

Accidental self-ignition of hydrogen released from pressurized cylinder

V. Jankuj^{a,c,*}, P. Lepik^a, E. Salzano^{b,c}, M. Mynarz^a

^a Faculty of Safety Engineering, VSB – Technical University of Ostrava, Ostrava, Czech Republic

^b Dipartimento di Ingegneria Civile, Chimica, Ambientale e Dei Materiali, Università di Bologna, Bologna, Italy

^c Centre of Excellence for Safety Research, VSB – Technical University of Ostrava, Ostrava, Czech Republic

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ABSTRACT

Hydrogen is a promising energy carrier with wide-ranging applications, but its safe storage and handling remain critical challenges. This study investigates the conditions that lead to the accidental self- (or spontaneous) ignition of hydrogen during controlled release from a pressurized cylinder. In the experimental setup, a hydrogen cylinder pressurized to 200 bar was penetrated by a bullet to simulate an accidental release. Thermocouples were strategically placed to measure the temperature of the escaping gas, while the event was monitored with high-speed cameras and drones equipped with thermal imaging.

Temperature measurements of the escaping gas showed minimal variation. However, ignition was observed a few meters from the release point, a surprising result suggesting the involvement of external factors, such as electrostatic discharge or environmental interactions, rather than direct ignition by hydrogen itself. These findings highlight the complexity of hydrogen behavior during high-pressure releases and underline the need for further research to understand and mitigate such risks.

1. Introduction

Due to the global needs for decarbonization of the energy sector, hydrogen is gaining a leading position as a potential energy source of the future [1], with a wide range of hydrogen usability, as in fuel cell electric vehicles (FCEV) [2], or in industry, including potential mixing into the natural gas grid. Hydrogen represents a versatile, zero-carbon energy carrier that can be produced from renewable or nuclear resources and applied across multiple hard-to-electrify sectors, including heavy industry, transportation, and long-term energy storage [3]. These attributes position hydrogen as a cornerstone of future low-carbon energy systems envisioned in global climate strategies. Recent studies have also examined the role of hydrogen within alternative-fuel concepts such as ammonia-diesel or methanol-diesel dual fuel engines, demonstrating the importance of low-carbon fuels in sustainable energy transitions [4–6]. Although hydrogen offers environmental benefits, particularly with respect to greenhouse gas (GHG) emissions [3,7], its physical and chemical properties pose specific safety risks that must be addressed [8]. These include a wide flammability range, very low ignition energy, and high diffusivity, which make hydrogen especially sensitive to electrostatic discharge and spontaneous ignition phenomena [9].

The importance of safety during the storage or handling of hydrogen

lies mainly in its high flammability and the wide range of explosion concentrations. For the safe operation of hydrogen technologies or equipment, it is essential to understand the detailed ignition mechanisms and to establish clear safety thresholds [8,10,11]. To determine the ignitability of gases and dust, the minimum ignition energy (MIE) is often used, defined as the minimum energy required to ignite. Compared to other materials, hydrogen is recognized as very sensitive to electrostatic discharge [12]. Several experiments were performed to assess the potential ignition hazard posed by brush discharges in various explosive atmospheres, including hydrogen-air mixtures. These criteria are essential for assessing safety in hazardous areas [10,13].

A brief overview of known mechanisms of ignition primarily involves electrical discharges. This ignition occurs between two electrodes when the voltage across the gap exceeds the gaseous breakdown limit, as given by Paschen's law. The exact timing of the discharge is a random process, influenced by the presence of a sufficient number of free electrons in an electric field. These electrons are accelerated, leading to the formation of an electron avalanche (Townsend mechanism) and, subsequently, a streamer channel that bridges the gap and results in a discharge [8].

Experimental studies have investigated the influence of various factors on the ignition energy of combustible mixtures, including mixture composition and concentration, electrode gap distance, and

* Corresponding author. Faculty of Safety Engineering, VSB – Technical University of Ostrava, Ostrava, Czech Republic.

E-mail address: vojtech.jankuj@vsb.cz (V. Jankuj).

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discharge circuit parameters such as capacitance, resistance, and discharge time constant. The results indicate that the minimum ignition energy is reached under specific optimal ignition conditions [12,14].

In addition to electrical discharges, other ignition mechanisms have been examined, such as laser-induced ignition [8] and the ignition of hybrid dust-gas mixtures [15], where ignition often occurs in the gap phase, while flame propagation is significantly affected by the interaction between dust particles and the surrounding gas. In this context, thermal and hydrodynamic effects have also been discussed, as they play a critical role in both the ignition process and subsequent flame development.

Although extensive studies exist on the safety parameters of hydrogen and its ignition mechanisms under controlled experimental conditions [8,10,13–15], recent work by Bragin and Molokov has provided insight into spontaneous ignition phenomena in high-pressure hydrogen releases, revealing that ignition can initiate within the boundary layer and propagate as a jet flame [16]. Complementary numerical analyses by Gong and Duan have shown that shock-wave interactions, turbulence, and local temperature gradients strongly influence ignition behavior during pressurized hydrogen release [17, 18]. Despite these findings, the role of sudden hydrogen release and the associated dynamic phenomena that can lead to potential autoignition remain insufficiently explored. While literature often discusses hydrogen leaks, their direct link to autoignition during sudden releases is not comprehensively addressed in ignition-focused studies. Most of these investigations have been performed under controlled nozzle or jet conditions, whereas real-scale failures involve irregular flow, pressure transients, and electrostatic effects [16,17,19]. Although investigations of high-pressure hydrogen behavior [2] and turbulent jet dynamics [12] exist, ignition mechanisms induced [2,15] by the dynamics of sudden release, such as discharge events triggered by fast-flowing hydrogen or associated pressure waves, require further experimental validation.

The objective of this study is to experimentally investigate the conditions leading to the autoignition of hydrogen-air mixtures during sudden hydrogen release. Specific mechanisms that may contribute to ignition under such scenarios, such as electrostatic discharges generated by high-velocity flow, thermal effects resulting from the Joule-Thomson effect, or compression of the surrounding air, will be examined to identify the critical parameters that lead to ignition.

2. Materials and methods

Hydrogen is increasingly recognized as a key alternative energy carrier in future low-carbon energy systems due to its high specific energy and clean combustion properties. With advances in modern technologies and new materials, it is now possible to store hydrogen at significantly higher pressures or in liquefied form. Today, hydrogen is routinely stored at pressures of 200–300 bar and more for hydrogen mobility at 700 bar. However, such conditions pose major safety challenges, particularly in scenarios involving sudden release, where thermodynamic effects—especially the Joule-Thomson (J-T) effect—can strongly influence ignition behavior and potentially lead to the formation of high-temperature fire jets.

Building on earlier experimental investigations [20] that studied the behavior of pressure cylinders exposed to fire in cooperation with special forces, this study focuses specifically on the risk of sudden mechanical failure and high-pressure hydrogen release due to accidental ignition. In the current investigation, a 50-L steel pressure cylinder filled with hydrogen at 200 bar was subjected to a controlled penetration via shooting to simulate an accidental release. The cylinder was fixed in a custom support frame, ensuring stability. Thermocouple measurements were carried out using Type K thermocouples (EN 60584) with GLGL wrap insulation suitable for ambient temperatures between -25°C and $+400^{\circ}\text{C}$, with the recording frequency 1 s. Two configurations were employed: (i) thermocouples with 2×0.50 mm conductors for general measurements, and (ii) thin-wire thermocouples with 2×0.20 mm

conductors used for higher temporal response near the gas release region. Thermocouples were positioned at two vertical heights - 55 cm and 135 cm - to monitor temperature changes on the cylinder shell, while additional thermocouples were arranged horizontally at distances of 15.5 cm (A), 25.5 cm (B), and 60 cm (C) (see Fig. 1) below the penetration point to capture thermal characteristics of the escaping gas. For the repeated tests, two types of thermocouples (normal and thin) were used for temperature measurement, and thermocouples for measuring the cylinder shell temperature were not used. High-speed video recording (60,000 fps) and drone thermal imaging (30/50 fps) provided visual documentation. Internal pressure was tracked using a DB Sensors 17.600 pressure transducer, with a recording period of 0.2 s.

The ignition observed during the experiment occurred several meters from the release point, suggesting the involvement of external ignition sources rather than direct nozzle ignition, raising critical questions about the roles of electrostatic and environmental effects in such events.

During the test, the entire experiment was recorded using drones equipped with thermal imaging systems and high-speed cameras (Fig. 2). All data were logged for subsequent analysis. Due to the high kinetic energy released upon penetration of the cylinder shell, the cylinder became unstable and fell from its support structure. As a result, the initial setup was modified, and follow-up tests were conducted focusing solely on temperature measurements of the escaping gas using thermocouples. The cylinder penetration was performed by a professional specialist using standard ammunition. All shooting operations were conducted under controlled conditions by qualified personnel with appropriate safety measures and local authority approvals in place. The first (initial) test was conducted at approximately 300 m, while the two subsequent repeat tests were conducted at a fixed distance of 100 m. The shooting position, firing angle, and ammunition type were kept constant for the repeat tests to ensure comparable experimental conditions. However, changing the experimental location should affect the results, as discussed in the next sections. In total, three experimental cases were performed – the initial outdoor test, in which spontaneous ignition was observed, followed by two repeated tests under identical conditions. Although the number of experiments is limited, the observed variability highlights the inherent unpredictability of hydrogen ignition during sudden high-pressure release.

3. Results

In this chapter, the results are divided into two experimental investigations. In the first of them, the ignition was observed, but due to the kinetic energy, the pressure cylinder fell, thereby influencing the results. In the repeating test conditions, results were clearer—either spark ignition or no ignition. However, in the first test case, described in

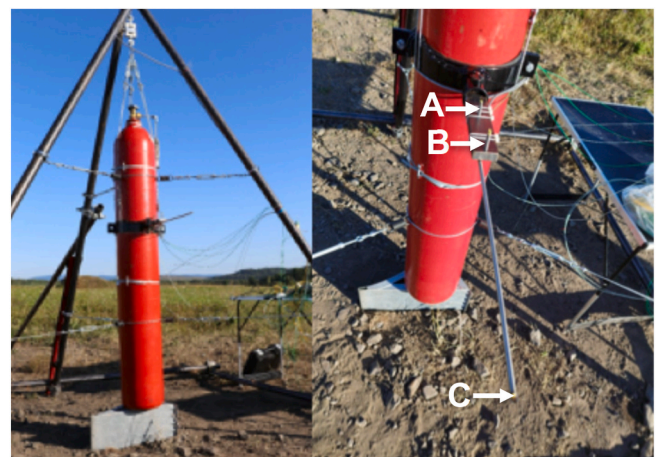


Fig. 1. Hydrogen cylinder and thermocouples positions.



Fig. 2. Experimental equipment set-up, high-speed and infrared cameras (left), shooting position (right).

detail here, a sudden ignition occurred at the gas release. This ignition event was not immediately visible during the test but was later confirmed from thermal imaging recordings. This finding is particularly interesting, as the footage clearly shows the gas being released under pressure from the cylinder and igniting in the space in front of it. Initial assumptions that the ignition was caused by the projectile penetrating the cylinder wall were disproved by video evidence. Similarly, the hypothesis of ignition by a hot particle generated during perforation was also ruled out.

The first outdoor experiment (in which spontaneous ignition was observed) was conducted at an ambient temperature of 24 °C, a relative humidity of 32 %, an atmospheric pressure of 928 hPa, and a wind speed of 2,2 m/s. In the subsequent two experiments, performed at a semi-enclosed site, the recorded ambient conditions at test start were 3.1 °C, relative humidity 75 %, and atmospheric pressure 970 hPa. The following tests were conducted in a semi-enclosed site, where wind influence was minimal or negligible.

Fig. 3 shows the hydrogen cylinder just a few milliseconds after penetration of its shell and the initial release of internal pressure (200 bar). Thanks to thermal imaging, it is clear that the released gas is not ignited and shows no noticeable temperature changes in the surrounding environment. Frame-by-frame analysis of the high-speed video revealed that ignition occurred approximately 0.33 s after the projectile penetration, coinciding probably with the visible interaction between the hydrogen jet and the nearby steel support rod. No direct temperature or discharge measurement was available at that location; thus, the proposed ignition by environmental contact with the steel element remains a plausible interpretation rather than a confirmed mechanism.

However, in the following Figs. 4 and 5, the ignition of hydrogen is clearly observable. At this point, the pressure cylinder begins to fall, and based on the recordings, it can be inferred that the ignition likely occurred upon contact between the escaping hydrogen and a steel rod used to secure the cylinder. Simultaneously, it is evident that at the nozzle, where the hydrogen is released, only unignited gas is present.

No significant temperature rise was recorded by the thermocouples at the moment of ignition, likely due to the spatial distance between the

ignition site and the sensors. However, pressure data confirms a rapid drop, indicating that the cylinder was fully depressurized within a few seconds.

Subsequent thermal imaging frames show how the ignition propagated from the initial contact point toward the release nozzle, eventually forming a fire jet originating from the initially ignited gas cloud. It is also evident that the originally invisible flame becomes a well-defined fire jet.

Further image sequences capture the development of a transient fireball composed of burning hydrogen gas. In later frames, the fallen cylinder can be seen on the ground, still releasing hydrogen.

To verify repeatability, two additional identical tests were conducted. In the first of these, ignition of the escaping hydrogen was observed. In this case, the ignition was clearly caused by a spark generated during the projectile's penetration through the cylinder wall, as confirmed by high-speed camera footage (see Fig. 6). The resulting fire jet reached a length of more than 7 m with visible flame. In the second case, no ignition occurred, and the hydrogen was released into open space without combustion. As shown in the high-speed camera recordings (Fig. 6), no spark capable of igniting the escaping gas was generated.

The following graphical representation (Fig. 7) illustrates the hydrogen release after the cylinder was penetrated. A slight difference in the gas release velocity is observed between the case with ignition and the case without ignition.

Regarding the temperature measurements of the escaping gas, a logical difference was recorded between burning and non-burning hydrogen releases. In the case of ignition (Fig. 8), temperatures reached up to 1000 °C. For the non-ignited hydrogen release (Fig. 9), an initial sharp drop in temperature was observed, followed by a gradual increase to approximately 40 °C. The observed initial temperature drop and gradual warming of the released hydrogen are consistent with the J–T effect reported in previous studies of rapid adiabatic expansion. Although no quantitative modeling was performed in this work, the magnitude and temporal evolution of the measured temperature profiles are consistent with literature data for adiabatic expansion at pressures around 200 bar. Further numerical modeling will be required to validate

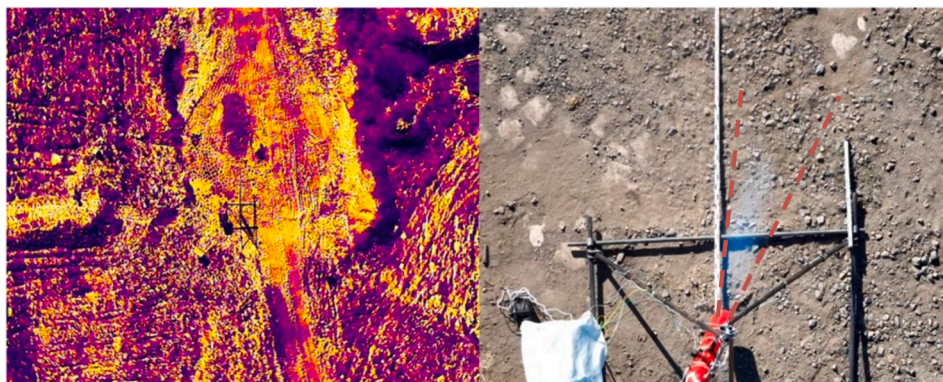


Fig. 3. Hydrogen release after shell penetration.

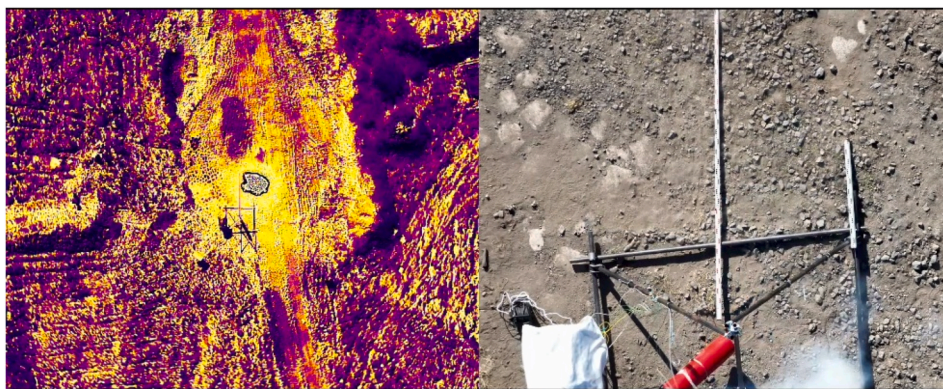


Fig. 4. Hydrogen ignition after accidental release.

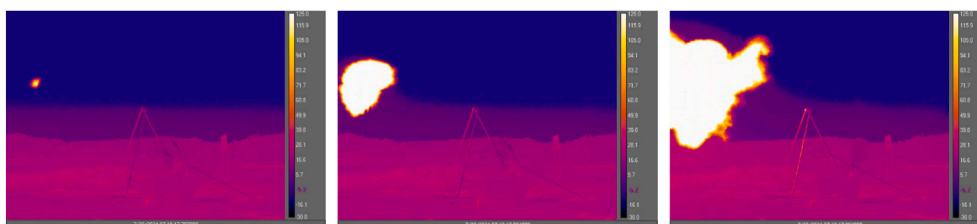


Fig. 5. Infrared ignition of escaping hydrogen.



Fig. 6. Hydrogen release with ignition (left) and non-ignition (right).

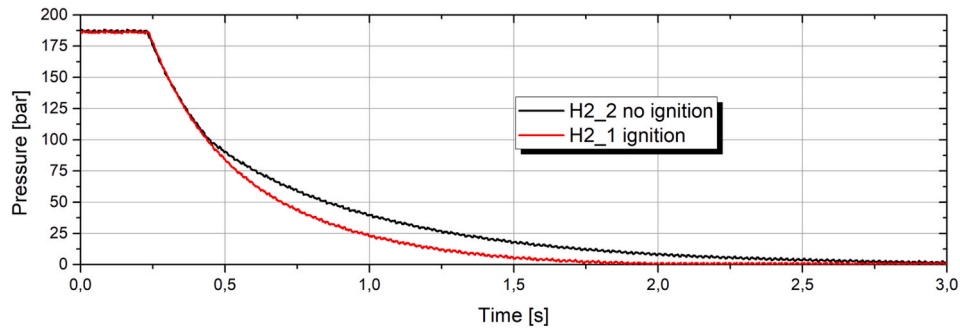


Fig. 7. Pressure drop during hydrogen release.

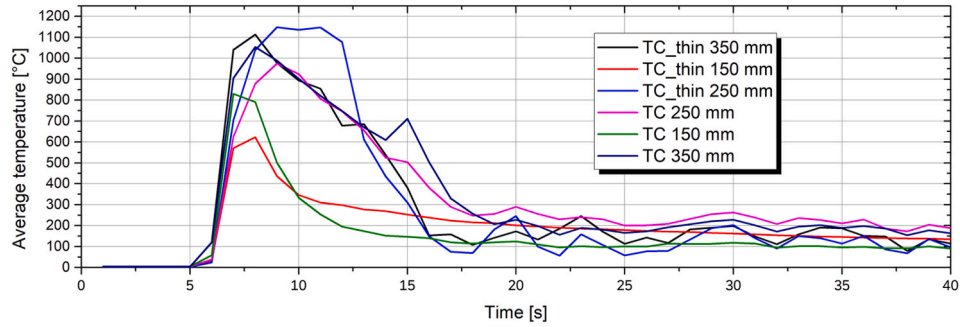


Fig. 8. Hydrogen release and subsequent spark ignition.

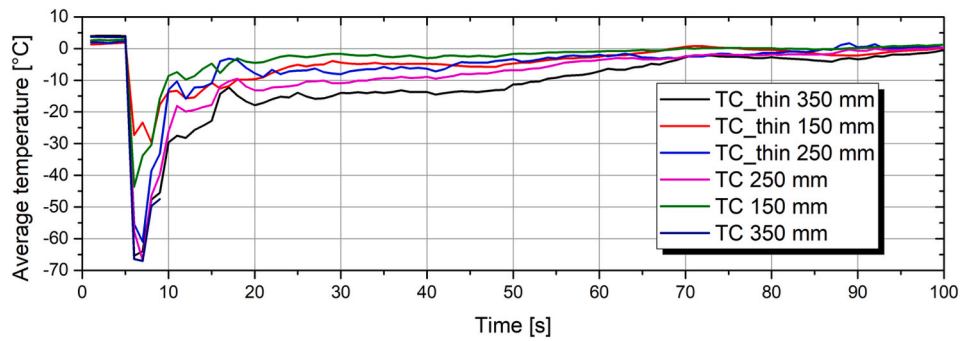


Fig. 9. Hydrogen release without ignition.

these trends under varied boundary conditions.

Although hydrogen has a negative J–T coefficient at room temperature and atmospheric pressure (meaning it typically warms upon expansion), it can exhibit cooling behavior under high-pressure conditions. Specifically, during rapid expansion from 200 bar to ambient pressure, the initial temperature drop may reach -50 to -80 °C, depending on flow rate and nozzle geometry. As the flow stabilizes and mixes with ambient air, the gas temperature gradually increases—possibly aided by recompression and environmental heat transfer.

The experiments did not confirm a consistent or clearly defined ignition mechanism. In two repeated tests, ignition was observed in only one case. This ignition was demonstrably caused by sparks generated during the impact of the projectile and the subsequent penetration of the pressure cylinder wall. The ignition in this case is clear and supported by both high-speed camera footage and the associated rapid temperature increase recorded by thermocouples. In contrast, during the non-ignition scenario, the escaping hydrogen jet gradually increased in temperature, with no combustion observed.

A particularly interesting case occurred during an external experiment, where visual observation initially suggested a simple release of

hydrogen without ignition. However, a detailed analysis of the recordings—especially thermal imaging—revealed that the escaping hydrogen had indeed ignited and sustained combustion. The flame subsequently propagated back toward the release point.

Despite a thorough investigation, the exact ignition source in this case remains unidentified. Initial assumptions leaned toward auto-ignition due to molecular effects or high-velocity gas flow. However, high-resolution footage confirmed that the hydrogen jet contacted a steel structural component. This interaction, likely involving friction or local turbulence, is considered the most probable cause of ignition. It therefore points to an environmental interaction, most likely turbulence-induced, as the dominant factor in this specific ignition event.

4. Discussion

The experimental results reveal a complex, not fully understood mechanism underlying the ignition of high-pressure hydrogen during sudden release events. While one of the experiments clearly demonstrated ignition due to mechanical sparking—caused by the projectile impact and subsequent penetration of the pressure cylinder wall—the

second test, conducted under nominally identical conditions, did not lead to ignition. This inconsistency underscores the stochastic nature of ignition in such dynamic scenarios and points toward a multi-factorial origin. The ignition attributed to projectile-induced sparks was identified based on visual recordings rather than direct energy or temperature measurements at the impact point. No quantitative estimation of spark energy or comparison with the minimum ignition energy of a hydrogen-air mixture was performed. The analysis presented in this work is based primarily on visual and thermal imaging data.

In the most intriguing case observed during the external test, ignition of the escaping hydrogen was not apparent in real time. Initial assumptions suggested a simple release without ignition. However, post-analysis of the high-speed and thermal imaging footage revealed a delayed ignition of the hydrogen cloud several meters from the release point. The flame then propagated backwards toward the nozzle. Several possible ignition mechanisms have been considered:

- electrostatic discharge: The high-velocity flow of hydrogen through the breach in the cylinder may have generated an electrostatic charge, potentially reaching critical energy levels sufficient to trigger ignition. The low minimum ignition energy (MIE) of hydrogen-air mixtures makes this a credible scenario;
- environmental interactions (turbulence, dust, humidity): The ignition point occurred near a steel structural rod used to stabilize the cylinder. It is plausible that turbulence-induced friction or interactions with environmental particulates (e.g., airborne dust or moisture) created localized hot spots or electrostatic effects that led to ignition;
- undetected mechanical sparks: Although the primary projectile-induced spark can be ruled out based on the timing and location of the ignition, secondary mechanical interactions, such as the falling cylinder striking metal supports or the steel rod, could have generated micro-sparks not captured directly on video.

From the practical point of view, the results show that the ignition can occur at a distance from the nozzle, highlighting the importance of evaluating not only release points but also surrounding infrastructure and potential contact surfaces. Due to hydrogen's reactivity, effective electrostatic discharge mitigation strategies are critical during high-pressure hydrogen handling, especially in open environments. Single-point safety assessments may underestimate risks. Redundant safety measures and real-time monitoring are essential and particularly in mobile applications (or transport) or in public infrastructure.

Several limitations have been acknowledged, including uncontrolled variables, incomplete identification of ignition sources, and limited repeatability. The accidental failure of the cylinder during the first test disrupted sensor alignment and compromised data continuity, particularly for thermal and pressure measurements. In the most interesting ignition case, the exact mechanism remains speculative, despite visual evidence of interaction with environmental elements. It is acknowledged that electrostatic discharge as a potential ignition source could not be directly confirmed, as no measurements of electrostatic potential or charge accumulation were performed. However, the observed ignition location and timing, combined with the absence of other plausible ignition sources, are consistent with previously reported electrostatic ignition scenarios in high-velocity hydrogen releases. Only two were valid after tests were completed. While one resulted in clear ignition, and the other one did not, a broader dataset is required to validate trends and conclusions with higher statistical confidence. It is recognized that the limited number of experiments restricts the statistical interpretation of ignition probability. However, the inconsistent ignition behavior observed under nominally identical conditions provides important insight into the stochastic and environment-dependent nature of hydrogen ignition during a sudden release event. These findings underline the need for further controlled and large-scale experimental campaigns to systematically investigate this phenomenon.

5. Conclusion

This experimental study demonstrates that the accidental release of hydrogen under high pressure can, under specific circumstances, lead to ignition without a clearly identifiable ignition source. In one of the test cases, ignition was likely caused by a spark generated during projectile penetration of the cylinder. However, in another test, ignition appeared to result from environmental interaction between the hydrogen jet and a steel structural element, potentially involving electrostatic discharge or turbulence-induced heating.

Key findings of this work have demonstrated that ignition can occur several meters away from the point of release and that electrostatic discharge, turbulence, and interactions with structural elements must be considered as potential ignition mechanisms. Further research should focus on:

- Controlled studies on electrostatic potential during high-velocity gas releases.
- Quantification of ignition probability under different environmental and geometric conditions.
- Development of detection methods for incipient ignition in hydrogen technologies.

These findings can be relevant for the development of safety standards and risk assessment methodologies in hydrogen storage and transportation, such as a potential ignition problem during release under pressure. The results suggest that ignition during sudden hydrogen release may plausibly involve electrostatic discharge, turbulence-induced friction, or environmental interactions. However, due to the limited experimental data, these interpretations should be regarded as hypotheses requiring further systematic investigation under controlled conditions.

CRedit authorship contribution statement

V. Jankuj: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **P. Lepik:** Writing – review & editing, Methodology, Investigation. **E. Salzano:** Writing – review & editing, Supervision, Data curation, Conceptualization. **M. Mynarz:** Writing – review & editing, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that support the findings of this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.17913628>.

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