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Enriching Natural Gas with Hydrogen: Implications for Burner Operation †

Róbert Dzurňák [1,*], Gustáv Jablonský [1], Katarína Pauerová [2] and Richard Eliaš [1]

[1] Department of Thermal Technology and Gas Industry, Institute of Metallurgy, Faculty of Materials, Metallurgy and Recycling, Technical University of Kosice, Letna 9, 042 00 Kosice, Slovakia; gustav.jablonsky@tuke.sk (G.J.); richard.elias@student.tuke.sk (R.E.)

[2] Faculty of Materials, Metallurgy and Recycling, Institute of Recycling Technologies, Technical University of Kosice, Letna 9, 042 00 Kosice, Slovakia; katarina.pauerova@tuke.sk

* Correspondence: robert.dzurnak@tuke.sk

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Abstract: This paper presents the results of increasing the hydrogen concentration in natural gas distributed within the territory of the Slovak Republic. The range of hydrogen concentrations in the mathematical model is considered to be from 0 to 100 vol.% for the resulting combustion products, temperature, and heating value, and for the scientific assessment of the environmental and economic implications. From a technical perspective, it is feasible to consider enriching natural gas with hydrogen up to a level of 20% within the Slovak Republic. CO_2 emissions are estimated to be reduced by 3.76 tons for every 1 TJ of energy at an operational cost of EUR 10,000 at current hydrogen prices.

Keywords: hydrogen; natural gas; combustion

1. Introduction

Reducing the carbon footprint in industry is one of the primary goals of the European Union in its fight against environmental change. Its energy policy has put alternative energy sources at the forefront, with a strong emphasis on the use of hydropower. Hydrogen, as a carbon-neutral fuel, holds promise as a foundation for reducing carbon emissions. Current trends in European gas distribution networks confirm the use of hydrogen for energy purposes where natural gas is enriched with hydrogen. One such project is Eustream's H2I (H_2 Infrastructure), which succeeded in the selection process of the IPCEI (Important Projects of Common European Interest) call [1]. In the framework of this project, Eustream, as the main gas transporter in the Slovak Republic, collaborates with SPP-distribution and Nafta on the project's implementation [1].

The practical implementation of this project would bring significant changes to the operation of combustion facilities in the Slovak Republic. Hydrogen injection can directly influence the thermodynamic characteristics of a gas, including parameters like density, heating value, and compressibility factor. These alterations in the properties of gas mixtures can consequently have implications for end users [1]. Verma [2] described the changes in the combustion and performance characteristics of a set of combustion equipment when implementing natural gas enriched with hydrogen. His study also included a description of the changes in the produced emissions. Sanusi [3] conducted experimental analyses of the combustion characteristics of oxy-methane and hydrogen-enriched methane in a stabilized swirling burner without premixing. The experiments were performed at different combustion rates and with a hydrogen content ranging from 0% to 20% in methane/hydrogen fuel mixtures. Soriano [4] presents the design and evaluation of an oxygen–hydrogen gas burner for atmospheric combustion processes. The experimental results show a 30% thermal efficiency of the gas burner at the minimum flow rate (1.5 L·min^{-1}) and 76% at a flow

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rate of 3.5 L·min^{-1}. Dagaut [5] modeled the kinetics of natural gas enriched with hydrogen and verified the results using a jet-stirred reactor (JSR) device. The risks associated with enriching natural gas with hydrogen are described by Vries [6] in his study. Based on his findings on existing burner systems, it may lead to heat loss in the equipment due to a low hydrogen calorific value, fuel flashback into the burner, and changes in the combustion process due to altered excess air. The results of research [7] also highlight variations in the ignitability of natural gas/hydrogen mixtures at different levels of enrichment. In Europe, natural gas transported through the gas network must adhere to the gas quality requirements outlined in the European standard EN 16726:2015+A1:2018 [7]. This standard also applies to consumer gas installations integrated into the network [7]. Within these sectors, end-user devices like boilers, burners, and gas engines have specific criteria for gas quality parameters such as calorific value, Wobbe index, specific gravity, and methane number (MN) to optimize their performance [7]. Ingo compared the impact of increasing hydrogen in gas mixtures commonly used within the European Union. A total of 16 gases were compared, evaluating the change in the Wobbe index as the concentration of hydrogen in the mixture was changed. The results showed that gases with a high percentage of methane, nitrogen, and carbon dioxide are not suitable for hydrogen enrichment beyond 13%. On the other hand, gases with a higher percentage of higher hydrocarbons have a higher heating value, making it possible to enrich the gas with up to 20% hydrogen [7].

The objective of the submitted article is to assess the influence of hydrogen addition to natural gas within the range of 0–100 vol.% of H_2 on the resulting combustion products, temperature, and heating value and to conduct a scientific evaluation of the environmental and economic implications of these modifications.

2. Analysis of Hydrogen Impact

The analysis of hydrogen concentration change was conducted on natural gas, the chemical composition of which is provided in Table 1. This natural gas is distributed within the territory of the Slovak Republic by the company SPP-distribution. The Wobbe index of the gas (at 15 °C and a pressure of 101.325 kPa) is 50.62 MJ·m^{-3}. Based on the technical conditions for the Slovak Republic, where SPP-Distribúcia specifies a Wobbe index range of 45.7–53.9 MJ·m^{-3}, it is suitable to enrich the natural gas mixture with hydrogen up to a concentration of 20%, resulting in a Wobbe index value of 46.15 MJ·m^{-3} [8].

Table 1. Natural gas composition in vol.% (adapted from [8]).

CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	C_6H_{14}	CO_2	N_2
%	%	%	%	%	%	%	%
95.171	2.7131	0.8729	0.2772	0.0486	0.0207	0.2266	0.6697

The obtained results were used to create a graphical representation, as displayed in Figure 1, demonstrating the impact of varying hydrogen concentrations in the fuel on the composition of flue gases. The graph illustrates a noticeable reduction in the CO_2 component and a corresponding increase in H_2O. The graph reveals that the addition of hydrogen to the natural gas mixture results in a significant reduction in CO_2 content, particularly evident at a 50% H_2 concentration. Similarly, at a 50% H_2 concentration, there is a substantial increase in the H_2O content in the flue gases. When contemplating enriching natural gas with hydrogen to a 20% level, it is anticipated that the CO_2 concentration will decrease to approximately 1.06%. At a combustion air excess (λ) set to 1.1, the quantity of air required for the combustion of one unit of fuel (referred to as stoichiometric air) is reduced from 10.82 when employing pure natural gas to a mere 2.61 in the case of pure hydrogen.

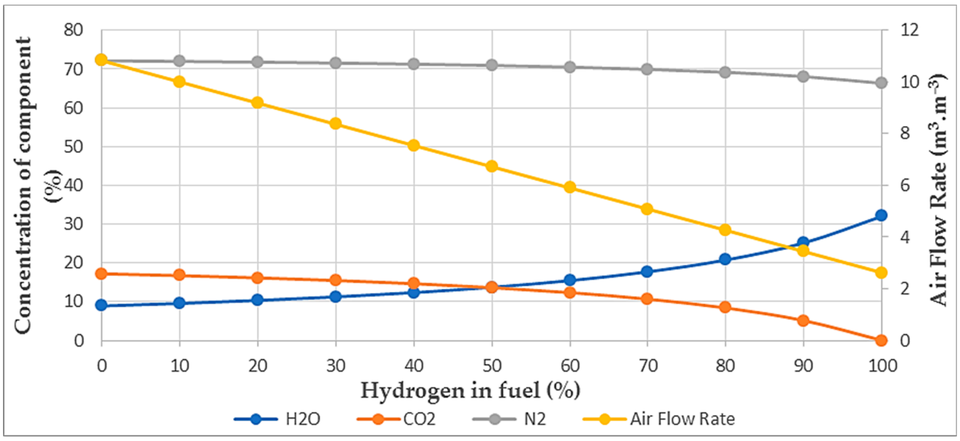

Figure 1. Effect of different hydrogen concentrations in the fuel on the composition of the flue gas.

The findings presented in Figure 2 demonstrate variations in combustion temperatures as the hydrogen concentration increases. As previously noted, as the hydrogen concentration in the gas mixture increases, the required quantity of combustion air decreases, resulting in a reduction in the production of flue gas. The reduced flue gas volume enhances the efficiency of heat utilization generated by the combustion of a unit amount of fuel, consequently elevating the combustion temperature. Furthermore, Figure 2 provides an insight into the theoretical temperature alterations when endothermic chemical reactions, such as the dissociation of CO_2 and H_2O in the combustion process, are taken into account.

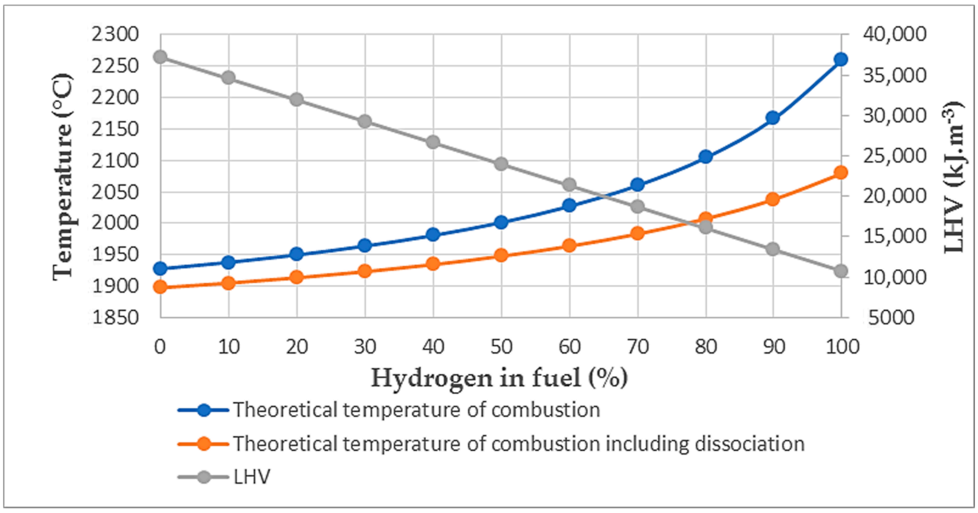

Figure 2. Effect of different hydrogen concentrations in the fuel on temperature and calorific value.

The low heating value (LHV) of hydrogen (10,748 kJ·m^{-3}) is approximately 3.5 times lower than the low heating value of natural gas (37,213 kJ·m^{-3}) [9]. This fact implies that increasing the concentration of hydrogen in a mixture with natural gas reduces the overall heating value of that mixture. The LHV represents a measure of the energy content of a fuel, indicating that increasing the content of low-heating-value hydrogen in the mixture reduces the energy content of the mixture. This can influence the energy efficiency and performance of the combustion process.

In practical applications with gas burners, it becomes necessary to compensate for the lower heating value of the gas by increasing the fuel consumption in order to achieve the same specified output. Table 2 provides a comprehensive set of recalculated parameters, including data on fuel consumption and the corresponding volume of combustion air required for a burner with a 10 kW-rated power input. This burner operates with an excess air factor of 1.1, which ensures efficient combustion while accounting for the lower heating value of the gas being utilized. These recalculated values are essential to maintaining the desired performance under these specific operational conditions.

Table 2. Flow rate of inlet media depending on hydrogen composition in the fuel.

Air Excess Coefficient	**(−)**					**1.1**						
Hydrogen in Fuel	(%)	0	10	20	30	40	50	60	70	80	90	100
Fuel Consumption	($m^3 \cdot h^{-1}$)	0.97	1.04	1.12	1.21	1.32	1.45	1.61	1.80	2.05	2.39	2.85
Air Flow Rate	($m^3 \cdot h^{-1}$)	10.51	10.40	10.27	10.12	9.94	9.73	9.48	9.16	8.75	8.21	7.46

Due to the lower heating value, the fuel consumption changes from 0.97 $m^3 \cdot h^{-1}$ to 2.85 $m^3 \cdot h^{-1}$. In practice, this change may require adjustments to the pressure conditions on the fuel inlet side of the equipment by increasing the pressure to ensure that the desired volume of gas is pushed through the local distribution network to the combustion device. On the other hand, the quantity of combustion air varies significantly, mainly due to changes in the stoichiometric requirements of the air. During the combustion of pure hydrogen, the volumetric flow rate of air is reduced by 29% compared to natural gas. Within the application of hydrogen into the mixture, heat transfer by convection will be reduced due to a lower volume of flue gases by approximately 10% in the case of pure hydrogen.

3. Discussion

At first glance, the use of hydrogen in a mixture with natural gas appears to be a promising concept for reducing CO_2 concentrations. However, the results of the above mathematical modelling indicate only a marginal reduction in CO_2 concentration, reaching approximately 1.06% within the current technical possibilities and without the necessary technical adjustments at the end-user points. The term "emission factor" has been introduced to represent the quantity of emissions generated when a certain amount of energy is produced. Table 3 presents the results of fuel consumption when changing the hydrogen concentration to achieve 1 TJ of energy with an economic evaluation. To calculate the costs of fuel enrichment, the price of natural gas was utilized at 0.53 EUR per m^3 [8], and the retail price of hydrogen for an average consumer in Slovakia amounts to 1.82 EUR per m^3 [8]. At a 20% concentration of H_2, the reduction in CO_2 production for 1 TJ of energy amounts to 3.76 tons. In the case of utilizing hydrogen, it is essential to consider only green hydrogen, which is produced by electrolysis using renewable energy sources, in order to achieve a positive impact on the environment.

Table 3. Economic evaluation of the enrichment of natural gas mixtures with hydrogen.

H2 (%)	**0**	**20**	**50**	**100**
Volume of fuel (m^3/TJ)	26,872.17	31,328.15	41,700.36	93,040.57
Natural gas price (EUR)	14,242.25	13,283.13	11,050.59	0
Hydrogen price (EUR)	0	11,403.45	37,947.32	169,333.83
Fuel price (EUR)	14,242.25	24,686.58	48,997.92	169,333.83
Difference in cost (EUR)	0	10,444.33	34,755.67	155,091.58
Emission factor (tCO_2/TJ)	55.80	52.04	43.29	0
CO_2 savings (t)	0	3.76	12.50	55.80

4. Conclusions

Current trends within the European Union are pushing for a reduction in carbon emissions across various industrial sectors. One of the potential avenues involves harnessing hydrogen in combustion processes and enriching natural gas with hydrogen. Application projects, including initiatives like H_2 Infrastructure, are seeking to optimize the parameters involved. Predictive model results indicate that, considering CO_2 production, the use of hydrogen in a natural gas mixture becomes prospective when the hydrogen concentration reaches around 50%. However, such high levels of hydrogen would necessitate modifications to burners and distribution networks.

Currently, the possibility of enriching gas with 20% hydrogen, resulting in a 1.06% reduction in CO_2 concentration, is viable. For the production of 1 TJ of energy, this corresponds to a reduction in CO_2 emissions of 3.76 metric tons. From an economic perspective, the costs associated with implementing hydrogen at current prices exceed EUR 10,000. In light of the above, this application appears to face challenges in terms of competitiveness under current conditions. However, as technologies evolve and environmental regulations become more stringent, the feasibility and economic viability of hydrogen utilization in gas mixtures may change, potentially rendering it a more competitive and sustainable option in the future.

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