EXPERIMENTAL PERFORMANCE ANALYSIS OF A FUEL CELL UNIT FOR VARIOUS NATURAL GAS-HYDROGEN FUEL MIXTURES

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ABSTRACT

In recent years, numerous policies have been issued with requirements to reduce the energy use of appliances and emission of greenhouse gases. As one of the biggest energy users, large attention has been given to reducing the energy use of residential buildings. With renovation techniques of these dwellings that lower the space heating demand, low temperature heating systems can be applied. In this regard, electrically driven air to water heat pumps are the most used low temperature heating systems. Due to their easy installation requirements and low price in comparison to other heat pumps, it is expected that these units will be the leaders in replacing gas-fired boilers that currently dominate the market. However, in severe winter conditions, these heat pumps have a decrease in thermal capacity while the dwelling has an increase in energy demand. In this case, the difference in energy supply is mostly compensated by electrical auxiliary heaters. With an increase in sales of electrically driven heat pumps, the current electricity grid could suffer from voltage instabilities and overloading. To face these challenges, fuel cell units that are capable to generate both electrical and thermal energy are nowadays a large topic of scientific interest. With the use of reformer units, natural gas can directly be broken up into hydrogen which further supplies the fuel cell stack. In this case, the existing natural gas grid could be used, and the provision of hydrogen ensured throughout the season. With aspirations towards the decarbonisation of the natural gas grid, a blend-in of 5 Vol% of hydrogen is already approved while a larger share of hydrogen in the gas grid is expected in the years to come. In the scientific literature, there is a lack of research devoted to analysing the experimental performance of the currently used fuel cells and their adaptations to natural gas-hydrogen mixtures. In this regard, this research analyses the performance of a fuel cell unit for different fuel mixtures containing up to 30 Vol% hydrogen. The results show deviations in efficiency values of less than 5% and no pattern in the total efficiency trends for the two different controlling strategies of the unit.

INTRODUCTION

To reduce the emissions of greenhouse gases (GHG), the biggest energy users per sector need to be evaluated in terms of their present performance and prospects towards future energy transitions. In 2016, a final energy use share of 25.71% was attributed to the residential buildings sector in the European Union (EU) making it the largest consuming sector after transport [1]. In the households, space heating and domestic hot water heating systems jointly represent a share of 78.9% of the final energy use. Currently, most of the residential buildings in the EU are built in the 70s [2]. These buildings are characterized by low construction level in terms of thermal insulation and they require high temperature heating for meeting the energy demand that is nowadays mostly achieved by gas boilers.

One of the possible solutions for replacing fossil-fuel-powered appliances is the electrification of the equipment. This would mean that all fossil fuel consuming technologies should be replaced by electrically driven appliances. In fact, if the electrical energy mix would be dominated by the energy coming from Renewable energy sources (RES), the average global temperature could be limited to the increase of well below 2°C as set by the Paris climate agreement [3]. In the case of today's households, the replacing action would concern the change of the traditional heating technologies (boilers) and vehicles with internal combustion engines into electrically driven heating appliances and electrical vehicles.

With the construction of new buildings and refurbishment of the existing buildings according to the newest standards that lead to lower heating demand, the application of low temperature heating systems is becoming possible. Due to their installation simplicity and price in comparison to other types, electrically driven air to water heat pumps are leading the replacement of the fossil fuel boilers [4]. However, at lower outdoor temperatures, the air to water heat pumps have decreased capacity while the dwellings have an increase of energy demand in those moments. Usually, the discrepancy between the heat pump's capacity and energy demand is compensated by the use of an electrical heater which leads to an increase in electricity consumption. Although modern houses are occasionally equipped with photovoltaic panels that generate electricity, this contribution is often not enough to satisfy the total electricity requirements even with the use of energy storages [5]. Moreover, if the electrically driven heat pumps would penetrate the market at high rates at the present electrical grid state, overloading and voltage instability of the grid could occur especially in the rural areas [6].

NOMENCLATURE

ṁ	[kg/s]	Mass flow rate
h	[kJ/kg]	Specific enthalpy
HHV	[kJ/m^3]	Higher heating value
LHV	[kJ/m^3]	Lower heating value
Q	[W]	Heat flow
T	[K]	Temperature
Special characters		
η	[%]	Efficiency of the unit
Subscripts		
el		Electricity
env		Envelope characteristics
ex		Exhaust gas
f		Fuel
FC		Fuel cell
hex		Heat exchanger
i		Compounds of the combustion gases
in/out		Inlet/Outlet parameters
w		Water

To aid electrification strategies and keep the stability of the electrical network, hydrogen-powered fuel cell units can be used. By creating a chemical reaction between hydrogen and an oxidizer (air or water), the fuel cell unit is capable to generate both electrical and thermal energy. In this way, besides keeping the electrical grid safe, losses in electricity transmissions are avoided as well since the electricity is produced locally.

The hydrogen itself can be produced locally by utilising the electricity generated by the PV panels or the grid which powers water electrolysers for creating hydrogen and further storing it in pressurised tanks [7]. However, due to the occasional unavailability of the RES and the limited surface of the PV panels, the amount of produced hydrogen might not be sufficient to cover the peak energy demand during the winter period which can still evolve into grid overloading and increase of energy bills [8]. Another way to locally produce hydrogen is through the use of natural gas reformers. These units are capable to deliver up to 4 molecules of hydrogen for one molecule of methane with minimal emissions. In this way, the developed natural gas grid can still be utilised especially considering the decarbonisation plan of the grid which already includes a blend of 5 Vol% of hydrogen in the grid with the plan to increase this amount in the following years [9].

In this article, the performance of a solid oxide fuel cell (SOFC) unit is experimentally evaluated through various steady-state laboratory measurements. For each of the measurements, the unit was subjected to different mixtures of natural gas and hydrogen with the highest share up to 30 Vol% hydrogen. The goal of the research was to analyse if the currently available fuel cell units can sustain the decarbonised natural gas grid and deliver the same performance. The acquired data can be used for the verification of different numerical models of these units. The results have shown that the total efficiency of the examined unit does not have large variations on the performance for different fuel mixtures.

CURRENT STATE OF THE ART

In the scientific literature, there is a lack of profound experimental results on the fuel cells which are using different natural gas-hydrogen fuel mixtures. Instead, the state-of-the-art spreads between extensive numerical estimations and limited experimental campaigns on the results when using these specific fuel compositions.

Cinti et al. [10] have made a numerical study of the performance of an SOFC fuel cell unit by varying the amount of hydrogen and methane (hythane) of the fuel blend. In total, six different gas compositions were applied in the proposed numerical simulations varying from 100% methane to 100% hydrogen. The numerical model is prepared by using a commercial tool Cycle Tempo that takes into account a system composed of an external reformer, SOFC stack and after burner unit (used to bring heat to the steam reformer). The modelling details of the used tool were not disclosed. The simulations were made for the constant fuel input and constant DC power output of 1.25 kW which were imposed in the model. When the system operates with pure methane, the electrical efficiency of 48.44% and total efficiency of 75.07% were found based on the LHV which coincides with the expectations. However, higher electrical efficiency is found for pure methane fuel composition than for hythane, while hythane fuel contributes more to the thermal efficiency and increases the total efficiency based on these simulations. The lower electrical efficiency in the case of hythane can be explained by the reduced performance of the reformer. For higher methane quantities, there is an increase in the hydrogen flow to the fuel cell stack which results in lower use of fuel for the same electricity output. When hydrogen is added to the composition, there is a decrease of heat absorption of the reformer system which results in higher heat residuals of the waste gases that leads to the higher heat production of the system. Still, despite that the use of hydrogen in the natural gas mixtures reduces electrical efficiency, the increase of total efficiency and lower emissions of waste gases keep this concept valuable according to this numerical analysis.

Panagi et al. [11] have experimentally analysed the influence of using biohythane fuel compositions on the performance of an SOFC fuel cell stack with external partial oxidation reforming process. This fuel is typically composed of 60 Vol% of CH_4, 30 Vol% CO_2 and 10 Vol% H_2 that are products of anaerobic digestion and low carbon biomass. In this work, the ratio between the three compounds was varied while the ratio between CO_2 and H_2 was kept as 3:1. For a fuel composition containing 75 Vol% CO_2 and 25 Vol% H_2, the SOFC unit resulted in higher electrical efficiency due to the higher presence of H_2 and increased CO_2 reforming process when compared to the pure methane fuel. Still, the most optimal fuel composition in terms of electrical efficiency proved to be a mixture of 50 Vol% CH_4 and 37.5 Vol% of CO_2 and 12.5 Vol% H_2 which led to the efficiency increase of 81.6% when compared to the use of pure methane. This fuel composition also decreases the use of methane by 76% if pure methane would be used as a reference.

The rest of the work is organized into three sections. The first section gives the description of the developed experimental set-up as well as the explanation of the conducted experimental measurements and data processing. The second section provides the main results of the experimental campaign while the last section concludes the work.

MEASURING EQUIPMENT AND PROCEDURE

Description of the test set-up

For the purpose of this study, a complete experimental set-up has been developed in the certified laboratory facility of the institute Gas.be [12]. The tested unit is the product of the company Solid power [13]. Table 1 gives an overview of the performance characteristics of the BlueGen SOFC unit.

Table 1 Nominal performance characteristics of the BlueGen SOFC fuel cell unit.

Electrical capacity [kW]	1.5
Thermal capacity [W]	850
Yearly electricity yield [kWh]	13 000
Electrical power use [W]	200
Energy label	A+++

The nominal electrical capacity is 1.5 kW while the nominal thermal capacity is 850 W for an inlet water temperature of 30°C. As a fuel, in regular conditions, this unit uses the natural gas from the grid which is decomposed in a steam reformer. The steam reformer is one of the typical external reforming processes in which water steam is used to break up methane at the temperature of about 700°C. The process takes place in four stages. In the first stage, called the reformer stage, most of the methane is converted into carbon monoxide and hydrogen. In the second stage, which occurs in two substages, steam at lower temperature and pressure is brought into the process for dissolving the residual carbon monoxide into an extra molecule of hydrogen. In the fourth stage, named pressure swing adsorption, the gases are filtered so that pure hydrogen is permitted into the fuel cell stack. Eq. (1) and Eq. (2) give the main stoichiometric reactions of the first and second two stages of the steam reforming process.

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (1)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (2)$$

In Fig. 1, a schematic overview of the experimental test set-up and the main measuring equipment can be seen.

At the natural gas side, a volumetric flow meter, a pressure sensor and a thermocouple have been placed to measure the thermodynamic properties of the gas. To feed the unit with the right gas mixture, pressurized gas bottles were used. These bottles were prepared prior to each of the executed tests. At the start-up of the unit, a small quantity of electrical energy is withdrawn from the grid to preheat the reformer, start the fans and circulation pumps. After this period, the fuel cell is capable of satisfying its own electricity demand and deliver the excess amount of generated electricity to the user or the grid. The electrical energy flow is monitored with a smart electrical meter. The useful heat output was measured with the use of a water circuit. To represent the low temperature heating, pressurised (2 bar) freshwater from the grid was firstly led through a natural gas heater that would increase the temperature of the water to about 30°C constantly. Further, the water is circulated and additionally heated in the fuel cell and then stored in a weighted water tank for measuring the water flow rate. The water circuit was equipped with four thermocouples placed at the inlet and outlet points of the boiler (two thermocouples at each point). To acquire the state of the exhaust gases of the unit, an additional thermocouple was placed inside the chimney of the unit while the quality of the exhaust gases was measured with the use of a gas analyser.

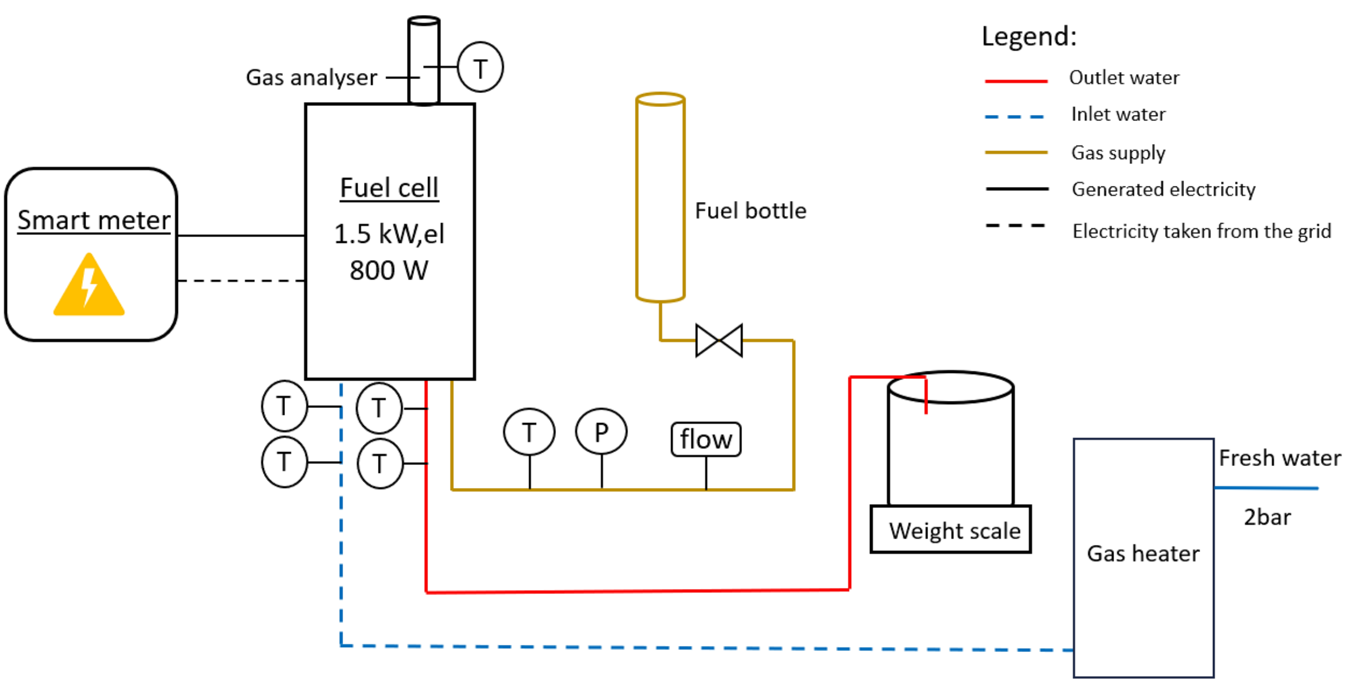

Figure 1 Illustrated overview of the developed experimental set-up.

Measurement procedure and data processing

The measurements were made in two phases for a total of 10 different gas mixtures. The goal of these tests was to analyse the effectiveness of using the decarbonised natural gas grid and to also analyse the performance of the fuel cell unit for the impure fuel mixtures when a certain amount of nitrogen, carbon dioxide and propane is permitted in the mixture. The overview of the used fuel mixtures is given in Table 2.

Table 2 Natural gas-hydrogen fuel mixtures.

G20 (-2)	100% CH_4
M1 (-2)	90% CH_4 + 10% H_2
M2 (-2)	80% CH_4 + 20% H_2
M3 (-2)	70% CH_4 + 30% H_2
M4	87% CH_4 + 13% C_3H_8
M5	57% CH_4 + 30% H_2 + 13% C_3H_8
M6	96% CH_4 + 4% CO_2
M7	66% CH_4 + 30% H_2 + 4% CO_2
M8	92.5% CH_4 + 7.5% N_2
M9	62.5% CH_4 + 30% H_2 + 7.5% N_2

Prior to each of these tests done under the first measurement phase, the properties of the gas mixture were communicated to the manufacturer of the unit. Due to safety and guarantee reasons, the manufacturer would wirelessly access the digital settings of the reformer and perform confidential adjustments.

In the second phase, with the consent of the manufacturer, the measurements were repeated without the intervention of the manufacturer for the first four mixtures of the list (-2 in Table 2). Each test was done in the time duration of one hour. The measurement acquisition would only start when the unit enters steady-state performance.

The efficiency of the unit η_{FC} was calculated with the use of Eq. (3):

$$\eta_{FC} = \frac{\dot{W}_{el} + \dot{Q}_w}{\dot{Q}_{in}} = \frac{\dot{W}_{el} + \dot{m}_w \cdot c_p \cdot (T_{w,out} - T_{w,in})}{\dot{V}_{gas\,flow} \cdot HHV} \quad (3)$$

From here, individual electrical efficiency (Eq. (4)) and thermal efficiency (Eq. (5)) can be derived:

$$\eta_{el} = \frac{\dot{W}_{el}}{\dot{Q}_{in}} = \frac{\dot{W}_{el}}{\dot{V}_{gas\,flow} \cdot HHV} \quad (4)$$

$$\eta_{th} = \frac{\dot{Q}_w}{\dot{Q}_{in}} = \frac{\dot{m}_w \cdot c_p \cdot (T_{w,out} - T_{w,in})}{\dot{V}_{gas\,flow} \cdot HHV} \quad (5)$$

In the numerator, the total energy output is calculated as a function of the electrical $\dot{W}_{el}$ and thermal $\dot{Q}_w$ output. The second is based on the water flow rate $\dot{m}_w$, specific water heating capacity at the constant pressure c_p and inlet and outlet water temperatures ($T_{w,in}, T_{w,out}$). The denominator gives the total heat input to the unit as a function of the fuel flow rate $\dot{V}_{gas\,flow}$ and higher heating value of the fuel HHV. All results have been referenced to the reference conditions of the temperature of 15°C and pressure of 101 325 Pa. Accordingly, the standard EN 6976 2016 [14] that specifies the calorific value of gases is used for the calculations.

RESULTS

In the first phase of the measurement data processing, the results have been compared based on the differences in performance of the unit for the used fuel mixtures and settings of the unit. For this purpose, the main parameters which account for the electrical, thermal and total efficiency were analysed.

Figure 2 shows the amount of heat input to the unit for the 10 different fuel mixtures and the two measuring phases. All results are based on the higher heating value of the fuel for the mentioned reference conditions. The figure shows lower heat input for the fuel mixtures which contain hydrogen in the case when the reformer has not been adjusted by the manufacturer. This result is logical as hydrogen fuel mixtures have a lower calorific value than pure methane (G20, reference gas). To keep the thermal output higher, it is assumed that the adjustments of the manufacturer implicated the higher heat input when hydrogen is used in the mixture. However, higher heat input does not necessarily imply higher efficiency (M4 fuel mixture).

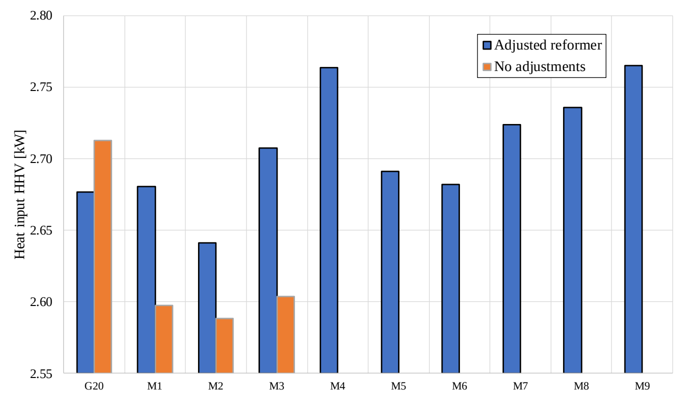

Figure 2 Heat input of the SOFC unit as a function of different fuel mixtures.

To have a better overview of the performance of the fuel cell, electrical and thermal efficiencies are accounted for separately and jointly. Figure 3 gives the electrical energy generation while Figure 4 gives the electrical generation efficiency (as calculated by Eq. (4)) for the used fuel mixtures. Throughout the measuring campaign, the electrical energy output remained quite constant at around 1.492 kWel. This performance could be explained by the fact that fuel cells units are not controlled by the electricity demand due to a decrease in electrical generation efficiency in part load conditions, impracticality in following the stochastic electrical energy demand of the users and price of such systems. As mentioned earlier, the adjustment of the manufacturer for the hydrogen fuel mixtures resulted in lower electrical efficiencies than in the regular case without adjustments. Despite that the electrical energy output remained fairly constant, the electrical efficiency drops for the fuel mixtures that contain other compounds besides methane and hydrogen. Still, both measurement phases result in differences in electrical energy generation efficiency which are less than 3.44 percent points (pp).

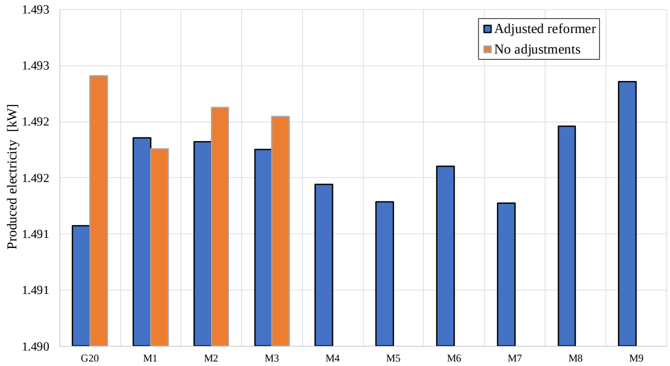

Figure 3 Electricity production of the SOFC unit as a function of different fuel mixtures.

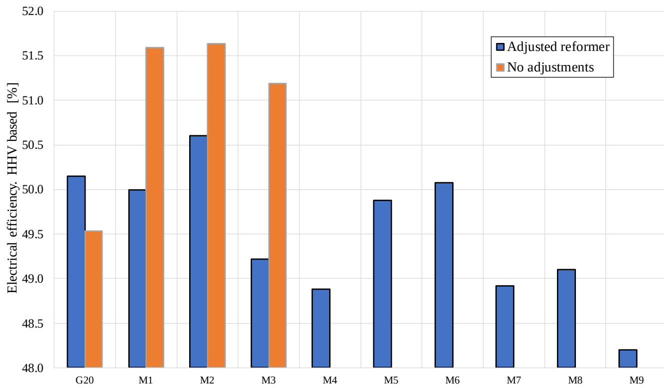

Figure 4 Electrical efficiency of the SOFC unit as a function of different fuel mixtures.

The nominal thermal output of the analysed SOFC fuel cell unit is reported to be 850 W. Figure 5 and Figure 6 show the thermal energy output and thermal efficiency (as calculated by Eq. (5)) for the carried-out measurement campaign. Due to the small difference in thermal energy output, the results were challenging to measure. The heat output differs for only up to 150 W. Still, it may be observed that the manufacturer adjustments have led to a slightly increased amount of generated heat output in the case of the second two methane-hydrogen mixtures compared to when adjustments have not been made. However, this trend is not noted for the use of 10% hydrogen which could be explained by the fact that this was the first measurement under these conditions which could have caused unaware mistakes from both sides (to be verified). The other fuel mixtures M4-M9 resulted in a rather stable thermal energy output which is close to the nominal value. The thermal efficiency values are noted to be almost half of the electrical efficiencies and they differ with a maximum of 4.34 pp for all the cases.

Lastly, in Figure 7 the total efficiency results (as calculated by Eq. (3)) of the considered fuel cell unit may be seen. For the first phase of the measurements (adjusted reformer), the maximum difference between the efficiency values was 4.2 pp. In the second phase (no adjustments) this difference is found to be only 1.5 pp. As the generated electrical energy was rather constant the difference in the results mainly comes from changes in generated thermal power (maximum difference 150 W) and fuel intake.

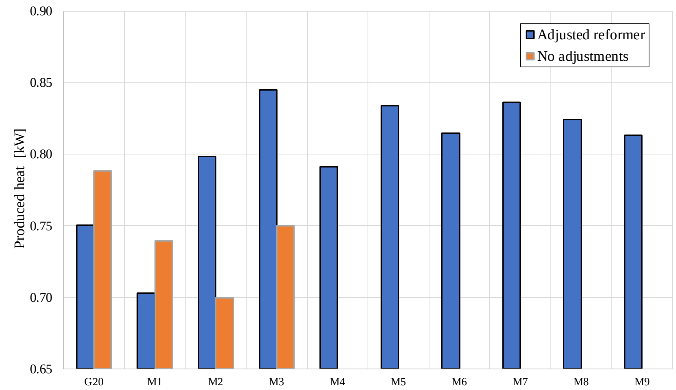

Figure 5 Heat generation of the SOFC unit as a function of different fuel mixtures.

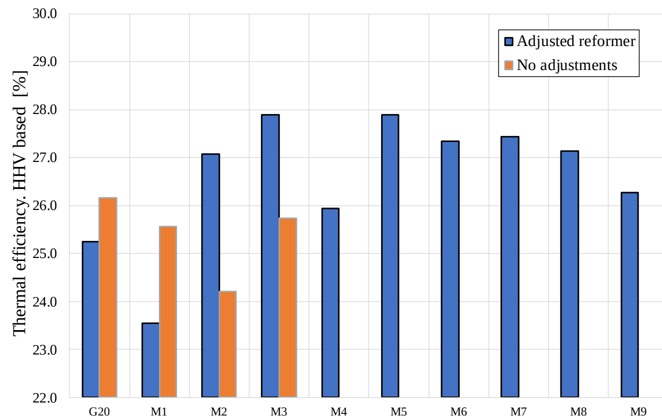

Figure 6 Thermal efficiency of the SOFC unit as a function of different fuel mixtures.

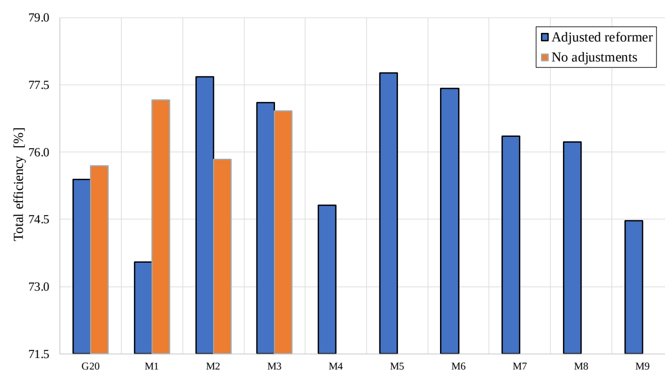

Figure 7 Total efficiency of the SOFC unit as a function of different fuel mixtures.

The total efficiency values do not suggest a clear pattern in relation to the applied fluid mixture and neither on the reformer adjustments. For a higher fraction of hydrogen in a fuel mixture, it is expected that the electrical efficiency will drop and thermal efficiency rise due to the lower operating temperature of the steam reformer. The measurements done in this study do not precisely show this pattern. Still, the tests have shown that fuel cell units are capable to operate with higher fractions of hydrogen in the natural gas grid.

To be able to more closely account for the influence of adding hydrogen in the natural gas mixture, the marginal calculations on the individual contribution of methane and hydrogen have been made (second phase of data processing). These calculations have been performed by the company CogenVlaanderen [15] that is specialised in cogenerated heat production energy performance of systems. By using the reference measurement results for pure methane G20, the marginal calculations for the first 4 fuel mixtures in both phases were performed by using the simple proportion calculation method that is based on the ratio of the compounds in the fuel mixtures. Similarly, to the previous results, in this calculation, electrical, thermal and total efficiency were recalculated for the individual shares of methane and hydrogen contained in the fuel mixtures. The results have shown that the addition of hydrogen leads to the improvement of the total efficiency of the unit except for the very first measurement M1 (already explained earlier). This phenomenon can be explained as the extra hydrogen in the mixture is simply carried by the methane and therefore, not subjected to the reforming process leading to the lower use of reforming energy and lift in total efficiency value attributed to hydrogen only. These results have confirmed the benefits of the decarbonisation plans of the natural gas grid for the performance of the analysed SOFC fuel cell unit.

CONCLUSION

With aspirations towards lowering the emission of greenhouse gases and using more efficient appliances, the phase-out of traditional fossil fuel boilers and higher use of electrically driven heat pump units is expected. However, the current electrical energy grid might suffer from overloading and restrictions especially in severe winter conditions. In order to face these challenges and generate both thermal and electrical energy independently at the site, fuel cell units have become a prominent topic of research. In this work, the performance of an SOFC fuel cell unit was experimentally analysed with the use of fuel mixtures that have an increased concentration of hydrogen. In total 10 different fuel mixtures have been used containing up to 30 Vol% hydrogen. The tests were performed in two testing phases that included different settings of the steam reformer of the unit while the data was processed by following two processing methods. The results have shown that there are no large oscillations in the efficiency of these units for the mixture and working conditions applied which are based on the total fuel inputs. However, when the individual contribution of both methane and hydrogen are analysed for the obtained energy outputs, clear benefits of introducing hydrogen in the natural gas grid have been noted. These results have shown prominent promises in decarbonising the natural gas grid and also the ability of the current fuel cell units to operate under decarbonized gas grid conditions. In the next step, these results can be used for calibrating the numerical models of these units and cross verifying the validity of the tests and simulation results.

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