Impact of hydrogen and mixtures of hydrogen and natural gas on forced draught burners for gaseous fuels

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To support the energy transition hydrogen can play an important role as a renewable energy source in industry and process technology in the future. However, the properties of hydrogen in terms of combustion strongly differ form the properties of natural gas. To analyse the effects of hydrogen and mixtures of hydrogen and natural gas on forced draught burners for gaseous fuels according to EN676, experimental studies have been performed using a modern non-premixed dreizler marathon® LOW-NO_x *burner based on the hollowflame®-technology. The focal points include the impact on* NO_x*-emissions and its reduction strategies, thermal load, the applicability of different flame detecting technologies and the impact on the air-fuel linkage. The results demonstrate the feasibility of the burner for the fuel-flexible use of hydrogen and natural gas.*

The electricity which is produced in Germany by renewable energies alone cannot cover the current and future demand of the entire final energy - even if the expansion goals of the renewable energies and the ambitious energy-saving targets are achieved. Therefore, the remaining energy demand in the industrial heat and steam generation must still be ensured by gaseous or liquid energy sources in the future.

According to BMWi [1], CO_2-free hydrogen in particular will play an important role in the energy transition as a future storable energy source in the long term. The hydrogen can ideally be generated as green hydrogen by renewable electricity using the electrolysis process. Due to the limited generation of renewable energy in Germany, part of the required hydrogen has to be imported from abroad. Alternatively, the hydrogen can be produced by reforming natural gas. If the resulting carbon dioxide is separated and stored (carbon capture and storage, CCS), the hydrogen is called ‘blue hydrogen’.

A number of research projects are going to test the hydrogen compatibility of existing gas devices in real environment in the near future. Here, hydrogen will be injected in a locally separated natural gas grid with an admixture of up to 20 vol.-% hydrogen [2] and 30 vol.-% hydrogen [3]. In the frame of the “Reallabore” (real-world laboratories) of the energy transition funded by the BMWi, the use of up to 100 vol.-% hydrogen will also be tested in hydrogen-based microgrids [4].

Even if natural gas will play an important role as an energy source beyond 2030, systems producing heat and steam that will be built or modernized in the next years should be adapted and optimized for the future use of renewable fuels due to their generally long service life.

Since the beginning of town gas, the Walter Dreizler GmbH has over 50 years of experience in the use of energy sources with a high percentage of hydrogen. The town gas (gas family 1), which was produced using coal gasification, was composed of up to 60 vol.-% hydrogen in addition to carbon monoxide, methane and nitrogen. In the 1980s, forced draught gas burners with a thermal power of several megawatt were still being operated in Berlin with gas reformed from gasoline with 50 vol.-% methane and 50 vol.-% hydrogen. Investigations that have already been carried out in 2019 [5] demonstrated that the current marathon® ARZ series with an ARZ exhaust gas recirculation system integrated in the burner head for NO_X reduction, is able to use an admixture of up to 10 vol.-% hydrogen with minor adjustments and an appropriate combustion manager.

In order to verify the ability to use up to 100 vol.-% hydrogen in the modern non-premixed marathon® LOW-NO_X forced draught gas burners based on the hollowflame® technology (EU-Patent EP 2126471 B1), extensive tests have been carried out at the Gas- und Wärme-Institut Essen e. V. in Essen (GWI). This combustion technology (see ***Figure 1***) is used, depending on fuel and application, in systems for heat and steam generation in industrial plants and heating plants with a thermal power of 1 to 44 MW.

Figure 1: *Examples of marathon® forced draught burners according to EN676*

Walter Dreizler GmbH produces combustion systems based on the hollowflame® technology for retrofitting or new installations for a variety of gaseous and liquid fuels for separate or combined simultaneous operation in the range of several gigawatts per year. It also offers competent service in Europe.

Combustion characteristics of hydrogen

Hydrogen differs significantly in many respects from natural gas[1], which mainly consists of methane. Due to the lower volumetric calorific value and the lower density of hydrogen, the calorific value and the Wobbe index of the natural gas-hydrogen mixture decrease with increasing percentage of hydrogen (see ***Figure 2***). The amount of air required for stochiometric combustion declines in line with the calorific value.

With incrementing the percentage of hydrogen, the adiabatic flame temperature increases, which leads to higher thermal NO_X formation. An increase in the adiabatic flame temperature from approx. 2050 to approx. 2200 K, as shown in ***Figure 2*** for an air fuel ratio of 1.2, results in an increase in the thermal NO formation rate by a factor of approx. 3.5 according to the NO velocity law [6].

The boost in the laminar flame speed and the strong decrease in the ignition delay time with raising hydrogen content shorten the flame and increase the thermal load on the components close to the flame.

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[1] For the comparisons presented in this report, the natural gas composition of the test campaign (calorific value: 10,26 kWh/m_N^3; wobbe-Index: 13,16 kWh/m_N^3) was used.

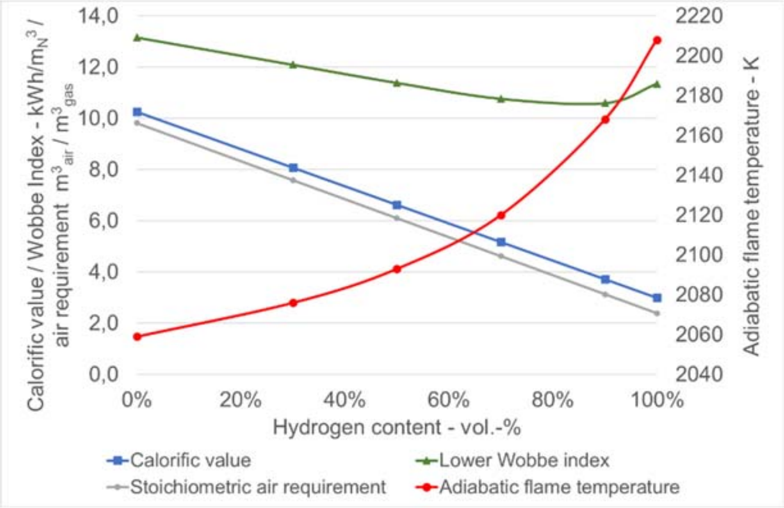

***Figure 2**: Comparison of calorific value, stoichiometric air requirement, lower Wobbe index and adiabatic flame temperature for different natural gas / H2 mixtures*

In order to achieve the same thermal power with a higher percentage of hydrogen, the gas flow rate or the gas nozzle pressure must be raised. If the setting of the gas pressure regulator is not adjusted, the thermal power decreases with higher hydrogen content due to the constant gas pressure. Here, a minimum is reached at about 90 vol.-% hydrogen. On the other hand, the lower stoichiometric air requirement reduces the necessary flow rate of the air. Without regulation of the air flow rate – for example by means of an O_2 control – the combustion efficiency and thus the system efficiency decrease. The effects with same gas pressure regulator settings and constant air flow are shown in ***Figure 3*** for an exemplary case with an air fuel ratio of 1.2 for natural gas operation. While the combustion output drops by approx. 19 %, the peak air fuel ratio increases by up to 42 % at 90 vol.-% hydrogen.

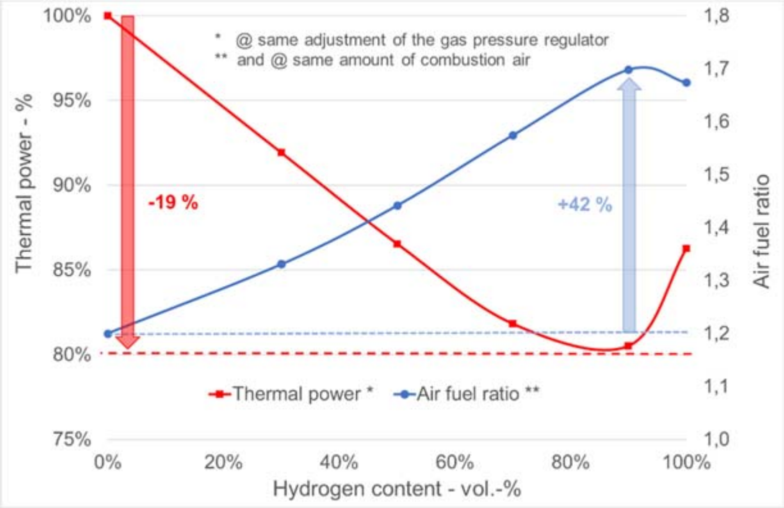

***Figure 3**: Influence of the hydrogen content on the thermal power and air fuel ratio in the case of uncontrolled operation*

Experimental setup

The focus of the experiment was to analyse the impact of up to 100 vol.% hydrogen on the thermal load, the NO_x-emissions and their reduction possibilities, the suitability of different flame detector technologies and the effects on the air-fuel linkage.

The burner used has a thermal power of up to 1.1 MW. Due to the existing infrastructure and the maximum possible hydrogen mass flow, the thermal power of the burner had to be limited to 600 kW for natural gas and mixtures of natural gas and hydrogen and to 450 kW for 100 vol.-% hydrogen. The combustion chamber cross-section and volume load on the test flame tube according to EN676 was max. 3.0 MW/m^2, or 1.53 MW/m^3 respectively. ***Figure 4*** shows the test burner and the test flame tube,

Figure 5 shows the R&I diagram of the experimental setup.

Figure 4: *Test burner and test flame tube*

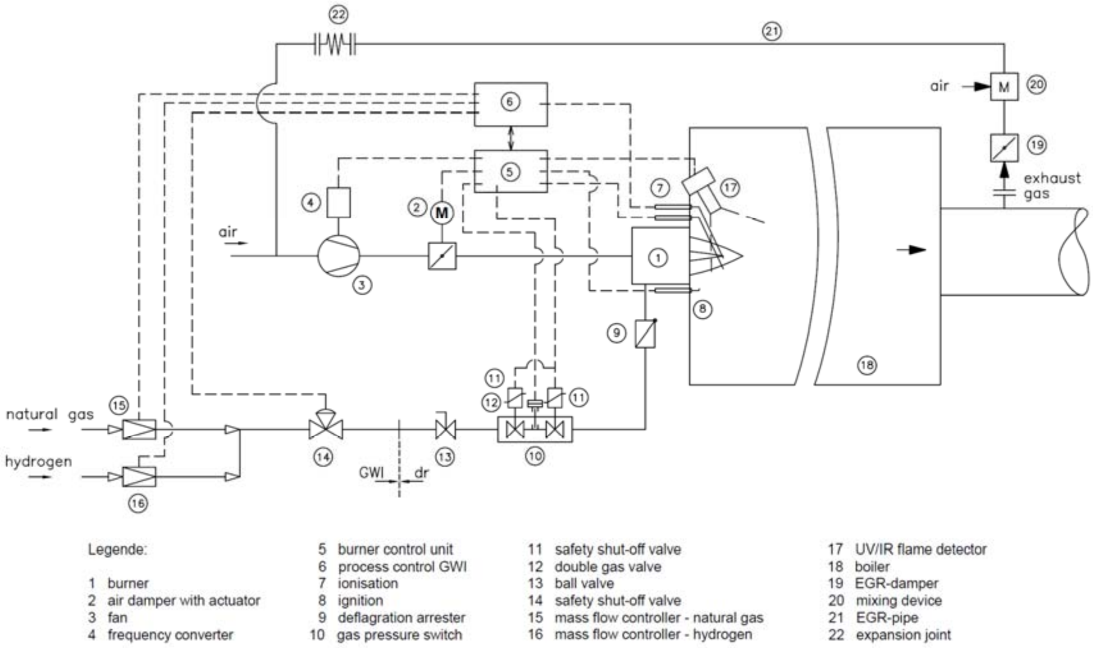

Figure 5: *R&I scheme of the experimental setup*

The flame was monitored using ionisation electrodes and optical, combined UV/IR flame detectors. The ionisation current, the flickering frequencies and the voltage of the UV and IR RMS[2] signals were recorded. Due to the adjustment of the gas mass flow by two mass flow controllers (natural gas / hydrogen), the control valve of the gas train used for standard operations was replaced by an additional safety shut-off valve. In addition, the gas damper with actuator was removed. A deflagration protection was used for safety purposes. An external exhaust gas recirculation (EGR) system - dreizler® ARF- was implemented to reduce NO_X-emissions. The NO_x- and CO-emissions were measured with analysers from Ecophysics (CLD 822 Sr) and Emerson (NGA2000). To determine the external exhaust gas recirculation rates, the oxygen content in the combustion air and in the exhaust gas was determined. To measure the material and surface temperatures, thermocouples were installed in different areas of the mixing device. In addition, the temperatures of the exhaust gas in the external exhaust gas recirculation, in the combustion air, in the gas pipe as well as the gas pressures upstream of the double gas valve and at the gas connection of the burner and the air pressure in the mixing device and in the combustion chamber were recorded.

The tests were carried out with 100 vol.-% hydrogen, 100 vol.-% natural gas and natural gas-hydrogen mixtures with 30, 50, 70 und 90 vol.-% hydrogen at up to 5 different load points. In addition, the influence of the air fuel ratio from near-stoichiometric to lean conditions (air ratio 1.5) and the influence of different external exhaust gas recirculation rates were examined.

Results

As the percentage of hydrogen increases, the shape, position and colour of the flame change, as can be seen in the overview of the flame images in
Figure 6. The optical changes are only minor up to a hydrogen content of 50 vol.-%. Here, basically distributed reaction zones are formed downstream the fuel injection location. With an admixture of 90 vol.-% and higher, the reaction zones become significantly more discrete and compact. This is due to the higher reactivity (higher flame speed & shorter ignition delay time) of hydrogen. In addition, the colour changes to blue / purple.

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[2] RMS: root mean square

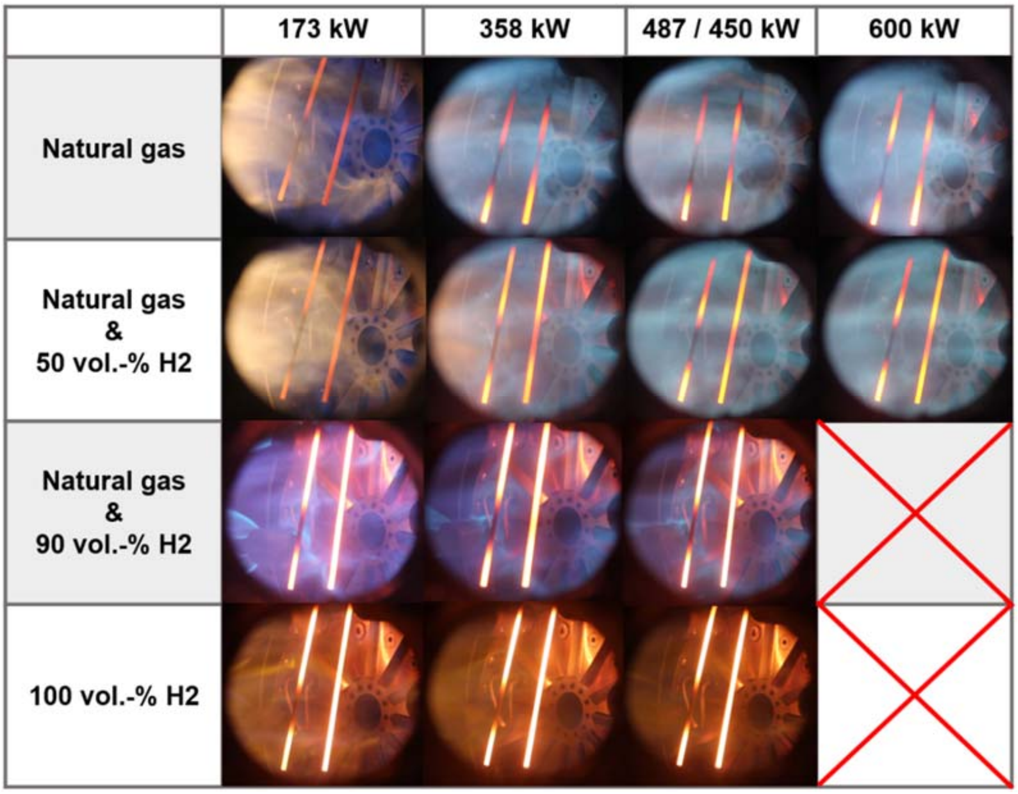

***Figure 6**: Photographic pictures of the flame with different thermal powers and fuel compositions up to 100 vol.-% hydrogen*

As expected, the reaction zones of the 100 vol.-% hydrogen flame are no longer clearly visible. Here, the flame appears yellowish which is mainly due to the glowing of the ionisation electrodes. In view of the visible increase of the thermal load of the ionization electrodes, it becomes clear that the main reaction zone of the combustion is moving upstream with increasing percentage of hydrogen.

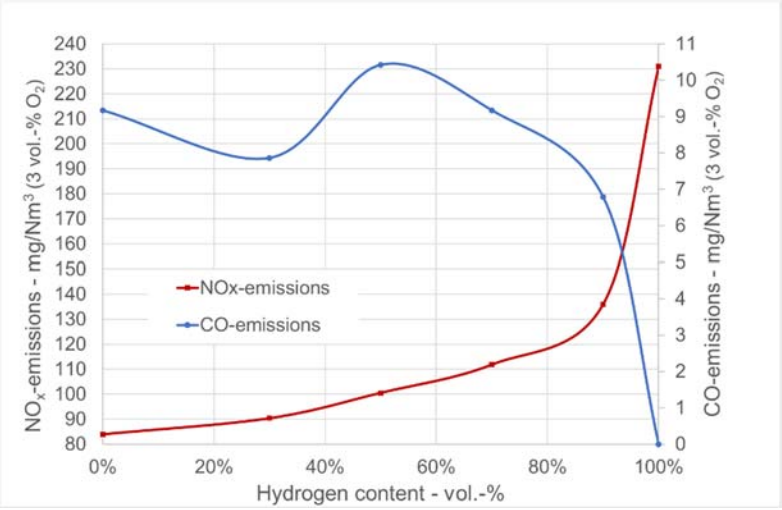

***Figure 7:** NO_x- and CO-emissions over the volume fraction of hydrogen with constant burner output and constant air fuel ratio*

With low and medium admixtures of hydrogen the increase of NO_x-emissions with increasing hydrogen content is moderate. From 70 vol.-% hydrogen and in particular from 90 vol.-% hydrogen, the NO_x-emissions rise sharply (see ***Figure 7***).

The increase in NO_x-emissions is primarily due to the formation of thermal NO due to higher adiabatic flame temperatures (see ***Figure 2***). In addition, the shorter flame and the associated reduced mixing of exhaust gas with air and fuel in the heat release zone enhances the NO_x-production. Another influencing factor is the particular mixture characteristics, which changes due to the different impulse ratio of the fuel and air. The CO-emissions drop slightly from a generally low level up to 90 vol.-% hydrogen. At 100 vol.-% hydrogen, no more CO can be determined due to the lack of carbon.

With the test conditions at GWI, a clear dependence of the NO_x-emissions on the volume load of the combustion chamber with a constant air fuel ratio was only visible at higher hydrogen contents above 70 vol.-%. Greater effects could be expected when using higher boiler temperatures (e.g. hot water and steam boiler) and other combustion chamber dimensions. Even a change in the air fuel ratio, as shown in ***Figure 8***, has no strong tendency with admixtures of up to 90 vol.-% hydrogen. At 100 vol.-% hydrogen, the increase in thermal power and the air fuel ratio have a positive impact on NO_x-emissions. However, compared to natural gas or natural gas-hydrogen mixtures, the emission level is in this case significantly higher. The reduction in NO_x-emissions at higher air fuel ratios can be explained by lower adiabatic flame temperatures and, compared to the other natural gas-hydrogen mixtures, to the greater change in the fuel impulse and the air / exhaust / fuel mixture.

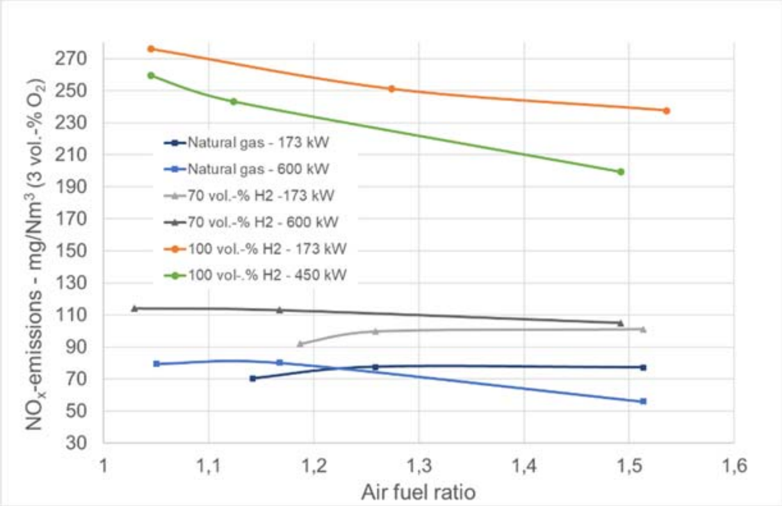

Figure 8: *Effects of the air fuel ratio on NO_x-emissions for natural gas, a mixture with 70 vol.-% hydrogen and 100 vol.-% hydrogen*

A significant NO_x reduction can be achieved, especially using 100 vol.-% hydrogen, by the external exhaust gas recirculation -dreizler® ARF-. With an exhaust gas recirculation rate[3] of 10 %, a reduction in NO_x-emissions of over 60 % to less than 100 mg/Nm^3 is achieved over the entire operating range (see ***Figure 9***). With a further increase of the exhaust gas recirculation rate, the NO_x-emissions can be reduced to less than 60 mg/Nm^3 in case of 100 vol.-% hydrogen combustion. However, at higher

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[3] Defined as the quotient of the exhaust gas volume flow of the recirculation and the total exhaust gas volume flow

exhaust gas recirculation rates, the condensation of exhaust gas components must be taken into account.

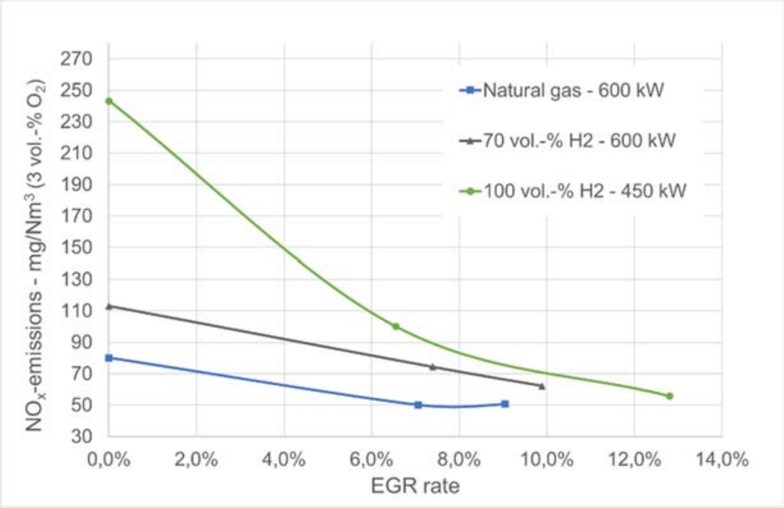

Figure 9: *Effects of external exhaust gas recirculation on NO_x-emissions for natural gas, a mixture with 70 Vol-% hydrogen and hydrogen*

The thermal load on the mixing device of the burner (e.g. gas nozzles, baffle plate) remains moderate even with increasing hydrogen content. While the influence of the thermal power is small using natural gas and natural gas-hydrogen mixtures, the influence of the shortened reaction zone can be observed clearly at low load with 100 vol.-% hydrogen. In medium and full load operation, the temperature drops to values comparable to natural gas even in the case of 100 vol.-% hydrogen combustion. In general, the component temperatures can be reduced with the external exhaust gas recirculation -dreizler® ARF- regardless of the fuel used.

Even with increasing percentage of hydrogen, the flame could be detected with the flame monitors used (Ionisation, UV and IR) in all operating ranges, as shown in ***Figure 10***. The ionisation current initially increases with higher share of hydrogen, which is also due to the shortened flame. At 100 vol.-% hydrogen the ionisation signal drops sharply as expected. The relatively high ionisation current measured may be explained by a minimal contamination of fuel and/or air. In addition, high exhaust gas recirculation rates lead to a further decrease of the signal. Here, the ionisation current is slightly above the threshold. The ionisation technique is therefore not suitable for reliable flame detection when using 100 vol.-% hydrogen and external exhaust gas recirculation.

The UV-RMS voltage decreases continuously with increasing hydrogen content, while the IR-RMS signal increases especially with high hydrogen content. In this test setup, however, the IR signal is influenced by the intensified glow of the ionisation electrodes.

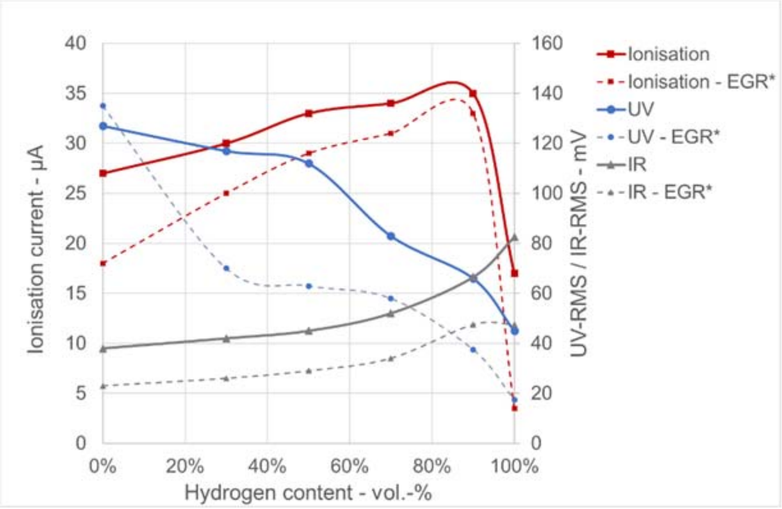

Figure 10: *Impact of hydrogen on flame monitoring (Ionisation, UV, IR) with constant thermal power*

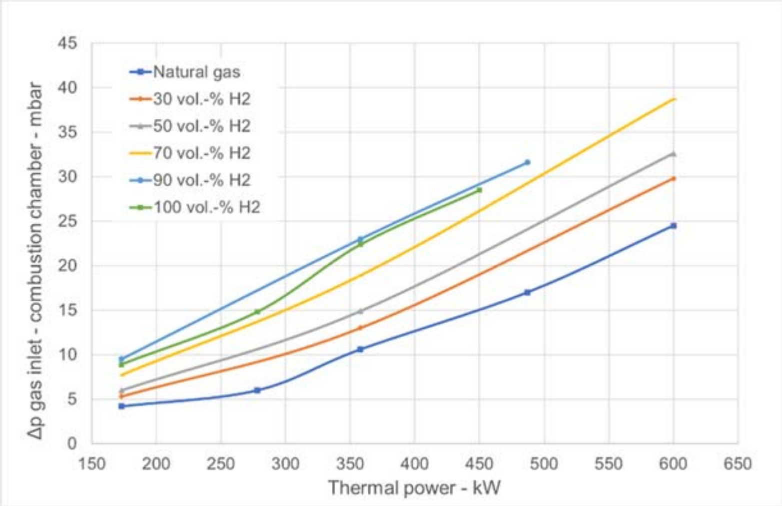

Figure 11: *Impact of hydrogen on the required pressure difference (gas inlet pressure – combustion chamber pressure) over thermal power*

Due to the lower calorific value of hydrogen in relation to its volume, a higher gas volume flow is required for the same thermal power.

Figure 11 shows the pressure difference between the gas inlet pressure upstream the open double gas valve and the combustion chamber pressure for natural gas, natural gas-hydrogen mixtures of any composition and 100 vol.-% hydrogen depending on the thermal power. Since the gas pressure is dependent on the gas volume flow and the gas density, it reaches a maximum at approx. 90 vol.-% hydrogen - analogous to the behaviour of the Wobbe number (see ***Figure 2***). It decreases again slightly for higher shares of hydrogen. At a thermal power of almost 500 kW, the pressure difference or the pressure loss respectively is nearly twice as much. However, in this test setup the pressure loss of the deflagration protection used is also taken in account for all gas mixtures, which is responsible for a large amount of the pressure losses measured.

In contrast to the gas volume, the required stoichiometric air volume flow per m^3 of gas decreases as the hydrogen content increases. Taking into account the higher gas volume flow to obtain the same thermal power the amount of air required is reduced by approx. 17 % for the use of 100 vol.-% hydrogen compared to natural gas. In the experiment, the reduction of the air flow could be demonstrated with comparable values.

Conclusion

The dreizler marathon® burners based on hollowflame® technology can be used with adaptations in a fuel-flexible manner for the operation of 100 vol.-% hydrogen, natural gas-hydrogen mixtures and natural gas. The increased thermal NO_x-emissions caused by the higher flame temperatures can be reduced to a value well below 100 mg/Nm^3 with moderate exhaust gas recirculation rates using the LOW NO_x hollowflame® technology combined with external exhaust gas recirculation -dreizler® ARF-. The measured thermal loads on the mixing device of the burner lead to greater wear, especially at low loads. This must be taken into account with adapted maintenance intervals and the appropriate selection of materials.

A volatile admixture of hydrogen requires additional measures to guarantee a safe operation, efficiency and compliance with emission regulations of a combustion plant. Fail-safe combustion control and optimisation is essential due to the changing air flow requirement of the gas mixture. In order to avoid underperformance or overloading of the boiler with increased volatile hydrogen feed-in, intelligent output control is required. The development of this safe fuel-air linkage control, for example on the basis of a fuel gas analysis and / or mass flow sensors, represents a future challenge for burner manufacturers, plant operators and gas suppliers.

In practice, for commissioning and maintenance, the commissioning engineers and service technicians have to know the currently prevailing gas composition for a safe adjustment of the devices. In the gas supply, attention must also be paid to hydrogen compatibility for all system components.

In order to generate long-term security for the manufacturers of burner systems for using fuels with hydrogen proportions higher than 10 vol.-%, the European regulations up to the requirements of the CEN standards must be developed and accepted as the basis for an EC-type examination.

References

[1] Bundesministerium für Wirtschaft und Energie, „Dialogprozess Gas 2030 - Erste Bilanz," Oktober 2019. [Online]. Available: https://www.bmwi.de/Redaktion/DE/Downloads/C-D/dialogprozess-gas-2030-erste-bilanz.pdf?__blob=publicationFile&v=4.

[2] Avacon Netz GmbH, DVGW-EBI, GWI, „H2-20 Wasserstoff in der Gasinfrastruktur: DVGW/Avacon-Pilotvorhaben mit bis zu 20 vol.-% Wasserstoff-Einspeisung in Erdgas," Oktober 2019. [Online]. Available: https://www.dvgw.de/themen/forschung-und-innovation/forschungsprojekte/dvgw-forschungsprojekt-h2-20/.

[3] H. Grüner, „Die Wasserstoff-Insel," *stadt+werk,* pp. 22-23, 5-6 2020.

[4] innogy SE, „Reallabor der Energiewende - SmartQuart: Energiewende im Quartiersmaßstab," [Online]. Available: https://projektinfos.energiewendebauen.de/projekt/smartquart-energiewende-im-quartiersmassstab/. [Zugriff am 9 Juni 2020].

[5] D. Dreizler, „Auswirkung von Wasserstoffbeimischung im Erdgas auf Gebläsebrenner," in *6.forum.feuerungstechnik TÜV Süd*, München, 2019.

[6] F. Joos, Technische Verbrennung, Berlin Heidelberg: Springer-Verlag, 2006.