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Hydrogen as an additive for biogas-powered combined heat and power plants

The use of hydrogen as an additive in internal combustion engines promises, in particular for gas-powered CHP plants, a reduction of harmful exhaust gas components, as well as an increase in the efficiency. For this reason, the inject of Hydrogenadditiv on the formation of formaldehyde has been studied. The experiments were performed for natural gas and two types of biogas with a hydrogen content of 0–9 vol.-%. The starting point for optimizing was the German emission standards of the Technical Instructions on Air Quality Control (TA Luft). Thereby it is possible to adjust the motor to reduced formaldehyde (HCHO), without degrading the efficiency.

Schlüsselwörter
Emissionen, Formaldehyd, Biogas, BHKW, elektrischer Wirkungsgrad

Keywords
Exhaust emissions, formaldehyde, biogas, CHP plant, electrical efficiency

Abstract

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The number of biogas plants in Germany has more than doubled between 2005 and 2010. This development has attracted more public interest and became a political issue. In 2002 the TA Luft (German Clean Air Act) set the limit for the formaldehyde (HCHO) emission produced by CHP plants at 60 mg/m_n^3. In the period thereafter significantly higher values were measured in a number of CHP plants, especially those using low gas operation. In 2012, the limit for formaldehyde was reduced to 40 mg/m_n^3.

For this reason, the formation of HCHO in biogas CHP plants has been studied in more detail [1, 2]. In their research on formaldehyde formation [2], Wachtmeister and Bauer concluded that state-of-the-art technology cannot meet such limits inside the engine without a negative effect on other parameters (efficiency, nitrogen oxides). Therefore, formaldehyde is being reduced by exhaust gas aftertreatment. The most commonly applied method for this purpose is the oxidation catalyst. Alternative possibilities include, for example, thermal post-combustion or systems based on gas scrubbing. Mixing hydrogen into the fuel gas is yet another possibility which has been studied in this research on CHP applications. Previous studies have already shown that in addition to the reduction of exhaust emissions an increase in efficiency could be achieved adding the hydrogen admixture into the fuel gases [3].

This study aimed at investigating the impact of hydrogen additive on levels of exhaust emissions and engine efficiency. The tests were designed to assess the potential of operating an engine without exhaust aftertreatment systems and still adhering to the limits set by the TA Luft.

Test Engine and Test Setup

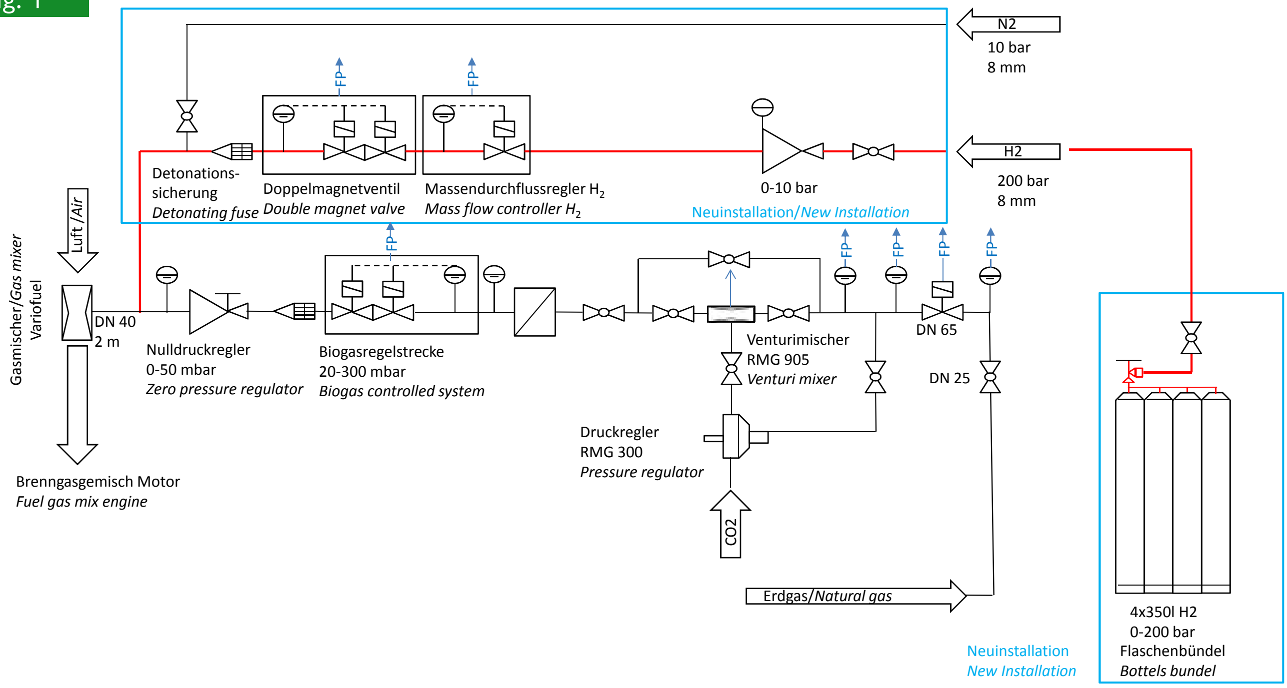
The investigation into hydrogen effects was performed using a turbo-charged gas engine. This 6-cylinder test engine had a maximum performance of more than 100 kW (**Table 1**). It was equipped with pressure and temperature sensors for oil, water

Table 1

Engine specification

Zylinderanzahl *Number of Cylinders*	6 in Reihe *6 in line*
Aufladung *Charging*	Abgasturbolader *Exhaust gas turbocharger*
Zündsystem *Ignition system*	Motortech MIC500
Gasmischer *Gas mixer*	Motortech Varifuel 2 für Erdgas/Biogas mit Luft RMG 985 für CO_2/Erdgas *Motortech Varifuel 2 for natural gas/biogas with Air RMG 985 for CO_2/natural gas*

Fig. 1



Scheme of the gas regulation unit of the engine test bench

and air as well as a pressure indicator for each cylinder. The engine was also fitted to measure fuel gas, airflow rate and exhaust gases.

Hydrogen was released between the zero-pressure regulator of the gas control knob and the gas mixer (**Figure 1**). Using the turbocharger compressor an almost ideal homogeneity of the fuel gas could be achieved. Safety was ensured with a control system using its own hydrogen detonation fuse, control valves and mass flow controllers. As well as this, a nitrogen releasing control circuit was installed, which would flush the hydrogen line with nitrogen, in case of a sudden engine stop. **Figure 1** shows the integration of the hydrogen control system as well as the structure of the existing gas control system for natural gas/biogas usage.

The exhaust gases were measured using an FAS-FTIR analysis system, provided by the Austrian engineering manufacturer IAG. The FTIR system was integrated into the test bed system for communication, data transmission and evaluation. With the view towards the TA Luft regulations, the primary focus of the measurements was on the nitrogen oxides (NOx), carbon monoxide (CO) and fomaldehyde (HCHO).

Test Procedure

Table 2 summarizes the conditions for the constant and **Table 3** the impact variables. The engine speed reached the standard 1 500 rpm in CHP applications.

The emission of exhaust pollutants was measured in ppm and adjusted to 5% oxygen (German standard TA Luft) in mg/m_n^3.

Table 2

General experimental conditions

Parameter/Parameter	**Bereich/Range**
Frequenz *Frequency*	50 Hz
Nenndrehzahl *Crankshaft rotation speed*	1 500 ± 5 min^{-1}
Leistung *Power*	83 ± 1.2 kW
Schmieröltemperatur *Lube oil temperature*	> 100 °C
Kühlwassertemperatur *Cooling water temperature*	90 °C ± 1 °C
Gemischtemperatur *Gas mixture temperature*	50 °C ± 1 °C

Table 3

Analyzed factors

Parameter/*Parameter*	**Bereich/*Range***
H_2 Vol.-% im Kraftstoff *H_2 Vol.-% in fuel*	0, 3, 6 and 9 Vol.-% ± 0.5 %
CO_2 Vol.-% im Kraftstoff *CO_2 Vol.-% in fuel*	40 and 50 Vol.-% ± 0.5 %
Luftverhältnis *Air-fuel ratio*	1.2; 1.3; 1.4; 1.5 and 1.6 ± 0.1
Zündzeitpunkt [°KW] *Ignition timing [°CA]*	334, 337, 340, 343 and 346

Table 4

Nomenclature

Abkürzung/*Abbreviation*	Beschreibung/*Description*
EG	Erdgas/*Natural gas*
BG 60/40	Biogas aus 60 % Methan (CH_4) und 40 % Kohlenstoffdioxid (CO_2)/*Biogas from 60 % methane (CH_4) and 40 % carbon dioxide (CO_2)*
BG 50/50	Biogas aus 50 % Methan(CH_4) und 50 % Kohlenstoffdioxid (CO_2)/*Biogas from 50 % methane (CH_4) and 50 % carbon dioxide (CO_2)*
ZZP	Zündzeitpunkt [°KW] *Ignition timing [°CA]*
λ	Luftverhältnis/*Air-fuel ratio*

The biogas composition (for biogas CHP) is strongly dependent on the substrate used. The experiment was therefore carried out using two different mixes and two types of biogas: biogas 50/50, biogas 60/40, and natural gas. The biogas mixture 60/40 was made up of 60 % methane (CH_4) and 40 % carbon dioxide (CO_2). The ignition timing points and air compositions were also varied. The investigation used differing hydrogen contents of the fuel gas mixture, varying between 0, 3, 6 and 9 volume percent. The lower limit of the air ratio was determined by a set NO_X limit. The upper limit was set with the engine just operating without misfiring.

Results and Discussion

In this paragraph, the impact of hydrogen injection on the exhaust gas and engine efficiency will be discussed, in particular focussing on the potential of biogas 50/50. This gas mixture is formed in the commonly found NaWaRo plants (renewable raw materials). These biogas CHP plants ferment manure and renewable raw materials (e.g. grass, grain, corn) to produce biogas. Parallel tests were carried out for natural gas and biogas gas 60/40 (**Table 4** and **5**).

For a plant operator it is important to achieve a high rate of efficiency and to adhere to the regulations set by the TA Luft. Therefore, the reference point was set close to the limit of the 500 mg/m_n^3 of nitrogen oxides. The limit for formaldehyde was set at 40 mg/m_n^3. These values define the possible ranges (**Figure 2**). The blue line represents the operating range for biogas 50/50 with hydrogen and the green line biogas 50/50 without the addition of hydrogen.

For purposes of comparison, the richest mixture was chosen, because it achieved the best efficiency in compliance with the emission limits (**Table 5**). Since the limit of CO emissions of 1000 mg/m_n^3 is always maintained by plants with less than 3 MW (**Figure 3**), this pollutant need not be considered further for determining a possible operating range. By adding hydrogen, the global and local combustion temperatures increased with the same ignition timing and same air ratio, allowing for NO_x emissions to exceed the permitted limit. Despite this, the formation of formaldehyde was inhibited. This observation was consistent with already known trade-off behaviour between nitrogen oxides and formaldehyde. By carefully selecting the air composition and ignition point, this phenomenon could be counteracted (**Figures 4**, **5** and **6**).

The hydrogen admixture changes the limit for the lean running of the engine, i.e. the limit for where no misfiring occurs. When operating under larger air ratios, the value of the NO_x limit can be maintained. In addition, the H_2 admixture increases the efficiency (**Figure 2**), which is all the more pronounced the later the ignition point is chosen. This is true for gas mixtures of natural gas and biogas 60/40 as well as for biogas 50/50. Moreover, the results of the analysed gas mixes revealed that H_2 admixture causes a shift of maximum efficiency to higher air ratios.

HCHO emissions behave differently to the emissions of nitrogen oxide. Due to the poorer combustion caused by the lower combustion temperature of the lean gas mixture, there is an increase in the HCHO emissions. This is clearly visible in biogas with air-fuel ratios λ = 1.51 (**Figure 5**). However, the need to run on biogas is not essential with air-fuel ratios (where

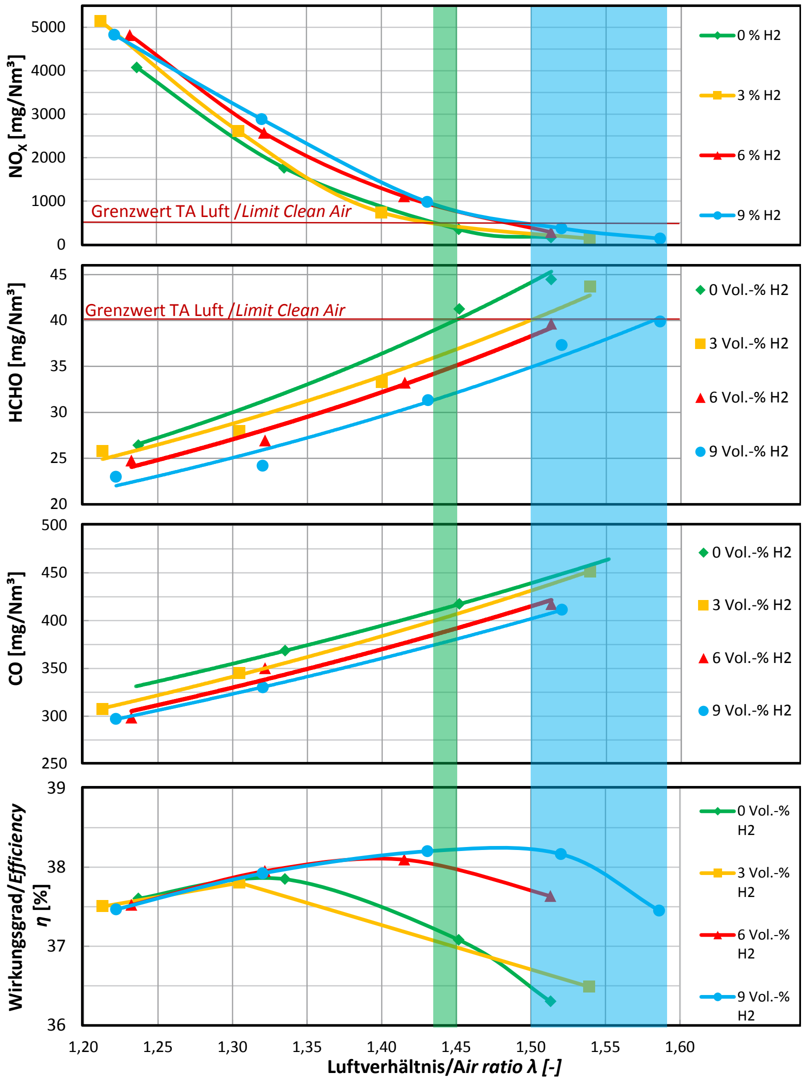
Table 5

Comparison of different fuel gases and their impact on hydrogen admixture

Gasart *Type of gas*	Wirkungsgrad *Effiency* [%]	NO_X [mg/m_n^3]	CH_2O [mg/m_n^3]	CO [mg/m_n^3]
EG	37.1	500	40	430
EG 9 Vol.-% H_2	37.7 (+1.34 %)[1)]	500 (-)[1)]	38 (-5 %)[1)]	420 (-2.3 %)[1)]
BG 60/40	37.7	500	40	428
BG 60/40 9 Vol.-% H_2	38.4 (+1.9 %)[1)]	500 (-)[1)]	37 (-7.5 %)[1)]	410 (-4.2 %)[1)]
BG 50/50	37.2	500	39.0	410
BG 50/50 9 Vol.-% H_2	38.2 (+2.7 %)[1)]	500 (-)[1)]	34 (-12 %)[1)]	375 (-10 %)[1)]

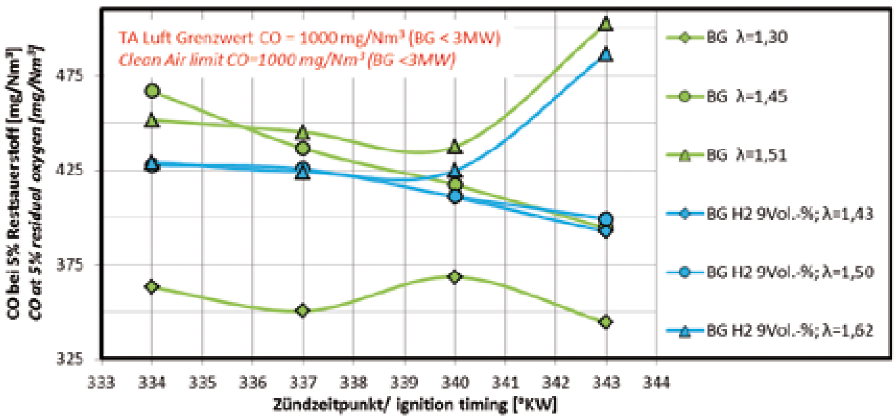
[1)] Der Wert bezeichnet den relativen Unterschied in % zu dem vergleichbaren Brenngas unter Einhaltung der TA-Luft-Grenzwerte./*This value means the relative difference in % of the similar fuelgas in terms of the TA-Luft limit values.*

Fig. 2



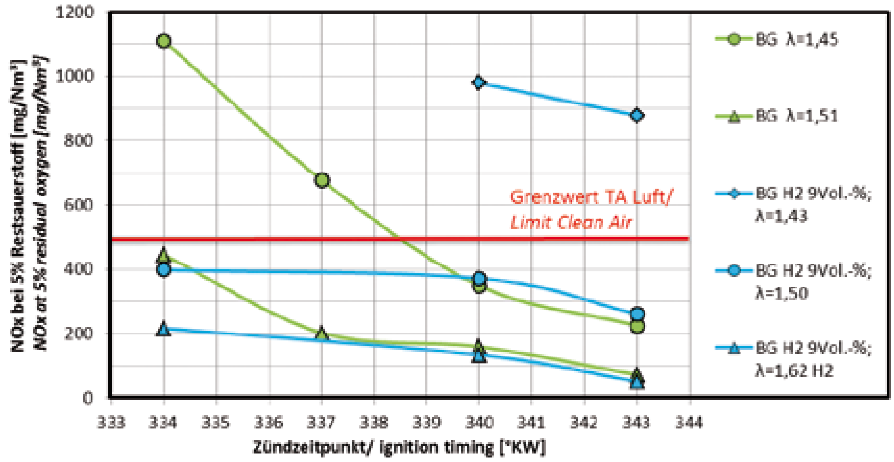
Influence of the hydrogen concentration and the air ratio on the efficiency and the exhaust emissions (NOx, HCHO, CO) at BG 50/50 [4]

Fig. 3



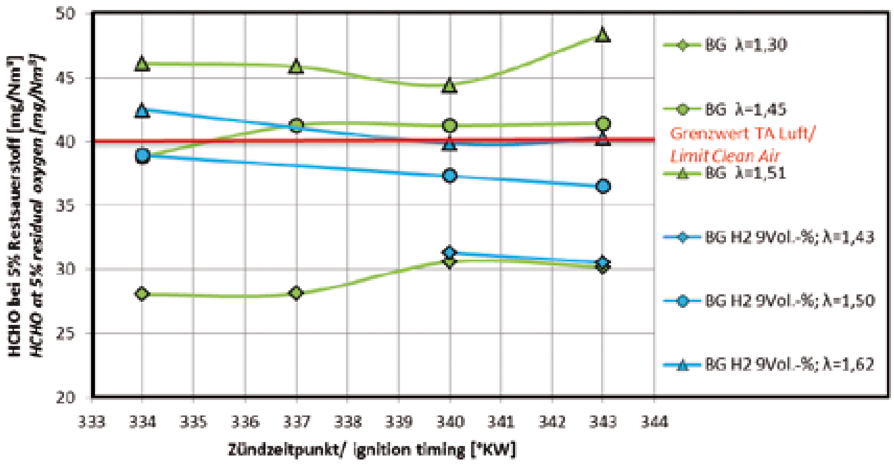
Influence of ignition timing on the CO-Emission of BG 50/50 with 0 and 9 vol.-% H_2 [4]

Fig. 4



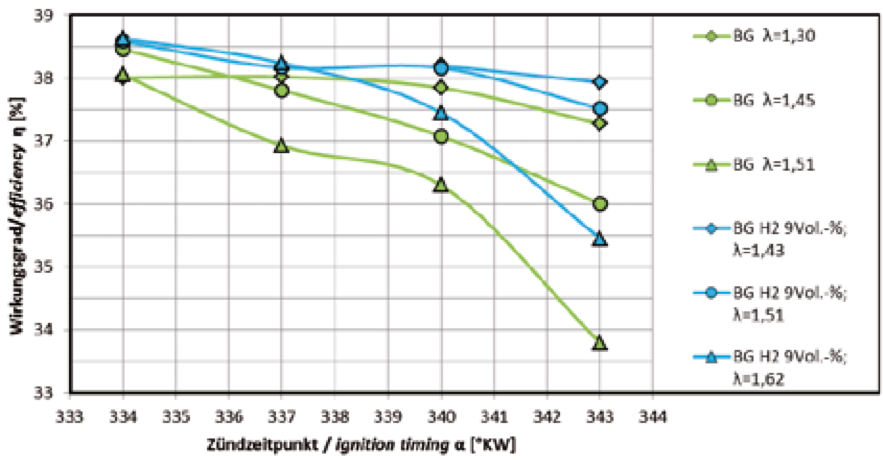
Influence of ignition timing on the NO_x-Emission of BG 50/50 with 0 and 9 vol.-% H_2 [4]

Fig. 5



H_2 / Influence of ignition timing on the HCHO-emission of BG 50/50 with 0 and 9 vol.-% H_2 [4]

Fig. 6



Influence of ignition timing and air ratio on the efficiency of BG 50/50 with 0 and 9 vol.-% H_2 [4]

λ > 1.45), since operations with biogas CHP for reasons of efficiency are rarely operated with air ratios, where λ > 1.40.

The engine, using the gas mixture biogas 50/50 with the addition of 9 volume percent hydrogen, saw an increase in efficiency to 2.7 % (1 % absolute). Simultaneously, the emission of HCHO decreased by 12 % and that of CO by 10 %. Only with the hydrogen additive it was possible to operate the engine without the need for exhaust aftertreatment (tested according to the current German Clean Air Act for CHP).

Overall, the results of the investigations into hydrogen as an additive for lean gas engines, can contribute to the development and optimisation of gas engines, improve the efficiency and reduce the impact on the environment, as the use of hydrogen increases the efficiency and reduces exhaust emissions.

Conclusion

The results from the research have shown that, with the addition of hydrogen to fuel gases, efficiency can be significantly enhanced and formaldehyde emissions reduced. However, with the addition of hydrogen, there is an increase in NO_x emissions. Nevertheless, the regulations set by the TA Luft can be met without the need for exhaust aftertreatment with parameters set for engine management, such as the air composition or the ignition timing point.

Although the effect of H_2 addition to all fuel gases is subjectively similar, the outcome is more pronounced in smaller calorific value fuel gases. Generally, all combustion gases show an increase in efficiency by increasing the hydrogen concentration in fuel gas.

The addition of hydrogen as a fuel additive in gas or biogas plans, which operate on lean gas, essentially depends on the costs that are incurred for hydrogen. As well as an economic study, leading measurements on other engines and biogas plants, continue to be made to improve the knowledge and mechanisms in the formation of HCHO and in the calibration of the engines.

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