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LDM COMPACT – A Methodology for Development of Gas Engines for Use with Low Environmental Impact Non-Natural Gas

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LDM COMPACT is a methodology, which permits the development of highly efficient combustion concepts for non-natural gas (NNG) engines without extensive testing on a multi-cylinder engine as well as tailor-made engine solutions for the special characteristics of NNG (LDM stands for LEC Development Methodology). Starting with a description of the baseline LDM, which incorporates the general approach for efficient engine development, this paper introduces the improved approach of LDM COMPACT and outlines each of the required steps, i.e., the preselection and basic design of essential engine parameters based on simulation, fundamental experiments on special test rigs, and experimental optimization of the concept on a single cylinder research engine. The fundamentals and main innovative features of the methodology are discussed. Two recent development projects (combustion of blast furnace gas and combustion of flare gases) are provided as examples of its application. In these examples, extensive use of simulation to evaluate different engine configurations permitted a significant share of optimization work to be completed in advance. The pre-optimized concepts were tested and validated on a single cylinder research engine. By applying LDM COMPACT, it was possible to develop the combustion concepts in a short amount of time and implement them into the multi-cylinder engine directly on-site.
Keywords: methodology, gas engines, combustion concept, non-natural gas, blast furnace gas, flare gas

Highlights
- *A novel methodology for the development of combustion systems for engines fuelled by non-natural gas (NNG) is presented.*
- *The methodology relies on the combination of simulation, fundamental experiments and optimization of the concept on a single cylinder research engine.*
- *Combustion systems using NNG can be developed on the single cylinder engine and transferred to the multi-cylinder engine without extensive further testing.*
- *Recent results of successful application examples for waste gases (blast furnace gas and flare gas) are presented.*
- *The methodology facilitates the exploitation of waste gases at low cost, thus, enabling energy production with low environmental impact.*

0 INTRODUCTION

The use of gas engines fuelled by non-natural gases (NNG) for power generation and heat is key to exploiting resources in a more environmentally friendly manner and achieving a general reduction in CO_2 emissions, Fig. 1. NNG encompasses landfill gas, flare gas, coal mine gas, sewage gas, biogas and a variety of other special gases. This group of special gases includes, above all, waste gases from industrial processes (e.g., gases from steel production). These gases are often used inefficiently or not at all to produce (thermal) energy. Large bore gas engines are best suited to exploit these waste gases.

Created during the steel production process, blast furnace gas (BFG) is a good example of a waste gas that would otherwise not be exploited that could be used to operate a gas engine. Another type of waste gas is flare gas that leaks from petroleum refineries, natural gas processing plants, and oil or gas production sites. The energy content of flare gas can also be used for power generation and to operate the plant itself. In general, NNG vary widely in their composition depending on where and how they are produced and how much is produced.

Due to their particular characteristics, each of these gases requires a specially designed engine concept. Gas engines that burn NNG are normally more difficult to operate than those that run on natural gas (NG), mainly because of the greatly fluctuating gas compositions and the intermittent availability of these gases. The gas properties that vary, for example, lower calorific value and methane number, require very robust combustion concepts and sophisticated monitoring and control strategies. An overview of the wide variety of compositions of gaseous fuels including NNG used in combustion engines can be found in [1]. Research [2] provides examples of gas engine applications that use waste gases. An engine series capable of burning non-

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natural gases is presented in [3] and [4]. These papers describe the engine concept, the design features, and the special adaptations of the engine for use with non-natural gases. Furthermore, [5] also presents the latest advances in NNG applications from simulation to single cylinder testing to the final customer applications.

Compared to conventional natural gas engines, which are often sold in large quantities, most NNG engine applications start off as individual solutions. On account of the very specific characteristics of each NNG, a specially designed engine concept is required for each gas. Due to the low production figures for engines that run on NNG, natural gas engines are modified for this application with the least amount of development effort, which results in disadvantages in efficiency and performance. Combustion system development of a multi-cylinder engine (MCE) on the site where the gas is produced is in most cases not economically viable. Consequently, these challenges prevent the expedient use of NNG. Likewise, the combustion system development of a multi-cylinder engine on the test bed of the engine manufacturer is equally unfeasible from an economic perspective. In this case, the factor that drives costs is the fuel since it must be mixed together from the main components. In addition, fuel consumption by the multi-cylinder engine is very high. The lower the number of engines initially expected for commercialization, the more economic concerns become aggravated. With gases with unfavourable properties, implementation is only possible if the cost of development is limited.

Given these boundary conditions, it is critical to employ a method for the economically viable design and optimization of a combustion concept for gas engines that apply to a wide variety of NNG. To achieve sufficient economic viability, it is vital that the method does not require testing on a multi-cylinder engine and that the result obtained from simulation and single cylinder engine measurements can be transferred directly to the on-site facility without any additional multi-cylinder engine tests.

It should be feasible to use the methodology with niche applications in which only a small number of engines are produced. It allows optimization of the combustion concept to be well directed and combined with an adapted control concept to achieve high-efficiency values and competitive mean effective pressures even with gases with unfavourable properties, such as large shares of inert gases or low calorific value. By enabling combustion system and controls optimization, this methodology can extend the applicability of large gas engines to NNG, thereby contributing to the environmentally sound and efficient exploitation of NNG. As a result, the application of the methodology described in this paper significantly reduces CO_2 emissions and consumption of natural gas from fossil fuels.

1 APPPROACH

1.1 Baseline Methodology

The classic LEC development methodology (LDM) was elaborated in order to support efficient engine

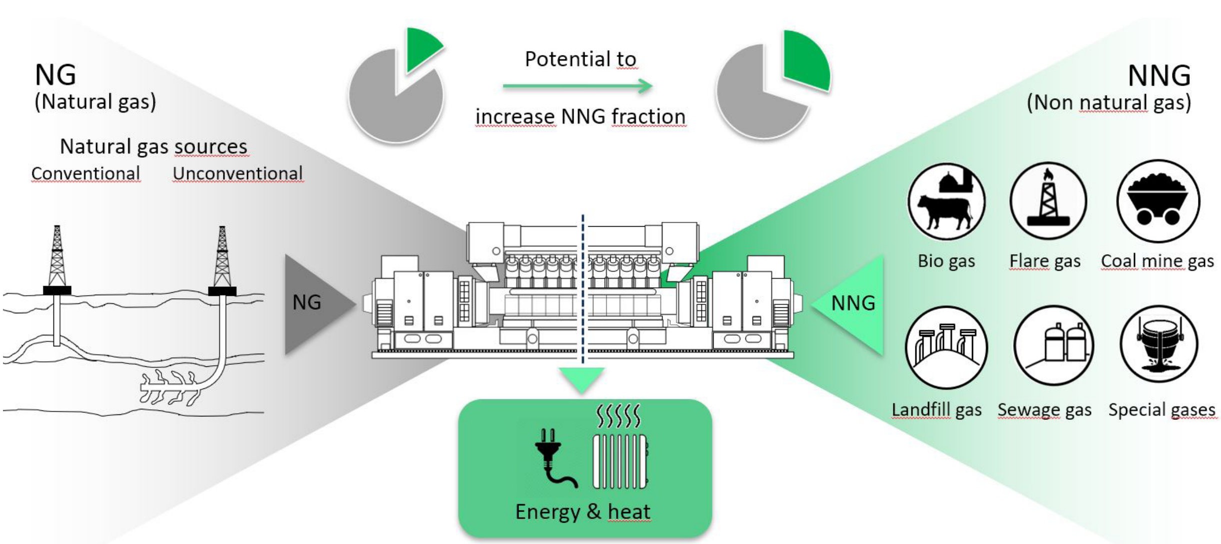

Fig. 1. *Low-emission energy production that maximizes the use of non-natural gases*

development [6] and [7]. It is a general methodology for developing and optimizing combustion concepts for large engines and is based on an intensive interaction between simulation and experimental investigation of single-cylinder research engines (SCE). Since its creation, many manufacturers and research institutions have come to rely on this method, which has established itself as the standard for large engines [8] to [10]. A more holistic approach to general performance and emissions development is described in [11] and applied in [12]; the key features are also intensive use of various simulation tools, a model-based development approach as well as experiments on a single-cylinder research engine. The use of a single-cylinder research engine as a tool for combustion system development can be regarded as a generally recognized approach [13].

Like the classic methodology, the improved methodology makes use of 0D and 1D engine cycle simulation as well as 3D CFD (3-dimensional computational fluid dynamics) simulation. While 3D CFD simulation is employed above all to optimize the details of relevant processes (e.g., piston geometry, charge motion), 0D/1D engine cycle simulation is applied to pre-optimize significant engine parameters (e.g., compression ratio, valve timing). In addition to the basic development of combustion concepts for steady-state engine operation, the methodology comprises integrated treatment of all combustion-related processes such as durability, wear, ignition and fuel supply as well as the development of transient combustion concepts and controls.

1.2 Improved Methodology

The main innovation of the approach presented in this paper is the further enhancement of LDM to meet the requirements for the development of NNG combustion concepts: LDM COMPACT methodology can be applied to development processes that are carried out without extensive testing on a multi-cylinder engine. These processes primarily rely on simulation tools as well as measurements on a single-cylinder research engine; they can be directly transferred to the engine operator's facility, Fig. 2.

LDM COMPACT consists of two basic steps:

- preselection and basic design of essential engine parameters based on simulation,
- experimental optimization of the concept on a single cylinder research engine.

1.3 Determining of Engine Parameters

To preselect the combustion concept including all required parameters, each gas composition is first characterized by determining several characteristic values. These values include knock index, laminar flame speed, and the density and lower calorific value of the gas composition.

First, an appropriate knock index must be selected. Various knock detection criteria can be applied depending on the fuel gas composition. These criteria yield major differences, especially for gas mixtures that contain hydrogen or higher hydrocarbons [14] and [15]. Knock occurs when the remaining fresh charge is suddenly consumed as ignition conditions are reached. In lean burn gas engines, knocking is monitored using the in-cylinder pressure signal (if available) by applying appropriate algorithms that focus on the sudden superposition of the in-cylinder pressure signal by high-frequency pressure oscillations [16] to [18].

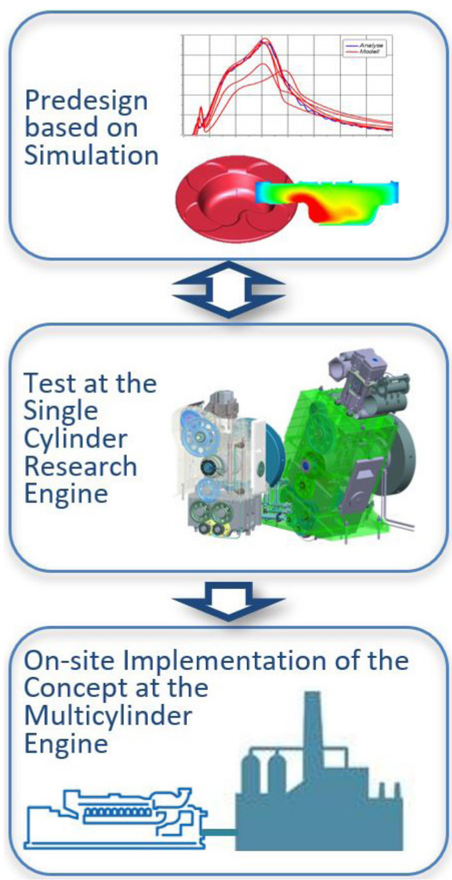

Fig. 2. *LDM Compact*

After the knock criterion is selected, the expected laminar flame speed of the gas composition under investigation has to be determined [19] by either performing experiments or making reaction kinetic calculations. Experimentally determined laminar flame speeds of methane-air mixtures [20], reference fuels (e.g., n-heptane, iso-octane) [21] and alternative gaseous fuels [22] are available in the literature. Most of the experimental values stated in the literature are measured at ambient conditions; however, some are relevant at engine conditions. In any case, to obtain values for engine-related operation areas, extrapolations should be avoided so as to prevent major inaccuracies. Instead, reaction kinetics calculations are performed to determine the laminar flame speed. However, these calculations are possible only if an appropriate reaction mechanism exists for the specific gas composition. Such a mechanism is often not available for NNG due to their highly specific compositions. To obtain reasonable values for NNG, it is possible to make flame propagation measurements in a rapid compression expansion machine (RCEM) under different conditions (pressure and temperature) and with different gas mixtures. This data can also be applied to characterize flame front propagation and to validate reaction kinetics and combustion models. Fig. 3 shows a rapid compression expansion machine with a highly flexible optical access. In the combustion chamber, different pressure and temperature conditions can be achieved. A gas mixing device (up to 10 components) allows investigation of a variety of gas mixtures.

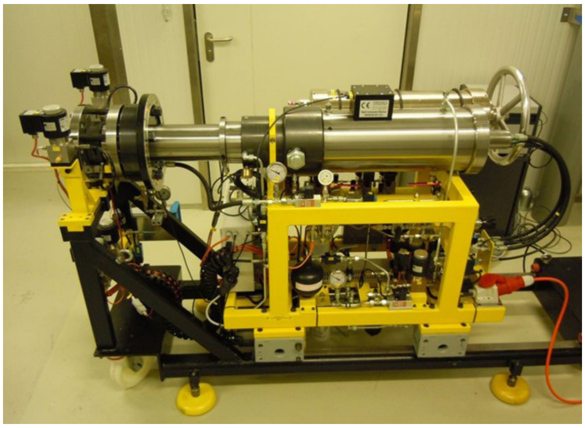

Fig. 3. *Rapid compression expansion machine (RCEM) with a highly flexible optical access*

After all the properties required for gas characterization have been determined, the combustion concept can be preselected. The possible concepts and the basic engine parameters are listed systematically in a table according to the gas category. 0D and 1D engine cycle calculations are then conducted to describe the operating parameters in detail. Trends are quickly estimated with the 0D simulation methodology, which uses models that calculate ignition delay, burn rate, NOx formation and knocking. Gases with a very high share of inert gas components typically have extremely small lower calorific values and thus very challenging characteristics. Stable and efficient combustion of such gases requires a high degree of turbulence in the combustion chamber. In certain applications, the laminar flame speed of NNG compared to that of pure CH_4 is very small because of the high inert proportion of CO_2 in some NNG. In these cases, it is preferable to increase the turbulence level in the combustion chamber in order to obtain higher reaction rates and subsequently accelerate the combustion process with the result of acceptable efficiency at low emission levels. To increase the turbulence level, an adequate combustion chamber design is necessary. 3D CFD simulation is applied to design and optimize the combustion chamber geometry. Based on the results from 3D CFD simulation, it can be decided whether the gas composition under investigation requires a combustion system with a prechamber or whether it can be operated in an open chamber combustion system. 3D CFD simulation is also preferable for pre-designing the combustion chamber geometry in order to avoid locations where knocking might occur; this is especially important with gases with very challenging compositions as well as gases that have a low calorific value. Further simulations are conducted to determine an appropriate excess air ratio (EAR) for the derived combustion concept so that the emission limits for nitric oxides are met. With each gas, the maximum load possible under the previously defined boundary conditions is determined, thereby ensuring stable, robust and knock-free combustion.

1.4 Experimental Optimization of the Concept

A very efficient and flexible test bed infrastructure was set up for experimental investigations on a single cylinder research engine. Progressive developments in the areas of gas mixing (up to 6 different gas components), gas supply, gas storage and safety technology enable testing of almost any gas composition on the single cylinder research engine. After the required engine components have been procured, the relevant engine operating areas are typically determined in a screening phase. To reduce test time when determining the optimal parameters, intensive use is also made of statistical design of experiments (DoE) methods. The focus of experimental investigations is on determining the efficiency and load potential of each gas while at the same time achieving the lowest possible emissions. Sensitivity observations that consider fluctuations in gas quality are also carried out. These fluctuations are critical to the design of an engine control concept and to the determination of whether higher quality gases need to be added. The results of this iterative process of just simulation and single-cylinder research engine measurements are ultimately used to directly implement the concept into the on-site multi-cylinder engine, Fig. 3.

The main innovation of the methodology presented here is that it improves the characterization of different gases and simulation possibilities to the point that a very advanced combustion concept for each gas can be achieved in combination with experimental development on the single cylinder research engine. As a result, it is finally economically viable to implement the concept in a variety of applications of NNG that could otherwise not be exploited. Critical to the development of the methodology are both the systematic evaluation of basic gas components with regard to their influence on knock behaviour and the derivation of a catalogue of basic combustion concepts selected based on prior NNG developments.

2 APPLICATION EXAMPLES FOR THE DEVELOPMENT OF COMBUSTION CONCEPTS FOR WASTE GASES

The development methodology presented in this paper is the result of many years of research and several successful projects at the LEC that have developed NNG combustion concepts for large gas engines that are almost exclusively concerned with sustainable solutions for energy production and transportation. The available database consists of several thousand measurements of different single cylinder research engines. The following section presents two examples of the development of combustion concepts for sustainable power generation in large gas engines that efficiently and flexibly exploit blast furnace gas (BFG) and flare gases.

2.1 Combustion of Blast Furnace Gas

Blast furnace gas (BFG) is an important yet difficult-to-exploit by-product of the steelmaking process. The objective was to develop a highly efficient, high power output combustion concept for a large gas engine in the 4 MW power range using blast furnace gas [23]. This concept must comply with the TA Luft emission limits, ensure sufficient combustion stability despite fluctuations in gas quality and exhibit good starting behaviour. As on-site development on the multi-cylinder engine was not feasible due to the reasons stated in the previous section, the innovative development methodology was applied.

2.1.1 Selection and Pre-Optimization of the Combustion Concept Using Simulation

In the first step, a suitable concept for the combustion of BFG was selected and pre-optimized mainly with simulation. The extremely unfavourable properties of BFG, which contains a large share of inert gases and whose calorific value is lower than 1 kWh/m3, require a very specific combustion concept. Large gas engines may employ pre-chamber concepts that are gas scavenged, mixture scavenged or un-scavenged as well as open chamber concepts. Engines of the size selected for the development of this combustion system are normally equipped with prechambers. However, 0D/1D simulation revealed that ignition could not be successfully induced due to the unfavourable mixture composition in the pre-chamber at ignition timing. This finding was obtained before any experiments were conducted by determining the mixture composition in the pre-chamber at ignition timing with a 1D simulation model. Based on the conditions in the pre-chamber, the simulation provides a detailed description of the mass overflow between the pre-chamber and the main combustion chamber. Thus, the main focus of combustion system development was on the open chamber concept. With this type of concept, a sufficient level of turbulence induced by charge motion must be achieved to obtain an appropriate flame speed. To achieve this level of turbulence in the combustion chamber during combustion, a very high swirl level was combined with an appropriate piston shape. 3D CFD simulation was extensively used during the optimization process.

Fig. 4 presents selected results from this process. The locally averaged turbulent kinetic energy (TKE) was chosen to evaluate the different variants.

The chart shows the optimized variant as well as two intermediate development steps (variants A and B) in relation to the baseline variant. Based on these investigations, the most promising piston shapes in combination with the swirl level were determined and preselected for experimental tests on the single-cylinder research engine. Further information on this study can be found in [24].

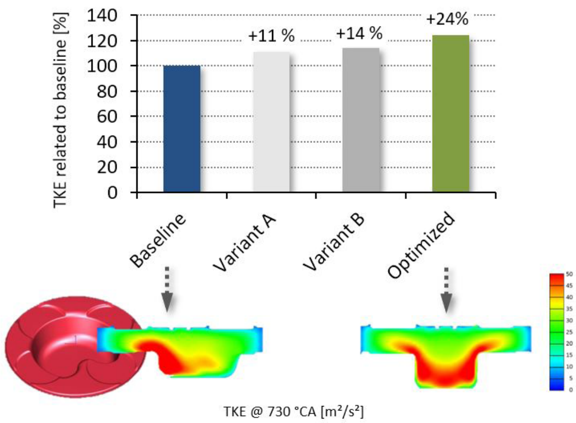

Fig. 4. *Predesign of the combustion concept using 3D CFD simulation* [24]

2.1.2 Experimental Development on the Single Cylinder Research Engine

Measurements were taken on a single cylinder research engine to verify the simulation results and to determine certain engine performance values (e.g., efficiency, emission level, combustion stability). Combustion chamber variants with increased turbulent kinetic energy had a shortened combustion duration, which resulted in significantly faster fuel conversion with the optimized variant. After the best piston variant had been chosen and the optimal compression ratio determined, the engine operating parameters (e.g., ignition timing, mixture temperature, charge pressure) were optimized. The goal was to obtain the largest operating range possible, i.e., the range between knock limit and misfire limit, which is crucial for robust gas engine operation.

The fluctuations in the composition of blast furnace gas cause dramatic changes in the combustion behaviour of the gas. If the share of hydrogen (H_2), in particular, noticeably varies, combustion is greatly impacted. Thus, investigations were carried out on the single cylinder research engine to evaluate the sensitivity of the engine concept to fluctuations in H_2 content. Figs. 5 and 6 present selected results of these investigations with the optimal variant; the misfire limit and the knock limit restrict the operating range. While Fig. 5 depicts the achievable engine efficiency versus load and H_2 content, Fig. 6 shows combustion stability versus the same parameters. Further information on these investigations can be found in [25]. The fundamentals that the study is based on can be found in [26].

A special control concept adapted to the blast furnace gas application was developed for the multi-cylinder engine in order to ensure stable engine operation with variable load and fluctuating gas quality. Through continuous optimization of both combustion and gas mixing, a maximum energy yield can be guaranteed at any time and at any operating point. The simulation-based control concept relies upon on-board cylinder pressure measurement and admixing of an additional gas (e.g., coke gas).

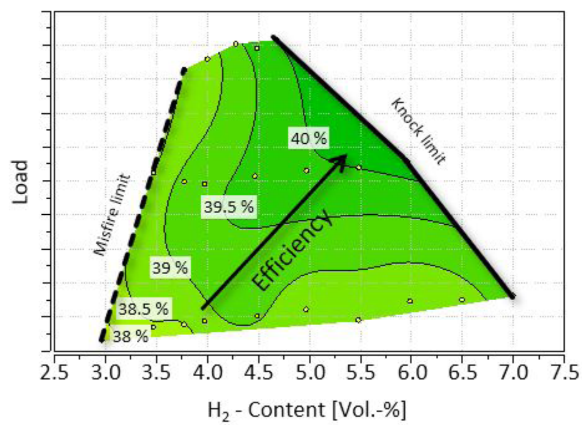

Fig. 5. *Operating range: Efficiency versus load and H_2 content* [25]

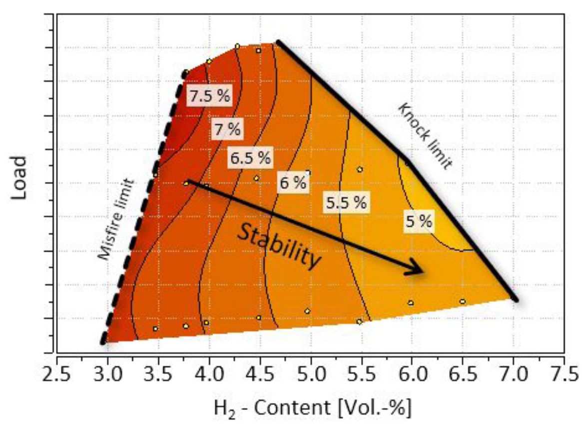

Fig. 6. *Operating range: Combustion stability versus load and H_2 content* [25]

2.2 Combustion of Flare Gases

As previously stated, a large amount of energy is lost from the flaring of waste gases from oil and gas production. According to [27], 150 billion cubic metres of natural gas resources are wasted each year worldwide by flaring, thereby generating the equivalent of 400 million metric tons of CO_2 greenhouse gas emissions. Instead of flaring these gases, efficient use of their energy content should be pursued.

Besides methane, flare gases originating from oil production contain a great share of nitrogen and carbon dioxide as well as ethane, propane and other higher hydrocarbons.

For the investigations conducted in this example, three representative gas compositions feasible for power generation with large gas engines were selected based on their gas properties, which are mainly characterized by different methane numbers in order to be comparable to pure methane.

2.2.1 Combustion Concept Predesign using Simulation

In the first step, 0D and 1D engine cycle simulation was applied to pre-select the combustion concept and define basic engine parameters such as compression ratio and pre-chamber volume. The simulation of certain engine operating parameters and limits such as exhaust gas temperature enabled the selection of potential hardware variants in the process of combustion concept predesign. 1D modelling is especially useful for investigating temperature and charge composition in the pre-chamber at ignition timing; these two parameters are critical to the ignition of the mixture. An important parameter for robust and stable ignition as well as NO_x formation, the excess air ratio (EAR) in the pre-chamber can be controlled by regulating the amount of gas that flows through the gas valve into the pre-chamber. Pre-chamber size and compression ratio are also important parameters. Fig. 7 compares the excess air ratio traces of three different gas scavenged pre-chambers: a baseline configuration, a pre-chamber with a larger volume and a pre-chamber with double the amount of energy. 3D CFD methods are applied to predetermine the combustion in detail. The rate of heat release history that results from 3D CFD simulation is then used in 1D simulation.

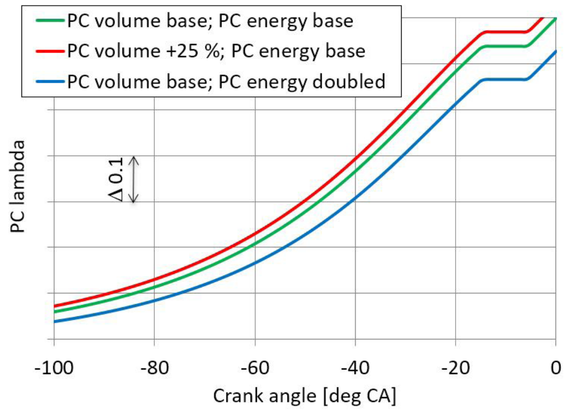

Fig. 7. *Excess air ratio in the pre-chamber calculated with 1D simulation*

Similar results can be obtained by applying 0D simulation alone. The advantage of 0D simulation is its short calculation times. Due to the missing gas exchange calculation, however, the initial values have to be estimated. Therefore, it is feasible to apply 0D simulation for determining the EAR in the pre-chamber within the methodology loop after the first measurement results are available. Improved boundary conditions for simulation can be derived from the measurements.

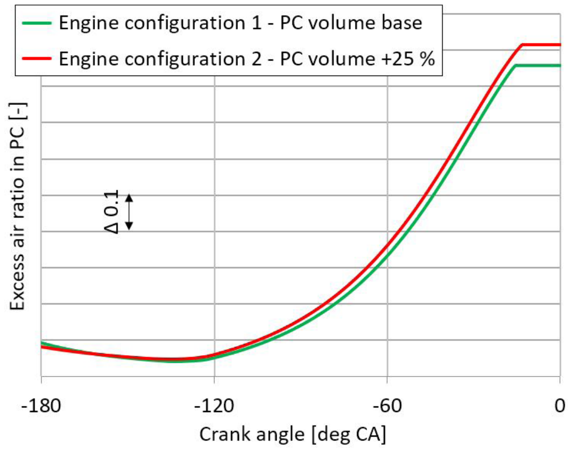

Fig. 8. *Excess air ratio (EAR) in the pre-chamber calculated with 0D simulation*

While Fig. 7 shows the 1D simulation results, Fig. 8 shows the 0D simulation results for the baseline pre-chamber and the pre-chamber with increased volume. The EAR with the larger pre-chamber is higher due to the flow of more of the lean mixture from the main chamber into the pre-chamber. Furthermore, the ignition timing is slightly retarded, which results in a longer mixing time.

2.2.2 Experimental Development on the Single Cylinder Research Engine

Since the simulation-based predesign process revealed that a scavenged pre-chamber combustion concept is the most feasible solution, such a concept was chosen for the experimental investigations on the single-cylinder research engine. Three different engine configurations were chosen to validate knock tendency and determine the maximum load possible with each gas composition, These configurations differ in terms of compression ratio and pre-chamber volume.

The first step of the testing process involved performing a load variation in order to determine the maximum achievable brake mean effective pressure

(BMEP) at a certain NO_x level limited by knocking combustion. The combustion timing (represented by the centre of gravity of combustion) was kept constant with all the gas compositions to ensure good comparability. Fig. 9 shows the measurement procedure that was applied. From a baseline of approximately 50 %, the load was continuously increased until the knock limit was reached. At constant combustion timing, the engine load can be further increased by leaning out the mixture, which leads to reduced NO_x emissions. Taking into account the further constraints of the misfire limit and exhaust gas temperature limit, the procedure was continued until either 10 % overload operation was reached or a NO_x emission level of 250 mg/nm³ was achieved. Further information on these investigations can be found in [28].

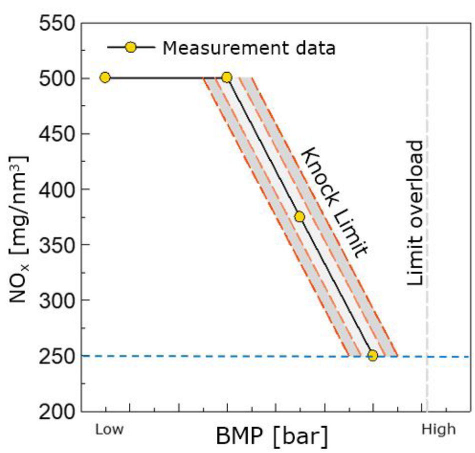

Fig. 9. *Maximum achievable BMEP limited by knocking* [28]

Although it cannot be guaranteed that full load operation is possible with all NNG, the tests of the selected gas compositions showed that in the cases considered, full load operation could be achieved by varying the excess air ratio and ignition timing (IT). Fig. 10 shows the operating ranges obtained with the three gas compositions.

Based on these results, it can be concluded that state-of-the-art combustion concepts for large gas engines are able to provide a sufficiently large operating range when they operate with the gas compositions of the flare gases that were investigated. Furthermore, with all three of the selected engine configurations, overload operation as well as compliance with the TA Luft [29] emission level of 500 mg/nm³ of NO_x were possible with all the gas compositions. It was shown that a high hydrogen content in the fuel gas significantly shifts the misfire limit to lower NO_x emission levels. An increased engine compression ratio can further widen the operating window because the exhaust gas temperature decreases, and the lean limit is shifted to even lower NO_x emissions.

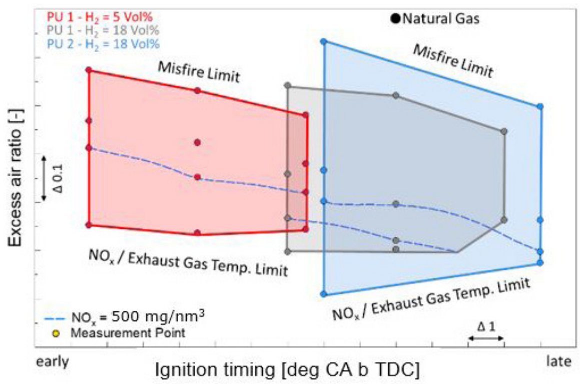

Fig. 10. *Operating range of selected gas compositions*

As shown in Fig. 3, simulation and measurement interact closely. The development methodology provides a loop that reuses the results from the single-cylinder research engine measurements to improve the simulation or to gain further insight into the processes being investigated. On the one hand, the measurement results serve to validate and optimize 3D CFD simulation models so that new piston shapes or pre-chamber designs can be developed. On the other hand, when the 1D simulation model is supported by measurement results, important parameters that cannot be measured can be determined by simulation.

3 OUTLOOK AND POTENTIAL

On a global level, there is enormous potential for economically and ecologically viable implementation of NNG applications into large gas engines. For example, the losses from drilling for natural gas alone are estimated to be about 5 % of global natural gas production [27]; these losses arise to a great extent from the flaring of components unable to be directly exploited. In terms of CO_2 emissions, this translates into almost 400 million tons of CO_2 [27] that could be saved by exploiting these gases for energy. Even if only a small fraction is saved, the potential is extremely high. Operation of gas engines with a variety of NG and NNG is contingent upon the adaptation of a combustion concept that runs on the type of gas currently in use. Developing individual combustion concepts for each gas is a time-consuming and cost-intensive process. LDM COMPACT combines state-of-the-art 0D/1D and 3D simulation tools and experiments on the single-cylinder research engine test bed and allows direct implementation of an engine concept into the on-site multi-cylinder engine without prior cost-intensive tests on a multi-cylinder engine. In this way the methodology is an important enabler for the implementation of technologies for the energy production with a low environmental impact.

4 ACKNOWLEDGEMENTS

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