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High-pressure cylinder failure under fire conditions – investigation of the consequences

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This study investigates the behavior of high-pressure hydrogen and nitrogen cylinders under fire conditions to assess the risks associated with their storage and use in industrial and domestic applications. Cylinders pressurized to 300 bar were exposed to flames generated by diesel fuel, with critical parameters such as destruction pressure, temperature distribution, and fragmentation patterns recorded. The experiments revealed distinct differences in the destruction mechanisms of flammable and non-flammable gases. Hydrogen cylinders failed at pressures significantly lower than their rated destruction pressure due to thermal stress, generating fewer but substantial fragments and a fireball. In contrast, nitrogen cylinders exhibited extensive fragmentation and dispersion with following ignition of diesel vapors, forming a large fireball despite being non-flammable. These findings provide valuable insights into the risks posed by high-pressure gas cylinders under fire exposure and highlight the need for enhanced safety protocols and emergency response measures to mitigate potential hazards.

* 1. Introduction

High-pressure gas cylinders play a pivotal role in industrial and domestic applications, offering applications, and offering an efficient means to store and transport gases such as hydrogen, acetylene, propane-butane, and nitrogen. These gases serve critical functions across various sectors. For instance, acetylene and hydrogen are indispensable in metal fabrication due to their high flame temperatures, enabling processes like welding, cutting, and brazing (Jankuj et al., 2022; Pasman et al., 2023). Propane and butane are widely used in kilns, drying systems, and industrial heating, while natural gas, compressed natural gas (CNG), and liquefied petroleum gas (LPG) provide cleaner alternatives for power generation and transportation. These applications highlight the versatility and growing importance of flammable gases in advancing sustainable energy and industrial operations (Tschirschwitz et al., 2019, 2017).

Despite their widespread use, the handling of high-pressure cylinders entails significant safety challenges, particularly under fire exposure. Elevated temperatures can compromise the structural integrity of cylinders, even when they are engineered to withstand substantial thermal and mechanical stresses. Prolonged exposure to fire can lead to material degradation, ruptures, and uncontrolled gas release (Wang et al., 2023). For flammable gases, this often results in catastrophic incidents, including fireballs, explosions, and fragmentation, which pose severe risks to personnel, infrastructure, and emergency responders. For non-flammable gases physical destruction and following fragmentation release occurred. Such scenarios necessitate robust safety measures, including early fire detection, timely cooling, and safe handling protocols, to mitigate these hazards effectively (Hora et al., 2016).

The transition to green energy has spurred the development of advanced technologies and systems aimed at minimizing environmental impacts. Among these, hydrogen stands out due to its clean-burning properties and versatility in applications ranging from transportation to industrial processes (Abbasi and Abbasi, 2011). However, ensuring the safe storage and handling of hydrogen, particularly in high-pressure cylinders, remains a critical challenge (Usman, 2022). These cylinders, widely used for storing technical gases in industrial and domestic applications, are prone to significant risks under fire exposure, including catastrophic failures that pose threats to safety and infrastructure (Barthelemy et al., 2017).

Hydrogen’s high reactivity and energy density demand specialized storage and safety measures, especially as its role expands as a key energy carrier in cleaner energy systems. The increasing deployment of hydrogen technologies highlights the urgent need to address these safety concerns and develop robust solutions to mitigate risks associated with high-pressure storage, particularly in fire scenarios. Understanding these challenges is crucial for advancing hydrogen's integration into sustainable energy systems while ensuring safety and reliability (Abohamzeh et al., 2021; Saffers and Molkov, 2014; Ustolin et al., 2020).

In fire scenarios, pressure cylinders represent a critical hazard, significantly amplifying risks to nearby environments and individuals. Predicting the behavior of these cylinders under elevated temperatures is both complex and uncertain. Cylinder ruptures can result in catastrophic consequences, including powerful blast waves, intense fireballs, and the ejection of high-velocity fragments from the cylinder or surrounding materials. These events often stem from the uncontrolled release of hazardous substances, such as toxic or flammable gases and vapors, leading to extensive property damage, severe health risks, and environmental harm. To mitigate these risks, it is essential to understand the mechanisms driving these incidents, the types of explosions that may occur, and the potential for domino effects that escalate the scale of destruction.

For the purpose of comparing the consequences, nitrogen was selected and stored in pressure cylinders exposed to the same conditions as the hydrogen-filled cylinders. This approach enables a precise evaluation of the differences in behavior between flammable and non-flammable gases under fire conditions, contributing to a better understanding of the risks associated with high-pressure gas storage and the optimization of safety measures. This paper consolidates the findings from experimental investigations, emphasizing the behavior of pressure cylinders in fire scenarios and the associated risks. By presenting critical data and identifying key failure mechanisms, this research contributes to improving safety protocols, developing effective risk mitigation strategies, and advancing the field of safety engineering. Furthermore, it outlines future directions for experimental and analytical research to support safer integration of high-pressure gas cylinders in industrial and domestic contexts.

* 1. Experimental setup

A large-scale experiment was conducted to evaluate the behavior of hydrogen- and nitrogen-filled pressure cylinders under fire conditions. Both types of cylinders, pressurized up to 300 bars, were exposed to flames generated by a flammable liquid. In this case, the fire was generated using 80 liters of diesel fuel distributed across four stainless steel trays. To enhance the flammability of the diesel fuel, approximately 0.5 liters of gasoline was poured onto its surface. The ignition of the gasoline was carried out remotely using pyrotechnic igniters, ensuring controlled and safe initiation of the fire. The experimental setup was designed to replicate real-world fire scenarios, ensuring the relevance of the findings to industrial and emergency response situations.

Pos. n. 1

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| A  C  B |  |

Figure 1 Pressure cylinder experimental setup

During the experiments, critical parameters such as the destruction pressure and the shell temperature of the cylinders were continuously monitored and recorded. High-speed cameras and advanced sensors were employed to document the sequence of events leading to cylinder failure. Fragmentation patterns were carefully documented and analyzed to assess the potential hazards associated with cylinder rupture.

The internal pressure during thermal heating was measured using a BD Sensors 17.600 G transducer with a specified range and an accuracy of 0.5%. The transducer was connected to the valve outlet via an adapter and insulated pipelines. To ensure accurate and safe measurements, the pressure pipelines and valve were fully insulated before each test.

Thermocouples (Type K) were installed circumferentially around the pressure cylinder at 90° intervals at three height levels: 1200 mm (A), 700 mm (B), and 250 mm (C) from the cylinder base. At each height, thermocouples were positioned at four points: 1, 2, 3, and 4, with position 1 aligned with the valve outlet. To ensure accurate temperature readings of the cylinder shell and minimize interference from external heat sources, the thermocouples were insulated with heat-resistant fabric. The placement of the thermocouples can be seen in Figure 1, which also illustrates the arrangement of the trays filled later with diesel fuel used to create the fire conditions including remote control pyrotechnical ignition.

This comprehensive setup allowed for precise data collection and analysis, providing valuable insights into the thermal and mechanical behavior of pressure cylinders in fire scenarios. The findings contribute to a deeper understanding of safety measures needed for high-pressure gas storage under extreme conditions.

* 1. Results and discussion

The table balow summarizes the results of experimental measurements. A total of four pressure cylinders filled with compressed gas at 300 bars were exposed to fire conditions. Specifically, this included two cylinders of hydrogen and two of nitrogen. For the cylinder "Nitrogen 1," a leak occurred through the pressure measurement piping system after two minutes. As a result, the cylinder was neutralized by successive releasing the pressure via shooting to ensure safety. The results of this intervention can be seen in Figure 2.



Figure 2 "Nitrogen 1" cylinder after neutralization

For the "Nitrogen 2" cylinder, failure occurred after 6 minutes at a pressure of 732 bar. The physical destruction generated 7 fragments that dispersed into the surrounding area. The "Hydrogen 1" cylinder failed after 8 minutes; however, pressure data recording was unfortunately lost during the test. For the "Hydrogen 2" cylinder, destruction occurred after 6 minutes at a pressure of 512 bar. The hydrogen cylinders generated one main fragment along with a few smaller pieces, specifically 2 and 4 fragments, respectively.

Table 1: Experimental tests results

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| Pressure  cylinder | Destruction  time | Destruction  pressure | Number  of fragments |
| Nitrogen 1 | - | - | - |
| Nitrogen 2 | 6 min | 732 bar | 7 |
| Hydrogen 1 | 8 min | - | 5 |
| Hydrogen 2 | 6 min | 512 bar | 3 |

The highest temperatures were recorded in the lower section of the cylinder, with a peak of 575°C at position C, followed by 370°C at position B, and 320°C at position A. In both cases of tested hydrogen cylinder failure, structural integrity was compromised in the lower section, resulting in its destruction. This confirms that the lower part of the cylinder experienced the highest thermal stress, leading to its failure. In these instances, the cylinders ruptured at a pressure of 512 bar, approximately 200 bar lower than the tested destruction pressure of 740 bar under normal conditions. In the case of "Nitrogen 2," the cylinder experienced total destruction, breaking into multiple pieces. Subsequent analysis of the recordings revealed approximately 7 fragments of the cylinder that were propelled into the surrounding area. The experiments revealed a definitive correlation between thermal exposure and the pressure increase that ultimately leads to cylinder failure. Notably, the degradation was most pronounced in the lower sections of the cylinders, which were subjected to the highest levels of thermal stress. The pressure at the moment of failure was considerably lower than the destruction pressure observed under normal conditions, highlighting the critical role of heat in compromising the structural integrity of the cylinder.

Fragmentation patterns varied significantly depending on the type of gas. For instance, nitrogen cylinders produced extensive fragmentation upon failure, with numerous high-velocity fragments posing a severe safety risk. In comparison, hydrogen cylinders generally fragmented into fewer large pieces along with smaller fragments, which still present hazards due to fireball generation and fragment dispersion.

* + 1. Hydrogen’s destructions

Figure 3 below depicts the destruction process of the hydrogen cylinder, specifically "Hydrogen 2." In the detailed ground view, the propagation of the pressure wave is visible, reaching a distance of approximately 66 meters in about 0.16 seconds. The thermal camera footage reveals two fragments propagating from the point of destruction, which are difficult to discern with a standard camera. In a later phase, the main fragment of the pressure cylinder is also visible, having been propelled to a distance of 6 meters. In the second case involving the hydrogen cylinder, the main fragment was located 7 meters from the point of destruction. Smaller fragments, totaling four, dispersed into the surrounding area, reaching a distance of 100 meters in approximately 0.63 seconds. The recording also captured their trajectories and the changes in movement upon impact with the ground. Unfortunately, it was not possible to locate the fragments in the open area, but it is likely that they travelled a final distance of more than 200 meters.

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*Figure 3 Destruction of “Hydrogen 2” pressure cylinder*

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|  | Obsah obrázku oheň, tráva, venku, exploze  Popis byl vytvořen automaticky |

*Figure 4 Detail of the “Hydrogen 1” fragment and explosion*

In the detailed footage of destruction events of the “Hydrogen 1” (see Figure 4), the main fragment of the pressure cylinder (circled) is clearly visible. The detailed image of the fragment highlights the sharpness of the shrapnel and the nature of its rupture, where a piece of the cylinder's lower section tore away, creating sharp edges. In this case, approximately 3 smaller fragments were generated, flying outward from the explosion site. Additionally, droplets of spread flammable liquid can be observed, which contributed to the development of a fireball that reached unusually large dimensions. This can also be described as an explosion of a so-called hybrid mixture under real-world conditions, as it involves the presence of both flammable gas and flammable liquid vapors.

* + 1. Nitrogen’s destruction

A nitrogen cylinder pressurized to 300 bar was exposed to the same conditions as the hydrogen cylinders, with notable differences observed in its destruction and effects. The nitrogen cylinder ruptured at a recorded pressure of 732 bar after 6 minutes of direct fire exposure. Although nitrogen is a non-flammable gas, the physical explosion created significant turbulence, see right photo of Figure 4. This led to the dispersion of diesel vapors and liquid and the formation of a large fireball as same as hydrogen destructions.

This test demonstrated more extensive fragmentation (see Figure 5) compared to the hydrogen cylinders. The furthest fragment was located 256 meters from the explosion site, though not all fragments could be recovered. Recordings captured the entire sequence: the physical rupture of the cylinder, rapid gas release, and the subsequent ignition of flammable vapors, culminating in the fireball. Figure 4 showcases the severity of fragmentation and highlights how the ignition of vapor contributed to the fireball’s size and intensity.

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Figure 5 Nitrogen cylinder destruction

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Figure 6 Nitrogen and hydrogen cylinder destruction post-scene

The above Figure 6 demonstrates the force of the nitrogen cylinder explosion. In comparison to hydrogen, the nitrogen explosion resulted in the complete destruction of the original setup and configuration. Conversely, in the case of hydrogen, a residual burning fire was observed.

These findings could have significant implications for process safety in industrial plants storing or utilizing high-pressure gas cylinders. One of the main aspects is that people often do not realize the severity of the consequences when handling high-pressure gas cylinders in general. Under fire conditions, these cylinders behave unpredictably, making It crucial to exercise heightened caution, which also applies to emergency responders dealing with fire incidents. Extensive fragmentation underscores the necessity of proper handling and, most importantly, an adequate level of fire suppression. Strategies to minimize the risk should include effective emergency response protocols, with training programs emphasizing rapid cooling techniques, controlled venting, and safe evacuation procedures to protect human life. Implementing these measures can significantly enhance prevention and protection strategies, reducing the likelihood and severity of catastrophic incidents in industrial settings.

* 1. Conclusions

The experiments conducted provide critical insights into the behavior of high-pressure gas cylinders under fire conditions, emphasizing the importance of understanding both flammable and non-flammable gas risks. Hydrogen cylinders, while environmentally advantageous, exhibited a pronounced susceptibility to thermal stress, failing at pressures considerably below their rated destruction pressure. This highlights the need for specialized materials and safety measures for hydrogen storage.

Nitrogen cylinders, though non-flammable, demonstrated the capacity to cause significant physical destruction, with fragments dispersing over long distances and generating fireballs through dispersing and following vapor ignition. These results underline the necessity of rigorous risk assessments and robust safety systems for all types of high-pressure gas storage. To improve safety and mitigate risks, future research should focus on developing advanced materials for cylinder design, implementing improved monitoring systems, and enhancing emergency response protocols. By addressing these challenges, the safe integration of high-pressure gas cylinders in various applications can be ensured, aligning with broader environmental and safety objectives.

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