueous foam on flame propagation (Fig. 1). Different foam expansion ratios were investigated. An interpretation of the mitigating effect of foam on the explosion effects is proposed based on the work of Kichatov [5] and Zamashchikov [2].

1.0 INTRODUCTION – PREVIOUS WORKS

There are few studies concerning the interaction of a hydrogen-air premixed flame with an aqueous foam. The first one to investigate the combustion of a hydrogen-air cloud in the presence of an aqueous foam were Baer et al [1]. Baer carried out small-scale tests:

- in a horizontal tube of 1 m length and 8 cm diameter closed on the ignition side and open at the opposite end. For safety reasons, only tests with low hydrogen concentration were performed;
- in a tube of 63 cm length and 15 cm diameter closed at both ends.

The foam was generated by means of an injection device whose carrier gas is the flammable hydrogen-air mixture. Two igniters were used: a spark generator and a glow plug. The concentrations of the hydrogen-air mixtures studied were between 9.5 and 45%. The expansion ratio of the studied foam is 1000. The results of the open tube and closed chamber tests show that the foam can significantly reduce the explosion overpressure as a function of the hydrogen concentration in the flammable mixture. For hydrogen concentrations below 10%, the reduction in pressure rise is substantial - a factor of two or more. Between 10% and 15% hydrogen concentration, the foam has a small effect on the pressure rise. For example, at 12%, the overpressure for combustion with foam is about 90% of that without foam. Above 15% hydrogen concentration, the foam causes a significant reduction in the explosion overpressure. The attenuating effect of foam is maximum near stoichiometry. The explosion overpressure is then reduced by a factor of two and a half. The authors explain this by the fact that at stoichiometry the flame temperature is maximum. Thus, more water would be vaporised, and the inhibiting effect would be increased. For higher concentrations, the attenuating effect decreases with increasing hydrogen concentration. However, despite this overall reduction in pressure, the flame velocity is more than an order of magnitude greater for combustion in foam for all concentrations. The

authors interpret this increase in flame propagation speed as being induced by the turbulence generated during the bursting of foam bubbles.

Zamashchikov et al [2] measured the flame propagation speed in tubes with diameters of 55 and 105 mm and lengths of 520 and 2750 mm respectively, for hydrogen-air mixtures of 10, 11.6, 13 and 15 %, for foam expansion rates of 30 to 1600, when the foam bubbles are filled with a flammable mixture. The study suggests that the flame speed is not monotonic with increasing foam expansion ratio. For 10% and 11.6% H2/air mixtures, there is an optimum expansion ratio in the range of 350 to 400. The minimum flame speed is around 0.6 m/s for the 10% H2/air mixture and 0.9 m/s for the 11.6% H2/air mixture. For concentrations higher than 15% H2/air in particular, the flame speed increases as the expansion ratio increases. The flame propagation speed of a 15% H2/air mixture in a foam with a high expansion ratio can become twice as fast as the flame propagation speed without foam. This was also suggested by the first Zamashchikov's study which also suggests that the speed of flame propagation in foam depends on the resistance of the liquid film forming the bubble walls. The experimental study shows that increasing the surface tension of the liquid film improves the mechanical strength of the foam. However, instead of slowing down the flame, it increases its speed of propagation in the foam.

Larger scale work in a 5 m^3 vertical chamber (4.27 m length, 1.22 m diameter) was carried out by Benedick et al [3]. The flammable hydrogen-air mixture is formed by partial pressure to the correct concentration prior to foam generation in the enclosure. The foam generator is installed near the top of the explosion chamber. It consists of a fan that recirculates the flammable mixture through a cone-shaped perforated metal plate. The water/surfactant mixture contained in a small, pressurised tank is injected directly near the operating fan. The foam generated has an expansion rate of 620. Ignition is achieved by means of an electrical spark with an energy of 30 J. Several hydrogen explosion tests with and without foam have been carried out. The hydrogen concentrations are 10%, 15%, and 20%. The test results show a significant reduction in peak overpressure due to the presence of aqueous foam for the 10 and 15% concentrations. The attenuation factors are in the order of 1.6 for a 10% H2-air mixture and 1.4 for a 15% H2-in-air mixture. The pressure rises times between the tests with and without foam for H2 concentrations less than or equal to 15% are of the same order of magnitude. For the tests with 20% H2 with and without foam, the peak pressures are of the same order of magnitude. Furthermore, if we compare the pressure rise times, the test without foam has a value of about 70 ms, while the test with foam had a value of about 9 ms, which would correspond to average combustion speeds of 49 m/s for the test without foam and 380 m/s for the test with foam. This shows that for H2/air mixtures with a concentration of 20% or more, the presence of a foam with an expansion factor of 620 can have an aggravating effect that leads to a strong flame acceleration.

More recently, Grune [4] studied the hydrogen flame propagation regimes in two types of foam (one of which is used for fire extinguishing) in a horizontal rectangular foam tank (2 m x 1 m x 0.3 m) open at the top and in an open-ended vertical tube with two different cross-sections: cylindrical (d = 0.09 m; l = 1.4 m) and rectangular (0.2 x 0.02 m; l = 2 m). The expansion ratio of the foam is between 20 and 200. The author shows that the flammability limits of the hydrogen-air mixture in the foam are comparable to that of pure gas (H2/air), that the flame propagation is similar for the two types of foam tested and that the speed of flame propagation in the foam is lower than the speed of sound in the foam. The author also observed sudden accelerations of the flame during its propagation.

The objective of this paper is to present the experimental study of the mitigation of hydrogen-air deflagration in a 4 m^3 vented enclosure by injection of aqueous with two expansion ratios of 20 and 200. After a description of the experimental setup, the main experimental results are presented for several tested configurations showing the influence of the presence of aqueous foam in the flammable cloud on flame propagation. An interpretation of the mitigating effect is proposed based on the work of Kichatov [5] and Zamashchikov [2].

2.0 DESCRIPTION OF THE EXPERIMENTAL SETUP

2.1 Explosion chamber

The explosion chamber is an enclosure of 4 m^3: 2 m long, 2 m high, and 1 m wide. It includes 3 transparent faces and a 60 cm square opening, located on one of the side faces of the enclosure and centered on its horizontal axis (Fig. 1). To keep the gas inside the explosion chamber during the injection process, the discharge opening is covered with a sheet of plastic film (opening overpressure about 80 mbar).

The explosive atmosphere is formed by the discharge of a 50-liter hydrogen tank pressurized to 40 bar. The tank is connected to a 3 mm circular hole located in the center of the floor of the explosion chamber. The hydrogen injection is vertical upwards. A study before explosion tests made it possible to calibrate the hydrogen injection times to reach the desired concentrations and verify that the hydrogen concentration was homogeneous in the chamber.

2.2 Foam injection device

The foam injection device consists of a disperser which creates the foam, connected by a flexible hose to the bottom nozzle of a 150-litre tank pressurised to a constant pressure of 5.5 bar. The foam dispersers consist of a liquid injection nozzle and a metal grid cone (Fig.2). The mesh width of this grid makes it possible to obtain the expected expansion rate. The disperser is installed in the upper part of the explosion chamber. The emulsifying agent dissolved in water (3% by volume) is injected at a constant rate through the injection nozzle. The injection is remotely controlled by a system of pilot valves. The liquid is sprayed onto the cone grid. The atmosphere in the explosion chamber is entrained by the momentum of the liquid, creating the bubbles of the foam. Thus, the flammable hydrogen atmosphere already present in the explosion chamber is encapsulated in the foam bubbles. It should be noted that for all the tests foam dispersers in the chamber withstood the various explosions without suffering any damage. Two foam dispersers were provided to create two expansion rates: 200 and 20 respectively (Fig. 3). For the expansion rate of 200, the foam seems to be composed of "big" bubbles surrounded by small ones, whereas the foam with an expansion rate of 20 seems to be more homogeneous composed of "small" bubbles.

2.3 Ignition

Ignition is achieved by a pyrotechnic match with an energy of 60 J. The ignition source is placed on the opposite side of the overpressure relief door to maximize the flame path. In order to study the interaction of a hydrogen flame with the aqueous foam and not the effect on the ignition, the ignition source is encapsulated in a 30 cm diameter, 20 cm thick metal cylinder covered with a plastic sheet held in place by an elastic band and previously filled with a hydrogen flammable mixture at the same concentration as in the explosion chamber (Fig. 4).

2.4 Instrumentation

The instrumentation is composed of:

- 3 oxygen analyzers to measure the oxygen concentration in the enclosure and thus to deduce the hydrogen concentration before foam injection,
- a piezoresistive pressure sensor (Pint) brand Kistler 0-2 bar located in the explosion chamber in the center of the metal face opposite the transparent face of 2 m x 2 m,
- a pressure sensor (Pint 2) piezoresistive brand Kistler 0-2 bar located in the volume to protect the ignition source,
- a pressure sensor (Plent 1) piezoresistive brand Kistler 0-2 bar embedded in lenticular support located in the axis of the explosion chamber 3 m from the overpressure relief port,
- a normal camera to film the foam injection,

- a fast camera to film the explosion (acquisition rate: 2000 frames/s).
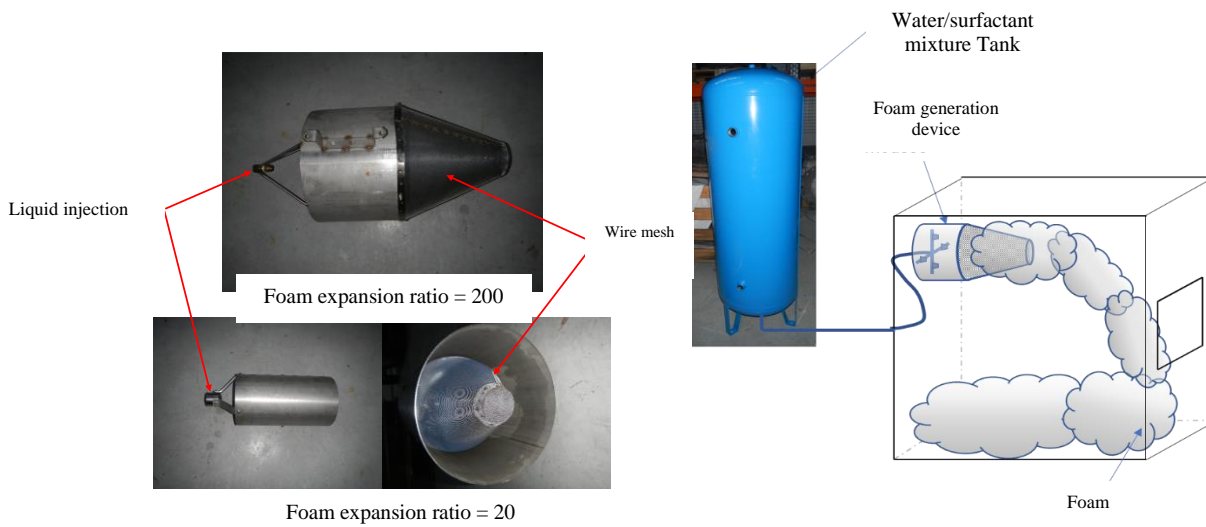

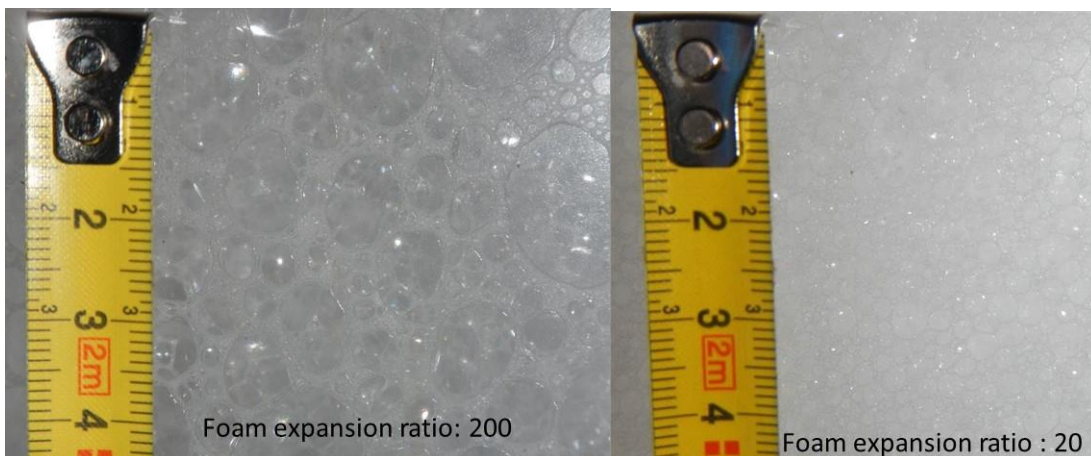Figure 1. 4 m^3 Explosion chamber

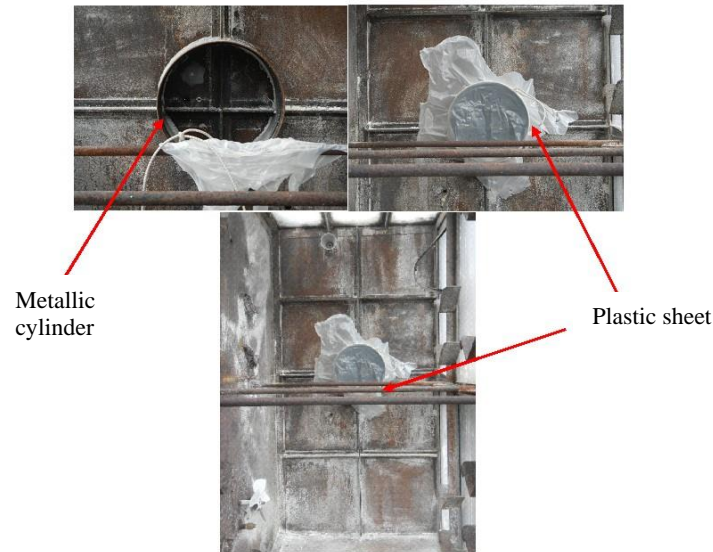Figure 2. Foam generation devices

Figure 3. Foam expansion ratio

Figure 4. Ignition protection encapsulation inside the explosion chamber

3.0 EXPERIMENTAL TESTS

3.1 Reference tests

In order to compare the influence of the aqueous foam on the explosion of the hydrogen-air mixture, a series of reference tests is carried out. The reference situations are the explosion of a quiescent hydrogen-air mixture at 16% and at 21 %. Fig. 5 presents the overpressure signal measured inside the ignition encapsulation (Pint2), inside the chamber (Pint) and outside (Plent1). Fig. 5 presents also the overlay of pressure signals from 2 tests performed under the same conditions to show the reproducibility of the tests. The explosion overpressures in the explosion chamber are about 275 mbar for the 16% test and 850 mbar for the 21% test.
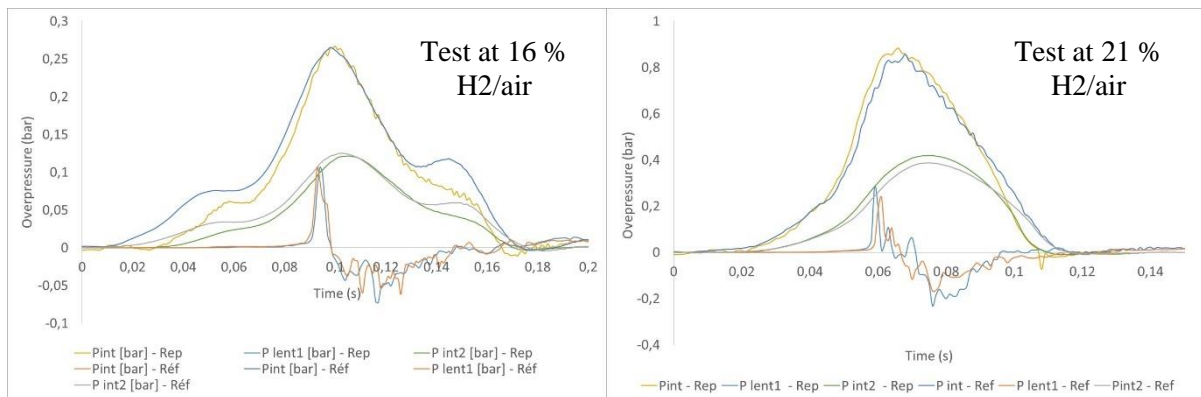

Figure 5. Overpressure signals Pint, Pint2 and Plent1 - 16% H_2 -air quiescent mixture and 21% H_2 – air quiescent mixture (Rep represents the reproducibility test – Ref represents the reference test)

3.2 Explosion tests with aqueous foam

The situation tested is that of the interaction of a hydrogen flame with the foam when the foam encapsulates the flammable hydrogen-air mixture. The flammable atmosphere is formed before the foam is injected so that the flammable mixture is trapped in the foam bubbles. The ignition is protected in a metal cylinder previously filled with a flammable hydrogen-air mixture. Thus, a premixed flame interacts directly with the foam.

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Three configurations were studied and presented in Table 1. Each configuration was repeated once.

Table 1. Experimental configurations.

n° of configuration	Concentration of flammable mixture	Foam expansion ration
1	Quiescent 16 % H2/air	200
2	Quiescent 16 % H2/air	20
3	Quiescent 21 % H2/air	20

The first configuration was to test the interaction of a high expansion ratio foam (200) with a 16% hydrogen-air mixture. Figure 6 shows the comparison of the overpressure signals between the test with foam and the reference test without foam.

First of all, we note a very good reproducibility of the tests with foam. It is also noted that the maximum pressure level reached in the chamber for the tests with foam is about 460 mbar whereas it is only 275 mbar without foam. We therefore observe an aggravation of the internal effects of overpressure as mentioned by William & al. [3]. Whereas William's work was performed in a closed tank, the 4 m^3 explosion chamber is vented, which leads to a secondary explosion phenomena in front of the vent. It is found that the presence of foam significantly reduces the overpressure levels recorded by the external pressure sensor from 100 mbar without foam to 30 mbar with foam.
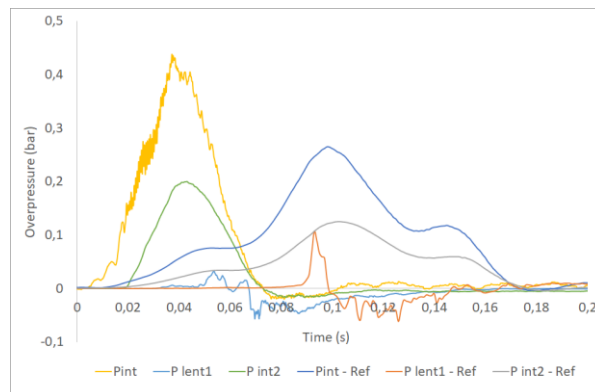

Figure 6. Comparison of overpressure signals between the two tests with foam and the test without foam - Foam at 200 expansion rate - 16% H_2/air mixture (Ref = reference test)

Due to the aggravation of the overpressure effects with the expansion ratio foam of 200, it was decided to test the same configuration using an expansion ratio foam of 20 (configuration 2). Figure 7 presents the overpressure signals for fully filled foam test (a) and the comparison of overpressure signals between the empty and fully filled foam tests (b).

First of all, a strong pressure increase can be observed in the ignition encapsulation, up to 180 mbar (Reference 1 in Figure 7a). This can be explained by the fact that the dense foam represents an obstacle to the opening of the plastic sheet covering the volume, which leads to a significant pressure increase.

Then when the test where the chamber is filled with foam, the overpressure in reaches a maximum of about 60 mbar and then decreases. There is a slight repressurisation of the ignition protection volume up to 30 mbar, probably due to the propagation of the flame in the foam. If we compare the internal and external pressure signals for the fully filled foam tests and the reference test (Figure 7b), we see a strong

decrease in pressure effects, the maximum overpressure for the foam tests is about 60 mbar while the overpressure level is about 285 mbar for the test without foam. It can also be seen that there is no secondary explosion for the tests with foam at an expansion ratio of 20. This highlights the efficiency of the low expansion ratio foam in mitigating the effects of internal and external pressures.

Configuration 3 addresses the interaction of the low expansion foam (20) with a higher flammable mixture reactivity than in Configuration 2, i.e. a 21% hydrogen-air mixture.

Figure 8 shows the overpressure signals for the fully filled foam test (a) and the comparison of overpressure signals between the empty and fully filled foam tests (b).

Like for the previous test with a low expansion ratio foam, a strong pressure increase is observed in the ignition encapsulation, caused by the foam which prevents the plastic sheet to open.(Reference 1 in Figure 8a). Then the overpressure in the chamber reaches a maximum of about 50 mbar and then decreases. In contrast to configuration 2, there is no repressurisation of the ignition protection volume.
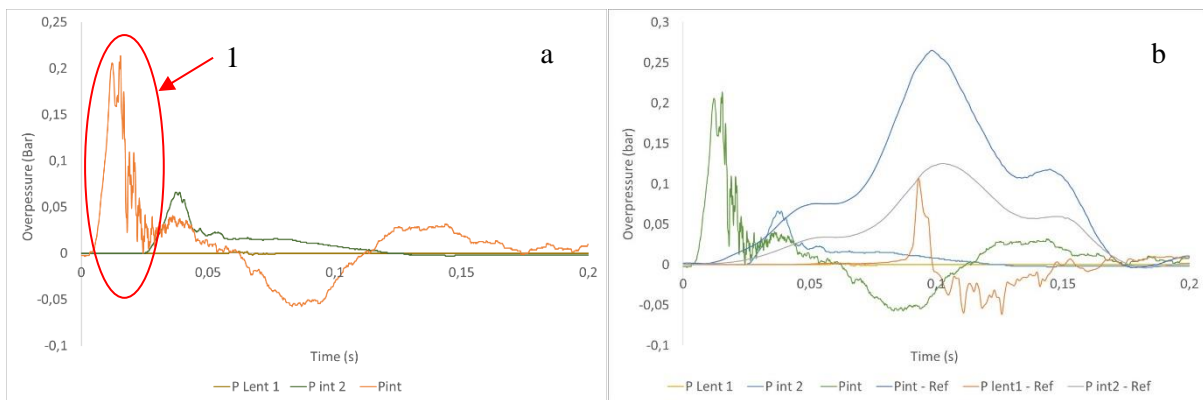

Figure 7. Overpressure signals for fully filled foam test (a) and comparison of overpressure signals between the empty and fully filled foam tests (b) - Foam with an expansion ratio of 20 - Mixture 16 % H_2/air

If we compare the internal and external pressure signals for the full foam test and the reference test (Figure 8b), a strong decrease in pressure effects can be observed. The maximum overpressure for the tests with foam is about 50 mbar while the overpressure level is about 850 mbar for the test without foam. Again, it can be seen that there is no secondary explosion for the tests with foam at an expansion ratio of 20. This also illustrates the efficiency of the low expansion ratio foam in mitigating the effects of internal and external pressures with a higher reactivity.
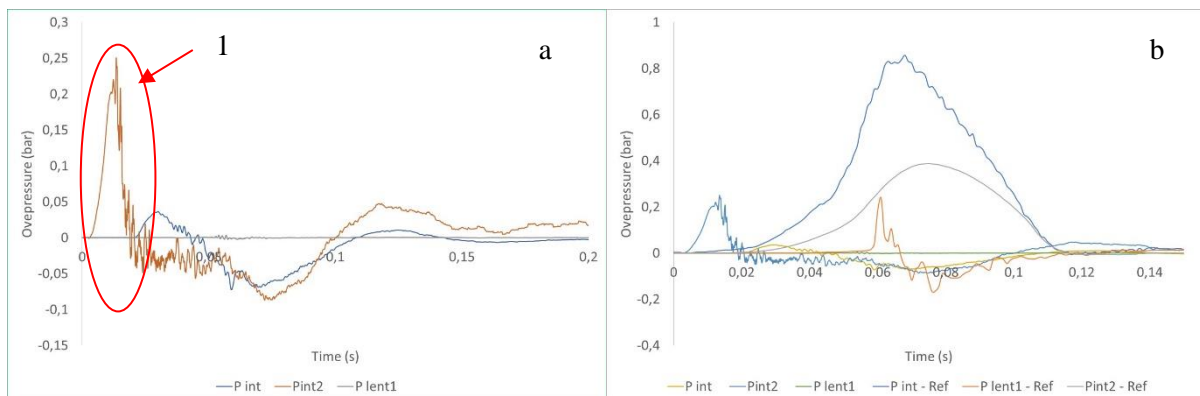

Figure 8. : Overpressure signals for the fully filled foam test (a) and comparison of overpressure signals between the empty and fully filled foam tests (b)- Foam with an expansion ratio of 20 - Mixture 21% H2/air

4.0 ANALYSIS OF EXPERIMENTAL RESULTS AND DISCUSSIONS

Zamashchikov et al [2] propose an interpretation of the interaction mechanisms of the premixed flame with aqueous foam. They suggest that the combustion process in foam consists of two steps: the rupture of foam bubbles containing the flammable mixture and the combustion of the released mixture. The rate of destruction of the foam bubbles depends not only on the strength characteristics of the foam, such as the thickness of the film, but also on the heat flow which depends on the heat loss from the burnt gases to the foam. When the foam is destroyed, most of the liquid atomises and disperses into an aerosol of fine droplets. The burnt gases are then effectively cooled by the dispersed liquid droplets. The average droplet size resulting from the rupture of foam bubbles increases when the foam expansion rate decreases. Within a certain range of expansion ratio values, this could lead to a reduction in the specific surface area of the aerosol formed upon foam rupture and, consequently, to reduced cooling of the combustion products and an increase in the burning rate. The authors specify that the verification of this hypothesis requires further studies. This phenomenological description does not distinguish high and low expansion foams.

Kichatov et al [5] propose a model for estimating the rate of flame propagation in a foam filled with a flammable mixture. Let us assume, as suggested by Zamashchikov, that the rupture of the liquid film constituting the foam bubbles leads to its atomisation and the formation of an aerosol of fine droplets composed mainly of water. The water droplets in the direct vicinity of the flame front will evaporate to some extent in the area of the combustion products. This leads to thermal pumping, which lowers the flame temperature and consequently decreases the flame speed. In order to take this effect into account, it is necessary to estimate the heat flux from the flame front to the reaction product zone required for the evaporation of the water droplets. The flame speed could be estimated by means of the Zeldovitch and Frank-Kamenetskii formula [6].

$$S \approx \exp\left(\frac{-E_a}{2.R.T'_b}\right) \tag{1}$$

where S is the flame propagation speed in the foam, E_a is the activation energy of the combustion reaction, R is the perfect gas constant, T'_b is the actual flame front temperature after cooling by the water droplets.

The heat balance equation taking into account the evaporation of water drops can be written as follows:

$$\rho.S.c_p.\frac{dT}{dX} = -G_w.L_wN_w \tag{2}$$

Where ρ is the density of the gas-droplet mixture, c_p is the mass specific heat of the gas-droplet mixture, T is the gas temperature (which is near to the flame temperature), X is the distance, G_w is the evaporation rate of the water droplets, L_w is the latent heat of vaporisation of water, N_w is the number of water droplets per unit volume.

The evaporation rate of water droplets decreases as their concentration (number per unit volume) increases. This rate can be written as :

$$G_w = \frac{4.\pi.r_w.\lambda}{c_{vw}}.\ln(1 + B_w) \text{ with } B_w = \frac{c_{vw}.\Delta T_b}{L_w} \tag{3}$$

where r_w is the average radius of the water droplets, λ is the thermal conductivity coefficient of the gas, ΔT is the difference between the adiabatic flame front temperature T_b and the initial temperature T_0, c_{vw} is the mass heat of the water vapour.

By introducing the coefficient $f_w = \frac{\ln(1+B_w)}{B_w}$, equation (3) can be rewritten as:

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$$G_w = \frac{4.\pi.r_w.\lambda.\Delta T_b.f_w}{L_w} \tag{4}$$

Using equation 2 and 4, it is possible to express the heat flux q from the flame front to the droplet evaporation zone as:

$$q = \frac{\gamma}{s} \text{ with } \gamma = \frac{4.\pi.r_w.\lambda^2.N_w.\Delta T_b.f_w}{\rho.c_p} \tag{5}$$

The energy balance, taking into account the heat loss due to the evaporation of water drops, can be written as:

$$\rho.S.Q.m_0 = \rho.S.c_p.(T_b' - T_0) + q \tag{6}$$

where Q is the energy released by combustion, and m_0 is the initial fuel concentration.

The combustion temperature of the flammable mixture can be determined from the energy balance equation:

$$Q.m_0 = c_p.(T_b - T_0) \tag{7}$$

Combining equations 5, 6 and 7, an estimate of the flame front temperature is obtained taking into account droplet evaporation:

$$T_b' = T_b - \frac{\gamma}{S_{lad}^2.\rho.c_p} \tag{8}$$

It follows from this expression that as the water content of the foam increases, the flame front temperature decreases.

Assuming that the flame front temperature during foam combustion differs only slightly from the temperature T_b of the gas mixture front and using the exponent expansion method [7], we can rewrite relationship (1) as:

$$S = S_{lad}.exp\left[\frac{-E_a(T_b - T_b')}{2.R.T_b^2}\right] \tag{9}$$

where S_{lad} is the adiabatic laminar burning velocity of the flammable mixture.

By combining equations 5, 8 and 9, the burning rate of the flammable mixture in the foam can be estimated using the expression :

$$S \approx S_{lad}exp\left[\frac{-2.\pi.r_w.\lambda^2.N_w.E_a.\Delta T_b.f_w}{R.T_b^2.S_{lad}^2.\rho.c_p}\right] \tag{10}$$

By knowing the thermodynamic quantities of water in the liquid state, water in the vapour state and the flammable mixture, it is possible to determine the characteristic thermodynamic quantities of the fuel gas/air-droplet mixture. However, it remains to characterise the average droplet diameter and consequently the average number of droplets per unit volume.

The work of Lhuissier et al [8] shows that the average droplet diameter d_g resulting from a bubble burst can be determined by :

$$d_g \approx R^{3/8}.h_b^{5/8} \tag{11}$$

where R is the radius of the bubble and h_b is the thickness of a liquid film forming the wall of the bubble.

As the average radius R of the foam bubbles is known (provided by the foam supplier), the thickness of the liquid film must be determined. For this purpose, assuming a spherical bubble, it is possible to calculate the amount of water constituting the bubble walls as:

$$V_{w\_bubble} = 4.\pi.R^2.h_b$$

(12)

The expansion ratio of the foam determines the volume of water V_w contained in the foam per unit volume. For example, an expansion ratio of 20 means that 1 litre of liquid gives 20 litres of foam. It follows naturally that a foam with an expansion ratio of 20 contains 50 kg of water per m^3 of foam, i.e. 0.05 m^3 of water per m^3 of foam. Thus, the volume of water per unit volume is equal to:

$$V_w = N_{bubble}.V_{w\_bubble} = N_{bubble}.4.\pi.R^2.h_b$$

(13)

Assuming that the thickness of the liquid film is small compared to the diameter of the bubble, it is possible to determine, as a first approximation, the number of bubbles N_{bubbe} of foam per unit volume. Thus, we obtain:

$$N_{bubble} = \frac{1}{\frac{4}{3}.\pi.R^3}$$

(14)

By combining equations 13 and 14, it is possible to determine the thickness of the liquid film as :

$$h_b = \frac{V_w}{N_{bubble}.4.\pi.R^2}$$

(15)

By applying this model to foams with an expansion ratio of 200 and 20, we will have the droplets number/unit volume. The foam with an expansion ratio of 200 has a water concentration of about 5 kg/m^3, i.e. a volume of water per unit volume of foam of 0.005. The average observed diameter of the foam bubbles is about 10 mm. Thus, applying the model described above, the average diameter of the water droplets would be about 200 µm. It follows that the average number of droplets per unit volume is about 1,6 x 10^9.

Applying the model to a 16% H2/air mixture with a foam-free S_{lad} laminar burning velocity of 0.90 m/s gives a burning velocity of about 0.85 m/s. Thus, this calculated decrease in burning speed is not sufficient to have an effect on the attenuation of pressure effects, which is consistent with the experiment. The aggravating effect of the high-expansion foam on the pressure effects observed experimentally could be explained by the creation of turbulence when the foam bubbles burst. This turbulence would interact with the hydrogen flame and thus increase the combustion rate.

The foam with an expansion ratio of 20 has a water concentration of about 50 kg/m3, i.e. a volume of water per unit volume of foam of 0.05. The average diameter of the foam bubbles is about 1 mm given by the company who provides the emulsifier agent and the foam generation device. Thus, applying the model described above, the average diameter of the water droplets would be of the order of 30 µm. It follows that the average number of droplets per unit volume is of the order of 3.5 x 10^{11}.

Applying the model to a 16% H2/air mixture with a foam-free S_{lad} laminar burning velocity of 0.90 m/s gives a burning velocity of the order of 0.05 m/s. Thus, this calculated decrease in combustion speed is large enough to severely reduce the explosion pressure, which is also consistent with experience.

Applying the model to a 21% hydrogen-air mixture with a foam-free S_{lad} laminar burning velocity of 1.6 m/s gives a burning velocity of the order of 0.6 m/s. Thus, this calculated decrease in combustion speed is sufficient to reduce the pressure effects, which is also consistent with the experiment.

The proposed equation of the phenomenon is based on the interaction between the flame front and the droplets formed as a result of the bursting of foam bubbles. The model shows that for foams with low expansion ratios, i.e. with a large amount of water, the burning rate decreases significantly. Under the conditions tested, low expansion aqueous foam can be effective in mitigating the pressure effects of a hydrogen-air cloud deflagration in a confined environment.

5.0 CONCLUSIONS

The low expansion foam has shown its potential to mitigate a hydrogen explosion in a confined space by significantly reducing the overpressure levels in the foam filled enclosure and significantly limiting the secondary explosion phenomenon. The encapsulation of the flammable mixture in the foam bubbles significantly reduces the combustion velocity. The mathematical model of the phenomenon based on the interaction between the flame front and the droplets formed following the bursting of the bubbles shows good consistency with the experiments.

To go further, it would be interesting to correlate the foam expansion ratio to the overpressure decrease. Indeed, a foam with an expansion ratio of 20 is effective for the mitigation of a hydrogen explosion. A foam with an expansion ratio of 200 is not. The question arises whether there is an expansion rate between 20 and 200 that would allow a good compromise between interesting mitigation and limited quantities of water and emulsifier. It also would be interesting to test different nature of emulsifying agents. This could highlight the influence of the surface tension of the foam bubbles on the explosion propagation.

The ability of the low expansion foam to mitigate the effects of pressure at industrial scale should be tested, typically in a larger chamber of several tens of m^3.

Then, it would be interesting to:

- characterise the distribution of hydrogen when the foam is injected during the hydrogen leak,
- test the influence of a partial filling with foam when the flammable atmosphere is already present,
- test real-life situations where foam injection is carried out at the same time as the formation of the flammable atmosphere.

This type of investigation on a more industrial scale would also provide information on the dynamics of filling a large volume with foam.

REFERENCES

1. Baer M, Griffiths S, Shepherd J. 1982, Hydrogen combustion in aqueous foams, Report NUREG/CR-2865 SAND82-0917
2. Zamashchikov V.V., Kakutkina N.A., "Experimental studies of the combustion mechanism of water base foams filled with fuel gases", Combustion. Explosion. Shock Waves, vol 29: pp 142–147
3. William B. Benedick, John C. Cummings, Peter G. Prassinos, 1984, "COMBUSTION OF HYDROGEN:AIR MIXTURES IN THE VGES CYLINDRICAL TANK", Sandia National Laboratories Albuquerque, New Mexico 87185 Operated by Sandia Corporation for the U.S. Department of Energy
4. Grune J, 2022, Deflagration propagation through fire extinguishing foam, HyTunnel-CS dissemination conference 14-15 July 2022, Brussels, Belgium
5. Kichatov B., Korshunov A., SonK., Son E., 2016, "Combustion of emulsion-based foam", Combustion and Flame, vol 176, pp 162-172
6. Zeldovich Ya.B., Frank-Kamenetskii D.A., 1938, "A theory of thermal propagation of flames", Acta Phys-Chem URSS IX, 2 , pp. 341-350

7. Zeldovich Ya.B., Barenblat G.I., Librovich V.B, Makhviladze G.M., 1985, "Mathematical theory of combustion and explosion", Consultants Bureau, New York

8. Lhuissier H., Villermaux E., 2012, "Bursting bubble aerosols", Journal of Fluid Mechanics , Volume 696 , pp. 5 - 44