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Design of an experimental stand for hydrogen explosions

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Abstract. Hydrogen, with its remarkable potential as a clean and abundant energy carrier, has gained significant attention as a promising solution for a sustainable future. However, the handling, storage, and utilization of hydrogen come with inherent risks, particularly the potential for explosions. The present work deals with the design of an experimental stand for hydrogen explosions in interconnected spaces, based on previous experience in the field of air-methane mixtures explosions. Considering the explosive properties of hydrogen, much more aggressive than methane gas, a comparative analysis is carried out between the results of a physical experiment of a methane explosion carried out on a spiral stand and the results obtained from a computational simulation of a hydrogen explosion on a similar geometry. The purpose of the comparative analysis is to highlight the vulnerable points of the future construction, bringing improvements to the new experimental model in the sense of increasing operational safety, while preserving, at the same time, the possibilities of recording the explosion parameters (pressures, velocities, flame front behavior) at a higher level of accuracy.

1 Introduction

Hydrogen is the most abundant chemical element in the universe and can be produced from various sources such as water, fossil fuels and renewable energy sources. Hydrogen is considered a potential fuel because of its advantages, such as producing energy without carbon emissions. However, the use of hydrogen as a fuel still requires technological and infrastructural advances to become a viable solution on a large scale [1].

One of the main advantages of hydrogen as a fuel is that, when burned, it produces no carbon emissions. The only product of the hydrogen combustion reaction is water. This makes hydrogen an option in the context of the fight against climate change and pollution.

Hydrogen can be used in various applications such as transportation, power generation and industry. In the transportation sector, hydrogen can be used as a fuel in fuel cell vehicles, which produce electricity by combining hydrogen with oxygen in the air. These vehicles have

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the advantage of only emitting water as a combustion product and have a range comparable to that of gasoline or diesel vehicles. Also, storing and transporting hydrogen poses challenges because it has a low energy density and can diffuse through many materials. Work is underway to develop safe and efficient hydrogen storage and transport technologies.

The characteristics of hydrogen explosions should be considered in engineering design and application, thus meeting the need for reference for risk assessment and explosion evacuation system design. Understanding the science behind hydrogen explosions is critical to ensuring safety in various industries, from power generation to aerospace, and how hydrogen interacts with risk mitigation systems in constrained infrastructures is indispensable [2].

Fundamental research in hydrogen explosions requires the existence of explosion chambers, stands where explosion overpressures can be controlled and recorded. This paper deals with how such a stand can be designed.

2 The explosive characteristics of hydrogen compared to methane

Methane and hydrogen are two flammable gases with explosive properties, but they have significant differences in their explosive limits and triggering factors [3]. More information about the explosive properties of methane and hydrogen is highlighted below.

2.1 Explosive properties of methane

The upper explosive limit of methane is approximately 15% by volume (15% methane by volume and 85% air by volume). If the methane concentration exceeds this limit, the mixture becomes too rich in methane to be flammable and the lower explosive limit of methane is about 5% by volume (5% by volume methane and 95% by volume air). If the methane concentration falls below this limit, the mixture becomes too low in methane to be flammable [4].

Methane explosions can be triggered by ignition sources such as sparks, open flames, electrostatics and other sources of high heat [5, 6].

In order to be flammable, methane requires an adequate amount of oxygen in the air-mixture. The critical oxygen concentration for the formation of an explosive methane mixture is approximately 9.53% by volume.

2.2 Explosive properties of hydrogen

The upper explosive limit of hydrogen is approximately 75% by volume (75% hydrogen by volume and 25% air by volume). If the hydrogen concentration exceeds this limit, the mixture becomes too rich in hydrogen to be flammable. The lower explosive limit of hydrogen is about 4% by volume (4% hydrogen by volume and 96% air by volume). If the hydrogen concentration falls below this limit, the mixture becomes too low in hydrogen to be flammable [7].

Hydrogen explosions can be triggered by ignition sources such as sparks, open flames, electrostatics, and other sources of intense heat. Hydrogen has a high capacity to form a flame and it's flammable even at low concentrations [8].

Hydrogen burns in the presence of oxygen, and the critical oxygen concentration for the formation of an explosive hydrogen mixture is about 4% by volume (4% oxygen by volume and 96% air by volume).
Table 1 below, [9, 10] shows some of the explosive characteristics of hydrogen and methane.

Table 1. Explosive characteristics of hydrogen and methane.

Parameter	Value	
	Hydrogen	Methane
Molecular weight [g/mol]	2.01594	16.043
Gas density [kg/m^3]	0.08345	0.657
Diffusion velocity [m/s]	< 0.02	0.006
Buoyant velocity [m/s]	1.2 - 9	4
Flammability limits in air [vol%]	4.0 - 75.0	5.0-15.0
Detonability limits in air [vol%]	13 - 70	4.9-5.3
Stoichiometric fraction in air [vol%]	29.53	9.53
Minimum ignition energy [J] for detonation	$1.9*10^{-5}$ ~ 10,000	0.00028
Auto-ignition temperature in air [K]	793 −1023	853 - 878
Adiabatic flame temperature [K]	2318	2236
Laminar burning velocity in the air [m/s]	2.65 - 3.25	0.35 - 0.45
Detonation velocity [m/s]	1480 - 2150	1512 - 1863
CJ detonation pressure ratio p_{CJ}/p_0	15.6	6.7
TNT equivalent [g TNT/g]	26.5	13.28

3 Stand for physical experiments

In the course of previous research, an experimental stand was made for methane explosions, which is in the shape of a quadratic spiral, consisting of 9 interconnected chambers. The construction is made of metal elements arranged vertically, welded together and reinforced by connecting elements, so as to allow the best possible visualization in the vertical plane, the transparency of the analysed enclosure being a mandatory requirement in Schlieren recording techniques. For this reason, the sealing of the spiral at the bottom and top was made with clear polycarbonate plates and rubber gaskets (figure 1).

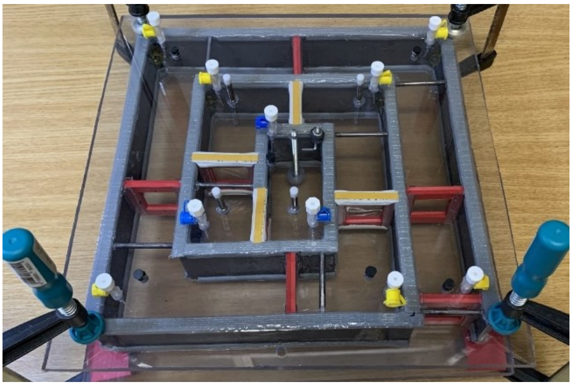


Fig. 1. Construction of the stand in spiral shape.

The intended route for the gas explosions goes through the spiral from its centre outwards, over a distance measured on the centre line of the tunnel of 1,350 meters.

Except for the corner areas, the spiral tunnel has the same cross-section of 50 x 50 mm.

The central chamber is equipped with electrodes for initiating the explosive mixture, with a fuel gas loading device and with a pressure sensor positioned at the ceiling level of this room. By construction, all 9 chambers benefit from gas loading devices and holes for mounting pressure sensors (figure 2).

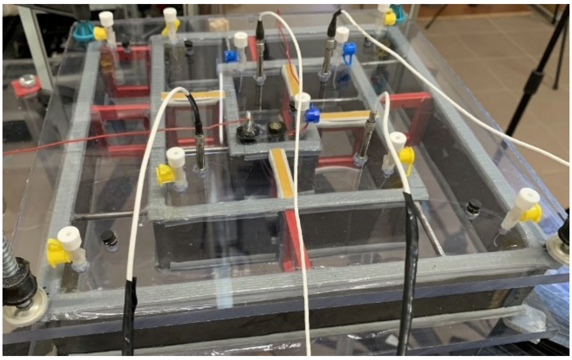


Fig. 2. Positioning of pressure sensors.

The spiral construction was arranged between two parabolic mirrors, the Schlieren technique being considered appropriate with the projection of the light beam in the shape of the letter Z, the parallel beam of light passing vertically through the inside of the construction, ending up being focused by the upper mirror in the high-speed camera lens, for making video recordings (figure 3).

a) b)

Fig. 3. The arrangement of the construction between the parabolic mirrors a) and the transparent frame for video recordings b).

The advantages that the stand presents consist of:
- allows configuring the volumes of the rectangular spiral by the number and placement of obstacles with membrane holes;
- allows the use of membrane obstacles with holes of different shapes (circular, square, rectangular, elliptical, etc.) and with membranes of different thicknesses;
- by means of Schlieren techniques, it ensures the continuous monitoring and recording of the rapid combustion process, from the occurrence of the effective source of initiation of the

explosive atmosphere, the evolution of the explosion process through the consumption of the fuel, until the withdrawal movement of the expanded gases, as a result of cooling;
- ensures a higher degree of precision in measuring local/global velocities and accelerations;
- ensures the recording of pressure values from each interconnected space;
- allows the analysis of pressure variations when changing the direction of propagation of gas explosions and when breaking through obstacles with different resistance;
- allows the analysis of gaseous explosions in the chain;
- allows the use of several types of combustible gases/combustible vapours within the same physical experiment;
- allows the testing of curtains to suppress the effects of explosions (using nitrogen, water, etc.);
- allows changing the location of the initiation source;
- allows the analysis of the increase in aggressiveness of gas explosions when the direction of propagation is changed.

4 Performing physical experiments

The physical experiments carried out on the previously described stand aimed, in the first stage, at testing the equipment for recording images and pressures during the explosion process. At the same time, attention was paid to the tolerance of the spiral construction to the overpressures developed inside it, the occurrence of leaks and the resolution of these deficiencies. Adjusting the parabolic mirrors and video recording equipment was also an important step in setting up the entire booth for quality results.

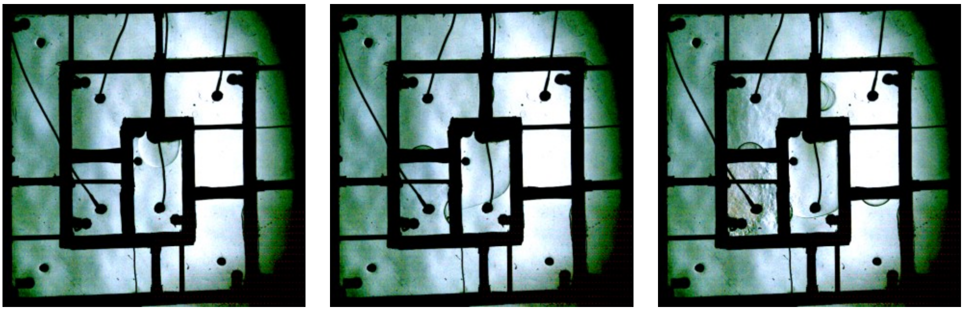
The fuel gas tested was methane, combined with air at concentrations around the stoichiometric value.

When carrying out the experiments, the first 4 chambers of the spiral were loaded with explosive mixture, starting from its centre towards the exit.

Images of the behaviour of the flame front were recorded at a speed of 12000 frames per second with the high-speed camera, but also at 240 frames per second with other video cameras.

The 4 chambers charged with explosive atmosphere were equipped with pressure sensors, the values obtained being stored electronically.

In the series of images below (figure 4), the initiation of the explosion and the evolution of the flame front can be observed, the images being obtained by applying Schlieren techniques.



a. b. c.

d. e. f.

Fig. 4. Series of images obtained during the process of rapid burning of methane.

The pressures and recorded values can be found in the graph in figure 5. An increase in pressures can be observed with the advance along the spiral path, the detailed investigation of the pressure waves behaviour generated inside the spiral may be the subject of future research.

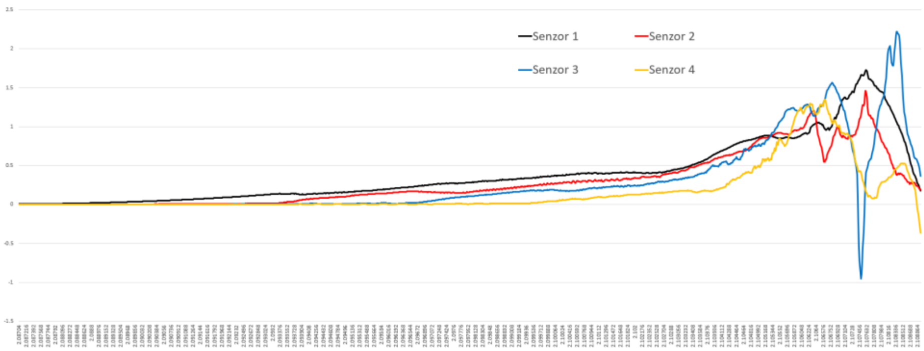


Fig. 5. Pressure evolution recorded by pressure sensors.

It should be noted that only the 4 chambers loaded with explosive atmospheres were separated by the foil mounted on the obstacles, the others having communication with the open atmosphere through the free openings of the obstacles, with dimensions of 30 x 30 mm.

5 Virtual simulation of the initiation of the hydrogen explosion on the virtual stand

Based on the experience gained from previous research on methane explosions, considering the explosive properties of hydrogen (much more aggressive than those of methane) on the same geometry on which the experiments on methane explosions were carried out, a virtual simulation of an explosion of an air-hydrogen mixture was carried out in order to identify the elements subjected to dangerous overpressures and adapting the experimental stand to be used to in safe conditions.

Virtual simulation of the air-hydrogen mixture, [11] aimed at the explosion process and considered only the fluid volume of the prototype, being recorded the pressure values on the surfaces of the boundary walls and the maximum overpressure values recorded in the cells set with an explosive atmosphere. The membranes between the cells have been removed (open surfaces), the cells being delimited only by the supporting frames of the membranes. The simulation was performed in ANSYS Fluent.

In order to verify the resistance of the model to the overpressures generated by the air-hydrogen mixture, the geometry of the prototype was transposed, on a real scale, in the virtual environment (Figure 6).

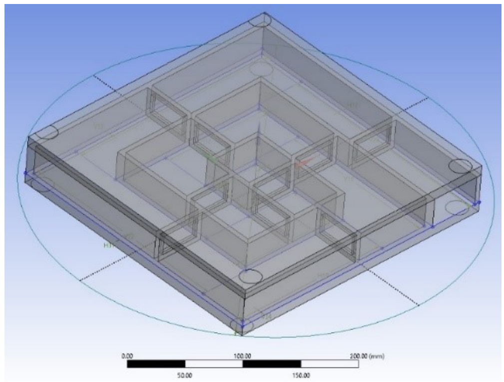


Fig. 6. Virtual geometry in ANSYS.

The initial settings for the explosion in the fluid medium involve several key parameters that determine the conditions under which the explosion will occur. These settings include the cells involved, the concentration of hydrogen in the air, the temperature, pressure, and the starting point within the spiral.

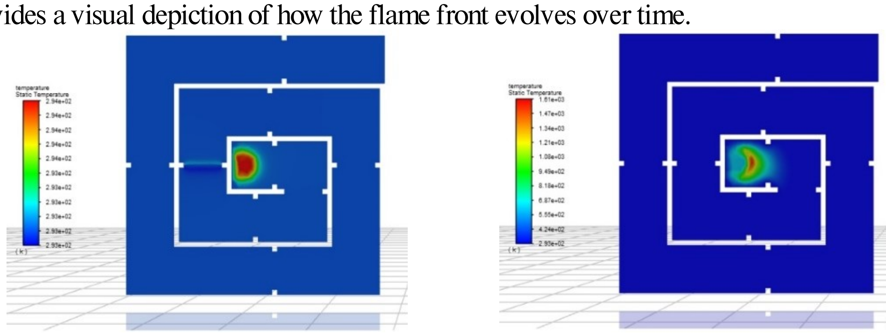
Firstly, the cells that are set with an explosive atmosphere are cells 1, 2, 3, and 4, with the explosion starting from the centre of the spiral. The concentration of hydrogen in the air is set at 20% volume. Hydrogen is highly flammable, and when present in sufficient quantities in the air, it can create a highly explosive atmosphere. A concentration of 20% indicates a significant amount of hydrogen, increasing the likelihood of a potentially powerful explosion.

The temperature is set at 20°C (degrees Celsius). Temperature plays a crucial role in determining the speed and intensity of chemical reactions. Higher temperatures generally lead to faster reactions, potentially resulting in a more rapid propagation of the explosion.

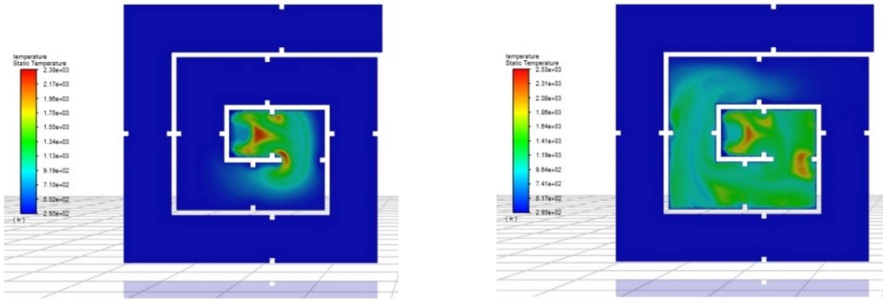
The pressure is set at 101325 Pa, which is equivalent to atmospheric pressure. The starting point of the explosion is cell 1, located at the center of the spiral. The choice of the starting point can impact the propagation and direction of the explosion.

5.1 Virtual simulation results

The behavior of the flame front can be observed through a series of images represented by color contours of temperatures. In Figure 7, the sequence of images, labeled from a) to d), provides a visual depiction of how the flame front evolves over time.



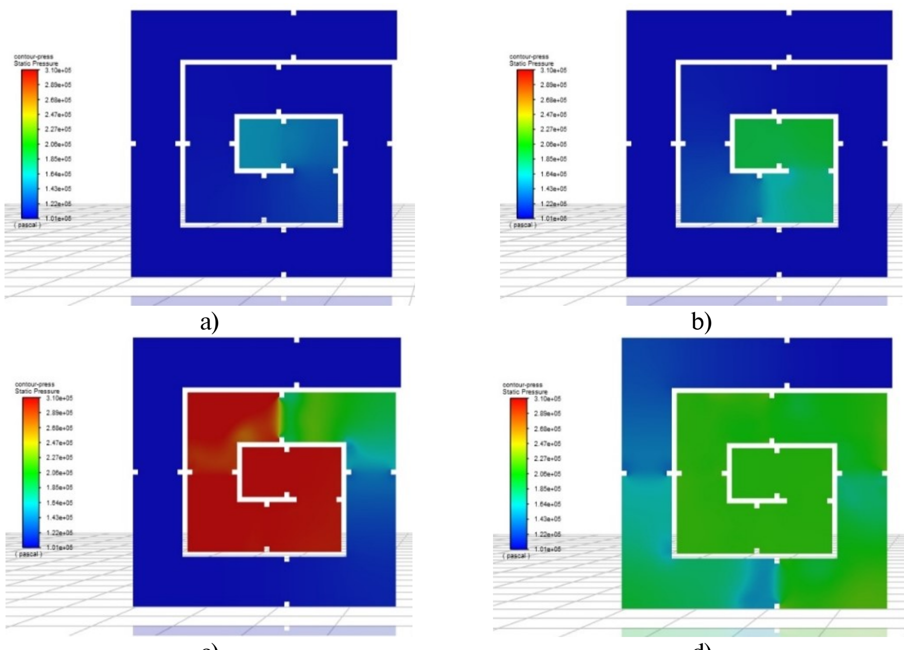
a) b)



c) d)

Fig. 7. Sequence of images with color contours of temperatures.

The evolution of pressure values can be visualized through a sequence of images represented by color contours. In Figure 8, the images labeled from a to d showcase the progression of pressure changes over time.



a) b) c) d)

Fig. 8. Sequence of images with colour contours of pressures.

In Figure 9, can be observed the maximum pressure recorded within the volume encompassing the four cells. At a specific time, t = 0.0044 s, the pressure reached its peak value, measuring 351119 Pa.

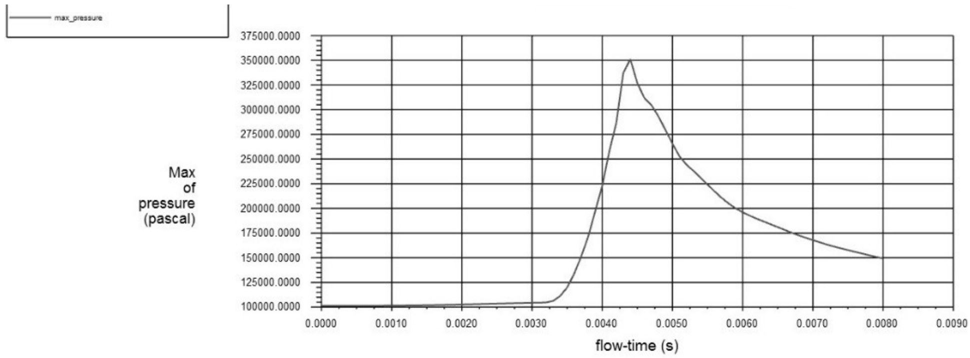


Fig. 9. Evolution of pressure values inside cells 1 to 4

Conclusions

This virtual simulation provided a platform for in-depth analysis and identification of the specific components, materials, and safety measures necessary to effectively conduct experiments involving air-hydrogen mixtures.

Given the fact that hydrogen has much more aggressive properties in terms of explosive dynamics compared to the explosive properties of methane, as well as from the data obtained from the virtual simulation, it is recommended that the dimensions of the cross section of the experimental stand of 50 x 50 mm be reduced to 30x50 mm.

By observing the virtual explosion scenario, researchers could gain valuable insights into the behavior of the air-hydrogen mixture, including its propagation, pressure build-up, and potential hazards.

The outcomes of the virtual simulation played a pivotal role in identifying the essential elements of the experimental stand. These elements encompassed safety measures, such as specialized containment systems, blast-resistant materials, and reliable ignition control mechanisms. Furthermore, the simulation helped in determining the optimal spatial arrangement of sensors, cameras, and other monitoring devices to ensure accurate data collection and analysis during the experimental process.

The outcomes of the virtual simulation have a significant role in identifying the essential elements of the experimental stand. These elements encompassed safety measures, such as specialized containment systems, blast-resistant materials, and reliable ignition control mechanisms. Furthermore, the simulation aided in determining the optimal spatial arrangement of sensors, cameras, and other monitoring devices to ensure accurate data collection and analysis during the experimental process.

Virtual simulation of the air-hydrogen explosion provided an indispensable foundation for the safe design and operation of the experimental stand. The findings obtained through this simulation contributed to enhancing the understanding of hydrogen's explosive nature, paving the way for improved safety and practices in the field of energy research and industrial applications.

It should be noted that the virtual simulation presented in this paper aims to approximate the overpressure values generated by the air-hydrogen explosion, the results not being validated based on physical experiments carried out on the same geometry. However, the set of values obtained provides the designer with a reference point in sizing the polycarbonate sheets and how to assemble the experimental model.

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