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Hydrogen Combustion in Conventional Industrial Furnaces

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Abstract **-** Using fossil fuels in industrial processes contributes significantly to greenhouse gas (GHG) emissions, but governments are advancing efforts to support decarbonization. This research explores the potential of hydrogen as a substitute for natural gas in industrial furnaces. The main objective of this research is to assess the effects of fuel change on heat-transfer efficiency and GHG emissions, focusing on nitrogen oxides (NO_x) and carbon dioxide (CO_2). Through this analysis, the study aims to demonstrate the feasibility of hydrogen as a viable alternative to using natural gas in industrial furnaces. Experiments are conducted in an industrial furnace with a 60 kW_t medium/high-speed burner that can run on traditional carbon-based fuels, such as natural gas or propane. The experimental set-up includes an air exchanger to simulate the typical process load of this scale and multiple measurement tools, including thermocouples, pressure gauges, air and fuel flowmeters, a spectrometer, and cameras RGB and Ultraviolet-Visible (UV-VIS) for combustion characterisation using computer vision techniques. The results show that, for a natural gas installation, it is possible to use hydrogen as fuel, obtaining similar heat transfer values. However, in terms of emissions, when hydrogen is used as fuel, a reduction of CO_2 in the exhaust gases is observed but an increase of NO_x, mainly due to the high flame temperatures.

Keywords**:** Hydrogen, Fossil fuels, Industrial furnaces, Combustion, Computer vision, Emissions.

1. Introduction

The combustion of fossil fuels, particularly natural gas in industrial processes, is a significant source of GHG emissions [1], contributing to climate change and air pollution. Natural gas, composed mainly of methane, has been widely used due to its availability, cost-effectiveness, and relatively lower CO_2 emissions than other fossil fuels [2].

The need to reduce atmospheric emissions leads to a growing interest in alternative fuels, including hydrogen [3]. When hydrogen is combusted, the primary by-product is water, making it a promising option for lowering CO_2 emissions [4]. Additionally, hydrogen can be produced by electrolysis of water, which can be powered by renewable energy sources [5] such as wind or solar, making it an even more interesting option as a sustainable alternative fuel.

However, despite these potential advantages, numerous technical challenges are associated with hydrogen combustion [6], especially in industrial-scale applications where natural gas has traditionally been used. One of these challenges is the increase in NO_x emissions. In addition, the different combustion properties of hydrogen, such as flame speed and calorific value, can influence the heat transfer characteristics and overall process performance.

This study investigates the feasibility of replacing natural gas with hydrogen in industrial-scale furnaces, including several technical challenges, such as its effects on combustion efficiency, heat transfer, and pollutant emissions. Experimental tests were conducted with 100% natural gas and 100% hydrogen to assess their impact on emissions and heat transfer. By analysing combustion behaviour and emissions data, this work aims to provide insights into the feasibility of hydrogen as a cleaner alternative for industrial combustion processes, focusing on environmental and operational factors.

2. Experimental setup and methodology

Experimental tests were conducted in an industrial-scale furnace with a commercial medium/high-speed burner of 60 kW nominal thermal power, prepared to operate with different fuels.

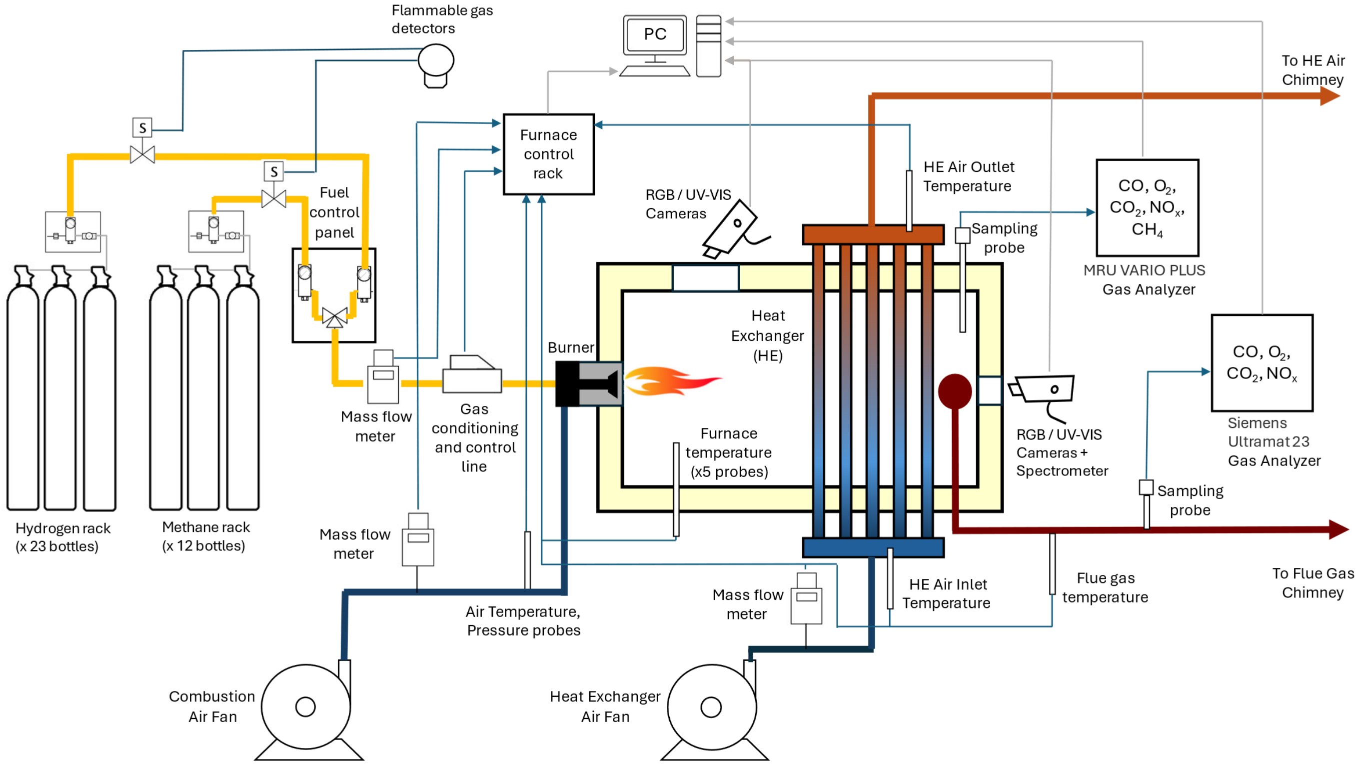

Figure 1 Diagram of the installation

Figure 1 illustrates the main elements of the test rig. On the one hand, the gaseous fuel is supplied by two racks of methane and hydrogen gas cylinders equipped with a valve to activate the corresponding line and a gas detector as a safety element to detect leaks. Forced ambient-temperature air is supplied to the burner through another line. Before entering the burner, both lines are monitored by mass-flow meters. The burner is a NBP BP M 5 GV S/70 medium/high speed flexible diffusion burner, with separate air and gas streams entering the burner, with a nominal power of 60 kW_t.

The furnace is equipped with an air-cooled heat exchanger designed to simulate the typical process load at this scale, enabling precise evaluation of the heat transfer during each test. A forced draft fan drives the cooling air, previously measured by a mass flow meter, through the tube bank. Inlet and outlet cooling-air temperatures are registered with type K thermocouples.

In addition, five type S thermocouples on the gas side measure the flame temperature at different points inside the combustion chamber. The system has two gas analysers to detect CO, O_2, CO_2, NO_x, and CH_4 concentration inside the chamber and CO, O_2, CO_2, and NO_x in the flue gas chimney.

Finally, the instrumentation setup includes a spectrometer, which identifies the spectral emission from species present in the exhaust gases, and four CCD cameras (two RGB and two UV-VIS), placed outside at the front and side of the flame to monitor combustion and develop computer vision algorithms based on the images obtained from the combustion (Figure 2). All electrical signals from the sensors and analysers are sent to a computer for further analysis.

Figure 2 Furnace chamber and camera set-up

2.1. Methodology

A test campaign was carried out to assess the impact of using 100% hydrogen instead of 100% natural gas for the combustion processes regarding emissions and heat transfer. The tests consisted of the combustion of each of the fuels at a fixed thermal power and under stoichiometric conditions until combustion stabilization was reached, i.e. until the oxygen value at the outlet remains stable. Once stability is reached, the air flow rate is gradually increased, and the operation is repeated until the air-fuel mixture is so unbalanced by the excess air introduced that the minimum fuel concentration required for combustion to be initiated or maintained is not reached. The excess air values were, in the case of natural gas combustion, from 0% to 74% excess and, in the case of hydrogen, from 0% to 50%. The values of the measurements for each of the points were averaged over 5 minutes of operation once steady state was reached.

4. Results

Figure 3 shows time-averaged temperatures inside the combustion chamber for both fuels, calculated as the average of the temperature values of the thermocouples located inside the chamber for the different operating points. A 4% increase in flue gas temperature inside the furnace is found when hydrogen is used as fuel. NO_x emissions are significantly higher during hydrogen combustion than natural gas combustion, as illustrated in Figure 4. This increase is mainly attributed to the higher temperatures of the hydrogen flame and the excess air in the combustion process, as stated by [7]. Regarding heat transfer, Figure 5 indicates that the heat transferred to the simulated load is similar for both fuels, although the temperature inside the combustion chamber is higher when using hydrogen as fuel, as shown in Figure 3.

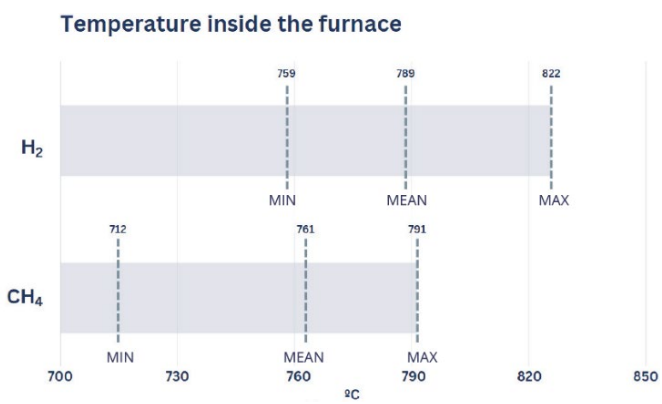

Figure 3 Temperature inside the chamber

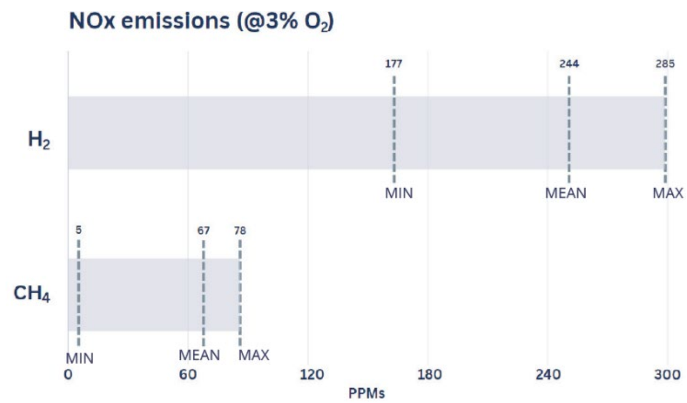

Figure 4 NOx emissions for both fuels

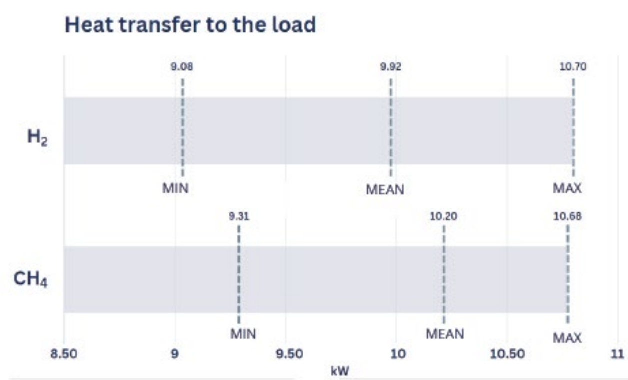

Figure 5 Heat transfer to the load for both fuels

On the other hand, the spectra obtained for both fuels (Figure 6) shows an increase in emission intensity values as combustion approached stoichiometric conditions with minimum intensity values at higher excess air. However, differences in species composition can be observed. In natural gas combustion carbon-containing by-products such as CH* and C2* are detected in the exhaust gases, in contrast to hydrogen combustion, where only OH* radicals are identified.

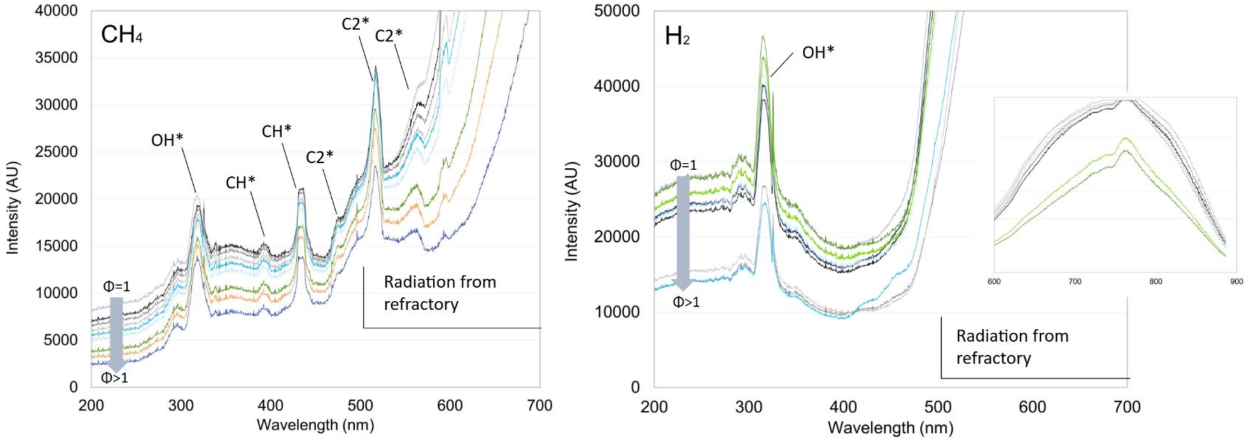

Figure 6 Average spectra for natural gas (left) and hydrogen (right) combustion

Finally, when using ultraviolet (UV) detection filters, it is observed that the hydrogen flame has a significantly higher higher emission intensity than the methane flame (Figure 7). This is because the emission spectrum of hydrogen is predominantly concentrated in the ultraviolet region, coupled with the higher temperature of its flame as also demonstrated by Rajpara et al. [8].

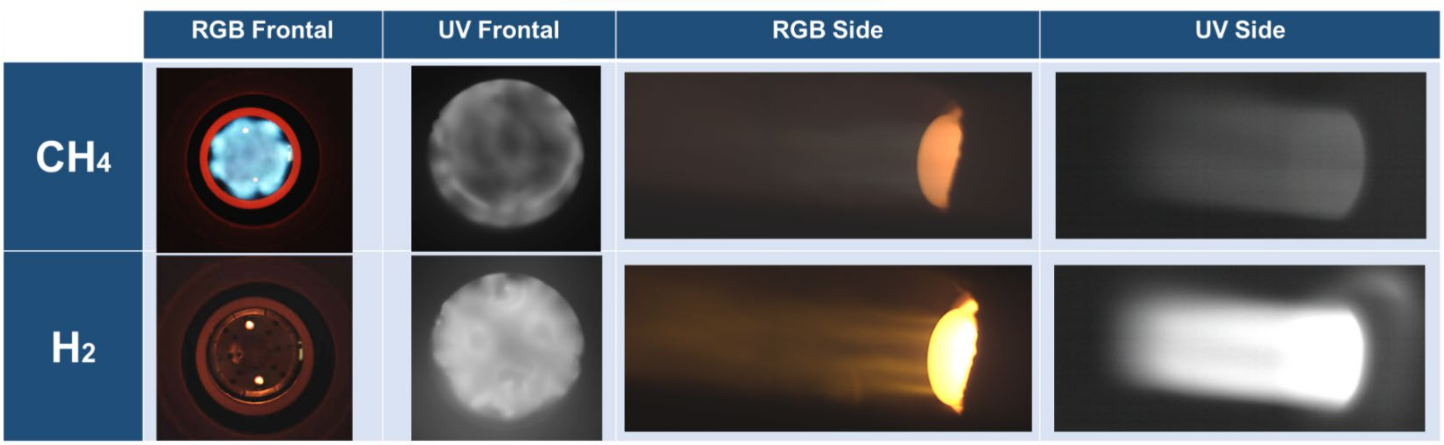

Figure 7 Images of the combustion flame. Front and side view

5. Conclusions and future work

Results from the experimental test showed that complete hydrogen combustion was possible in an existing infrastructure designed to burn natural gas, with similar results in heat transfer. However, the burner must be modified to accommodate hydrogen's higher flame speed than methane to avoid potential flashback problems a very common problem in hydrogen combustion due to its reactivity.

Regarding pollutant emissions, it has been found that hydrogen combustion has been associated with a significant increase in NO_x emissions. Therefore, optimisation of the excess air ratio, flue gas recirculation, burner design modifications or the possible use of oxy-combustion techniques are essential to reduce NO_x emissions.

In future work, the heat transfer to the load will be evaluated for different fuels consisting of hydrogen and methane in different proportions, and computer vision algorithms for combustion monitoring will be developed based on the images obtained from the installed cameras.

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