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Sealing performance of pipes and joints in pure hydrogen

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Abstract. The transition toward hydrogen as a clean energy carrier requires reliable infrastructure, particularly for its distribution through pipelines. This study evaluates the sealing performance of various pipe and joints under pure hydrogen, the most challenging condition for leakage. An experimental setup was developed to test four representative pipe samples taken from the Italian gas distribution network, differing in their dimensions and in the constituent material, including galvanized steel, polyethylene PE100, and API 5 LGR B steel. Each sample was pressurized with hydrogen and the pressure was monitored over one week under controlled temperature conditions. Results showed no measurable leakage in steel pipes, confirming their readiness for hydrogen integration. On the other side, the PE100 pipe exhibited a measurable pressure drop attributed to gas permeation, which however resulted to be lower than the predicted value based on average polyethylene permeability, suggesting material-dependent behaviour. Notably, literature suggests that hydrogen permeability in polyethylene may decrease over time as the material crystallinity increases. Since gases cannot diffuse through the crystalline phase, this implies that hydrogen losses due to permeation could diminish rather than intensify, a reassuring insight for long-term pipeline applications. These findings suggest that much of the current steel-based infrastructure may already be compatible with hydrogen, while polymeric components require further study due to their variable permeation behaviour.

1. Introduction

In recent years, hydrogen has gained increasing attention as a clean energy carrier capable of reducing carbon emissions and mitigating global warming. Under the framework of the European Green Deal, the European Union has set the goal of becoming the first climate-neutral continent by 2050 (European Commission, 2019). Hydrogen is expected to play a crucial role in achieving this target as part of the future energy mix.

A key challenge in accelerating the decarbonization process lies in evaluating whether the existing natural gas infrastructure can be repurposed to transport hydrogen-natural gas blends or pure hydrogen. This topic has been addressed by various studies [1], [2], [3]. However, a significant gap in the literature remains: the lack of standardized laboratory testing methods to assess the compatibility of current pipelines with hydrogen service, especially concerning test on pipe sections at laboratory scale.

Despite these open issues, several studies and technical assessments suggest that a substantial portion of the existing infrastructure may already be suitable for hydrogen service, particularly in low- and medium-pressure networks. However, hydrogen introduces additional



challenges, especially with steel pipelines; to ensure the safe and effective use of blended or pure hydrogen, increased inspection frequencies may be necessary to prevent structural failures[4].

Another significant issue is the higher-pressure drop of hydrogen, and hydrogen blends, compared to natural gas when transported through the same infrastructure, which can reduce the energy delivered to end users [5]. Current literature indicates that hydrogen blending up to 5% by volume is generally considered safe and compatible with residential applications[2], [6]. However, the effects of higher hydrogen concentrations in existing pipelines remain poorly understood and require further investigation.

Although design standards such as ASME B31.12, which specifically address hydrogen pipelines, are already available, they primarily focus on pure hydrogen systems. Their applicability to hydrogen-natural gas blends is still unclear and requires further experimental validation and standardization. Recent demonstration projects such as Snam Contursi and H21 have also begun exploring the operational feasibility of hydrogen injection into natural gas networks, highlighting the need for consistent laboratory validation of pipeline materials.

Another standard used to assess sealing performance, although not specifically developed for hydrogen, is UNI 9165, which was taken as a reference for this study. This standard suggests a 24-hour monitoring period, during which temperature compensation is applied to isolate pressure variations from leaks. To complete the qualification, the test pressure depends on the operating range: for systems operating below 40 mbar, a fixed test pressure of 100 mbar is applied; for higher-pressure systems, the test pressure is set at 1.5 times the maximum operating pressure.

This paper aims to contribute to closing this gap by proposing an experimental setup designed to monitor hydrogen leaks under varying temperatures, simulating real-world service conditions. The study focuses on four pipes and their respective joint commonly used in national gas distribution networks and different in pipe material: a polyethylene (PE100) pipe, an API 5 LGR B steel pipe, and two galvanized steel pipes for low-pressures application were considered. The pipes and joints studied were sampled directly from operational pipelines to ensure realistic and representative results. The PE100 pipe and the API 5 LGR B steel pipe typically operate at 5 barg, while the galvanized steel pipes are used at low pressures around 40 mbarg.

This approach is intended to support efforts to improve system robustness and safety in a future hydrogen-based energy infrastructure.

1.1 Steel Pipelines

It is well known that many types of steel are susceptible to hydrogen embrittlement (HE). Upon contact with steel surfaces, molecular hydrogen dissociates into atomic hydrogen, which can then diffuse into the bulk of the material [7]. Higher concentrations, i.e. pressure, of hydrogen typically lead to more severe embrittlement. Interestingly, the presence of certain impurities, such as carbon monoxide and oxygen, has been reported to improve resistance to hydrogen embrittlement [8], [9].

Hydrogen embrittlement is primarily influenced by three categories of factors: environmental conditions, mechanical stress state, and the material microstructure. Its effects are typically observed in reduced tensile strength, fracture toughness, and fatigue resistance[10], [11], [12]

In this work the focus is limited to leak detection in commonly used joints for steel pipelines, without evaluating mechanical degradation or structural failure due to hydrogen exposure.

1.2 Polymeric Pipelines

In gas distribution networks, polymeric pipes are typically made from polyethylene (PE), used at higher pressures and with larger diameters, or polyvinyl chloride (PVC), for lower pressure applications and with smaller dimensions. Unlike metals, hydrogen diffuses through polymers in its molecular form. Hydrogen can get trapped inside a polymer if insufficient time is allowed for permeation, raising concerns such as blistering due to rapid gas decompression [13].

Current findings suggest that short-term hydrogen exposure at low pressures does not significantly affect PE mechanical performance, while high-pressure conditions may lead to reduced ultimate tensile strength and failure strain [14], [15], [16]. As stated before, a critical issue in polymeric systems is gas permeation. Defining a general permeability value for hydrogen is difficult due to large variability among material types and processing. For example, hydrogen permeability in PE can vary widely due to different crystallinity contents [17], that depend strongly on how the PE pipe is made by the manufacturer. Anyway, it is typically around four times that of methane [4], which raises additional concerns depending on the specific application and service environment.

Although gas losses from polymeric pipelines are often deemed economically negligible [2], [18], they may still pose safety risks, particularly in unventilated or underground environments.

2. Experimental section

2.1 Implemented system

Figure 1 illustrates the process flow diagram of the experimental setup developed to evaluate the sealing performance of different material pipe joints under hydrogen exposure. Hydrogen was supplied from a pressurized cylinder equipped with a pressure regulator to precisely control the internal pressure of the tested pipes during charging. An evacuation valve connected to a hydrogen dilution unit allowed for the safe venting of gas when necessary.

Each pipe was made independent from the others, allowing for individual or simultaneous pressurization at different pressure levels. This configuration enabled flexible testing, reduced gas consumption, and increased safety, which was particularly useful during leak detection procedures. All pipes were equipped with an analogical pressure gauge for manual control and a digital pressure transducer connected to a PC for real-time data acquisition.

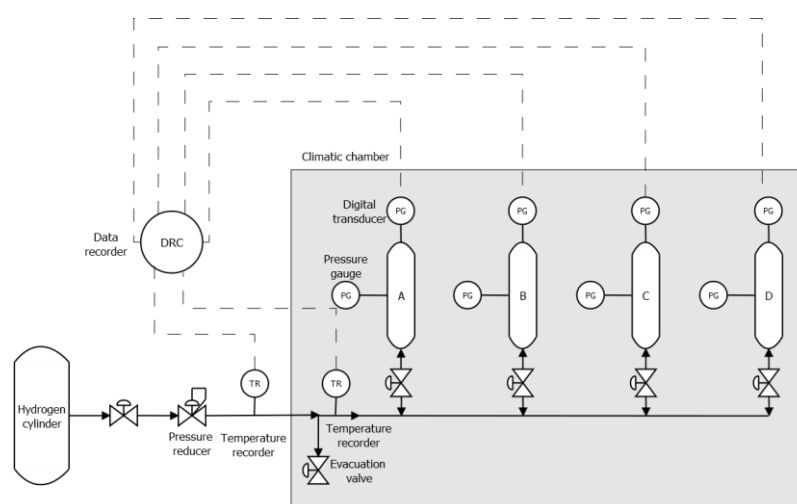






Figure 1. Process flow diagram of the implemented system to test pipelines.

To avoid temperature fluctuations that could interfere with pressure readings, especially relevant for low-pressure systems, the entire setup was placed inside an Angelantoni climatic chamber. Daily temperature variations were found to significantly affect pressure, even in medium pressure pipes. A hydrogen detector installed inside the chamber provided continuous monitoring of the atmosphere inside the chamber, enabling early detection of leaks that might develop over extended test durations

Table 1. Picture and relevant description (pipe material, joint type, and applied testing pressure) of each tested sample.

	
Galvanized stell 1" ¼	Galvanized stell ¾"
F-F coupling	Three-piece union
60 mbarg	60 mbarg
	
PE 100	API 5 LGR B steel
Electrowelded coupling closed with weldable caps	F-M Nipple NPT ¾, ISO 228, AISI 316L stainless steel
5.2 barg	6 barg

2.2 pipes and joints

As mentioned in the Introduction section, the pipes selected for testing were taken directly from the Italian natural gas distribution network, ensuring that the results are representative of real-world systems. As presented in Table 1, two galvanized steel pipe with mechanical joints, commonly used in low-pressure domestic installations, were included. For medium-pressure distribution systems, a PE100 pipe with an electrowelded joint and an API 5 LGR B steel pipe with a mechanical joint were tested.

2.3 Methods

Prior to hydrogen testing, the fittings of the system we made were verified to be leak-free. This validation step was critical to ensure that any subsequent pressure losses could be confidently attributed only to leaks in the joint or, for the PE pipe, leaks through the pipe itself.

The first phase involved leak testing using compressed air and a soap-based solution to identify and fix potential leaks in fittings and connections. After confirming airtightness, the system was tested again using a gas mixture containing 95% nitrogen and 5% hydrogen. Leaks were monitored using a Testo 316-1 handheld electronic hydrogen sniffer. Only after successful verification, the system was declared ready for pure hydrogen testing. The same procedure was used to monitor leaks during the first hydrogen pressurization.

For the main test, each pipe was pressurized with 100% hydrogen and monitored continuously for one week at a constant temperature of 20 °C. According to UNI 9165, the sealing efficiency is evaluated over 24-hour; however, a one week monitoring was chosen to understand if any long term effect would be present, especially concerning gas permeation through PE100 pipes, that for shorter times period could be negligible or hard to measure. The two galvanized steel pipes and joints were tested at 60 mbarg pressure. The API 5 LGR B steel pipe joint was tested at 6 barg, while the PE100 pipe joint was tested at 5.2 barg. These pressures were chosen because are slightly higher than their typical operating conditions, to assess sealing in conservative conditions. Usually, galvanized steel pipes operate at 40 mbarg, while the API 5 LGR B and PE100 pipes operate below 5 barg.

Temperature near the samples was carefully monitored. Two thermocouples were placed directly on the low-pressure galvanized steel pipes, and a thermoresistor was used to record the ambient temperature inside the chamber. This monitoring made it possible to distinguish between actual gas leaks and apparent pressure drops caused by temperature variations.

3. Results

3.1 Low pressure pipe joints

Figure 2 reports the pressure evolution of Pipe A and Pipe B initially pressurised at 60 mbarg over a 7-day period at a controlled temperature of 20 °C. Despite the temperature regulation, some fluctuations in pressure, of the order of 10 mbarg were observed, raising initial concerns about potential leaks or system instability. However, further analysis revealed that these variations were driven by minor fluctuations in the chamber temperature, of about 2°C, which significantly affect pressure in low-pressure systems. The small temperature fluctuations inside the chamber are caused by the outside temperature, meaning that the chamber is not perfectly insulated.

Using the ideal gas law ($PV = nRT$), it was estimated that a temperature variation of 1 °C at 60 mbarg would correspond to a pressure change of approximately 0.2 mbarg. However, this theoretical value did not match the magnitude of the pressure fluctuations observed during the experiment. This discrepancy suggests the presence of additional factors influencing the pressure,

such as thermal lag, localized heating, or measurement noise. Similar behaviour was also observed during tests conducted without active temperature control.

These findings highlight the importance of thermal stabilization when interpreting low-pressure hydrogen data, making difficult to assess if some leaks are present outdoor or in non-insulated installations.

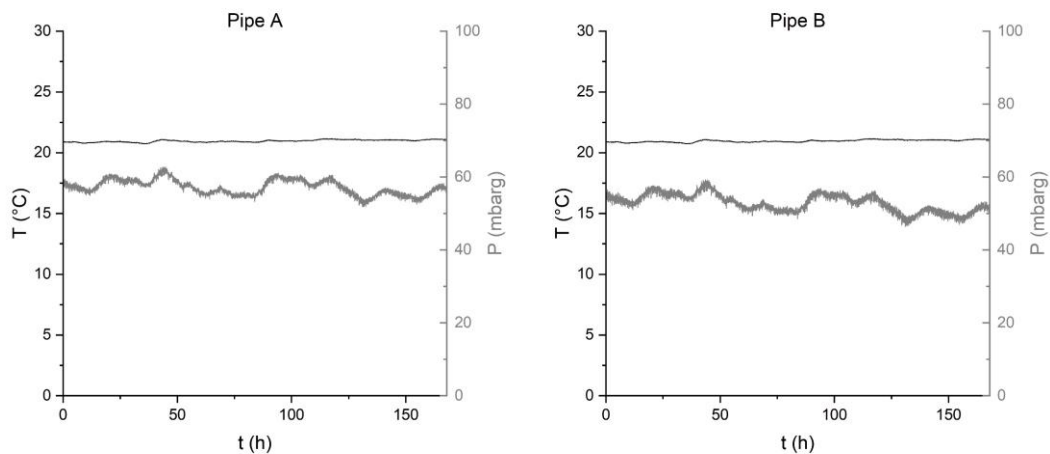


Figure 2. Temperature (T) and pressure (P) values plotted versus time for pipe A (on the left) and pipe B (on the right).

3.2 Medium-pressure pipe joints

PE100 Pipe (Pipe C)

Figure 3 shows the pressure decay for Pipe C (PE100) initially pressurised at 5,2 barg over the 7-day test at 20 °C. Like the low-pressure cases, some temperature-related pressure fluctuations were detected, but the fluctuations were not significant. At this pressure range, the system response to temperature variation is smaller, and pressure readings are less susceptible to minor thermal drift.

Table 2. Values used to define the mole loss

quantity	value	units
Permeability (Φ)	$8.5 \cdot 10^{-16}$ [19]	$\text{mol} \cdot \text{m} / (\text{m}^2 \cdot \text{s} \cdot \text{Pa})$
Initial pressure P_0	$5.2 \cdot 10^5$	Pa
Pipe length (L)	0,8	m
Inner radius (a)	0,01475	m
Outer radius (b)	0,01625	m
Temperature (T)	293	K

A linear pressure drop was observed, attributed to hydrogen permeation through the pipe wall. To validate this hypothesis, the experimental pressure loss was compared with the theoretical loss calculated under the assumption of transient permeation. In Table 2 the data used for the theoretical calculation of the pressure are reported.

Using the cylindrical geometry for radial permeation, the number of moles permeated over time was estimated solving the following equation [19]:

$$n(t) = \frac{2\pi L\Phi t}{\ln\left(\frac{b}{a}\right)} P_0 e^{-\frac{t}{\tau}} \text{ mol} \quad (3.1)$$

where τ is

$$\tau = \frac{a^2 \ln\frac{b}{a}}{2RT\Phi} \quad (3.2)$$

The initial number of moles in the pipe was estimated using the ideal gas law:

$$n_i = \frac{(520000 \text{ Pa}) * (5.46 * 10^{-4})}{R * 293 \text{ K}} = 0,116 \text{ mol} \quad (3.3)$$

After 7 days, the estimated number of moles lost by permeation is:

$$n(168 \text{ h}) = 1.31 * 10^{-2} \text{ mol} \quad (3.4)$$

$$n_f = n_i - n_p = 0.103 \text{ mol} \quad (3.5)$$

From this, the theoretical pressure is calculated as:

$$P = \frac{n_f RT}{V} = 4.62 \text{ bar} \quad (3.6)$$

The measured pressure at the end of the test, which was 4.68 barg, is very close to the predicted one. The slightly higher value suggests that the actual permeability of the tested PE100 pipe is lower than the average literature value used in the theoretical calculation. This discrepancy, as explained in the introduction, can be explained by the fact that permeability in PE100 is highly dependent on the material producer and pipe manufacturing process, both affecting its crystallinity degree, and thus its gas permeability [13], [20]. Even within the same PE100 classification, significant differences exist between suppliers.

In practical applications, the steady-state regime is more representative than the transient case, due to the presence of a constant pressure in the pipe. In that case, the governing equation becomes simpler, and the permeation rate stabilizes over time. For comparison the steady state gives the following theoretical pressure drop[19]:

$$n(t) = \frac{2\pi L\Phi t}{\ln\left(\frac{b}{a}\right)} P_0 \text{ mol} \quad (3.7)$$

The quantity used are the same indicated in Table 2 and the result is

$$n(168 h) = 1.39 * 10^{-2} mol \quad (3.8)$$

$$n_f = n_i - n_p = 0.102 mol \quad (3.9)$$

$$P = \frac{n_f RT}{V} = 4.58 bar \quad (3.10)$$

Moreover, several studies [16], [21] have shown that long time exposure of polyethylene to hydrogen increases its crystallinity, which in turn reduces its permeability to hydrogen because gases don't diffuse in the crystalline phase of PE. This means that hydrogen losses due to permeation may decrease over time, rather than increase, a reassuring insight for long-term pipeline applications.

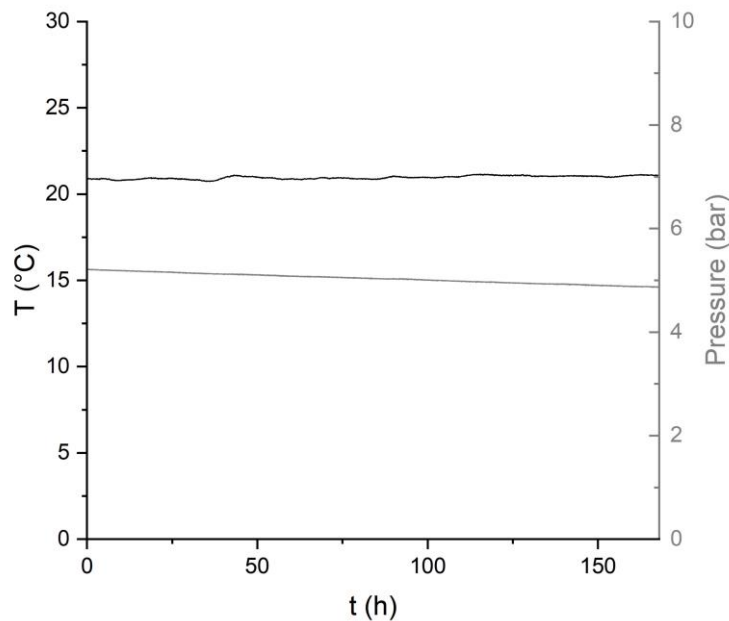


Figure 3. Temperature and pressure plot of H₂ in pipe C (PE100)

Steel Pipe (Pipe D) joint

Figure 4 reports the pressure evolution for Pipe D (API 5 LGR B steel) initially pressurised at 6 bars, over 7 days at 20°C. No pressure drop was detected, and the influence of temperature was negligible, according to the evidence that temperature sensitivity influences more the low-pressure recording.

This indicates that, under the specific pressure and environmental conditions studied, the steel pipe joint can be safely used for hydrogen service without the need for immediate adaptation or modification.

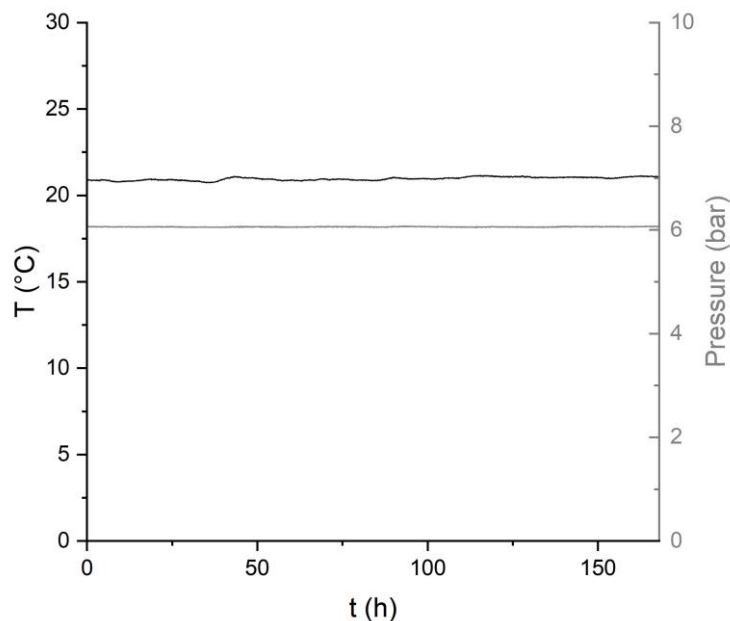


Figure 4. Temperature and pressure plot of H₂ in pipe D (API 5 LGR B)

4. Conclusions

The findings of this study provide encouraging evidence that the existing natural gas infrastructure turns out to be more suitable for hydrogen transport than previously assumed, particularly in the case of steel pipelines. Over the period of one week, the welded joint of API 5 LGR B steel pipe showed no measurable hydrogen leakage or pressure drop when loaded with pure hydrogen under pressure at 6 barg, even under thermal fluctuations. This result confirms that, at least in terms of sealing performance and leak tightness, steel pipes joints and fittings commonly used in the Italian distribution network are ready for partial or full hydrogen integration, without requiring modifications. As for the PE100 pipe joint it did show a measurable hydrogen losses which resulted to be almost consistent with gas permeation through the pipe wall. The observed differences between the predicted and the measured pressure loss can be ascribed to polymer permeability dependence on the polymer grade, pipe manufacturing quality, and potential aging of the polymer. However, it is important to emphasize that in realistic applications, where hydrogen is blended with natural gas, permeation losses are expected to be proportionally lower, reducing both economic and safety concerns. To further develop this work, two main follow-up steps are planned. First, long-time exposure will be carried out to assess how sealing performance and gas permeation evolves in time, especially concerning polymeric pipes.

Second, the effect of temperature will be explored by carrying out tests in the range of -10°C and 40°C , to assess how the materials performance will be influenced.

Overall, this study highlights the importance of case-specific analysis and supports the notion that much of the current infrastructure, especially metallic, is closer to being hydrogen-compatible than commonly perceived. While polymeric materials require more attention regarding permeation, particularly at medium pressures and in closed environments, these challenges are manageable and can be further mitigated by thoughtful system design and continuous monitoring.

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