Overcoming Misfire in Large Bore Gas Engines Fueled with High Inert Content Flare Gases

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Abstract

A byproduct of the oil and gas industry, flare gas represents a significant source of energy that should not be wasted. Different wells or refinery stages produce waste gases of various qualities. Using these non-standard quality gases for power generation in a large gas engine requires a robust combustion concept and engine controls. For cost-effective use of stationary gas engines in power generation, the key factors are power output, compliance with emission legislation and anomaly-free engine operation (misfire or knock). Higher hydrocarbons and hydrogen increase the knock tendency. Inert gases, on the other hand, decrease it but can lead to misfire. Flare gases are typically rich in carbon dioxide (CO_2), an inert gas that destabilizes the combustion process. The research described in this paper concentrates on operation of a single cylinder large gas engine (SCE) with inert gas-rich propellants. Sixteen different gas blends consisting of natural gas (mainly CH_4), propane (C_3H_8), hydrogen (H_2) and carbon dioxide (CO_2) were investigated. The inert gas fraction was increased until stable combustion behavior at minimal power output (considering engine start behavior) and knock-free overload capability in compliance with standard European emission controls (TA Luft) appeared to be feasible with a multicylinder engine. The SCE results indicated that there was a sudden transition to unstable engine operation with several of the gas blends. Misfire occurred due to misfire in the prechamber. Tests revealed two operating parameters that influence the misfire/start-up behavior: the global air-fuel ratio and the prechamber fuel gas supply. Under the chosen boundary conditions, all gas blends were capable of overload. Following the tests, 1D simulations were conducted to determine the cause of the sudden transition to misfire and therefore unstable engine operation at a gas blend-specific power output. Increasing the carbon dioxide content replaces oxygen and hence enriches the prechamber. If the prechamber air excess ratio (AER) drops below a certain level, the prechamber starts misfiring. Further investigations with various gas blends revealed an almost steady AER value for and an abrupt transition to misfire.

Kurzfassung

Flaregas, ein Nebenprodukt der Öl- und Gasindustrie stellen eine wichtige Energiequelle dar, weshalb sie nicht verschwendet werden dürfen. Unterschiedliche Förderquellen und Prozesse in der Raffinerie liefern Gase unterschiedlicher Zusammensetzung. Eine Nutzung dieser nicht standardisierten Gase in der Energieerzeugung mittels Großgasmotoren erfordert robuste Brennverfahren und Regelungsstrategien. Die Schlüssel für eine wirtschaftliche Nutzung von Stationärmotoren zur Energieerzeugung sind Leistung, Einhaltung der Emissionsvorschriften sowie ein Motorbetrieb ohne Anomalien (Klopfen und Aussetzen). Höhere Kohlenwasserstoffe und Wasserstoff steigern die Klopfneigung. Demgegenüber verringern Inertgase die Klopfneigung, können aber zu Zündaussetzern führen. Flaregase enthalten typischerweise große Anteile an Kohlendioxid (CO_2), ein Inertgas, welches den Verbrennungsprozess destabilisiert. Die präsentierten Forschungsergebnisse konzentrieren sich auf den Betrieb eines Einzylinder-Forschungsmotors (SCE) mit Inertgas-reichen Kraftstoffen. Sechzehn verschiedene Gaszusammensetzungen, bestehend aus Erdgas (hauptsächlich CH_4), Propan (C_3H_8), Wasserstoff (H_2) und Kohlendioxid (CO_2) wurden untersucht. Der Inertgasanteil wurde gesteigert, wobei eine stabile Verbrennung bei minimaler Leistung (zur Abbildung des Motorstartverhaltens) und Klopf-freier Überlastbetrieb unter Einhaltung von Europäischen Abgasgrenzwerten (TA Luft) auch für einen Vollmotor möglich sein sollte. Die Ergebnisse vom Einzylinderforschungsmotor zeigten einen spontanen Übergang zur instabilen Verbrennung mit einigen Gaszusammensetzungen. Aussetzen trat aufgrund von Zündaussetzern in der Vorkammer auf. Die Versuche offenbarten weiterhin zwei Betriebsparameter, welche starken Einfluss auf Aussetzen in der Teillast besitzen: das globale Luftverhältnis und die Vorkammergasversorgung. Unter den ausgewählten Randbedingungen war ein Überlastbetrieb für alles Gaszusammensetzungen möglich. Im Anschluss an die Versuche wurden 1D Simulationen zur Bestimmung der Ursache für das plötzliche Auftreten von Zündaussetzern und damit den instabilen Motorbetrieb bei gasspezifischen Leistungen durchgeführt. Eine Steigerung des Kohlendioxid-Anteils verdrängt Sauerstoff und führt damit zu einer Anfettung der Vorkammer. Fällt das Luftverhältnis in der Vorkammer unter einen gewissen Schwellwert führt dies zu Zündaussetzern. Weitere Untersuchungen mit unterschiedlichen Gaszusammensetzungen enthüllten eine nahezu konstante Schwelle im Luftverhältnis welche den plötzlichen Übergang zum aussetzenden Betrieb markiert.

Introduction

As the global population continues to grow, world energy demand is increasing. Incentives through new and proposed emission policies are pushing energy suppliers to invest into alternative fuels. These fuels might originate from biomass feedstock (e.g., biogas), power-to-gas technologies (hydrogen-rich gases) or industrial processes. To further reduce costs, previously neglected fuel sources are becoming more and more interesting. Waste gases from oil and gas production or industrial processes have been flared in the past because of technical, regulatory, or economic constraints. Approximately 140 billion cubic meters of natural gas are flared every year, causing more than 300 million tons of carbon dioxide emissions. [1][2] Flare gases vary in quality (composition) and quantity, from source to source on the one hand and over time on the other hand. This places high demands on the exploitation concepts. Large bore gas engines in combined heat and power applications are a valuable option that make it possible to exploit these non-natural gases (NNG) in an economically sound manner. [3]

Today's large bore gas engines for power generation have to provide high power output along with high energy conversion efficiency. At the same time, they have to fulfill stringent emission regulations. Low NO_x emissions in particular can be achieved by employing a lean combustion concept. To ensure ignition, short combustion durations, and high conversion efficiency for cylinder bores in the range of 200 mm and above, it is necessary to amplify the spark ignition. A proven approach is to use a scavenged prechamber, which facilitates stable ignition by optimizing the conditions in the spark gap. Flame torches that exit the bores that connect the pre-combustion chamber to the main combustion chamber cause improved inflammation of the lean cylinder charge. In scavenged prechamber concepts, a small amount of gas is fed into the prechamber through a specially designated gas valve. The scavenging process usually takes place during the cylinder intake process. Lean mixture from the main combustion chamber is forced into the prechamber during the compression phase. The lean mixture from the main combustion chamber mixes with the pure propellant inside the prechamber. This creates a mixture with high energy density and favorable conditions for ignition. [4][5][6]

However, as the previous statement is true for natural gas applications it is still worth to investigate the suitability of scavenged prechamber combustion concepts also for non-natural gas applications. A high carbon dioxide fraction of the fuel gas in particular might give some drawbacks to using off-the-shelf combustion concepts.

Experimental Investigations

The experimental investigations of the suitability of standard combustion concepts for flare gases were carried out on a single-cylinder research engine (SCE) using the LDM Compact development method (cf. [3]). The single-cylinder research engine is based on a large gas engine for power generation with two-stage supercharging, gas-scavenged prechamber and a lean-burn combustion concept with spark ignition (Table 1). The LEC single cylinder engine consists of a base frame that houses the engine's power unit and the single cylinder crankshaft. This engine also has first and second order mass balances, an oversized flywheel and a four-quadrant dynamometer to drive and brake the engine. The charge air is delivered by a screw-type compressor. The air is cooled for dehydration and then heated to the desired level. The water content of the cylinder charge is adjusted via steam admixed to the charge air. The fuel gas is mixed with the charge air on the high pressure side using a Venturi mixer. To simulate the exhaust back pressure of the multi-cylinder engine, a throttle flap is placed in the exhaust duct. The engine back pressure is calculated using the turbocharger equilibrium equation for constant gas properties on the compressor and turbine side, constant charging efficiency and constant control reserve and constant ambient conditions. As a result, the exhaust back pressure is a function of intake manifold pressure and exhaust gas temperature.

Table 1: Engine setup

Displacement [dm³]	~ 6
Rated speed [rpm]	1500
Nominal BMEP [bar]	22
Engine process	Four stroke spark ignited
Combustion concept	Scavenged prechamber with passive prechamber gas valve
Mixture preparation	Homogeneous with lean A/F mixture
Gas exchange	Single four valve cylinder heads Advanced early Miller timing
Ignition	High energy capacitive discharge
Charging concept MCE	Two stage (4 TC) with two stage mixture cooler Power control via compressor recirculation and throttle valve

The SCE test bed is equipped with an exhaust gas analysis device that determines the concentrations of the most important components, namely CO_2, O_2, CO, THC, CH_4 and NO_x. The cylinder head of the engine houses fast pressure transducers that indicate the pressure trace in the main combustion chamber and prechamber as well as in the intake duct and exhaust duct.

In developing combustion concepts for non-natural gases, the most important infrastructure consists of the gas mixing device along with gas supply, storage and safety technology. Using the gas mixing device, virtually every gas composition consisting of natural gas, propane, hydrogen, carbon dioxide, nitrogen and carbon monoxide can be tested on a single cylinder engine.

The aim of the investigations was to demonstrate the application limits for different flare gas qualities with a standard combustion process and off-the-shelf components. A total of 11 different gas compositions were investigated, with a focus on high hydrogen and high CO_2 contents. The measurement program provided for a simplified screening of the different gas compositions with regard to maximum achievable mean pressure and knock limit. A brake mean effective pressure increase was carried out starting at 50 % load and constant NO_x emissions of 500 mg/nm³ (TA-Luft [7]) and constant center of gravity of combustion up to an overload of 110 %. If the overload could not be achieved due to knocking combustion, the NO_x emission level should be lowered in a further step to enable a further increase in power output by increasing the distance to the knocking limit. The screening showed that with almost all investigated gas compositions it was possible to achieve overload without abnormal combustion. Only with one specific gas composition (GT5) stable operation was not possible at the starting point of 50 % load, which is why the rest of the investigation was also suspended. GT5 has a high inert gas content of 55 $\%_v$ and a low hydrogen content of just 4 $\%_v$. Table 2 compares three representative gas compositions of the prior investigations regarding their specific properties.

Table 2: Investigated base gas compositions

Gas		NG	GT4	GT5
CH_4	$\%_v$	100	39	35
C_3H_8	$\%_v$	0	6	6
H_2	$\%_v$	0	5	4
CO_2	$\%_v$	0	50	55
MN excl. Inerts	-	100	60	60
MN incl. Inerts	-	100	111	125
Density	kg/nm^3	0.717	1.398	1.463
LHV	kJ/kg	50125	14529	12706
Energy Density	kJ/nm^3	35930	20304	18588

In order to investigate the reason for the inadequate combustion stability at low mean effective pressures, the CO_2 content should be increased based on a gas composition (GT4) in small increments, thus determining the limit of stable combustion. An effective means to increase the combustion stability at low mean effective pressures is to substitute a part of the non-natural gas with natural gas. In order to determine the lower mean effective pressure limit of stable combustion as a function of natural gas substitution and CO_2 content, the measurement program of the initial screening was reversed. Starting from the overload operating point, the mean effective pressure was reduced under constant NO_x emissions and constant combustion phasing until misfiring occurred. The misfire limit was determined by a threshold value in the coefficient of variation of the indicated mean effective pressure. This procedure was performed for a matrix of 12 different gases (Table 3).

Table 3: Altering gas composition for a detailed assessment of the lower BMEP stability limit

CO2 / NG	0 $\%_v$	+5 $\%_v$	+10 $\%_v$
0 $\%_v$	GT4 (Baseline)	GT4-5	GT4-10
5 $\%_v$	GT4/5	GT4-5/5	GT4-10/5
10 $\%_v$	GT4/10	GT4-5/10	GT4-10/10
20 $\%_v$	GT4/20	GT4-5/20	GT4-10/20

Thus, for the base composition it can be shown that a sufficiently stable combustion can be achieved over the entire investigated load range (Figure 1). However, substitution by natural gas does not significantly improve combustion stability. As soon as the inert gas content is increased starting from GT4, the lower mean effective pressure limit changes. Even if the inert gas content is increased by only 5 $\%_v$, the lowest possible mean effective pressure rises from 12 bar BMEP to 17 bar BMEP. However, it can be seen that a substitution of flare gas by natural gas increases combustion stability, so that lower loads can be demonstrated. A further increase of the inert component by 5 $\%_v$ (GT4-10) means that not even the overload can be operated without misfire. Again, a substitution causes a possible mean effective pressure reduction.

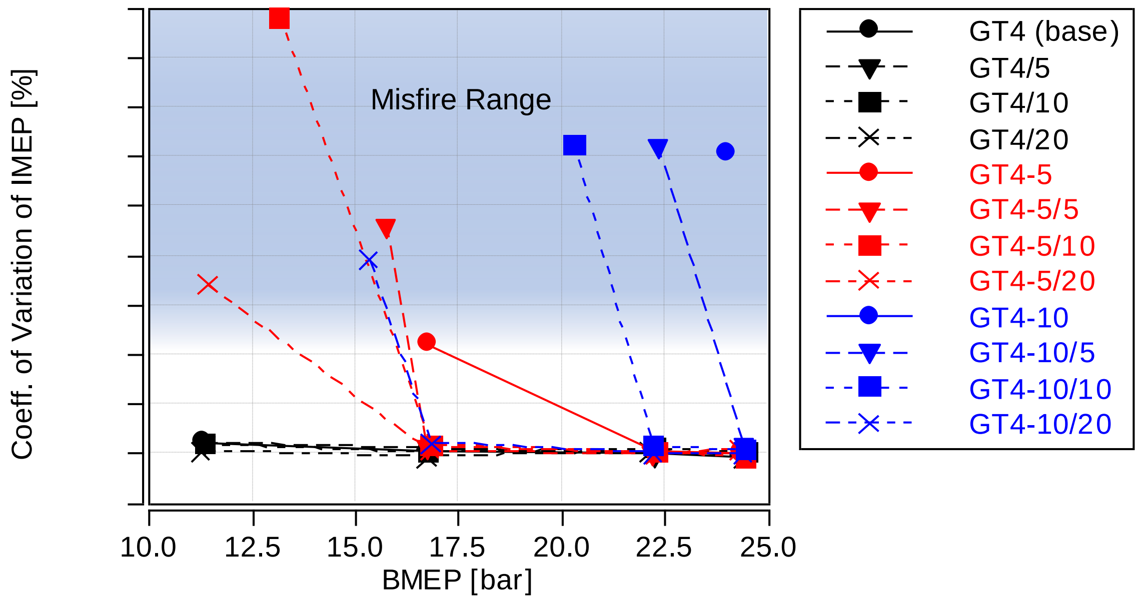

Figure 1: Increasing part load combustion stability by NG substitution

A closer look at the indicated cylinder pressure revealed the cause of the low combustion stability. The operating points with a high coefficient of variation of the indicated mean effective pressure showed individual cycles without combustion, i.e. actual misfiring. As Figure 2 shows, the cause for the misfiring is not an inadequate combustion in the main combustion chamber. Rather, there is already a lack of combustion in the prechamber which subsequently cannot initiate combustion in the main combustion chamber. It should be pointed out here that these are not regular but stochastically occurring misfires events in the prechamber.

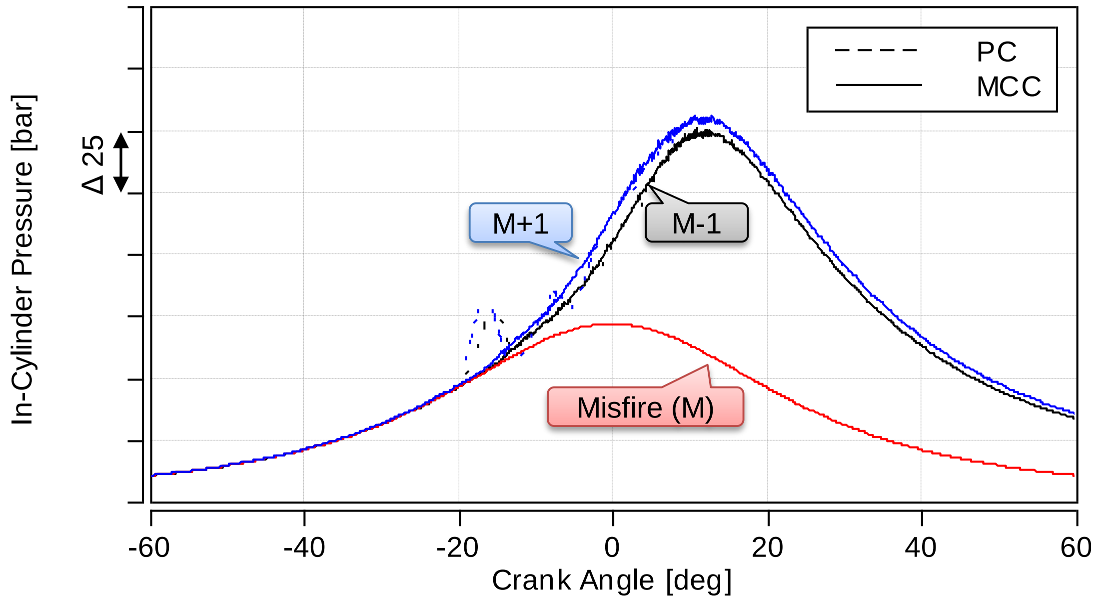

Figure 2: Stochastic misfire events in prechamber

Since the step size for determining the minimum stable load was roughly defined during the screening phase, the next step was to clarify whether the transition to misfire was continuous or erratic. Figure 3 shows the comparison of two measurement series with coarse and fine screening for the gas composition GT4-5. With a correspondingly small step width of only 0.25 bar BMEP (red curve), it can be seen that the transition occurs abruptly. However, the lower stability limit is approximately at the same mean effective pressure.

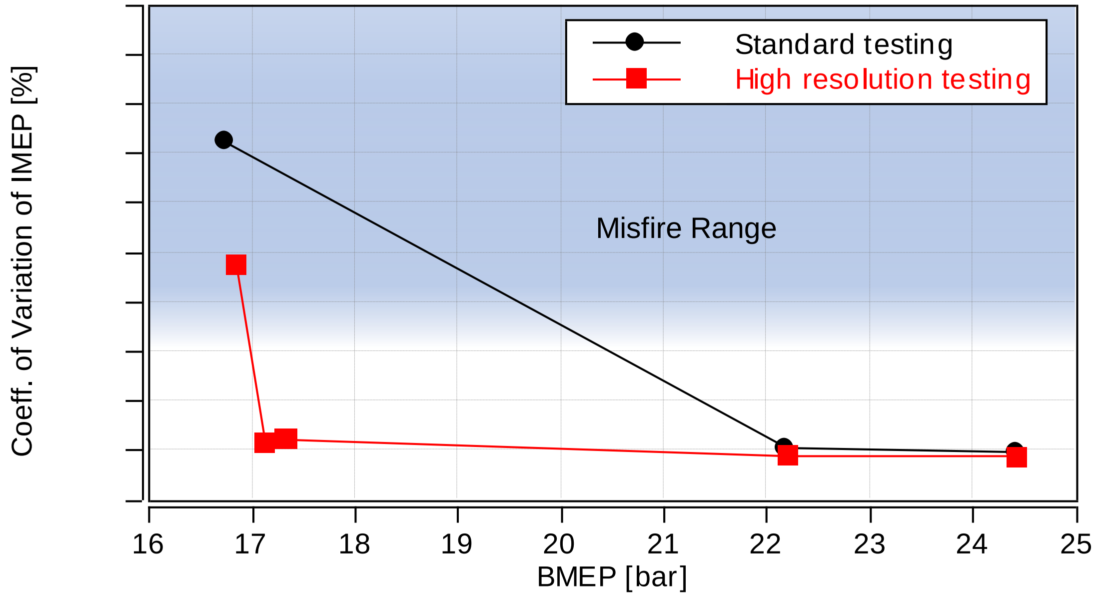

Figure 3: Determination of the transition to misfire

Since the phenomenon could now be reproduced with sufficient accuracy, it was necessary to determine the cause of the misfiring in the prechamber. Two possible factors can be identified here, which are the velocity in the spark gap and the charge composition at time of ignition. The identical hardware configuration was used for all the operating points examined, so that any influence on the flow conditions can be ruled out here. In addition, the pressure level in the combustion chamber decreases with decreasing mean effective pressure. As a result, less lean mixture is pushed from the main combustion chamber into the prechamber during the compression phase. A further indication that the velocity in the spark gap can be excluded from the list of sources of disturbance. In contrast, in order to keep the NO_x emission level constant as the load decreases, it is possible to enrich the mixture in the main combustion chamber. As a result, the mixture pushed from the main combustion chamber into the prechamber is also richer. As a consequence, the air-excess ratio in the prechamber must also decrease. Thus, an underrun of the local ignition limit in the air-excess ratio in the prechamber at the time of ignition was identified as the source of unstable combustion. This in turn results in two levers to raise the air-excess ratio in the prechamber. This the NO_x emission level is on the one hand and the amount of fuel gas with which the prechamber is scavenged via a prechamber gas valve on the other hand. The first causes the mixture in the main combustion chamber to lean out. A reduction of the prechamber scavenging volume raises the air-excess ratio in the prechamber before the compression stroke and thus also the air-excess ratio at the time of ignition. These two paths are shown schematically on the basis of measurement points in Figure 4. The overload operating point (1) at a NO_x emission of 500 mg/nm³ is stable. A reduction of the mean effective pressure at constant emission level and constant prechamber gas quantity leads to unstable combustion at a BMEP of about 21.5 bar (2). A reduction of NO_x emissions by half to 250 mg/nm³ allows a further reduction of the mean effective pressure down to almost 18 bar BMEP (3). This operating point can only partly be described as stable. If, however, starting from point 2 or point 3, the prechamber gas quantity is reduced by 70 percent at both emission levels, stable engine operation at 50 % load is achieved (4, 5).

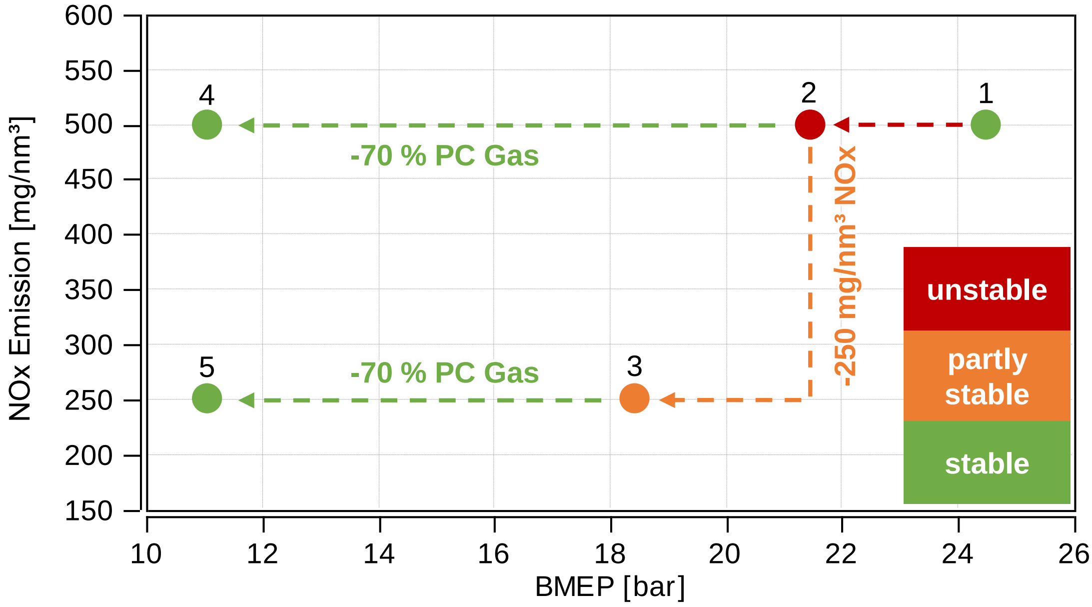

Figure 4: Pathways to increased part load combustion stability

Analysis of Misfire Limit Using 1D Simulation

The measurements at the SCE showed a very distinct mean effective pressure limit between stable and unstable combustion. Subsequently, it was therefore of interest whether such a strict distinction could also be made for the conditions in the prechamber at the time of ignition. A simplified model of the SCE was set up for a detailed analysis of the condition of the prechamber (Figure 5) according to a methodology presented in [8]. The model shows the main combustion chamber and the prechamber as separate components. The overflow from the prechamber into the main combustion chamber and from the main combustion chamber into the prechamber is represented by an orifice. Based on the measurements at the SCE, the boundary conditions for the inlet side on the one hand and the outlet side on the other hand are imposed. The mass flow on the inlet side is adjusted according to the measurement data. A further control loop controls the amount of scavenging gas flowing into the prechamber. Combustion in the main combustion chamber is simulated on the basis of analyzed burn rates. The combustion in the prechamber is represented by a Vibe combustion process, which results in an identical prechamber pressure increase. The mixture formation in the main combustion chamber and prechamber is represented by ideal mixing. As a result of this simplification and the fact that the modelling approach is a one-dimensional model, only spatially averaged results for temperature and mixture composition in the main combustion chamber and prechamber can be determined. An analysis of the mixture distribution in the precombustion chamber using 3D-CFD simulation appears disproportionate due to the large number of engine operating points to be analyzed.

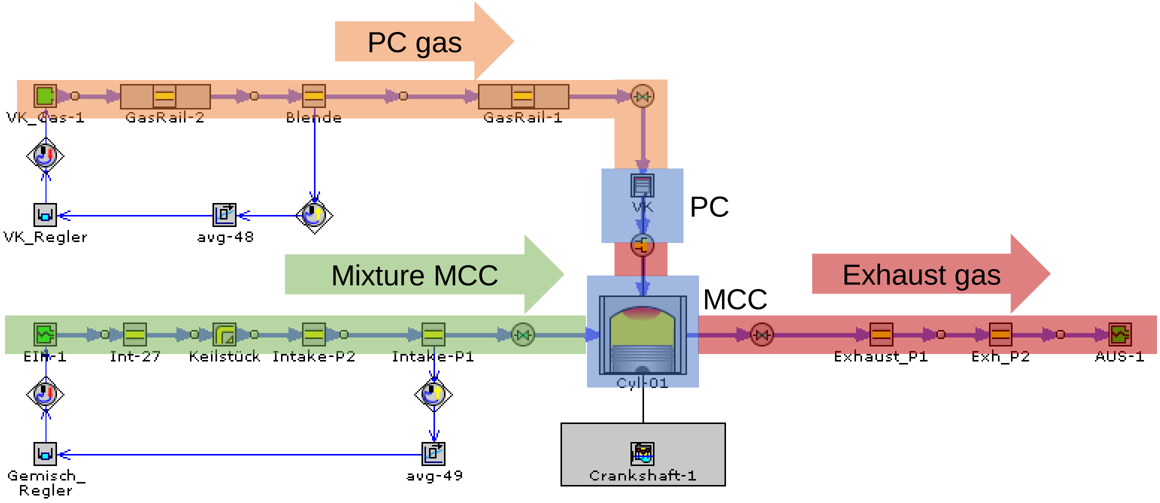

Figure 5: Setup of the simplified SCE model in GT-Power

Figure 6 shows exemplary measurement results of the operating points achieved with the gas composition GT4-10/10 and compares these with the analysis results for the air-excess ratio in the prechamber at the time of ignition from 1D simulation. During the tests on the single-cylinder research engine, the lower mean effective pressure stability limit was first approached with the standard scavenging gas quantity (base, 100 %). The TA Luft nitrogen oxide emission level of 500 mg/nm³ was maintained. At the achieved mean effective pressure of about 20 bar BMEP, the amount of scavenging gas was subsequently reduced. This shows that even a small reduction of the prechamber gas quantity to 90 % enables stable engine operation. However, a further reduction does not improve the combustion stability. The load was then further reduced for the various prechamber gas quantities. For a scavenging gas quantity of 90 %, a lower stability limit of 14.5 bar BMEP could be achieved. With a further reduction of the scavenging gas quantity to 70 %, unstable combustion only occurs at a mean effective pressure of 12 bar. For even lower scavenging gas quantities, stable combustion down to 12 bar BMEP is possible. For the reduced prechamber gas quantities, the nitrogen oxide emission level was additionally lowered at the lower mean effective pressure limit by leaning to ½ TA Luft. In the case of 90 % and 70 % scavenging gas quantity, this results in a significant improvement in combustion stability.

An explanation for this behavior can be seen in the air-excess ratio in the main combustion chamber and in the prechamber. When lowering the mean effective pressure, a reduced air-excess ratio in the main combustion chamber is necessary to keep the NO_x emission constant. This also leads to a reduction of the air-excess ratio in the prechamber at the time of ignition. When the lower stability limit is reached, a lower threshold value in the air-excess ratio in the prechamber is also undershot in accordance with the simulation results. As a consequence of the lack of oxygen no combustion can be initiated by the spark and spontaneous misfiring occurs. Both the reduction of the prechamber scavenging quantity and the leaning to achieve lower NO_x emissions counteract this effect.

By a purposeful choice of the prechamber gas quantity it is therefore possible to demonstrate a wide operating range also without substitution of flare gas by natural gas.

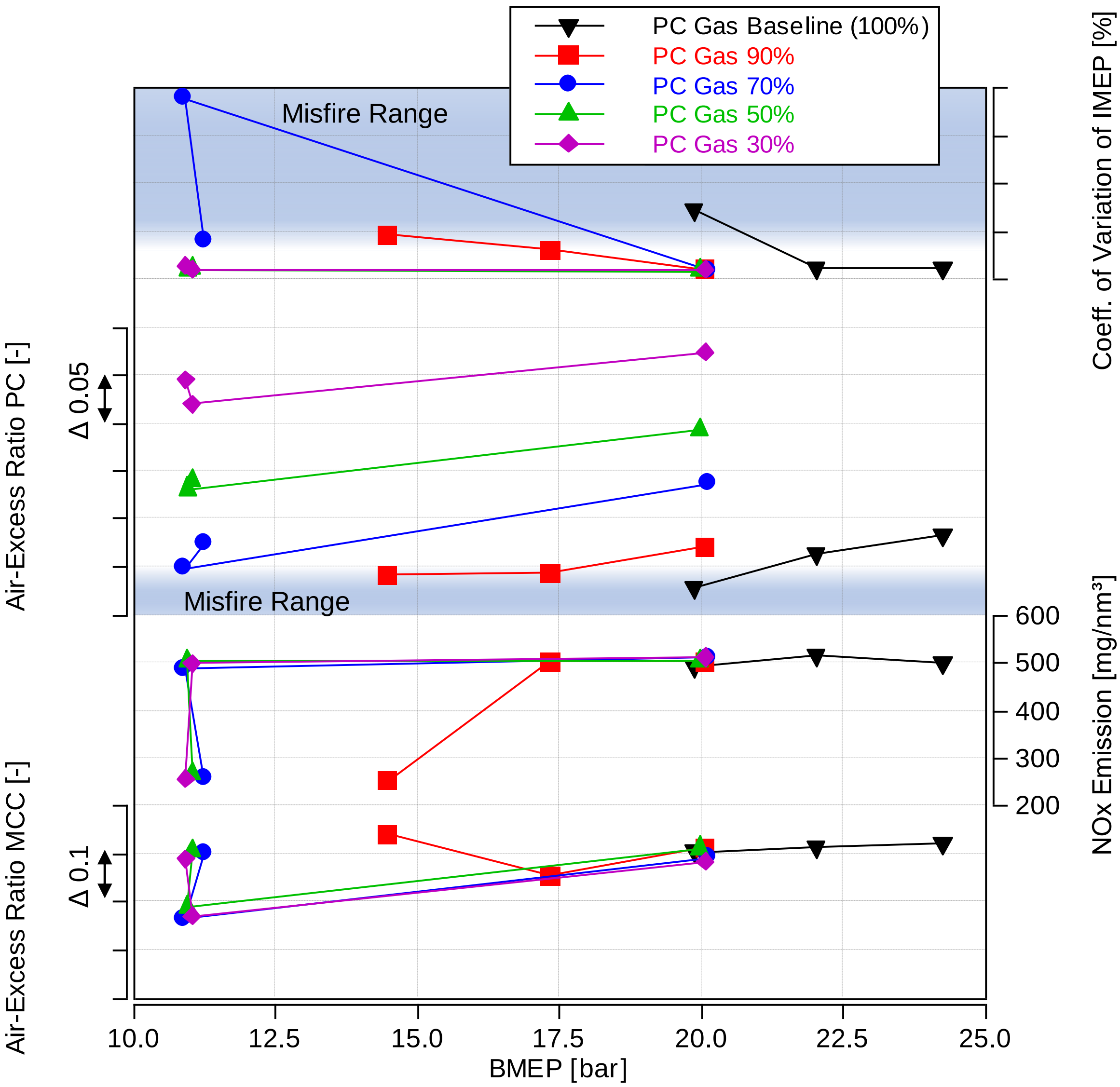

Figure 6: Comparison of measurement results and the simulated air-excess ratio in the prechamber

Summary

The paper showed that off-the-shelf combustion concepts of large gas engines can be used to exploit gases that would otherwise have to be flared. Special attention was paid to flaregas qualities with increased hydrogen and very high carbon dioxide content. If the fraction of carbon dioxide in the propellant gas rises above a certain threshold value, this leads to unstable combustion in combustion concepts with gas-scavenged prechambers. In particular, a lower limit of the specific engine power was identified for each gas composition investigated. By substituting the non-natural gas with natural gas, this lower mean effective pressure limit could be further reduced. In the course of the experimental investigations, stochastic misfire of the prechamber, which initiates combustion in the main combustion chamber, was identified as the cause. Subsequently, strategies could be developed to avoid misfiring in the prechamber, allowing an extension of the stable engine operating window to lower power. Both a reduction of the nitrogen oxide emission level and a reduction of the scavenging gas quantity fed to the prechamber had a positive effect on the part load combustion stability. The analysis of the measurement results by 1D simulation revealed a correlation of the misfire limit with a threshold value for the mean air-excess ratio in the prechamber at the time of ignition. The reduction of the prechamber

scavenging quantity leads to an enleanment of the prechamber and thus to the surpassing of the lower ignition limit in the air-excess ratio in the prechamber. A reduction of the nitrogen oxide emission from TA Luft level to ½ TA Luft by leaning out the mixture in the main combustion chamber has almost the same effect.
Through selective control of the prechamber gas quantity versus the engine output, it will thus be possible to use fuel gases with a very high inert gas content also in lean burn gas engines with prechamber ignition down to low power output.

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