

# EXPERIMENTAL STUDY OF THE MITIGATION OF HYDROGEN-AIR EXPLOSIONS BY INHIBITING POWDER

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## ABSTRACT

The development of hydrogen production technologies and new uses represents an opportunity to accelerate the ecological transition and create a new industrial sector. However, the risks associated with the use of hydrogen must be considered. Mitigation of a hydrogen explosion in an enclosure is partly based on prevention strategies such as detection and ventilation and protection strategies such as explosion venting. Even if applications involving hydrogen probably are most interesting for vented explosions in weak structures, the extreme reactivity of hydrogen-air mixtures often excludes the use of regular venting devices, such as in highly constrained urban environments. 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 experimental studies of the mitigation of hydrogen-air deflagration in a 4 m<sup>3</sup> vented enclosure by injection of inhibiting powder (NaHCO<sub>3</sub>). After describing the experimental set-up, the main experimental results are presented for several trial configurations showing the influence of inhibiting powder in the flammable cloud on flame propagation. An interpretation of the mitigating effect of inhibiting powder on the explosion effects is proposed based on the work of Proust et al.

## 1.0 INTRODUCTION – PREVIOUS WORKS

Significant work has been carried out by Hoorelbeke [1] and Roosendans et al. [2] on the injection of inhibiting powder for conventional hydrocarbon/air mixtures. The objective of this work was to:

- Determine the relationship between inhibitor characteristics (concentration, type, etc.) and the flame burning rate of a 20 L sphere air-fuel mixture on the laminar burning velocity and the pressure rise rate.
- verify the effectiveness of medium-scale inhibitors in a volume of 50 m<sup>3</sup> on flame spread rate and explosion overpressure.

The work focused on potassium bicarbonate KHCO<sub>3</sub>. It reduced the pressure rise in the 20-liters sphere by more than 80 % and the burning rate by at least 70 % for conventional hydrocarbons with a concentration of 100 g/m<sup>3</sup> inhibitor.

Luo et al [3] experimentally studied the influence of sodium bicarbonate (NaHCO<sub>3</sub>) injection in hydrogen/methane/air mixtures. The explosion chamber used was a Hartmann tube of 5 liters. The sodium bicarbonate was deposited in a cup and blown using a gas injection into the cup. The concentration of sodium bicarbonate in the mixture was 200 g/m<sup>3</sup>, which is the optimal concentration for the suppression of an explosion of the methane/stoichiometric air mixture in the explosion chamber. The median diameter  $D_{v0,5}$  of the particles was 45 μm. The work showed that when the proportion of H<sub>2</sub> in the mixture was greater than 70%, sodium bicarbonate no longer had an inhibiting effect. On the contrary, it would rather promote the explosion.

However, Mitani et al [4] studied (and theorized) the extinction of H<sub>2</sub>/O<sub>2</sub>/N<sub>2</sub> flames on a bunsen burner by NaHCO<sub>3</sub>. The median diameter of NaHCO<sub>3</sub> particles was 15 μm. Two mixtures of H<sub>2</sub> / O<sub>2</sub> / N<sub>2</sub> were studied with the following characteristics:

- The adiabatic flame temperature was respectively of the order of 1200 and 1800 ° C

- The laminar burning velocity was about 0.8 and 2 m/s, respectively.

The work showed that:

- For the mixture with a laminar burning velocity of 0.8 m/s, the hydrogen flame is extinguished with 50 g/m<sup>3</sup> of NaHCO<sub>3</sub>.
- For the mixture with a laminar burning velocity of 2 m / s, the hydrogen flame is extinguished with 200 g/m<sup>3</sup> of NaHCO<sub>3</sub>.

Mitani's work shows sodium bicarbonate's efficiency on the premixed hydrogen-air flame.

The objective of this paper is to present a preliminary experimental study of the mitigation of hydrogen-air slow deflagration in a 4 m<sup>3</sup> vented enclosure by injection of inhibiting powder (NaHCO<sub>3</sub>) of median diameter  $D_{v0.5}$  of 60, 25, and 10  $\mu\text{m}$ . The NaHCO<sub>3</sub> used in this experimental work is classically used for fire extinguishing. It has the particularity of having a hydrophobic treatment that prevents clogging clog and facilitates injection. After describing the experimental setup, the main experimental results are presented for several tested configurations. An interpretation of the mitigating effect of inhibiting powder on the explosion effects is proposed based on the work of Proust [5].

## 2.0 DESCRIPTION OF THE EXPERIMENTAL SETUP

### 2.1 Explosion chamber

The explosion chamber is an enclosure of 4 m<sup>3</sup>: 2 m long, 2 m high, and 1 m wide. It is equipped with two transparent polycarbonate faces and a 60 cm<sup>2</sup> 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) or a 3 mm thick PMMA plate (opening overpressure about 900 mbar) held by a metal frame.

The explosive atmosphere is formed by the discharge of a 50-liter hydrogen tank pressurized to 40 bars. 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. The turbulence of H<sub>2</sub> injection is sufficient to create a homogeneous mixture in the chamber. It was verified by Duclos (2017)

### 2.2 Powder injection device

The first device (powder injection device *a*, Fig. 2a) consists of a 10-liter tank connected to a 5-liter tank. The 10-liter tank can be powder-loaded. The 5-liter tank serves as an air reserve for the discharge of the powder. These two tanks are pressurized with air at 15 bar. The air in the 5-liter cylinder pushes the powder in the 10-liter cylinder into the explosion chamber through a 6 mm injection nozzle. This device allowed the injection of 60 and 25  $\mu\text{m}$  powders. The level of turbulence generated by the powder injected was not directly measured. But, its influence was characterized by comparing quiescent and turbulent tests with powder.

For the dispersion of the finer powder, it was necessary to design a new device (powder injection device *b*). The powder is suspended using pneumatic injection under a pressure of 15 bar of air on a powder bed in a container with a curved bottom. The powder leaving the container is dispersed using a fan and an auxiliary air injection located in the chamber of 4 m<sup>3</sup> (Fig. 2b).

The homogeneity of the powder cloud was not verified with sensors as an opacimeter. The only verification was done through an analysis of injection videos.

### 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. To study the interaction of a hydrogen flame with the powder 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. 3).

### 2.4 Instrumentation

The instrumentation is composed of:

- three oxygen analyzers to measure the oxygen concentration in the enclosure and thus deduce the hydrogen concentration,
- 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 standard camera to film the powder injection,
- a fast camera to film the explosion (acquisition rate: 2000 frames/s).



Fig 1. 4 m<sup>3</sup> Explosion chamber

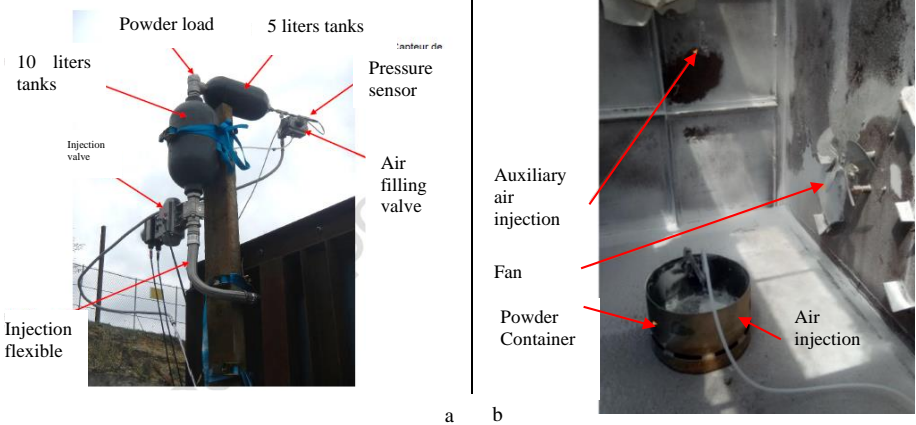


Fig 2. Powder injection devices



Fig 3. Ignition protection volume

### 2.5 Test sequence

The test sequence with powder injection is the following:

- 1- hydrogen injection in the explosion chamber and in the ignition encapsulation at the same time,
- 2- powder injection,
- 3- ignition 150 ms before the end of powder injection.

## 3.0 EXPERIMENTAL TESTS

### 3.1 Reference tests

A series of reference tests are carried out to compare the influence of the inhibiting powder on the explosion of the hydrogen-air mixture. The reference situation is the explosion of a quiescent hydrogen-air mixture at 16%. Hydrogen is injected in excess to consider the dilution effect caused by the pressurized air injected in the chamber with the inhibitor.

To investigate the impact of the inhibiting powder alone on flame propagation and not the joint impact of the powder and its injection system, tests with a turbulent atmosphere at the same hydrogen concentration as the quiescent mixtures tests are performed. The turbulence is produced by the powder injection system but without powder. Ignition occurs 150 ms before the valve of the powder injection system is completely closed. The explosion overpressure in the chamber is about 275 mbar for the quiescent mixture and around 375 mbar for the turbulent mixture, with a plastic sheet covering the vent area. Reference tests are reproducible (Fig. 4).

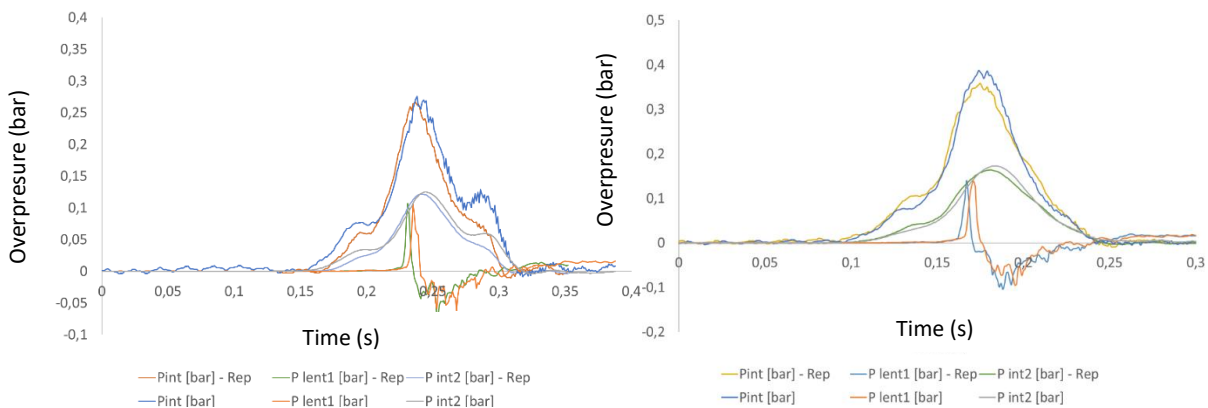


Fig 4. Pint, Pint2, and Plent1 overpressure signals – quiescent 16% H<sub>2</sub> test in air (left) and turbulent 16% H<sub>2</sub> test in air (right) (Rep represents the reproducibility test)

It was necessary during the experimental campaign to modify the experimental setup. To increase the residence time of the flame in the explosion chamber, the plastic sheet covering the explosion discharge port was replaced by a 3 mm thick PMMA plate with a higher opening pressure. A new reference test was carried out in the turbulent conditions previously mentioned (Fig. 5a). The switch from powder injection device a to powder injection device b also required a new reference test (Fig. 5a). The explosion overpressure in the explosion chamber is about 950 mbar.

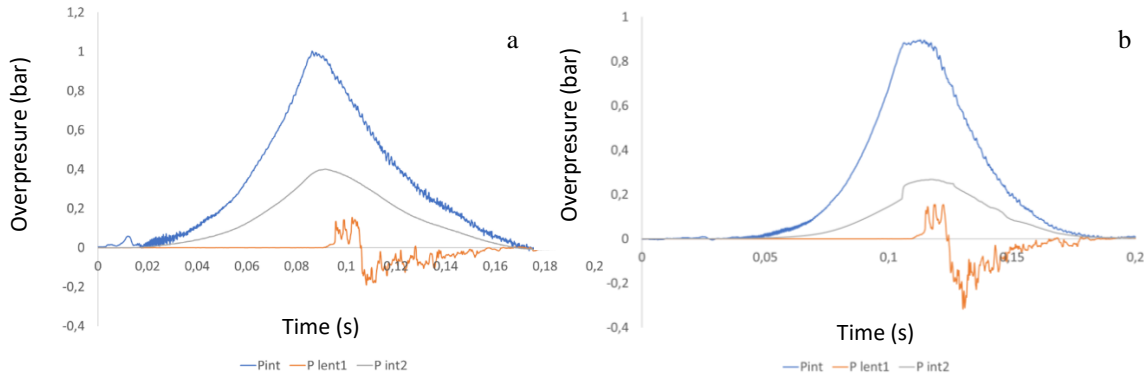


Fig 5. Pint, Pint2 and Plent1 overpressure signals – turbulent 16% H<sub>2</sub> test in air with PMMA plate and respectively powder injection device *a* and *b*

### 3.2 Explosion tests with powder

The powder tested is sodium bicarbonate that has undergone a hydrophobic treatment. It is a powder used initially for extinguishing fires.

The parameters studied to evaluate the efficiency of the inhibiting powder are:

- the amount of powder dispersed (2 kg, 4 kg, and 8 kg)
- the particle size distribution of the powder (Figure 6): The used powders are called in the rest of the study 60 μm powder, 25 μm powder, and 10 μm powder.

Then, 10 experimental configurations were investigated (Table 1). All tests were carried out with a hydrogen concentration of 16% in air.

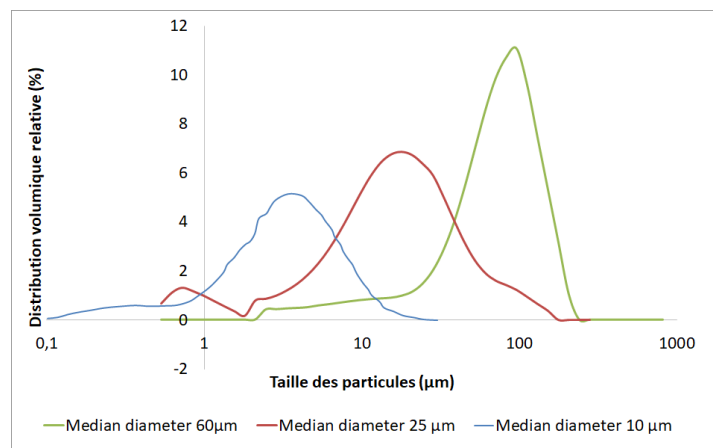


Fig 6. Particle size distribution for 60 μm powder, 25 μm powder, and 10 μm powder

A selection of test results is presented hereafter. Fig. 7 compares the internal overpressure signals (Pint 2) and external overpressure (Plent1) measured in configurations 3 and 4 with a 25 μm powder and corresponding reference tests.

It is found that the internal overpressure signals are of the same magnitudes and the same durations with or without powder, so the 25  $\mu\text{m}$  powder at a concentration less than or equal to 1  $\text{kg}/\text{m}^3$  does not seem to have any effect on the explosion or tends to aggravate the explosion slightly. These observations are the same for configurations 1 and 2. On the other hand, we see a change in the amplitude and shape of the signals in the presence of powder for external overpressure. This suggests that the 25  $\mu\text{m}$  powder with concentrations of 500 $\text{g}/\text{m}^3$  and 1  $\text{kg}/\text{m}^3$  modifies the combustion process during the external explosion and has had a mitigating effect. The fact that there is a reduction of external pressure effects without any impact on the internal pressure suggests that during the initial flame development in the chamber, a large amount of dust is ejected very quickly outside after the plastic sheet is opened. This would not allow the flame enough time to interact with the powder within the chamber.

Table 1. Experimental configurations.

Config	Powder median diameter $D_{v0.5}$	Powder Mass	Powder expected concentration ( $\text{kg}/\text{m}^3$ )	Vent panel	Injection device
1	60 $\mu\text{m}$	2 kg	0.5	Plastic sheet	a
2	60 $\mu\text{m}$	4 kg	1	Plastic sheet	
3	25 $\mu\text{m}$	2 kg	0.5	Plastic sheet	
4	25 $\mu\text{m}$	4 kg	1	Plastic sheet	
5	25 $\mu\text{m}$	4 kg	1	3 mm PMMA plate	
6	25 $\mu\text{m}$	8 kg	2	3 mm PMMA plate	
7	10 $\mu\text{m}$	2 kg	0.5	3 mm PMMA plate	b
8	10 $\mu\text{m}$	4 kg	2	3 mm PMMA plate	

The third series (configurations 5 and 6) carried out two tests with 1  $\text{kg}/\text{m}^3$  and 2  $\text{kg}/\text{m}^3$  concentrations, i.e., the dispersion of 4 kg and 8 kg of sodium bicarbonate at 25  $\mu\text{m}$ . Fig. 8 compares the internal overpressure signals (Pint 2) and external overpressure (Plent1) measured with powder and the powder-free reference test.

Even when trying to increase the residence time of the flame in the explosion chamber, the internal overpressure signals have the same magnitudes and durations with or without powder. The 25  $\mu\text{m}$  powder at a concentration less than or equal to 2  $\text{kg}/\text{m}^3$  still does not seem to attenuate the internal explosion. There is no change in the external overpressure signals as observed for configurations 3-4. The presence of the PMMA plate can explain this. Indeed, the external explosion is not present, so the external pressure sensor only records the discharge of the internal explosion overpressure.

The last experimental phase of this campaign (configurations 7 and 8) consisted in testing a powder with an average particle size of about 10  $\mu\text{m}$ . The powder concentrations are 500  $\text{g}/\text{m}^3$  and 1  $\text{kg}/\text{m}^3$ . Fig. 9 compares the internal overpressure signals (Pint 2) and external overpressures (Plent1) measured with powder and the powder-free reference test.

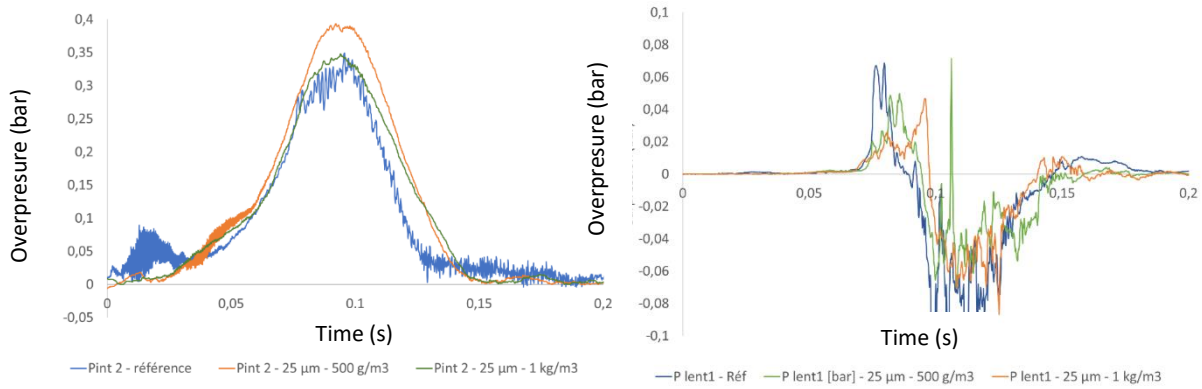


Fig 7. Comparison of internal overpressure (Pint 2) and external overpressure (Plent1) measured with powder and the reference test without powder – Powder at 25  $\mu\text{m}$  (Configurations 3 and 4)

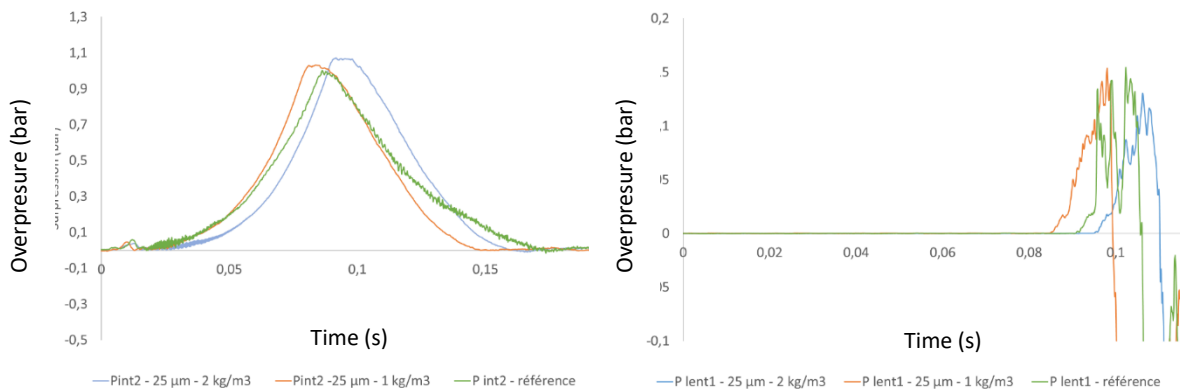


Fig 8. Comparison of internal overpressure signals (Pint 2) and external overpressures measured with powder and powder-free reference test – 25  $\mu\text{m}$  powder with 3 mm PMMA plate (Configuration 5 and 6)

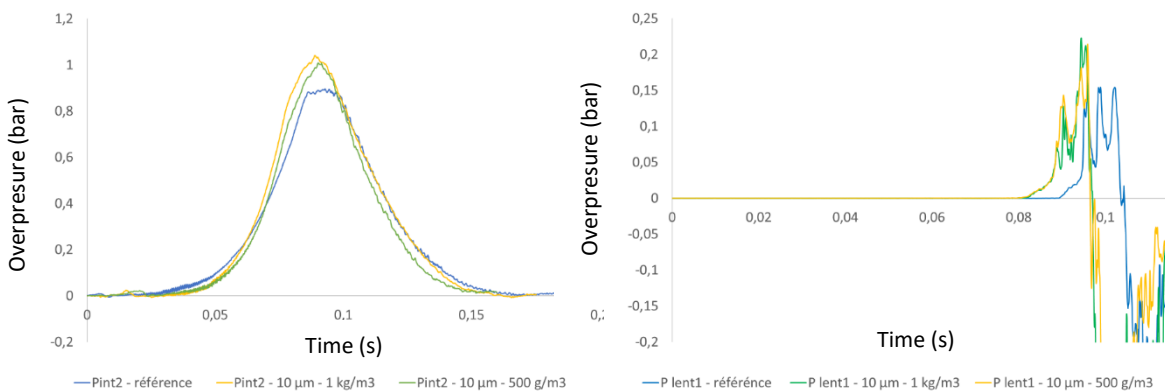


Fig 9. Comparison of internal overpressure signals (Pint 2) and external overpressures measured with powder and powder-free reference test – 10  $\mu\text{m}$  powder with 3 mm PMMA plate (Configuration 7 and 8)

The conclusions drawn from the previous tests remain valid for the fine powder at 10  $\mu\text{m}$ . The internal overpressure signals have the same magnitudes and durations with or without powder. The same is true for external pressure effects with similar amplitude and duration. The 10  $\mu\text{m}$  powder at a concentration less than or equal to 1  $\text{kg}/\text{m}^3$  still does not appear to have any effect on the explosion.

While this type of powder is known to have a mitigating effect for hydrocarbon explosions, none of the tests carried out with the inhibiting powder have demonstrated an attenuating effect for internal overpressure of the hydrogen explosion. However, a mitigating impact on the external overpressure was found when the vent was a plastic sheet.

#### 4.0 ANALYSIS OF EXPERIMENTAL RESULTS AND DISCUSSIONS

Several authors have attempted to apply heat loss theories to the interaction of a premixed flame with non-combustible particles to study extinction [6, 7, 8]. Overall, the dominant extinction mechanism would be thermal conduction heat transfer to the particles. Proust et al [5] used the work of Joulin [6] to identify the parameterization of the flame-particle interaction and apply these criteria to the extinction of methane-air premixed flame. First, the authors are exclusively interested in the thermal conduction effects between particles and flame. The influence of vaporization, thermal radiation (heated particles and flue gases), and chemical effects on combustion are neglected. In addition, to simplify the equations, the thermal conductivity of the gases is assumed to be constant. The theory summarized below is applied to the case of the extinction of hydrogen-air flames by sodium bicarbonate particles.

Heat losses to non-vaporizable inert particles are expressed as follows:

$$L(T) = \frac{N_p \cdot Nu \cdot \lambda \cdot \pi \cdot d^2 (T - T_p)}{d} \quad (1)$$

With  $d$  the diameter of the particles,  $Nu$  the Nusselt number ( $Nu = 2$ ),  $T_p$  the temperature of the particles, and  $N_p$  the number of particles per unit volume.

It is possible to develop equation 1 by assuming that the particles are monodisperse, non-vaporizable, and inert and that the thermal diffusivity of the mixture is constant [6]. It is also assumed that there is no interaction between the particles.

By introducing the thermal inertia parameter  $K$ , the ratio between  $t_t$  the transit time of the particle in the flame, and  $t_c$  the heating time of the particles (time required to heat a particle), and  $h$ , the thermal power taken from the flame by the inert particles and  $K_0$  the ratio between the laminar flame velocity with powder and without powder, we obtain:

$$(K + K_0^2)^2 \cdot \ln(K_0^2) + h \cdot (K + 2 \cdot K_0^2) = 0 \quad (2)$$

with :

$$K = \frac{t_t}{t_c}; t_t = \frac{\lambda}{\rho \cdot C_p \cdot S_{lad}^2}; t_c = \frac{\rho_{part} \cdot C_{part} \cdot d^2}{6 \cdot \lambda \cdot Nu} \quad (3)$$

$$h = \frac{K \cdot N_p \cdot \rho_{part} \cdot C_{part} \cdot \pi \cdot d^3 \cdot E \cdot (T_{ad} - T_u)}{6 \cdot \rho \cdot C_p \cdot R \cdot T_{ad}^2}$$

With  $\rho_{part}$ : the density of the constituent material of the particles,  $C_{part}$ : the specific heat of the constituent material of the particles,  $T_{ad}$ : the adiabatic flame temperature,  $T_u$ : the initial temperature of the flammable mixture,  $E$ : the activation energy of combustion reaction.

A graphical representation of equation 2 is provided in Fig. 10.



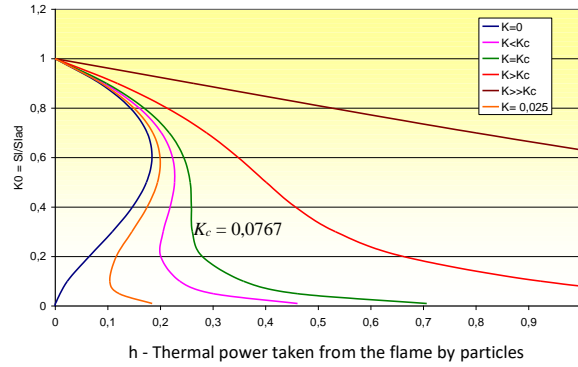


Fig 10. Dimensionless burning velocity  $K_0$  as a function of the thermal power  $h$  taken from the flame by the particles

It can be noted that the thermal inertia  $K$  is a characteristic parameter of the particle size. In contrast, the thermal power  $h$  characterizes the concentration of these particles, the size being fixed. For large  $K$  values (small particles), the thermal power taken from the flame is very low because the temperature of the particles remains very close to that of the mixture (equation 3), so even when injecting a considerable quantity of particles, the temperature does not drop sufficiently to reach extinction. For small values of  $K$  (large particles, therefore of great thermal inertia), the flame is extinguished when the thermal power taken by the particles (proportional to the quantity of particles) reaches a critical value for a value of  $K_0$  of the order of 0.5. As in the conduction regime, extinction occurs by quenching to cold walls. Finally, there is a critical particle size value, corresponding to  $K = K_c = 0.0767$ , which separates the two extinction regimes by "quenching" and "dilution". This theory was first applied to extinguishing a flame propagating in a 16% hydrogen-air mixture seeded with monodispersed sodium bicarbonate particles. The proposed model is only valid for a single particle size. However, in practice, the inhibiting powders used during the experimental campaign are powders whose particle size is:

- between 1 and 100  $\mu\text{m}$  approximately for powder of average particle size 60  $\mu\text{m}$ ,
- between 0.1 and 100  $\mu\text{m}$  approximately for powder of average particle size 25  $\mu\text{m}$ ,
- between 0.1 and 100  $\mu\text{m}$  approximately for powder of average particle size 10  $\mu\text{m}$ .

An adaption of this model to polydispersed particles is possible, noticing that each class of particles of concentration  $C_i$  corresponds to a value of thermal inertia  $K$  and a thermal power taken from the flame  $h$ . It is, therefore, possible to deduce for each class of particles composing the powder tested the temperature drop  $T_i$  induced by heat losses. The application of the model shows that the temperature drop must be 330°K to extinguish the flame.

The main characteristics of the flammable mixture and the powder are summarized in Table 2.

Table 2. Characteristics of sodium bicarbonate and flammable mixture.

Hydrogen/ Air mixing at 16 %	Sodium Bicarbonate Particles
$E_a = 60875 \text{ J/mol}$ ; $Le=0,38$	$\rho_{\text{part}} = 2200 \text{ kg/m}^3$
$T_0 = 293 \text{ K}$ ; $T_{\text{ad}}=1550^\circ\text{K}$	$C_{\text{part}} = 1200 \text{ J/kg/K}$
$C_p = 3176 \text{ J/kg/K}$ ; $\rho=1,013 \text{ kg/m}^3$	$Nu = 2$
$\lambda = 0,1 \text{ W/m/K}$ ( $\grave{a} 1200 \text{ K}$ )	

Fig. 11 presents the evolution of the temperature drop by particles as a function of particle concentration for particles of monodispersed and polydispersed 60  $\mu\text{m}$ , 25  $\mu\text{m}$ , and 10  $\mu\text{m}$ .

For the experimental conditions tested, Table 3 summarises the values of the temperature differences induced by the polydisperse particles.

Table 3. Values of the temperature differences induced by the polydisperse particles.

	Median particles diameter	Particles concentration	Temperature drop ( $^{\circ}\text{K}$ )	Extinction threshold ( $^{\circ}\text{K}$ )
Polydispersed powder	60 $\mu\text{m}$	0.5 $\text{kg}/\text{m}^3$	6	330
		1 $\text{kg}/\text{m}^3$	14	330
	25 $\mu\text{m}$	0.5 $\text{kg}/\text{m}^3$	51	330
		1 $\text{kg}/\text{m}^3$	110	330
		2 $\text{kg}/\text{m}^3$	237	330
	10 $\mu\text{m}$	0.5 $\text{kg}/\text{m}^3$	128	330
		1 $\text{kg}/\text{m}^3$	272	330

Even without considering the powder's chemical action on the flame, the flame could not have been extinguished because the concentrations tested were too low. However, we could have expected that the influence of the powder would be more marked, especially for powders 25  $\mu\text{m}$  at 2  $\text{kg}/\text{m}^3$  and 10  $\mu\text{m}$  at 1  $\text{kg}/\text{m}^3$ , since the flame temperature drop induced by the powder is close to the extinction threshold. Several factors could explain that sodium bicarbonate does not significantly influence even for configurations where the powder-induced flame temperature drop is close to the extinction threshold. An important parameter that is not considered and difficult to quantify is the powder concentration in the flammable mixture and the homogeneity of the powder distribution in the explosion chamber. It is also questionable whether the hydrophobic treatment of the powder does not alter its thermal and chemical properties.

Even if this represents a realistic situation, the experimental configuration is particularly penalizing for assessing the efficiency of the mitigation technique:

- The ignition on the opposite side of the vent causes a strong flame acceleration as the flame approaches the vent, thus decreasing the interaction time of the flame with the powder,
- the opening of the weak wall (e.g., plastic sheeting) causes part of the powder-laden flammable cloud to be ejected, thereby reducing the powder concentration encountered by the flame,
- the amount of flammable gas consumed by the flame is relatively small when the overpressure in the chamber is maximum, limiting the flame/powder interaction.

To confirm this last point, it is possible to analyse the initial flame development until the vent is opened. Based on the pressure signal, the amount of fuel gas consumed can be determined using the following formula [9]:

$$\frac{1}{P} \cdot \frac{dP}{dT} \approx \gamma_s \cdot \frac{S_{lad} \cdot A_F(t) \cdot (E - 1)}{V}$$

where  $A_F(t)$  is the flame surface,  $S_{lad} A_F(t) (E-1)$  is the excess volume per unit of time,  $\gamma_s$  is the ratio of the specific heats of the reactants,  $E$  is the expansion ratio of burnt gases, and  $V$  is the volume of the enclosure.

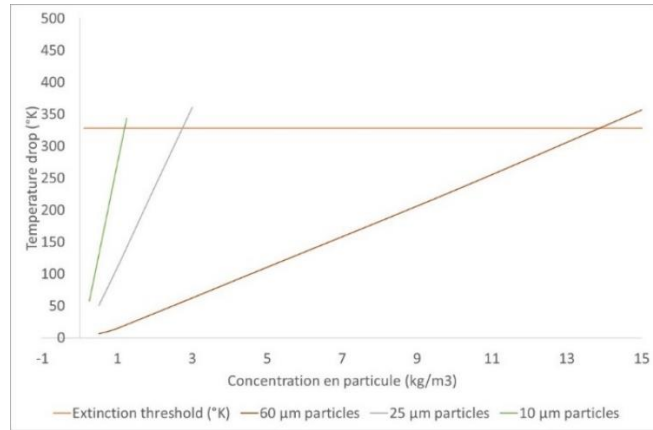


Fig 11. Evolution of the temperature drop by particles as a function of particle concentration for particles of polydispersed 60  $\mu\text{m}$ , 25  $\mu\text{m}$ , and 10  $\mu\text{m}$

Based on this equation, it is possible to determine the evolution of the flame area  $A_F$  and, thus, the development of the volume of combustion products produced by the flame (burnt gases). Consider the case of the configuration 7 test, i.e., the explosion of a 16%  $\text{H}_2/\text{air}$  cloud seeded with 25  $\mu\text{m}$  sodium bicarbonate particles, whose overpressure signal is shown in Fig. 8. Fig. 12 shows the evolution of the flame area over time. The maximum flame area is about 30  $\text{m}^2$ . Multiplying this area with the laminar burning velocity gives the burnt gas production rate, and by integrating this rate, it is possible to calculate the evolution of the burnt gas volume produced by the flame over time. The volume of burnt gas at peak overpressure is of the order of 1.1  $\text{m}^3$ . This order of magnitude is consistent with the volume that can be determined based on the standard video just before the opening of the PMMA plate (Fig. 13). Considering the flame as an ellipsoid of revolution, the semi-major axis in the axis of the chamber is of the order of 1.5 m. The other semi-major axis is of the order of 0.65 m. This gives a volume of the order of 1.3  $\text{m}^3$ . To find out the amount of gas involved in combustion, this volume must be divided by the expansion ratio of the combustion products, which is equal to 4.6 for a 16%  $\text{H}_2/\text{air}$  mixture.

Thus, the amount of gas involved in combustion before the PMMA vent is opened is of the order of 0.3  $\text{m}^3$ , which is just under 10% of the volume available for combustion. This suggests that the amount of fuel gas-air-powder mixture is relatively small during the explosion, so the flame's interaction with the powder is somewhat limited. The expansion phase would push most of the powder out, like a piston.

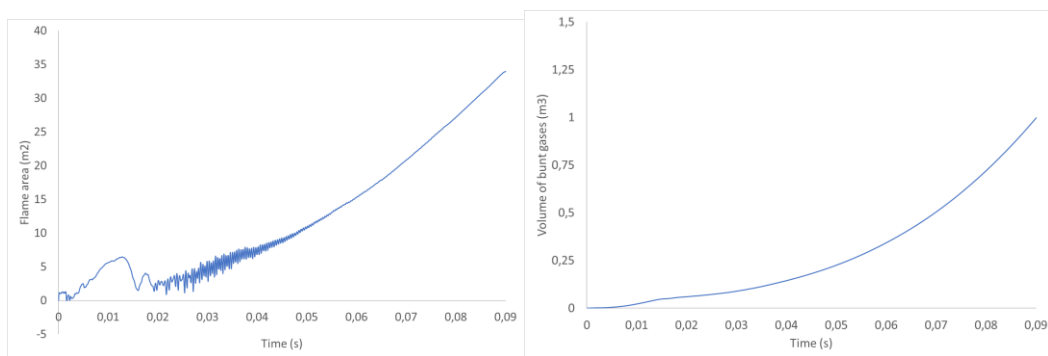


Fig 12. Evolution of the flame area over time and the volume of burnt gases produced by the flame over time

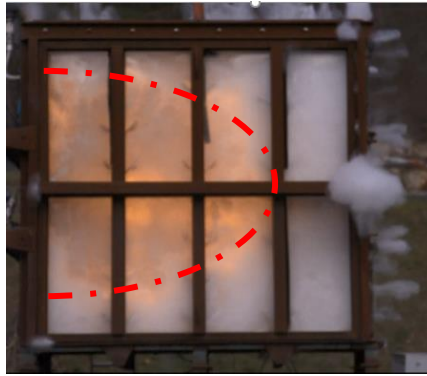


Fig 13. The image just before the PMMA plate opening

#### 4.0 CONCLUSIONS

This paper presents the results of a preliminary experimental study on the mitigation of hydrogen-air explosion by injecting sodium bicarbonate powder. This technique has yet to prove to be effective. Even neglecting the chemical action of the powder on the flame, the theoretical analysis based on the thermal influence of the powder shows that the experimental conditions would not have allowed the flame to be extinguished, but an effect could be expected. It would not be wise to abandon this mitigation technique too quickly. To go further, it would be interesting to check the efficiency of the powder on another hydrocarbon like methane. It would be possible to inject a larger quantity of sodium bicarbonate or another type of powder. It would also be possible to consider a more detailed characterization of the powder concentration and verify the homogeneity of the fuel gas-air flame mixture. Finally, work on a smaller scale in a non-deformable, leakproof, and explosion-proof 1 m<sup>3</sup> chamber could be envisaged to maintain the entirety of the dispersed dust inside the chamber, to maximize the interaction times of the hydrogen flame with the dust in suspension and to optimize the quantity and particle size distribution of the powder to be dispersed.

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