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Assessment of Natural Gas–Hydrogen Fuel Blends for Industrial Melting Furnaces in Secondary Aluminium Production

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Abstract. The decarbonization of the aluminium industry requires a transition from fossil fuels to sustainable energy carriers. This study investigates the substitution of natural gas (NG) with hydrogen (H_2) in reverberatory furnaces, analyzing the impact on melt quality, furnace integrity and exhaust emissions. Experimental investigations were conducted in a specifically designed furnace setup combining electrical heating with a burner system capable of operating with variable fuel blends ranging from pure natural gas to 100 vol.-% hydrogen. The results demonstrate that the hydrogen content in the aluminium melt depends on the atmospheric conditions — water vapour content in the atmosphere — during the melting and heating phases. In contrast, the holding phase exhibited a quasi-static behavior with negligible further hydrogen uptake, due to the isothermal process control. Numerical simulations (CFD) revealed that admixture rate exceeding 80 vol.-% H_2 leads to significantly higher adiabatic flame temperatures. This results in the formation of local hotspots on the furnace walls and requiring the use of high-performance refractory linings. Furthermore, these thermal conditions correlated with a major increase in NO_x emissions, despite a successful reduction in CO_2 output. Considering the material quality, X-ray computed tomography (XCT) analysis indicated a marginal increase in volume porosity with higher hydrogen fractions. However, tensile testing confirmed that this porosity did not compromise the mechanical performance, as yield strength and ultimate tensile strength remained unaffected across all fuel mixtures. The study concludes that standard degassing procedures are sufficient to reduce the increased initial hydrogen load, showing that hydrogen combustion for secondary aluminium production is feasible.

Introduction

The global demand for aluminum is experiencing a major change, with a growing emphasis on recycling and circular economy principles. Secondary aluminium production is continuously increasing because it offers different economic and environmental advantages compared to primary extraction methods [1]. However, although recycling needs less energy than primary electrolysis, the melting process in secondary production is still energy-intensive and relies heavily on fossil fuels, mainly natural gas. To reach international climate targets, the decarbonization of these thermal processes is necessary. Therefore, green hydrogen (GH_2) is a key solution. The integration of GH_2 into aluminium production not only links the mining and metals sector with the renewable energy sector but also contributes significantly to a more sustainable energy system. While in primary production GH_2 can function as a reducing agent for alumina [2], its role in secondary aluminium facilities lies in the substitution of fossil fuels for thermal energy. Recent assessments have highlighted the economic and environmental feasibility of integrating green hydrogen into aluminium

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recycling facilities, especially evaluating its potential as a replacement for natural gas in smelting, melting and refining furnaces [3].

The transition from natural gas to hydrogen is not only a binary choice but often involves a gradual blending process. The impact of this fuel switching on carbon footprint is significant. As shown in Fig. 1, there is a direct correlation between the hydrogen fraction in the fuel blend and the resulting environmental benefit. The graph shows that while initial blends provide small benefits, a complete transition to a 100 vol.-% equivalent hydrogen content is required to eliminate direct combustion emissions of CO_2 entirely [4].

This study focuses on the correlation between the hydrogen content in the fuel blend and the hydrogen uptake in the aluminium melt (solubility), assessing whether high-percentage hydrogen blends can be used without compromising the quality of the melt and the secondary aluminium produced.

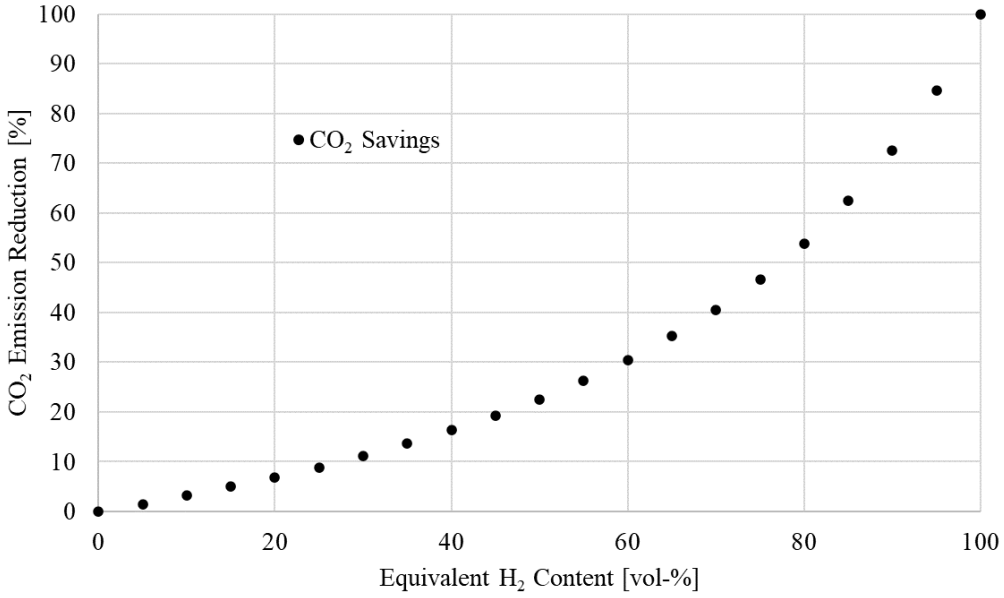


Fig. 1. CO_2 emission reduction with equivalent H_2 admixture (constant thermal output)

However, the implementation of hydrogen fuel blends introduces various challenges such as plant engineering, safety management, and metallurgical integrity. From an operational perspective, the significantly higher adiabatic flame temperature of hydrogen leads to increased thermal stress on the refractory lining, especially within unmodified furnace geometries. Nevertheless, this thermal load can be effectively mitigated through appropriate design adaptations. As the hydrogen fraction increases, the furnace atmosphere undergoes a substantial shift. Crucially, the substitution of natural gas with hydrogen implies a water vapor increase of approximately 84 % under air-fired conditions and 50 % under oxy-fuel conditions, which raises concerns about enhanced attack mechanisms on refractory materials [5]. While partial additions up to 20 % may not drastically compromise kiln lifespan, the strong increase in emitted water vapor at higher blends requires close monitoring [5].

Furthermore, the clear combustion characteristics require major modifications to safety protocols and maintenance plans. Conventional maintenance strategies show limitations here. Furthermore, time-based or condition-based approaches are difficult because continuously monitoring material changes (e.g., hydrogen embrittlement) is challenging [4].

Hydrogen Absorption. The interaction between the furnace atmosphere and the molten metal depends on the presence of hydrogen sources and the thermodynamic laws of solubility. In gas-fired furnaces, the primary source of hydrogen is the decomposition of moisture and hydrocarbons derived from the fuel combustion process. The transition from natural gas (CH_4) to hydrogen (H_2) significantly alters the chemical composition of the combustion gases. While the combustion of

natural gas produces both carbon dioxide (CO_2) and water vapor (H_2O), the combustion of pure hydrogen results exclusively in the formation of water vapor, as described by Eq. 1 [6,7]:

$$2H_2 + O_2 \rightarrow 2H_2O. \quad (1)$$

Therefore, replacing natural gas with hydrogen significantly increases the partial pressure of water vapor (H_2O) in the furnace atmosphere. This leads to a wetter environment above the melt. The water vapor does not dissolve directly. Instead, it reacts at the liquid aluminium interface, reducing the vapor to atomic hydrogen and forming aluminium oxide, see Eq. 2 [6-8]:

$$3H_2O + 2Al \leftrightarrow 2Al_2O_3 + 6\bar{H}. \quad (2)$$

This reaction drives atomic hydrogen ($\bar{H}$) into the melt, where it diffuses rapidly. The solubility of this atomic hydrogen in the liquid phase follows Sievert's Law. This law states that the equilibrium concentration of a diatomic gas dissolved in a metal is proportional to the square root of the partial pressure of the gas in equilibrium with the melt. The relationship is expressed as Eq. 3 [6-8]:

$$S = K(T) \cdot \sqrt{p_{H2}}\,. \quad (3)$$

Where:

- S is the solubility of hydrogen (typically in $cm^3/100$ g).
- p_{H2} is the partial pressure of hydrogen gas.
- K(T) is the temperature-dependent equilibrium constant.

Since *K(T)* follows an Arrhenius-type relationship, hydrogen solubility increases exponentially with molten metal temperature. Therefore, the combination of a high-temperature flame (characteristic of hydrogen combustion) and a high partial pressure of water vapor creates the worst-case scenario for hydrogen uptake, significantly increasing the risk of porosity in the casting process. The increase in water vapor content directly drives hydrogen solubility in the molten aluminium. Since the solubility drops so sharply, this excess hydrogen becomes supersaturated and precipitates as molecular gas (H_2), forming interdendritic porosity in the casting structure. Therefore, precise temperature control is important; higher melt temperatures not only accelerate oxidation but also exponentially raise the saturation limit, compare Fig. 2 [6].

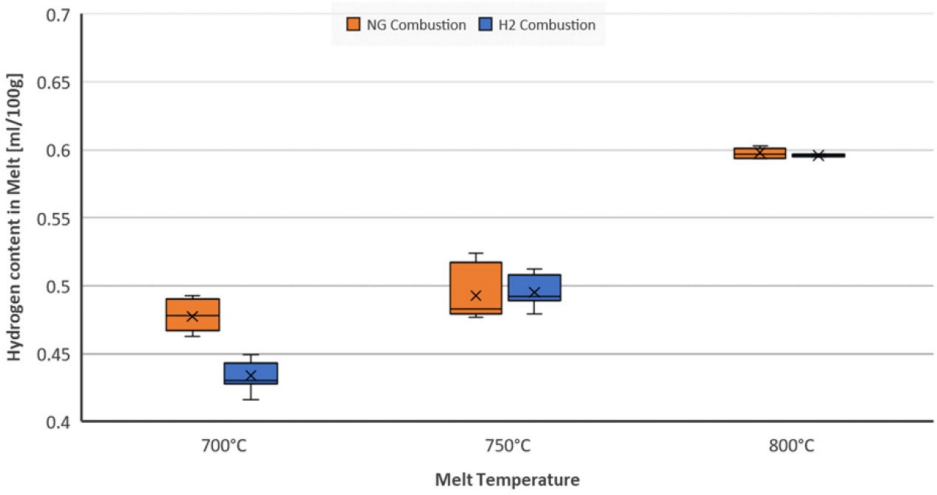


Fig. 2. Temperature dependence of hydrogen absorption in Al99.8 exposed to natural gas and hydrogen combustion atmospheres. Experiments were conducted in a 3-chamber furnace with closed-loop melt circulation, using an AlSCAN probe for continuous hydrogen measurement in the melt. [9]

Syvertsen et al. [8] demonstrated a correlation between the water vapor fraction in the combustion gas and hydrogen uptake in the melt. Data derived from Fig. 3 indicates that doubling the H_2O content in the exhaust gas results in an approximate 33 % increase in dissolved hydrogen concentration.

While the general trend of increased hydrogen absorption is valid, the quantitative results require critical review. Given that the measurement methodology relies on Sievert's Law and is therefore highly sensitive to temperature, the reported values may overpredict the actual amount of dissolved hydrogen in the aluminium melt due to thermal variations.

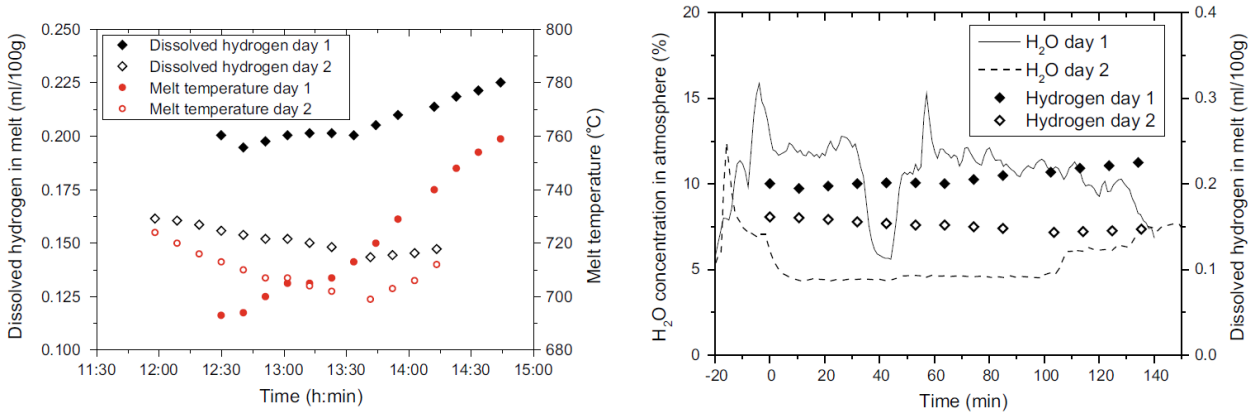


Fig. 3. Temporal evolution of furnace atmosphere and melt parameters during natural gas combustion over two experimental days. Experiments were conducted in a 20-ton furnace equipped with a launder loop and metal pump. [8]

Tichy et al. [7] investigated the progression of hydrogen uptake across specific process stages. A critical observation seen in Fig. 4 is the significant rise in dissolved hydrogen during the transition from melting to heating. While the initial melting phase shows comparable low levels for both fuels, the heating phase drives a clear increase in hydrogen absorption. During the subsequent holding phase, this trend stabilizes; the hydrogen content remains elevated with no significant further uptake or natural degassing observed. However, the final process step provides the most vital conclusion for process safety: regardless of the higher initial gas load induced by H_2 combustion, degassing treatment proves highly effective. As shown in the *after degassing* data, the hydrogen content for both Natural Gas (NG) and H_2 is successfully reduced to nearly identical, low levels, demonstrating that standard refining procedures can fully compensate for the increased uptake.

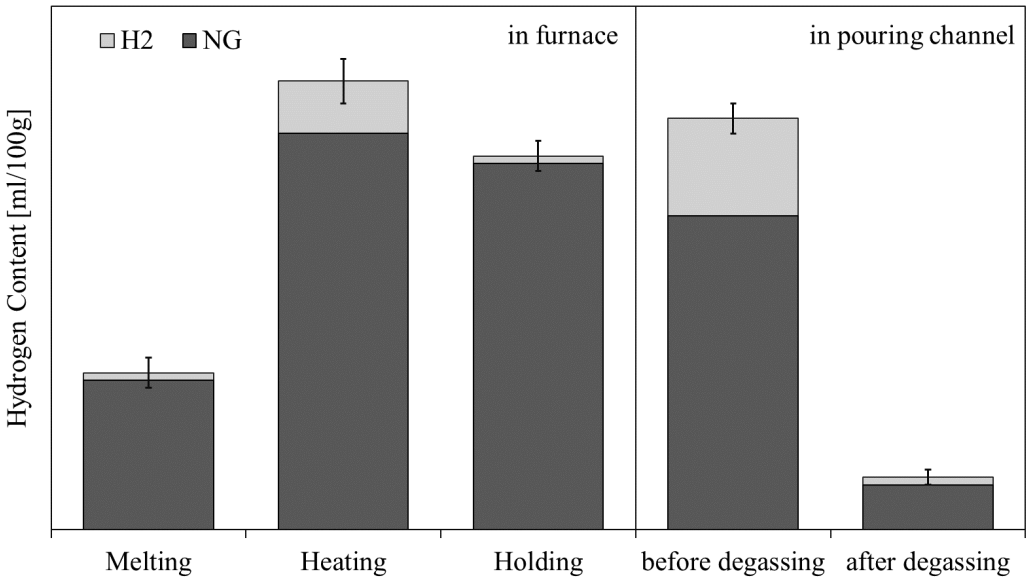


Fig. 4. Hydrogen levels at different process steps under NG and H2 combustion atmospheres. Direct melt measurements were performed in a rotary tilting furnace (melting) and a single-chamber furnace (holding). [7]

Experimental Methodology

Material. A remelted secondary alloy with 0.40 – 0.45 wt. % of Si and a Mg content of 0.45 – 0.5 wt. % was used in this work. The typical chemical composition of the base alloy is presented in Table 1.

Table 1. Chemical composition of the aluminium alloy

Alloy	Si	Mg	Fe	Cu	Mn	Cr	Zn	Ti	Al
AA6060	0.3 – 0.60	0.35 – 0.6	0.10 – 0.3	0.10	0.1	0.05	0.15	0.10	Rem.

Experimental Setup. The main part of the investigation is the experimental furnace shown in Fig. 5. It is equipped with extensive instrumentation for temperature monitoring, exhaust gas analysis and in-situ hydrogen measurement equipment. In this setup, the aluminium melt is maintained electrically at a constant target temperature of 720°C, while the headspace above the melt is exposed to a defined combustion atmosphere. These atmospheres are generated using a self-made and modified small-scale burner. A gas mixing system utilizing mass flow controllers (MFCs) allows for the precise variation of the fuel gas composition, ranging from 100 vol.-% natural gas (NG) to 100 vol.-% hydrogen (H_2). To prevent the ingress of ambient air (false air), the furnace chamber is maintained under constant positive pressure. This configuration allows long-term experiments under strictly controlled boundary conditions. Consequently, changes in melt quality — specifically the hydrogen content — can be detected via continuous direct measurement (in-situ) to characterize the absorption behavior as a function of the prevailing atmosphere.

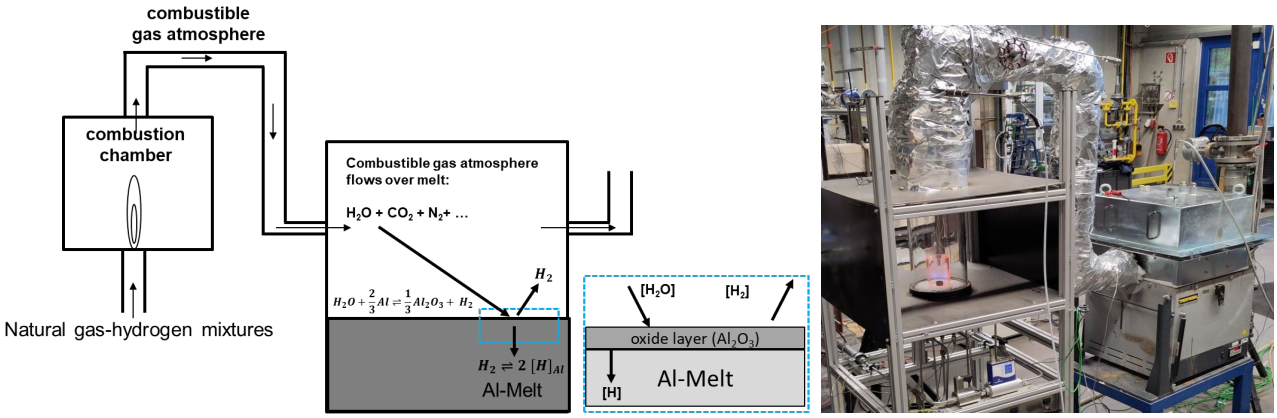


Fig. 5. Experimental setup long-term test, based on [6].

In-Situ Hydrogen Measurement. For the quantitative determination of the dissolved hydrogen content in the liquid aluminium melt, the portable analysis system Hycal (IDECO GmbH / EMC) was applied. In contrast to the Density Index Method (Reduced Pressure Test), this system enables a direct, real-time measurement of the hydrogen concentration within the melt [10].

The sensor employed is based on the principle of an electrochemical hydrogen concentration cell. The core element of the sensor consists of a proton-conducting ceramic $CaZrO_3$-In acting as a solid-state electrolyte. A solid-state reference material is enclosed within the sensor, providing a constant and known hydrogen concentration (reference electrode). The final value in *ml/100g* is calculated taking into account Eq. 3 Sievert's Law as well as alloy-specific correction factors stored within the device [10].

Numerical Setup and Boundary Conditions. The numerical investigation of the reverberatory furnace burner was performed using the commercial CFD code ANSYS Fluent 2023 R2. The simulations were conducted under steady-state conditions by solving the Reynolds-Averaged Navier-Stokes (RANS) equations. To ensure geometric fidelity and solution accuracy, the computational domain was discretized using a polyhedral mesh consisting of approximately 3.1 million cells.

For the physical modeling of the flow field, the Realizable k-epsilon turbulence model was selected because its improved performance in flows involving rotation and strong pressure gradients. The combustion process was simulated using the Probability Density Function (PDF) equilibrium model, assuming fast chemistry. Radiative heat transfer, which is dominant in this high-temperature environment, was calculated using the Discrete Ordinates (DO) radiation model. Furthermore, the simulation fully accounted for the heat transfer to the furnace walls to accurately predict the thermal boundary conditions and wall loads.

Porosity Analysis. Additionally, the specimens underwent tomographic inspection (GE Nanotom) with source settings of 80 kV and 160 µA. Post-reconstruction analysis of the volume data (voxel size: 20 µm) was performed using Volume Graphics Studio MAX to determine the volume porosity.

Tensile Test. Specimens were taken from casted round bars for tensile tests, which were performed in a Hegewald and Peschke model inspect 250 with 250.000 kg maximum load and a head displacement speed of 1 mm/min. The elongation was measured with an extensometer type MFN-A. The size of the test specimens corresponded to the DIN 50125 - B 6 × 30 standard with a diameter of 6 mm.

Results

Dissolved Hydrogen. In Fig. 6, the dissolved hydrogen levels in the melt rise significantly with increasing water vapor content in the fuel gas. Corresponding to [7], these results show that the atmospheric conditions during the melting and heating phases determine the final hydrogen concentration. Specifically, the water vapor content is the main factor. The in-situ measurement results from the reference natural gas process and the stepwise hydrogen admixture up to 100 vol.-% demonstrate a quasi-static behavior of the hydrogen content (see Fig. 7), effectively ruling out significant hydrogen uptake during the holding periods after melting.

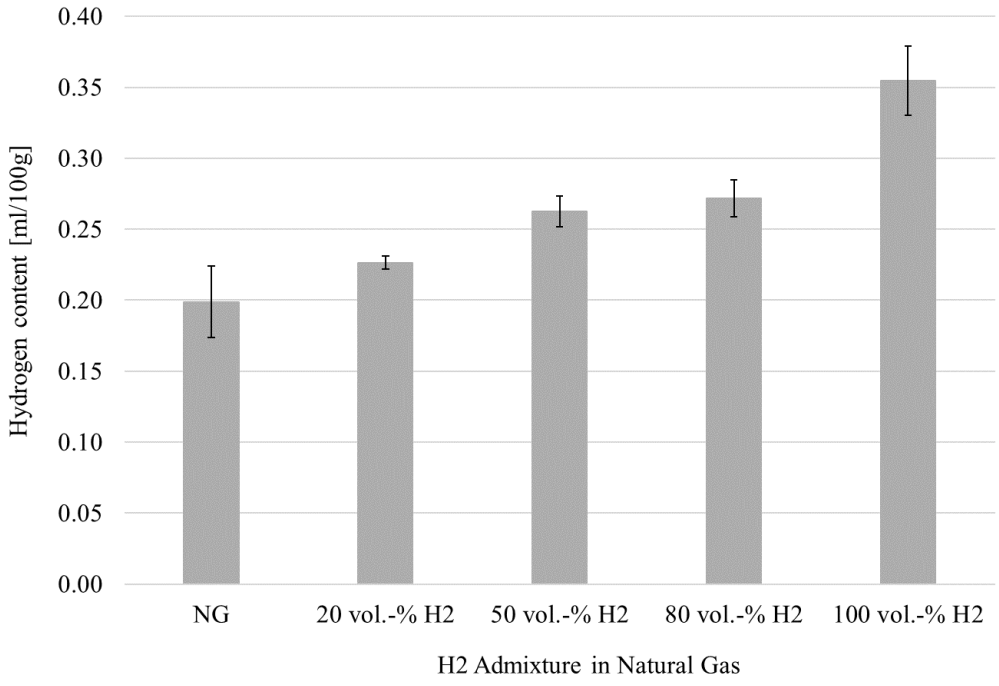


Fig. 6. Impact of fuel gas composition on melt quality (regarding dissolved hydrogen content). Experiments were conducted on an electrically maintained melt (720°C) under positive pressure, exposed to variable burner atmospheres (NG to 100 vol.-% H_2) with continuous in-situ hydrogen monitoring.

Furthermore, the critical hydrogen uptake occurs mainly during the melting and heating phases as the aluminium scrap transitions from the solid phase through the semi-solid state to the fully liquid phase. In contrast, the subsequent holding period shows a quasi-static behavior with no significant change

in hydrogen content, compare Fig. 7. This observation differs from the findings of [8], a discrepancy likely due to the strict isothermal conditions maintained in this study (constant Temperature), whereas [8] may have operated under fluctuating temperatures. However, these results confirm the data reported by [7, 11].

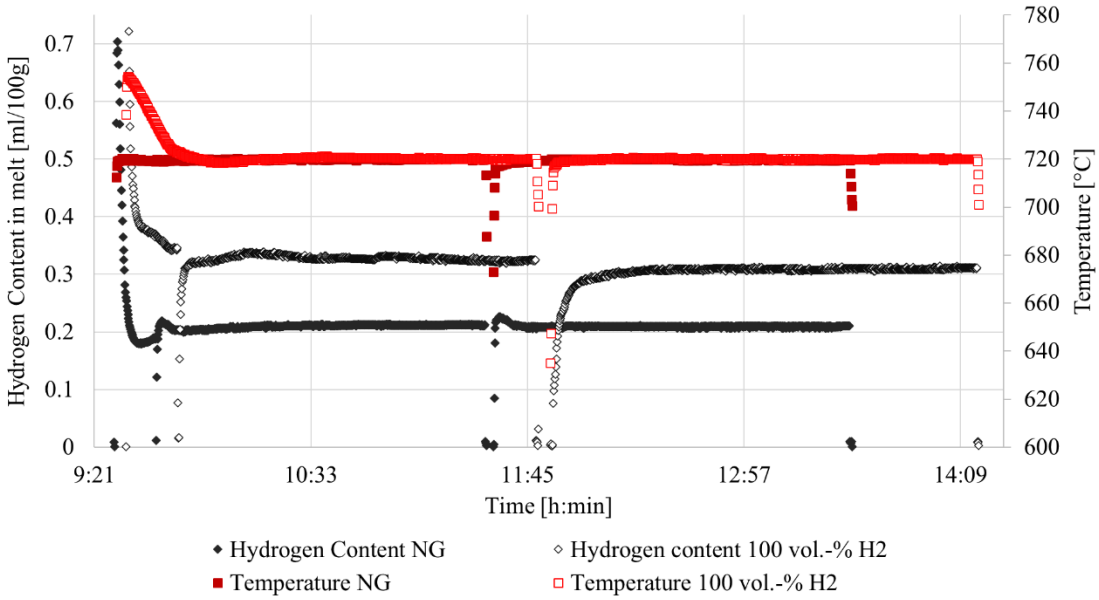


Fig.7. Temporal evolution of dissolved hydrogen content and melt temperature during long-term holding experiments.

Simulation. The combustion of 100 vol.-% hydrogen leads to a significantly higher adiabatic flame temperature. This increases the thermal load on the furnace walls and creates a risk of localized overheating (hotspots). These hotspots can cause reduction of strength or structural damage, see Fig. 8. Consequently, a modification of the furnace lining is necessary for hydrogen application. This requires a specific selection of refractory materials specifically engineered to withstand the elevated thermal stresses caused by hydrogen firing.

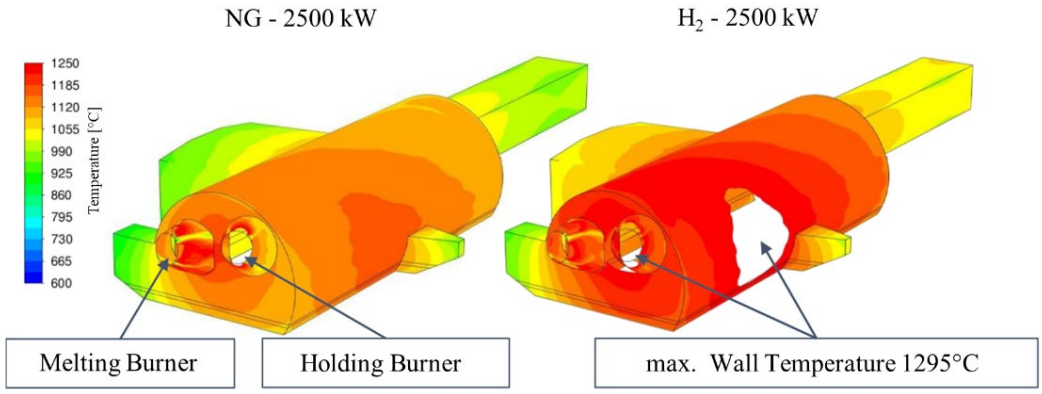


Fig. 8. Comparison of simulated wall temperatures for Natural Gas (NG) and Hydrogen (H_2) combustion at a constant thermal power of 2500 kW.

Exhaust Emissions. An 80 vol.-% hydrogen blend achieved a CO_2 reduction of up to 50 %. However, a disadvantage was observed due to nitrogen oxides. The NO_x levels increased noticeably at admixture rates higher than 70-80 vol.-% H_2 (see Fig. 9). These results match the findings of Tichy et al. [7], identifying the increased flame temperatures as the primary driver for thermal NO_x formation - an effect that can be suppressed through appropriate burner adjustments and process optimization.

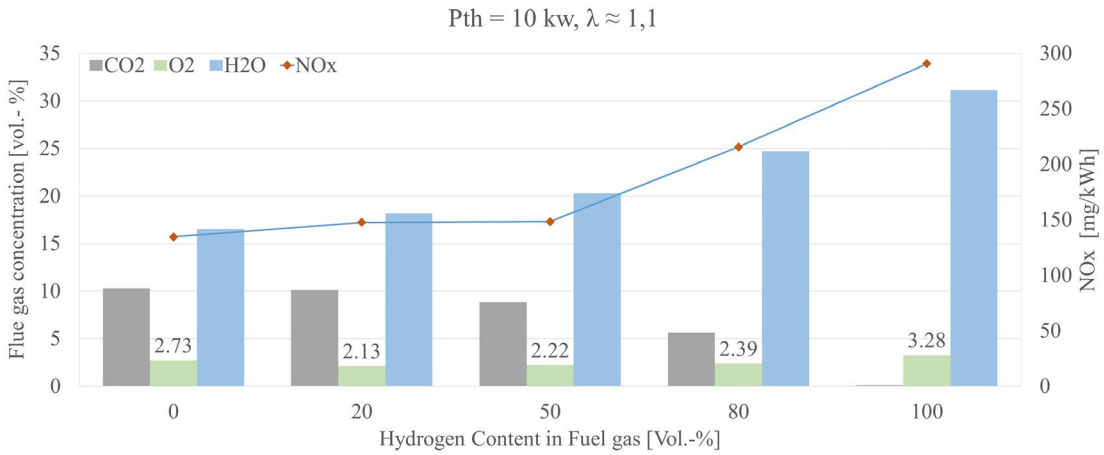


Fig. 9. Flue gas composition and NO_x emissions as a function of hydrogen content in the fuel gas.

Volume Porosity. The X-ray computed tomography (XCT) analysis reveals a clear correlation between the hydrogen fraction in the combustion gas and the resulting volume porosity in the cast specimens, see Fig. 10. While the reference natural gas process produced the lowest porosity of approximately 0.25 %, the porosity increased with rising hydrogen admixture, reaching a peak of roughly 0.38 % at the 80 vol.-% blend. This graph confirms that the elevated water vapor concentration in the furnace atmosphere leads to increased hydrogen uptake and subsequent pore formation during solidification. However, the mechanical testing data (Fig. 11) shows that this slight increase in porosity did not result in significant loss of the static mechanical properties, as yield strength and tensile strength remained largely consistent across all fuel mixtures. This indicates that the porosity induced by hydrogen combustion remains within a critical tolerance range, preserving the macroscopic structural integrity of the components.

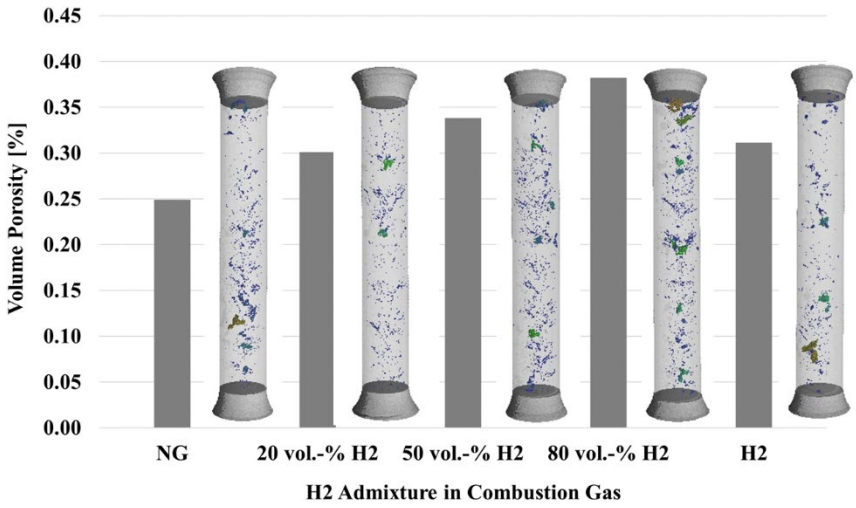
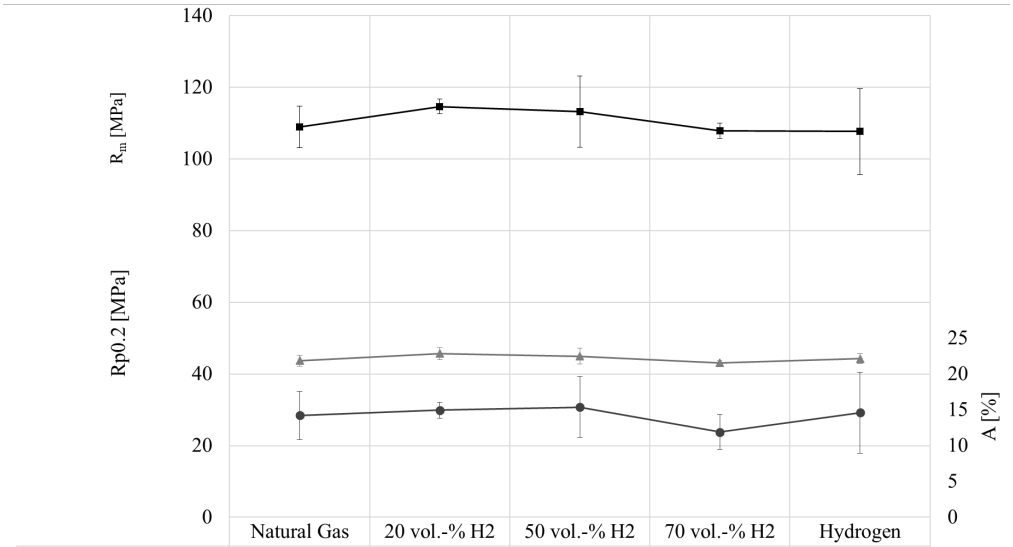


Fig. 10. Volume porosity of cast specimens determined via X-ray computed tomography (XCT).

Mechanical Strength. The yield strength ($R_{p0.2}$) remained largely unaffected by the variation in fuel gas mixtures, as shown in Fig. 11. There was no significant difference between natural gas, hydrogen blends, and pure hydrogen, with an average value of approximately 44 MPa observed across all casts. Similarly, the ultimate tensile strength (R_m) and elongation at fracture (A) appeared to show no major dependence on the fuel mixture. The highest tensile strength was recorded for the 20 vol.-% hydrogen blend (115 MPa), while the lowest value of 108 MPa was observed for both the 70 vol.-% mixture and pure hydrogen, resulting in a maximum difference of only 7 MPa. Taking into account the ductility, 50 vol.-% hydrogen blend provided the highest elongation at fracture (15 %), whereas the 70 vol.-% mixture resulted in the lowest value of 12 %. Despite prolonged holding

periods under a combustion atmosphere, the mechanical properties remained consistent with the results from melting trials with direct flame contact and no holding time reported in [11]. This is notable even though the hydrogen content in the melt increased, as shown in Fig. 6.



	Natural Gas	20 vol.-% H2	50 vol.-% H2	70 vol.-% H2	Hydrogen
tensile strength [MPa]	109	115	113	108	108
yield strength [MPa]	44	46	45	43	44
elongation [%]	14.21	14.95	15.38	11.90	14.61

Fig. 11. Impact of fuel gas composition on aluminium quality (regarding tensile strength).

Conclusion

This present study examines hydrogen uptake throughout the melting and holding stages and assesses the effects of H2 and NG/H2 combustion on casting properties. The results demonstrate that the hydrogen content in the melt depends on the atmospheric conditions — specifically the water vapor concentration — during the melting and heating phases. In contrast, the subsequent holding phase showed no significant increase in dissolved hydrogen, indicating a quasi-static behavior once the target temperature is reached. Due to the process boundary conditions, numerical simulations identified a critical challenge for furnace integrity: Admixture rates over 80 vol.-% H_2 lead to significantly higher flame temperatures. This causes local hotspots on the furnace walls, which require high-performance refractory linings. Furthermore, these elevated adiabatic flame temperatures correlated with a measurable increase in NO_x emissions. In terms of material quality, a slight increase in volume porosity was observed with higher hydrogen admixtures. However, this effect can be effectively reduced through standard degassing procedures. In conclusion, the study confirms that despite the changed combustion atmosphere, there is no negative influence on the tensile properties of the cast components. This validates that hydrogen firing is feasible in secondary aluminium furnaces.

Acknowledgments

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