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VIRTUAL NITROGEN OXIDE SENSOR FOR IMPROVED EMISSION CONTROL IN NATURAL GAS/HYDROGEN COGENERATION POWER PLANTS

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ABSTRACT: This study demonstrates the need for novel gas engine control systems for combined heat and power plants, also known as cogeneration power plants, connected to natural gas grids. Hydrogen addition to natural gas grids in a range of up to 5% by volume is already permitted throughout Europe. This offers the possibility to reduce carbon dioxide emissions of end consumers connected to public natural gas grids and contributes to climate protection. However, conventional engine controls are not designed for natural gas/hydrogen mixture operation. We tested fuels with up to 30% hydrogen by volume using a commercial six-cylinder spark ignition engine, designed for natural gas or biogas operation in power plants. With engine settings according to usual cogeneration operation, nitrogen oxide emissions increased exponentially with increasing hydrogen amounts. We demonstrate that the usual approach of using the lower heating value of the fuel mixture to regulate the engine is unable to accommodate the hydrogen induced changes. For this reason, we developed a mathematical model to determine the nitrogen oxide emissions based on boost pressure and power output. The idea behind this novel approach is to regulate the engine based on emissions, regardless of the fuel gas. In this work the approach for this virtual sensor is described and its performance demonstrated.

KEY WORDS: *Hydrogen; Virtual Sensor; CHP-unit; Natural Gas; Cogeneration.*

1. INTRODUCTION

The transition to a climate-neutral energy supply is a critical challenge facing society, as it has the potential to mitigate the impacts of climate change, reduce dependence on fossil fuels, and promote sustainable economic growth. One of the key challenges in achieving a climate-neutral energy supply is the storage of large amounts of green energy. Among the various energy carriers, hydrogen has emerged as a promising candidate due to its

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ability to store and convert back into electricity in large quantities relatively easily. As a result, the establishment of hydrogen storage and transport infrastructure is being planned in the European Union (Hydrogen Council, 2017).

However, the transition to a hydrogen-based energy system also presents a number of technical challenges, particularly in the context of existing natural gas grids. To reduce the carbon dioxide emissions of current natural gas consumers, hydrogen is intended to be injected into existing natural gas grids as intermediate step. However, the impact of this on consumers connected to the grid is still the subject of current research.

Focus of the present study are the challenges for natural gas engines in combined heat and power plants (CHP-units) that usually employ a control system to keep the lower heating value (LHV) of air/fuel mixture $h(\lambda)$ at a preset value. If a change in this value is registered, the system reacts by making the mixture richer or leaner (decrease or increase the equivalence ratio λ), ensuring that ideal engine running is guaranteed while complying with the legal exhaust gas limits (Zacharias, 2001). However, if hydrogen is part of an air/fuel mixture with an equivalence ratio λ according to the manufacturer's recommendation for pure natural gas, the air/fuel mixture can and must be made leaner in order to comply with the legal nitrogen oxide (NO_x) emission limits (Mehra et al., 2017; Yan et al., 2018).

The analysis reveals that the usual approach of using the lower heating value of the air/fuel mixture $h(\lambda)$ to adapt the equivalence ratio λ to different fuels is not suitable in case of hydrogen admixture. The LHV of hydrogen itself is lower that the LHV of natural gas, but the air demand for a complete combustion is also lower. Hence, an air/fuel mixture with a certain LHV corresponds to a certain equivalence ratio λ, independent of the hydrogen amount in the fuel. As a result, the faster and hotter burning hydrogen would cause exponentially rising NO_x-Emissions. To address this issue, a mathematical model to determine the nitrogen oxide emissions from boost pressure and power output is presented. This virtual sensor can be used as the key component of a novel mixture control system for natural gas engines in cogeneration power plants, which do not rely on the lower heating value of the air/fuel mixture.

2. EXPERIMENTAL SETUP

Figure 1 depicts the fuel supply system utilized in this study, which enables the engine to operate with mixtures of natural gas (NG) and hydrogen (H_2). The H_2 is obtained from bottles, whereas the NG is derived from the public grid and consists of 96% methane, 3% ethane, and 1% traces of other gases. Precise measurement of the flow rates and stepless mixing ratios of both gases are facilitated through separate mass flow controllers. The NG/H_2 fuel gas mixture is blended with air in a venturi gas mixer. The resultant fuel/air mixture is then compressed with a turbocharger, intercooled, and delivered to the engine through a throttle valve.

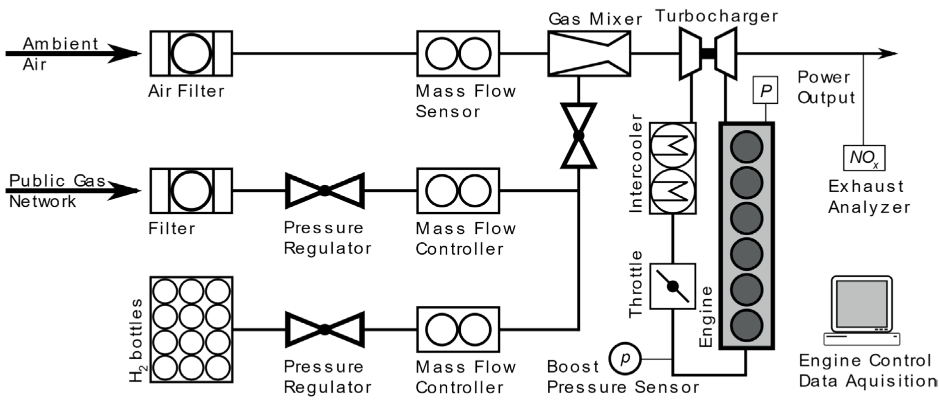

Figure 1. Schematic drawing of the engines fuel supply system.

The six-cylinder MAN engine used in this study was specifically designed for natural gas and biogas operation. The engine is controlled by self-developed software, which allows for the variation of engine parameters such as ignition timing, throttle valve position, and mixture control. Additionally, the software is able to record the values of all sensors installed at the engine test bench.

The input variables for the virtual sensor are the boost pressure and the output power. The boost pressure is measured after the throttle valve using a common pressure sensor, while the power output is calculated using the torque measured at the crankshaft and the engine speed.

To verify the calculated NO_x emissions, an MRU 'Vario plus' exhaust analyzer is employed.

3. RESULTS

3.1 Lower Heating Value of Hydrogen containing Fuels

The standard reference variable for gas engines in cogeneration power plants is the lower heating value (LHV) of the fuel gas mixture h(λ). If e.g., the methane content of the natural gas changes, the LHV of the air/fuel mixture also changes. However, substitution of natural gas with hydrogen within the currently allowed range in Europe (up to 5%) does not have an impact on the LHV (as shown in Figure 2), and therefore, conventional gas engine controls do not react and instead, keep the equivalence ratio λ constant. This poses a challenge as the nitrogen oxide emissions exhibit an exponential increase with rising amounts of hydrogen if the engine control system does not intervene by leaning the air/fuel mixture (Mehra et al., 2017; Yan et al., 2018; Fichtner et al., 2023).

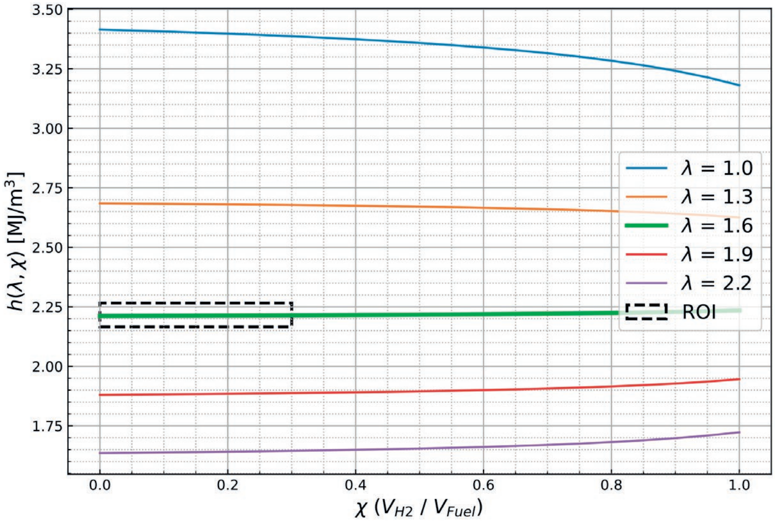

Figure 2. Lower Heating Value h of air/fuel mixtures with various equivalence ratios λ versus hydrogen fraction χ. The region of interest (ROI) for the experiment is indicated by the dashed black box.

3.2 NOx-Emissions – Correlation with Boost Pressure and Power

To address this issue, a comprehensive parameter scan was conducted. The parameter space included power outputs P ranging from 60kW to 110kW in steps of 10kW, hydrogen concentrations of 0 - 30% vol., and equivalence ratios of $\lambda = 1.55 - 1.95$. Figure 3 shows the most interesting correlation found in the experiment. The nitrogen oxide emissions measured at the stable operating points are plotted against the boost pressure. Each data point corresponds to a distinct engine adjustment in terms of power output, equivalence ratio, and hydrogen content of the fuel supplied. Each engine parameter was measured continuously at an interval of one second. The data points shown in Figure 3 represent the average of 100 consecutive measurements taken over a period of 100 seconds, the error bars represent the standard deviation.

Apparently, the data is on asymptotically falling curves. As a first approach to describe the correlation between boost pressure and nitrogen oxide emissions mathematically, a power law model was used.

3.3 Mathematical Model

Plotting the NO_x emissions against the boost pressure revealed that the emissions follow asymptotically falling curves, with each curve corresponding to a specific power output P. When plotted on a double-logarithmic scale, a family of parallel lines emerged,

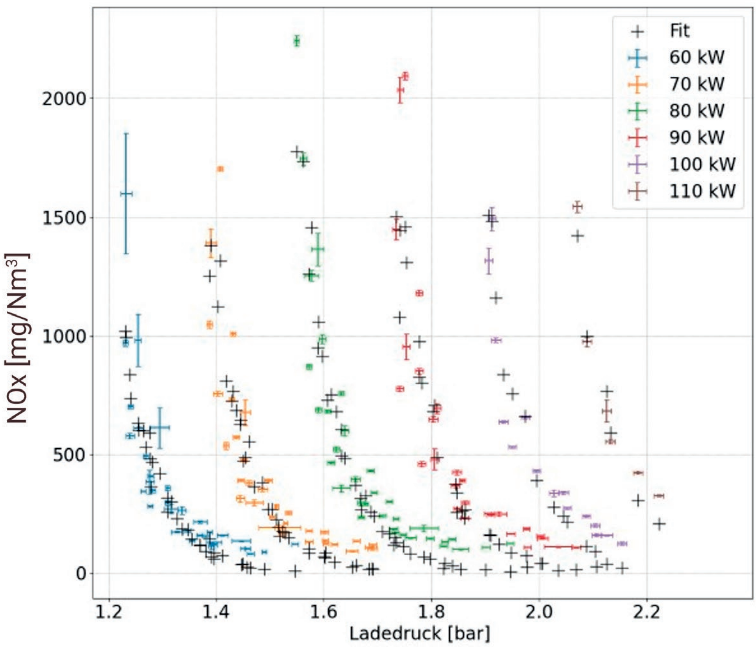

Figure 3. Nitrogen oxide emissions versus boost pressure. The measured data forms exponentially falling curves. Each curve represents a certain power output.

suggesting that the relationship between NO_x emissions and boost pressure could be approximated using the following equation:

$$\log(NO_x\,(p)) = \log(a) + b \cdot \log(p) \tag{1}$$

Thus, $\log(NO_x(p))$ can be represented by a straight line with intercept $\log(a)$ and slope b, where both parameters depended on the power output P. For simplicity of the model, a linear dependency was assumed for both parameters, resulting in the following equations:

$$b = \alpha + \beta \cdot P \text{ and } \log(a) = \gamma + \delta \cdot P$$

The final model for NO_x emissions, $NO_x(p,P)$, is thus given by the following expression:

$$NO_x\,(p,P) = e^{\gamma+\delta \cdot P} \cdot p^{\alpha+\beta \cdot P} \tag{2}$$

It is important to keep in mind, that the given model is a first approach. The exponential relationship and the power relationship are not based on physics but justified by straight lines in a log-log plot of the data. The linear dependency of the parameters (b and $\log(a)$) and the engines power output are just a first try.

The mathematical model was fitted to the data and was found to describe the curve progressions well (see Figure 3). It must be mentioned that the constants are probably individual for each engine. The optimal fit for the engine in the experiment presented here was obtained using the following constants:

$$NOx\ (p,P)=e^{-(4.03-0.23\cdot P)}\cdot p^{-(8.56+0.10\cdot P)} \tag{3}$$

The comparison between measured data and fit shows that there is still potential for optimization in the model. For a first approach, however, the result is quite promising. The circumstance that nitrogen-oxide emissions decrease as boost pressure increases is reproduced well. This outcome was expected since a high boost pressure at a fixed power output implies a lean mixture. A leaner mixture results in a colder combustion process, which in turn leads to lower nitrogen-oxide emissions (Ma, 2008).

3.4 Real-Time Capability

After the determination of the model constants, a continuous engine run lasting 140 minutes was conducted to test the model. During the engine run, the hydrogen content in the fuel was varied between 0 and 30 percent by volume. Power output, equivalence ratio, and ignition timing were also varied. Each of the mentioned parameters has a significant impact on NO_x emissions (Fichtner et al. 2023; Ma et al. 2010; Quader 1974).

The results are presented in Figure 4, which shows that the model provides a good approximation of the actual measured emissions. In general, our model is suitable for

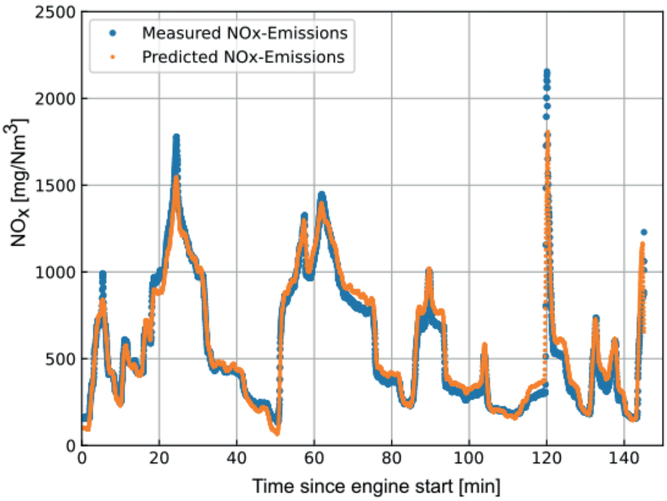

Figure 4. Nitrogen-oxide emissions during a continuous engine run of 140 minutes. Blue dots represent the measured data, orange dots are calculated from boost pressure and power output with the help of the presented mathematical model.

application as virtual NO_x sensor which can detect emissions independently of the fuel gas supplied. Before that, the model needs to be further improved, but the first approach presented here is promising. This also means that the chosen approach is suitable for the development of a mixture control system for cogeneration power plants that can effectively respond to hydrogen-containing fuel gases.

4. CONCLUSION

In summary, our study investigated the impact of hydrogen-containing fuel gases on nitrogen oxide emissions in cogeneration power plants. We found that gas engine controls which keep the lower heating value of the air/fuel mixture constant, are unable to respond to hydrogen admixture within the allowed range in Europe and above. This results in exponentially increasing nitrogen oxide emissions with increasing hydrogen content. To address this issue, we conducted a comprehensive parameter scan and developed a mathematical model that describes the impact of hydrogen content and other engine parameters on nitrogen oxide emissions. The model was validated in a continuous engine run, demonstrating that it can effectively detect emissions independent of the supplied fuel gas. Our findings highlight the potential of our approach to develop a mixture control system that can respond appropriately to hydrogen-containing fuel gases in cogeneration power plants, thereby mitigating their impact on nitrogen oxide emissions.

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AUTHOR CONTRIBUTIONS

Johannes Fichtner: *Conceptuation, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Supervision, Visualization, Writing – original draft.* Adrian Gegner and Jan Ninow: *Validation.* Joerg Kapischke: *Funding acquisition.*

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