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Influence of vent distribution on the violence of a gas explosion

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Abstract

The development of new energies (battery, fuel cell, electrolyser, storage, etc.) leads to the implementation of these applications in ISO shipping containers. Depending on the technology, such containment can lead to a risk of accumulation of flammable gas and therefore explosion. Indeed, the explosion of an ISO container can have major effects, as in the case of the accident that occurred in British Columbia (Canada) in 2013. This accident destroyed completely the container. The adjacent containers were deformed, and houses' and vehicles' windows were blown out within 150 m. One door of the container was projected to 100 meters. To avoid such future disasters, an efficient strategy of mitigation should be implemented. The use of vent panels is one of the most popular protection techniques to mitigate the confined explosion risk. The role of explosion vents is to discharge the excess gas produced by the combustion to limit the explosion overpressure to an acceptable value compatible with the mechanical strength of the enclosure to be protected. The calculation of the vent area can be difficult due to the multiplicity of parameters that will influence the venting process. In most cases, the widely studied situation is that of an enclosure filled with a flammable mixture with explosion discharge orifices generally concentrated in one single area. There is little research into the influence of the distribution of the explosion venting area on the surface of the enclosure to be protected. This paper presents the results of an experimental study where 1.2 m² of vent area was spread over the surface of a 37 m³ explosion chamber. Four configurations of vent areas distribution are studied. Two flammable mixtures are used respectively 15.5% and 17.4 % hydrogen-air with two locations of the ignition source.

Keywords: *Vented gas explosion, vent, secondary explosion*

1. Introduction

The development of new energies (battery, fuel cell, electrolyser, storage, etc.) leads to the implementation of these applications in ISO shipping containers. Depending on the technology, such containment can lead to a risk of accumulation of flammable gas and therefore explosion. Indeed, the explosion of an ISO container can have major effects, as in the case of the accident (WorkSafeBC, 2013) that occurred on April 13th, 2013 in Saanich in British Columbia (Canada). At around 6:30 AM, an explosion occurred in a shipping container used for various storage, resulting in the destruction of the container and damage to the surroundings. Adjacent containers were deformed, and houses and vehicles' windows were blown out. The container was torn off, the walls were flattened, and some parts of the container were landed up to 275 meters away. The explosion blew out both ends of the container, hurtled the roof 15 meters, and shot one of the doors about 100 meters across

the site (Fig 1.). The blast also damaged windows in the surroundings "as far about a half a block away" i.e., glasses were broken around 150 meters. The cause of the explosion (WorkSafeBC, 2013) is a leak from the 20lb propane tank of a barbecue, stored inside a large steel shipping container. The leak resulting from the open valves created an explosive atmosphere inside the shipping container. A soft drink cooling circuit that cycled and sparked ignited the flammable mixture and triggered the explosion. Damage analyses allow to estimate the maximum overpressure involved in the explosion. The level of overpressure inside the container is around 2.5 bar. So, to avoid this kind of disaster, it's necessary to define some strategy of mitigation.



a. Container after the explosion



b. Container's door projected at 100 m



c. Container after the explosion



d. Broken windows on the apartment block

Fig. 1. Damage of explosion in ISO container (from WorkSafeBC, 2013)

The use of vent panels is one of the most popular protection techniques to mitigate the confined explosion risk. The role of vents is to discharge the excess gas produced by combustion outside a volume to limit the explosion overpressure to an acceptable value compatible with the mechanical strength of the enclosure to be protected.

The physics of vented deflagration has been studied for a long time (Cooper et al, 1986, Bimson et al, 1993, Catlin et al, 1996, Proust et al, 2010, Bauwens et al, 2011, Daubech et al, 2011). The widely studied situation is that of an enclosure filled with a flammable mixture with explosion discharge orifices generally concentrated in one single area.

After the ignition of the flammable mixture, the initial flame growth leads to the production of hot combustion products. Due to the thermal expansion of the burnt gases, the internal pressure in the enclosure increases. When the pressure in the enclosure reaches the opening pressure of the explosion vents, the reactive mixture can be expelled to the outside forming a swirling cloud. When the flame

reaches the openings, it can ignite this reactive cloud, producing a secondary explosion in front of the vent.

Catlin (1991) accurately studied the evolution of the flame front contour from ignition to flame exit through the vent. He noticed 3 different stages during flame propagation. Immediately after ignition, the flame front grows spherically around the ignition source. It then elongates into an ellipsoid of revolution and evolves into an ellipsoid truncated from its base as the flame approaches the vent. As a result of the pressure increase in the enclosure, part of the flammable cloud is expelled from the enclosure and takes the shape of a mushroom (Cooper et al, 1986). Other authors agree that it is shaped like a ball with a radius of the same order of magnitude as the hydraulic diameter of the vent (Harrison et al, 1987). The physics of the combustion of the outer cloud in the secondary explosion is poorly understood. But it is possible to describe the combustion process (Catlin, 1991) of this flammable cloud in 3 phases:

- Phase I: The flame velocity does not vary significantly from the flame velocity inside the enclosure, while the mushroom shape of the vortex continues to develop. During this phase, there are no high levels of overpressure associated with the secondary explosion.
- Phase II: The flame arrives at the head of the mushroom and suffers from an abrupt increase in the surface area. It is at this point that the pressure effects of this explosion occur.
- Phase III: This last phase is characterized by a spherical flame propagation through the remaining reactive volume

Some authors (Bauwens, 2010, 2012, Daubech, 2013, Sommersel, 2017, Skjold, 2019) show experimentally the influence of different parameters such as the initial concentration of the flammable mixture, the initial turbulence, and the presence of obstacles or the position of ignition source the explosion chamber. But the major problem with vent installation is that vent panels are generally located in the same area. This situation can create a very huge external explosion (Daubech et al, 2011) with a high level of overpressure. The distribution of vents on the surface of the enclosure to be protected has been little studied.

This paper proposes to study the influence of vent distribution on the violence of a gas explosion. The vent holes are distributed on the walls of the 37 m³ explosion chamber. The total surface of vents is 1.2 m². Several configurations of vent surface installation are proposed. Two hydrogen flammable mixtures are used with two positions of an ignition source.

2. Experimental set-up

The explosion chamber is a 37.5 m³ parallelepipedal volume (internal dimensions: 6 m long, 2.5 m wide, and 2.5 m high) designed to withstand an explosion overpressure of 2 bar (Fig 2.). It is a metal structure made of H-irons and modular side frames which can be fitted with solid walls to completely block the surface or can be customized to accommodate the vent panels or viewing windows.

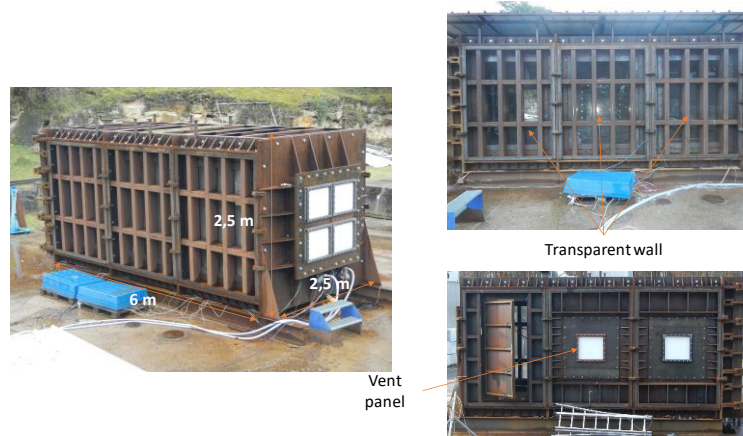


Fig. 2. 37.5 m³ explosion chamber

The injection of flammable gas into the explosion chamber is carried out from a 5 m³ tank. The gas injection pressure is monitored by a pressure sensor located upstream of the injection pilot valve. It is set to 5 bar. The injection is carried out through a 20 mm diameter circular orifice. The leakage rate is about 50 g/s. The H₂ concentrations are monitored by 6 oxygen analysers located at different heights in the explosion chamber. The turbulence generated by the leak is sufficient to completely homogenize the flammable atmosphere. The turbulence generated by the leak is sufficient to completely homogenize the flammable atmosphere. To ensure that the flammable atmosphere is completely quiescent, a time of 30 s is allowed between the end of the hydrogen injection and ignition.

The instrumentation includes 2 internal pressure sensors P1 and P2 (Kistler 0-2 bar piezoresistive sensors) and 2 external pressure sensors settled in lens supports Lent 1 and lent 2 (Kistler 0-2 bar piezoresistive sensors). To visualize the explosion and opening of the vents, a high-speed camera (Phantom MIRO – 2000 i/s) and an HD camera are used. The flammable mixture is ignited with a pyrotechnical match of 60 J.

A total vent area of 1.2 m² divided into 4 unit areas of 0.3 m² (0.6 m x 0.5 m) is used to study the influence of vent distribution on the explosion dynamics. Four vent distribution configurations were studied (Fig. 3). The first configuration is the reference for which the 4 unit vents are in the same area. For the following configurations, the unit vents are distributed on two sides of the explosion chamber. The external pressure sensors are always located on the vent axes so that their location changes from one configuration to another. Fig 3. also presents an overview of the instrumentation location for each configuration.

Two ignition source locations are studied:

- at the centre of the wall opposite the 4 unit vents of configuration 1,
- at the centre of the explosion chamber.

Two quiescent flammable mixtures are used:

- 15.5 % vol. hydrogen-air mixture,
- 17.4 % vol. hydrogen-air mixture.

For each vent panel distribution, one experimental configuration is conducted twice to test the reproducibility with a good level of success.

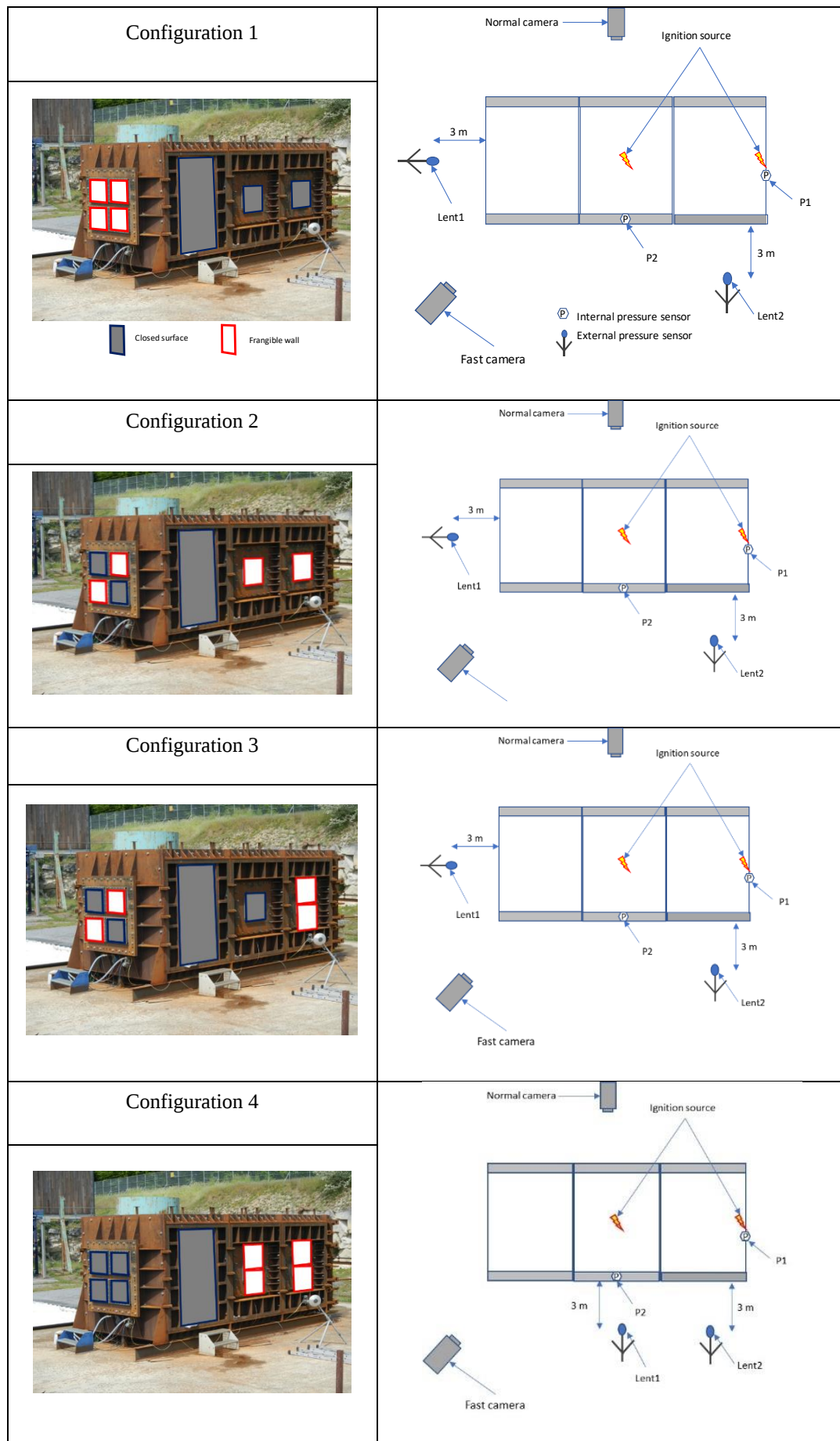


Fig. 3. Four vent distribution configurations and instrumentation positions

The unit safety vents have an area of 0.3 m². Vents are made of a PE plastic sheet held in place by a 5 cm square or flat iron frame screwed to the support plate (Fig. 4) depending on the chosen configuration. The opening overpressure of this plastic sheet is about 80 mbar when held by the square iron frame, and 50 mbar when held by the flat iron frame. The values of opening overpressure are experimentally determined. The surface density of the plastic sheet is 0.150 kg/m².

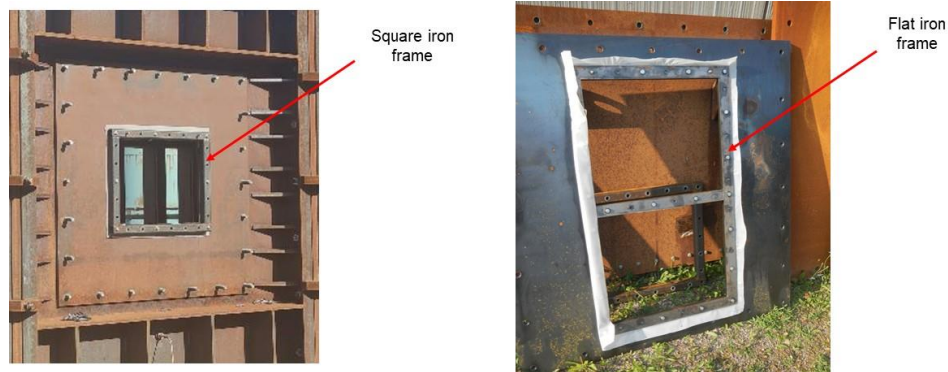


Fig. 4. Fixing iron frame

16 tests were carried out crossing:

- the 4 frangible wall distributions (Configuration 1 to 4)
- the 2 explosive atmospheres
- the 2 ignition positions

3. Results and discussion

Typical results

Fig 5. presents the characteristic internal and external overpressures for the first configuration with the ignition on the side opposite the 4 unit vents located on the same flange for the 15.5 % and 17.4 % hydrogen-air quiescent mixtures. The phenomenology observed was already presented by Daubech et al (2013) and can be divided into the following steps:

1. Ignition
2. Flame propagation and pressure increase in the explosion chamber,
3. Opening of the vent as soon as the internal pressure reaches its opening pressure,
4. Discharge of part of the flammable cloud to the outside,
5. Formation of the external vortex,
6. Competition between the production of burnt gases by the flame and the discharge of the gases through the vent,
7. Ignition of the external cloud by the flame reaching the vent and explosion
8. Internal combustion in progress
9. Discharge of combustion products through the vent and pressure drop in the enclosure
10. End of internal combustion

For the 15.5 % H₂-air mixture, the maximum inside overpressure reaches 250 mbar and the external overpressure reaches 50 mbar.

For the 17.4 % H₂-air mixture, the maximum inside overpressure reaches 400 mbar and the external overpressure reaches 165 mbar.

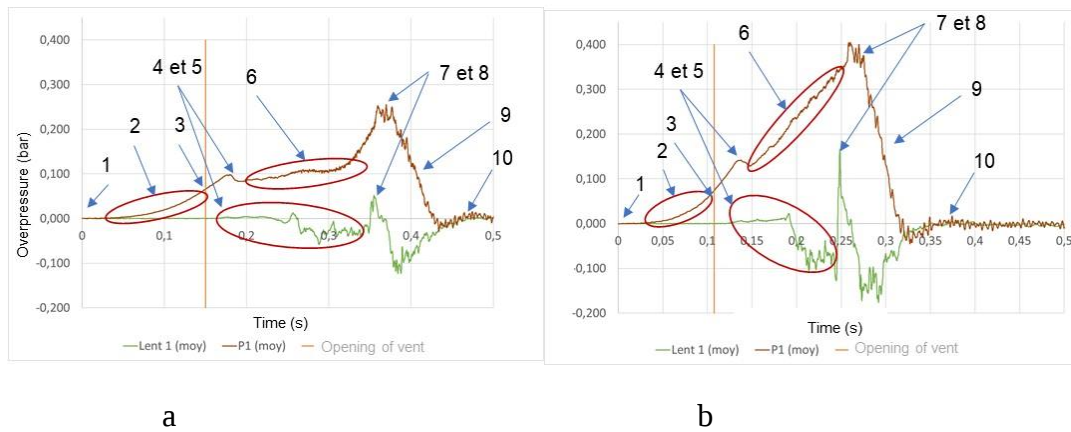


Fig. 5. Internal and external overpressures for configuration 1 - Ignition on the side opposite the 4 unit vent surface located on the same flange – 15.5 % (a) and 17.4 % (b) hydrogen-air quiescent mixtures.

Influence of ignition location

Fig 6. presents the internal and external overpressures for the first configuration with the backwall and the central ignition for the 15.5 % hydrogen-air quiescent mixtures.

For an identical venting configuration, the internal overpressure is greater when the ignition takes place as far as possible from the vents (250 mbar for the backwall ignition vs. 160 mbar for the central ignition). With the backwall ignition, the flame takes longer to reach the discharge surfaces of the explosion than for the central ignition. The amount of burnt gas produced by the flame when it runs every 6 m of the explosion chamber is greater than the amount of burnt gas produced for a central ignition.

The external overpressure related to the secondary explosion is greater when the ignition is central compared to the backwall ignition (90 mbar vs. 50 mbar). It can be explained by the fact that the flame reaches the vent earlier in the central ignition. The external cloud is still in the form of a vortex at the time of ignition. In the case of backwall ignition, the external vortex can degenerate in a form of a fresh gas jet during the internal flame developments already as observed by Daubech et al (2017). The flame propagation in a compact external cloud as a vortex leads to a more powerful secondary explosion.

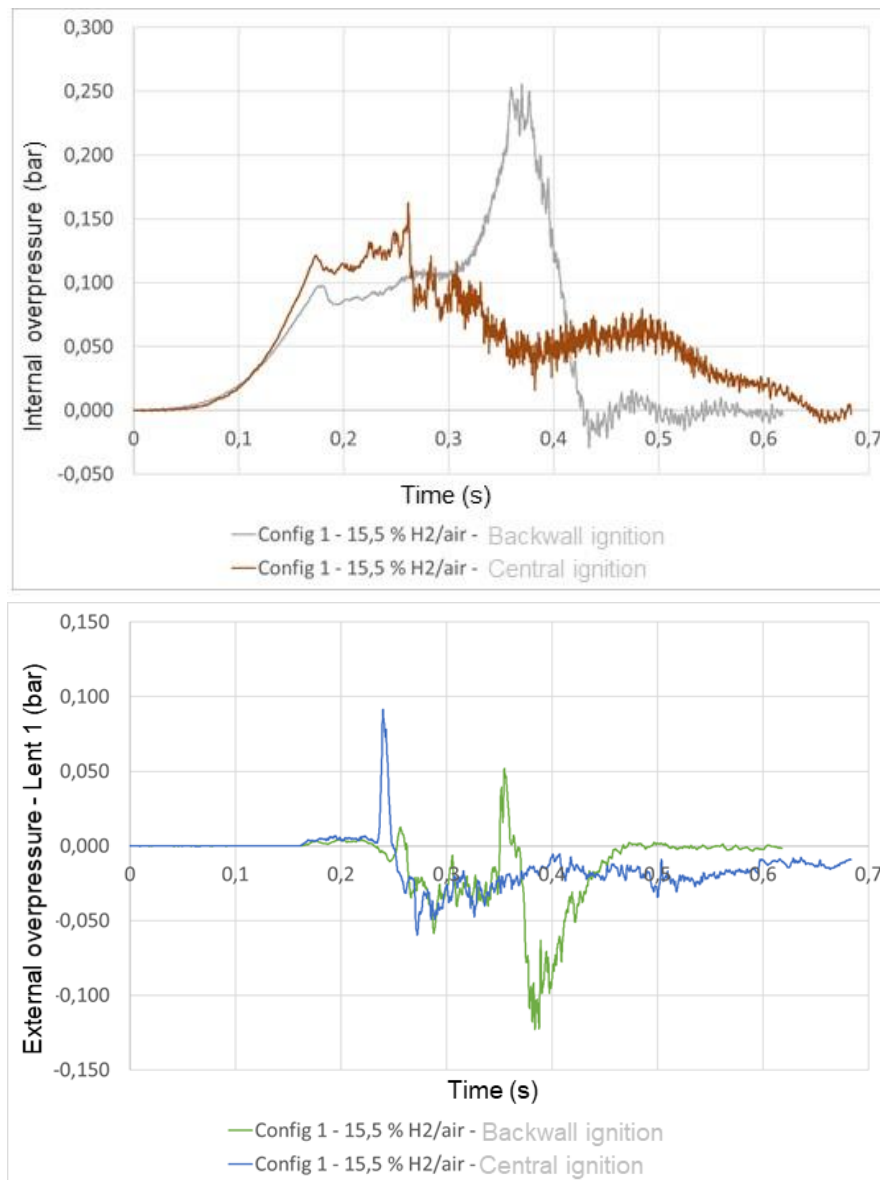


Fig. 6. Internal and external overpressures for configuration 1 - Backwall and central ignition – 15.5 % hydrogen-air quiescent mixtures

Influence of the distribution of vent areas on the explosion violence

Fig 7. presents the internal and external overpressures for configurations 1 to 4 with the backwall ignition for the 15.5 % hydrogen-air quiescent mixtures. Table 1 sums up the values of overpressures.

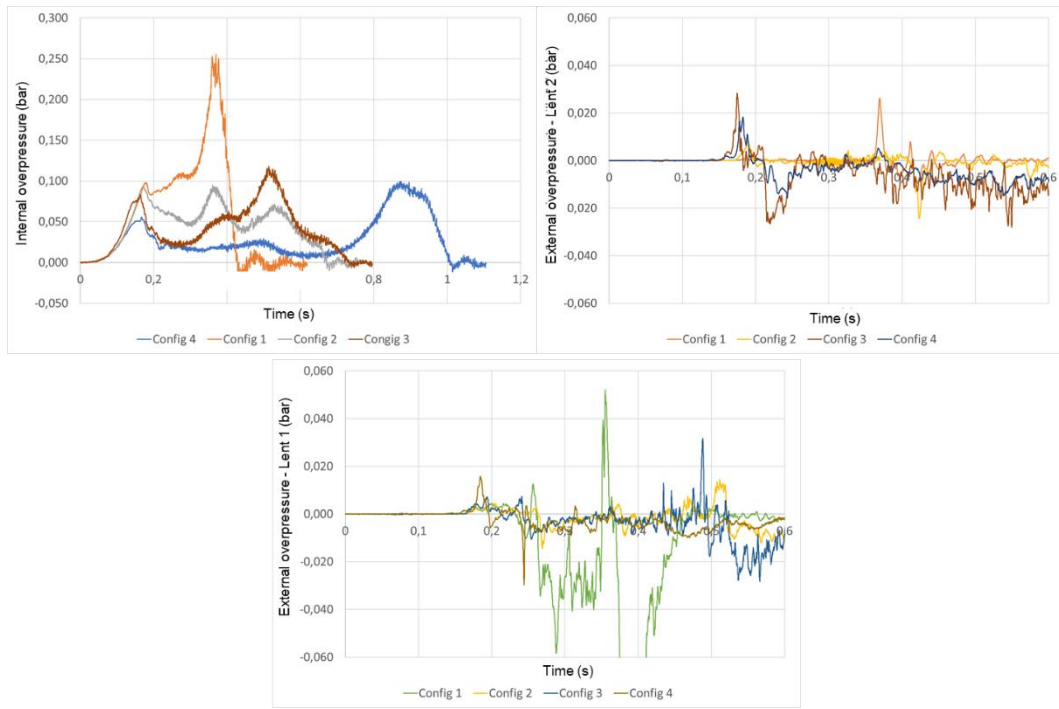


Fig. 7. Internal and external overpressures for configurations 1 to 4 - Backwall ignition – 15.5 % hydrogen-air quiescent mixtures

Table 1. Internal and external overpressure for configurations 1 to 4 - Backwall ignition – 15.5 % hydrogen-air quiescent mixtures

n° Configuration	Internal overpressure (mbar)	External overpressure – Lent 1 (mbar) ^b	External overpressure – Lent 2 (mbar)
Config 1	250	50	25
Config 2	90	16	7
Config 3	110	30	28
Config 4	95	18	16

We notice that higher internal and external overpressures are reached for configuration 1. The internal overpressures for configurations 2, 3, and 4 have the same order of magnitude around 100 mbar. Configurations 2 and 4 give the same order of magnitude for internal and external overpressures. In comparison, the overpressures of configuration 3 are higher.

Fig 8. presents the internal and external overpressures for configurations 1 to 4 with the backwall ignition for the 17.4 % hydrogen-air quiescent mixtures. Table 2 sums up the values of overpressures.

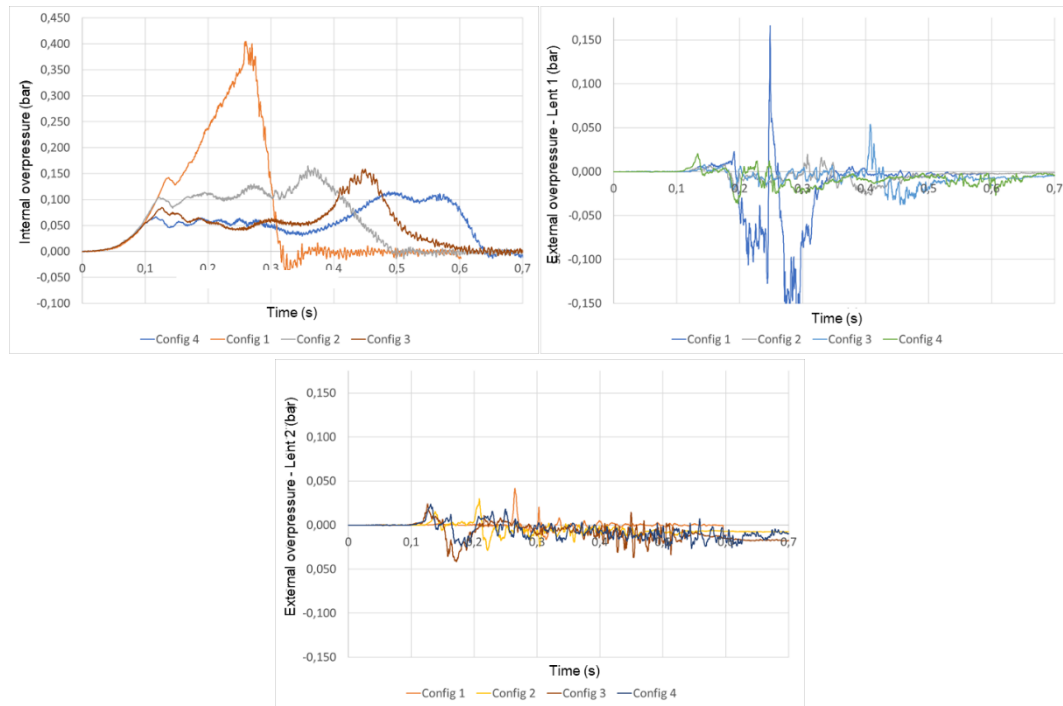


Fig. 8. Internal and external overpressures for configurations 1 to 4 - Backwall ignition – 17.4 % hydrogen-air quiescent mixtures

Table 2. Internal and external overpressure for configurations 1 to 4 - Backwall ignition – 17.4 % hydrogen-air quiescent mixtures

n° Configuration	Internal overpressure (mbar)	External overpressure – Lent 1 (mbar) ^b	External overpressure – Lent 2 (mbar)
Config 1	400	165	40
Config 2	150	17	30
Config 3	150	55	21
Config 4	110	20	22

We notice that higher internal and external overpressures are reached for configuration 1. The internal overpressures for configurations 2, 3, and 4 have the same order of magnitude around 135 mbar. But the internal overpressure for configuration 4 is lower than for configurations 2 and 3. Configurations 2 and 4 give the same order of magnitude for external overpressures.

In the above-mentioned experiments for backwall ignition, a strong decrease in internal overpressure of at least a factor of 2 and a decrease in external overpressures of at least a factor of 3 is observed. If we try to understand the behavior of the flame in the case of configuration 1 (Fig. 9.a), the discharge of the explosion is performed at a single point. This maximizes the flame path between the ignition source and the vents. It also results in the formation of a single large cloud outside the explosion

chamber which explodes violently. In the case of vents distributed over the surface of the explosion chamber (Fig. 9.b), the discharge of the explosion takes place at several points. This results in a significant reduction of the flame path between the ignition source and the venting surfaces. Several external clouds are generated but with smaller volumes, which results in potentially less powerful explosions because the explosion energy is lower. After the explosion of these external clouds in front of the venting surfaces, the combustion products inside the test chamber are discharged. Thus, the flame is no longer subject to the volume expansion of the combustion products, which leads to a decrease in the flame propagation velocity.

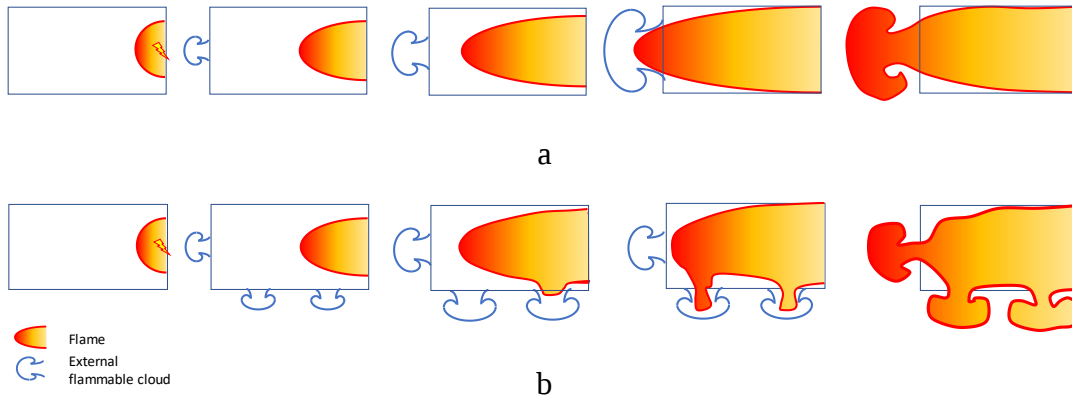


Fig. 9. Flame behavior in case of vent surfaces in the same location (a) and in case of distributed vent surfaces for backwall ignition

In general, configuration 2 leads to the lowest external overpressure levels if we combine the measurements of Lent 1 and Lent 2 for both concentrations. Even if the internal overpressures for configurations 2, 3, and 4 have the same order of magnitude for both concentrations, there are some differences. Specific work should be done to explain these differences. Several causes could be put forward: the influence of external explosion on the internal overpressure or the interaction of flame with the Rayleigh Taylor instability whose intensity could be modified by the vent distribution.

Fig 10. presents the internal and external overpressures for configurations 1 to 4 with the central ignition for the 15.5 % hydrogen-air quiescent mixtures. Table 3 sums up the values of overpressures.

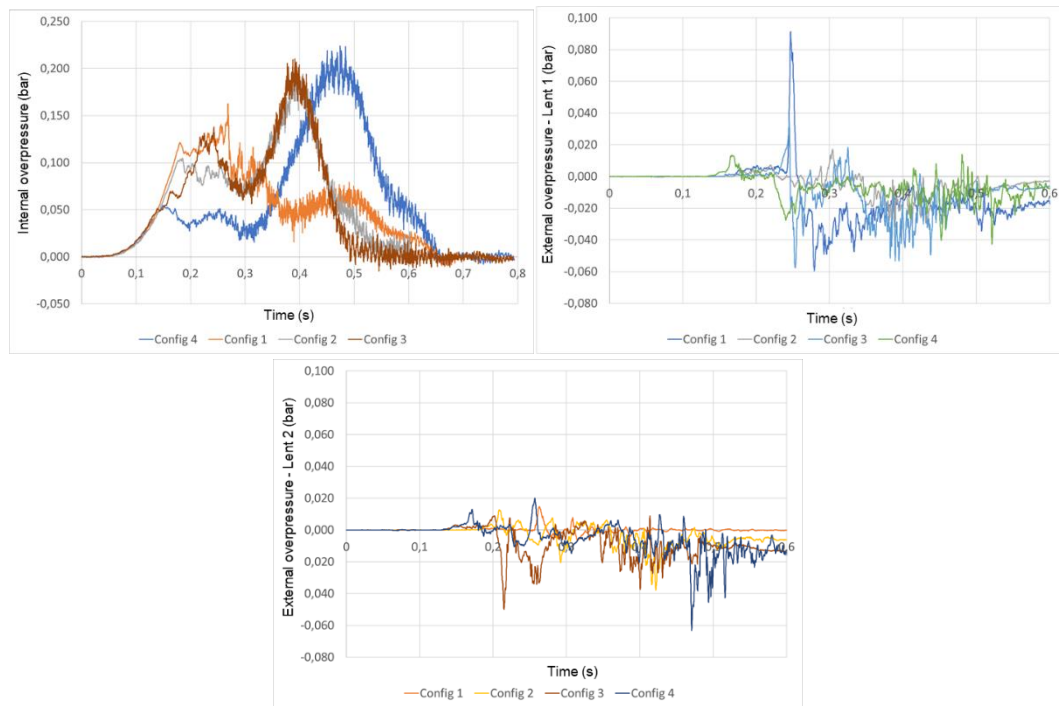


Fig. 10. Internal and external overpressures for configurations 1 to 4 - Central ignition – 15.5 % hydrogen-air quiescent mixtures

For a central ignition, the tests are only performed for 15.5 % hydrogen-air quiescent mixtures. We see that the internal overpressures are of the same order of magnitude with or without distributed surfaces. On the other hand, there is a strong attenuation of the external explosion overpressures by a factor of about 3.

Table 3. Internal and external overpressure for configurations 1 to 4 - Central ignition – 15.5 % hydrogen-air quiescent mixtures

n° Configuration	Internal overpressure (mbar)	External overpressure – Lent 1 (mbar) ^b	External overpressure – Lent 2 (mbar)
Config 1	200	90	14
Config 2	160	16	11
Config 3	200	33	8
Config 4	210	20	20

If we try to understand the behavior of the flame in the case of configuration 1 (Fig. 11.a), the discharge of the explosion occurs at a single point. The flame path from the ignition source to the vent surfaces is shorter compared to the backwall ignition. But this results in the formation of a single large cloud outside the explosion chamber that explodes violently. But, after the explosion of this large outer cloud, the combustion products inside the test chamber are discharged while the internal

combustion is not yet finished. Thus, the flame is no longer subject to the volume expansion of the combustion products, resulting in a decrease in the flame propagation velocity. This explains the significant increase in combustion time between tests with backwall and centre ignition. In the case of vents distributed over the surface of the explosion chamber (Fig. 11.b), the explosion discharge takes place at several points. As with the backwall ignition, several external clouds are generated but with smaller volumes, resulting in potentially less powerful explosions because the explosion energy is lower. But it is found that the inside overpressure peak occurred approximatively at the same time from one configuration to the other. This could be explained by the fact that, in the case of the central ignition for all the studied configurations, the vent surfaces are approximately equidistant from the ignition source. Thus, the flame would reach the vent surfaces at approximately the same time.

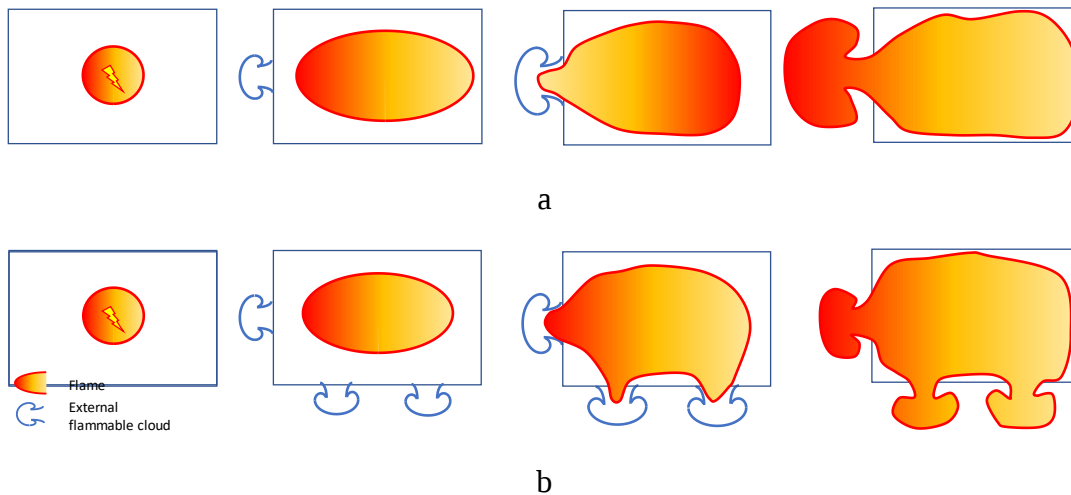


Fig. 11. Flame behavior in case of vent surfaces in the same location (a) and in case of distributed vent surfaces for central ignition

4. Conclusion

The influence of the distribution of venting surfaces depends strongly on the location of the ignition source. If the ignition point is located close to a wall, the distribution of vents on several sides is very favorable. In the case of a central ignition point, however, the distribution of vents has little influence on the reduced pressure.

On the other hand, the distribution of venting surfaces over the surface of a building or a confined space leads to a significant reduction in external explosion overpressures compared to the situation with a single venting surface. This greatly reduces the risk of a secondary explosion.

The secondary explosion phenomenon is often responsible for significant damage and large overpressure effect distances around hazardous installations. There could be a significant advantage in distributing venting or explosion discharge surfaces on the surface of new energy installations to facilitate their installation in highly constrained environments such as urban environments.

In general, distributing the venting panels across the entire surface of the enclosure seems to be the best option: this leads to the lowest external overpressures in experiments, and it enables to have at least one vent not too far from any hypothetical ignition source.

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