Achieving best-in-class OPEX and Emissions with Siemens E-Series Gas Engine

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Abstract

The new best-in-class E-series gas engine is based on the thermodynamic Miller cycle combustion technology that ensures high reliability, minimal emissions, and longer run times between service intervals. With a mechanical efficiency of 46.6% percent and an electrical efficiency of 45.4 %, the engine offers a high level of performance for both prime power generation and cogeneration applications.

The new gas engine E-series includes the SGE-86EM for the 50-Hz market, running at 1,500 rpm, and the SGE-100EM for the 60-Hz market, running at 1,200 rpm, both with 12 cylinders. They are the result of in-depth market research that identified key product benefits. In turn, they offer the best efficiency in the market, lowest emissions, and at the same time longer service intervals and a compact footprint, providing a broader spectrum of efficient products and solutions for clean distributed power generation and combined heat and power.

The unique configuration of Siemens E-series gas engines allows for an extremely stable combustion process that achieves low emissions without an exhaust gas after-treatment system, representing the perfect choice for a power generation market that faces increasingly stringent emission limits.

At the same time, the engine's capacity to deliver on-site power, heat, and cooling for a wide variety of commercial, industrial, and municipal applications translates into an excellent cost-performance ratio and makes this engine a critical product for combined heat power applications.

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Nomenclature

BTE	Brake thermal efficiency
BMEP	Brake mean effective pressure
CFD	Computational fluid dynamics
CO	Carbon monoxide
CO_2	Carbon dioxide
COV	Coefficient of variation
IED	Industrial emission directive
IMEP	Indicated mean effective pressure
λ	Excess air ratio
MC	Main combustion chamber
MCE	Multi-cylinder engine
NOx	Nitrogen oxides
O2	Oxygen
PC	Pre-chamber
SCE	Single-cylinder engine
SCR	Selective catalytic reduction
SGE	Siemens gas engine
SEB	Siemens engine business

TA Luft	Technische Anleitung zur Reinhaltung der Luft
THC	Total hydrocarbons

1. Introduction

A main driver in the power generation market today is the fulfillment of emissions requirements. Reducing carbon emissions that arise primarily from the production and consumption of energy is a worldwide environmental target. Therefore, new emissions legislations enforced in the power generation market during the last several years will become even more stringent in the near future.
The possibility of generating clean energy and at the same time ensuring market profitability and sustainability becomes a challenge that must be overcome with new power generation solutions. To provide final customers a clean but also competitive solution, low cycle costs and high electric efficiency are key factors.

Large gas engines are becoming more and more important within the global energy generation market due to the reduced CO_2 emissions of the natural gas compared to the use of conventional fuels. The long-term availability of the gas, together with the engine efficiencies and the low emission levels are placing gas engines in a competitive position, especially for decentralized power generation.

Beyond these requirements, Siemens has developed the new E-series gas engine that can deliver 2 MWe with best-in-class efficiency. The product presents an excellent cost-performance ratio and complies with the latest emissions requirements achieving stable engine operation with 200 mg NOx/Nm3 @ 5%O_2.

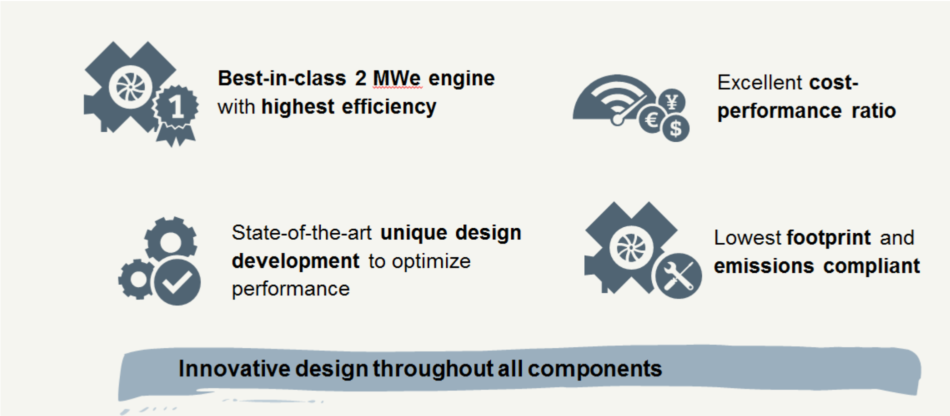


Figure 1. Positioning the new E-series engine.

The new E-series engine was developed to have a robust and compact design, providing long-lasting performance. The innovative pre-combustion chamber design provides efficient, stable combustion; whereas the self-developed GCS-E and GCS-G control systems are highly flexible to adapt the engine to different customer demands. The detailed design has been realized for a 12V engine with two different piston strokes, for 1,500 rpm and 1,200 rpm operation, increasing the power output in 60 Hz applications where users want to avoid using an intermediate gear box.

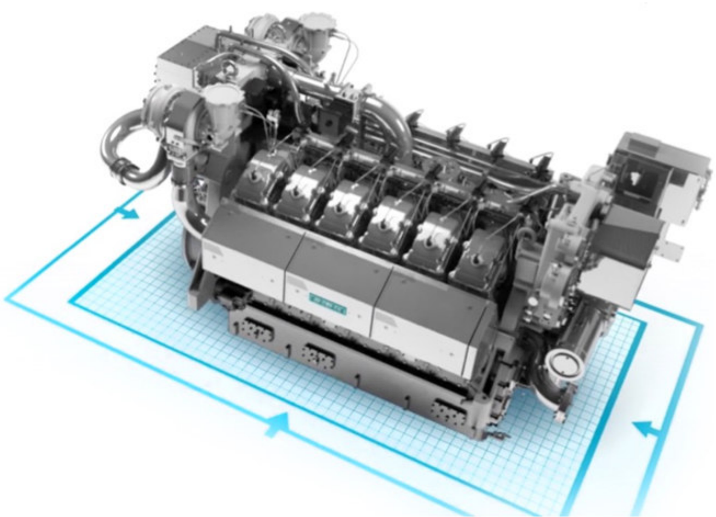


Figure 2. New SGE-86EM engine

With the launch of the new gas engine E-series, Siemens is providing a broader spectrum of efficient products and solutions for clean, distributed power generation. This new E-series engine is especially well-suited for industrial power generation and cogeneration, and combined heat and power applications, like the one planned for the Siemens Campus in Erlangen, Germany.

1.1 Emission regulation

Environmental legislation is always a key driver for technology. Over the last few years, there has been a clear trend towards reducing the emission levels of pollutant gases in large power plants. There are several emission regulations in force worldwide, but in many European countries, the German emission limits defined in the TA Luft are used as the standard [1] for natural gas engines. According to the TA Luft normative introduced in 2002, the NOx emission level limit for lean-burn gas stationary engines is 500 mg NOx/Nm3 @ 5% O2. The ratified UNECE Gothenburg Protocol [2] further reduced the limits for NOx emissions down to 250 mg NOx/Nm3 for lean-burn natural gas engines. Figure 3 shows the limits for both the TA Luft and the Gothenburg Protocol internal combustion engines.

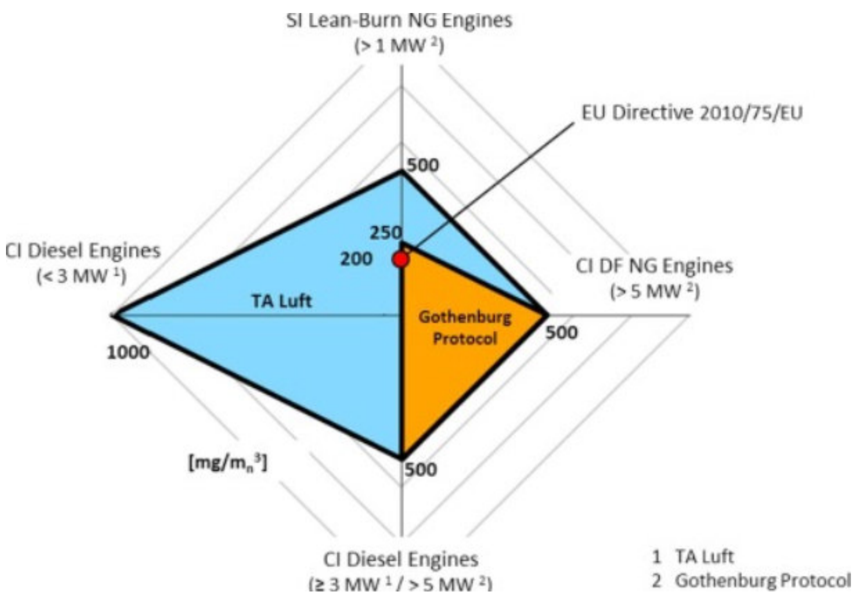


Figure 3. NOx emissions limits for TA Luf [1], Gothenburg Protocol [2] for internal combustion gas engines

On the other hand, the Industrial Emission Directive (IED) prepared by the European Union defines the acceptable emission levels for natural gas engine power plants [3]. The restriction level is different depending on the size of the plants which is defined by the rated thermal input power (Pn). Table 1 shows the NOx emission limits for power plants for 5% referent oxygen.

CATEGORY		NOx (mg/Nm3)
Pn > 50 MWth	Before January 2013 for operation not later than 7 January 2014	265
	After January 2013	200
1 < Pn < 50 MWth	Existing Plants	500
	New Plants	250

Table 1. NOx emission limits for power plants for referent oxygen of 5%

According to the IED, the NOx emissions levels for new plants are becoming more restrictive: NOx emission limits were reduced to 250 mg NOx/Nm3 for medium power plants (1< Pn<50 MWth) and 200 mg NOx/Nm3 for large power plants (Pn > 50 MWth). The acceptable emission levels for new large power plants established a real challenge for natural gas engines operating without exhaust gas after-treatment.

In the future, the tendency for stricter emission reduction will follow not only for NOx emissions but also for CO and especially for HC emissions in lean-burn gas engines. Figure 4 shows the proposed emission reductions by the new TA Luft drafts 2017 [4] (red line) and 2022 (green line) compared to the actual TA Luft normative established in 2002 (blue line).

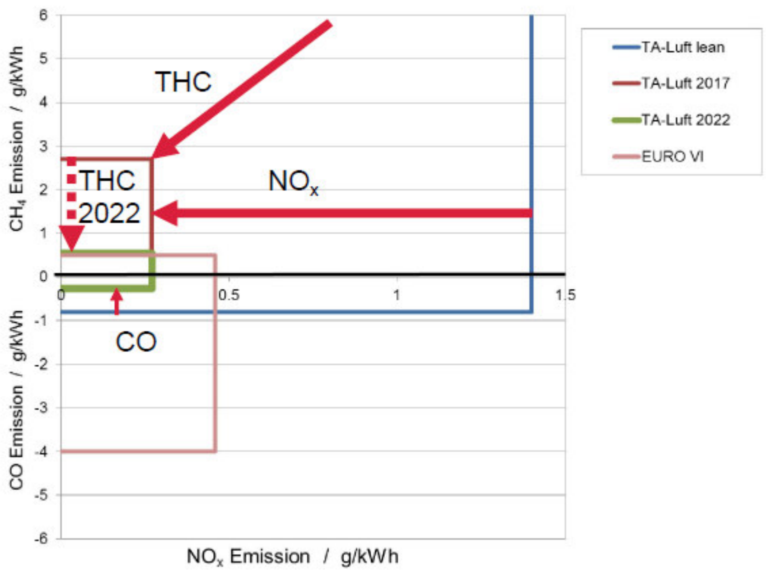


Figure 4. Future TA Luft emissions limit proposal compared to the actual TA Luft normative in force for lean-burn gas engines.

In the 2016 TA Luft working draft, the proposal is to reduce the NOx emissions by factor 5 (from 500 mg NOx/Nm3 down to 100 mg NOx/Nm3). A limitation of 1,300 mg THC /Nm3 is set for total HC emissions. CO emissions are also reduced by factor 3, down to 100 mg NOx/Nm3.

For the future TA Luft 2022, the primary objective is to reduce the THC emissions by factor 5 while NOx and CO remain the same.

2. Lean-Burn combustion gas engines

Large engine manufacturers are continuously increasing the power density of the engines as well as engine efficiency to remain competitive in the industry. The emissions limits required by law for various pollutants such as NOx, CO, or HC have a great influence on the development processes and push engineers to look for new solutions.

Over the last decade, the NOx limit of 500 mg/Nm3 @ 5% O2 set by TA Luft has exerted considerable influence on the development of the combustion systems for gas engines. To meet this emission level while achieving high engine efficiency, engine manufacturers have focused their efforts on improving lean-burn combustion concepts.

Figure 5 shows the trend operation range depending on the excess air ratio for a pre-mixed gas engine. NOx emissions are strongly linked to the combustion temperature, and they reach the maximum value for $\lambda=1.1$ while they are dramatically reduced as the air excess ratio increases. Lean-burn concepts are those with an excess air ratio greater than 1.6 and in contrast to the familiar rich-burn concept ($\lambda=1$), lean-burn engines offer the advantage to meet TA Luft NOx requirements without exhaust gas after-treatment.

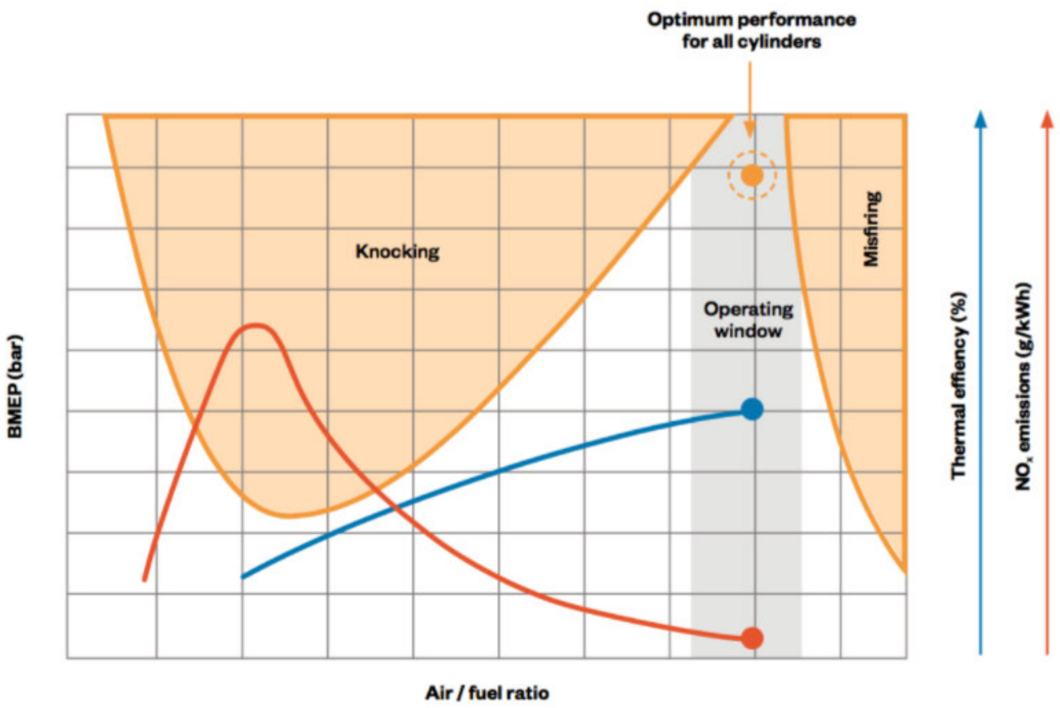


Figure 5. Operation range of a lean-burn gas engine related to the air excess ratio.

As observed in the previous figure, as air excess ratio increases, detonation tendency is reduced. This allows the use of higher compression ratio which improves the efficiency of lean-burn gas engines compared to rich-burn engines; however, higher air excess ratios increase the tendency for cylinder misfire, as well as HC and CO emissions.

Figure 6 shows the different combustion concepts used within the lean-burn gas engines. From left to right, the evolution of the combustion systems over the last few years is shown to operate with higher air excess ratios, thus increasing engine efficiency. The main challenge for the development of these concepts has been stable engine operation at low emissions levels (high air excess ratios).

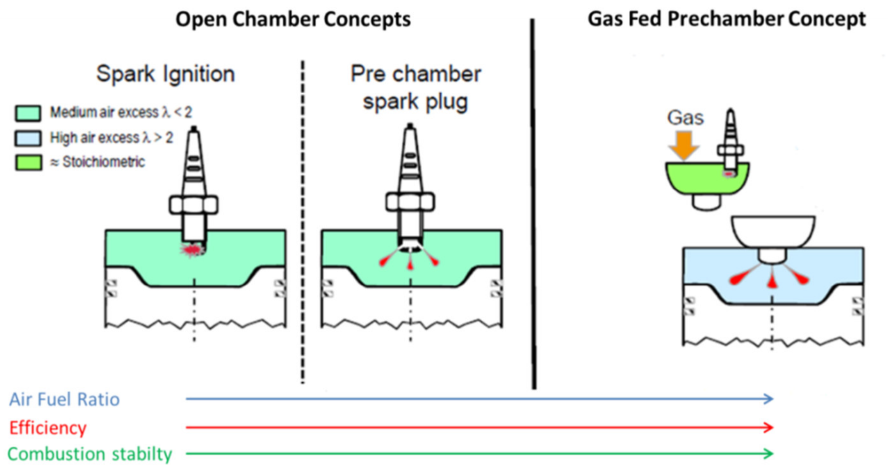


Figure 6. Different combustion concepts for lean-burn gas engines.

Among the three systems used for lean-burn engines, a gas-fed pre-chamber concept has proven to have the greatest capability to operate with high air excess ratios and thus to obtain the highest engine efficiency. Gas injection provides great ignition energy and helps generate powerful flame torches which come out of the pre-chamber tip towards the main combustion chamber and burn the complete cylinder mixture. Furthermore, the use of a gas-fed pre-chamber is found to be the most suitable technology for engines with cylinder bores in the range of 200 mm or more as strong flame jets can reach the cylinder periphery faster leading to a shorter combustion duration and higher engine efficiency (Figure 7).

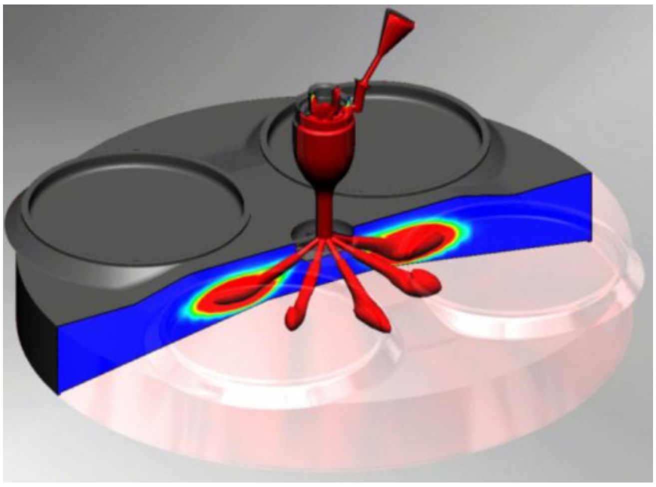


Figure 7. Simulation of the flame torches coming out of a fuel injected pre-chamber.

On the other hand, compared to a gas-fed pre-chamber, open chamber concepts require strong optimization efforts to achieve low emissions. Open chamber systems are ignited only via the electrical energy supplied by ignition systems. Ignition systems' energy capability has been increased over the last years [5], but the performance at low emissions even with these improvements is still a big challenge for this type of combustion concept. Furthermore, it has been demonstrated that there are significant challenges [6] for the design of a pre-chamber spark plug which can operate at low emissions levels, while maintaining long plug durability and acceptable engine efficiency.

3. Development of a new pre-chamber combustion system for SGE-EM operating at low NOx emission levels

3.1 Characteristics of a Conventional Gas-Fed Pre-chamber System

Pre-chamber gas injection is a common method for extending the lean limit and reducing the combustion variability in large bore natural gas engines; however, most of the existing pre-chamber designs operate under rich-burn conditions, resulting in less than optimum combustion performance regarding BTE/NOx trade-off. The achievable NOx exhaust emission level of the engine is limited by the high amount of NOx generated in the pre-chamber as a result of stoichiometric combustion (λ=1).

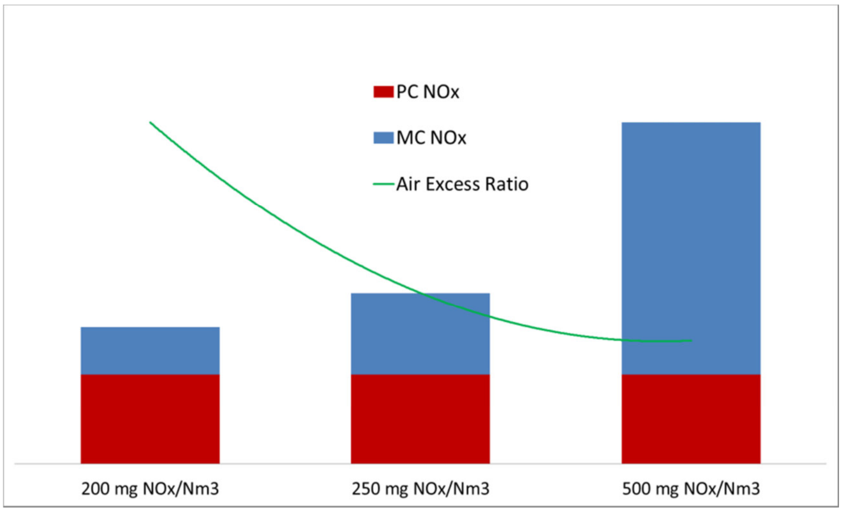


Figure 8. Estimation of the emissions of the NOx emissions coming from the pre-chamber and main combustion chamber related to the overall engine NOx emissions.

Figure 8 shows the relation between the NOx emissions generated in the pre-chamber (PC NOx) and the NOx emissions generated on the main chamber (MC NOx) depending on the total emissions of the exhaust gas of the engine for a rich-burn pre-chamber. The specific weight of the NOx generated on the pre-chamber becomes increasingly important as the engine emission level is reduced, which leads to high air excess ratios (green line) on the main chamber to compensate the effect of the pre-chamber and fulfill the NOx emissions requirements.

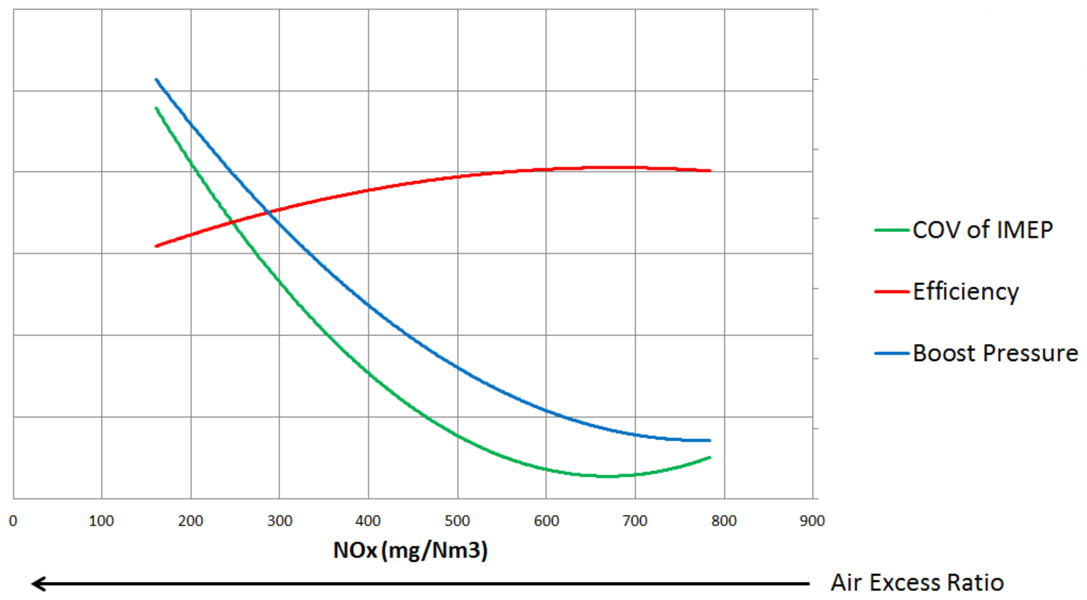


Figure 9. A trend of the engine efficiency, COV of IMEP and boost pressure depending on the NOx emissions and air excess ratio.

Figure 9 shows the trend of the engine efficiency, COV of IMEP and boost pressure depending on the NOx emissions and air excess ratio. This data was obtained in the Siemens R&D center testing an SGE-86EM engine with a rich-burn pre-chamber at full load. It can be observed that increasing the lambda (air excess ratio) when operating at low NOx emission levels has a significant impact on engine performance affecting both the engine efficiency and combustion stability.

Increasing the air excess ratio increases the gas exchange losses and also the losses related to the imperfect combustion of the mixture leading to higher HC and CO emissions. These two factors are the main contributors to the considerable engine efficiency reduction from 500 mg NOx/Nm3 to 250 and 200 mg NOx/Nm3.

On the other hand, poor combustion stability is mainly influenced by the lambda and flow field distribution inside the pre-chamber and is a clear limiting factor for low NOx emission operation because this could cause a cylinder misfire.

Finally, the use of higher air excess ratios leads to higher mixture flows and higher boost pressures especially for engines operating with high piston compression ratios and advanced Miller cycles. The big increase of the boost pressure becomes a limiting factor for operating at low emissions as the required high turbocharger compression ratios are unachievable for a single stage turbocharger.

The results of the test also showed the incapacity of the rich-burn pre-chamber to operate at NOx emission levels lower than 150 mg NOx/Nm3 for the two reasons explained above. To mitigate these effects, the amount of gas injected in the pre-chamber was reduced to obtain lower NOx emissions inside the pre-chamber; however, no improvement was observed because the reduced amount of gas led to cylinder misfire due to poor lambda distribution inside the pre-chamber.

3.2 Lean-burn Pre-chamber Concept

As explained above, the NOx generated in a rich-burn pre-chamber represents the main limitation to operate the engine at low NOx emission levels with acceptable engine efficiency. Therefore, to improve the performance of the engine at lower NOx emissions a redesign of the pre-chamber was considered changing to a lean-burn pre-chamber.

Optimizing a gas-fed pre-chamber is a complex task that requires the most advanced development tools available on the industry. The development of a new pre-chamber for the SGE-EM engine series was carried out combining 3D CFD simulation, single-cylinder research (SCE) and multi-cylinder engine engines (MCE).

As a first step, the CFD model of the engine was calibrated using data from the rich-burn pre-chamber. Once the CFD model was calibrated, several simulations were conducted to find alternative pre-chamber designs which could improve the BTE/NOx trade-off. During the simulation phase, the potential of the new solutions for operating at low NOx emission levels was also estimated.

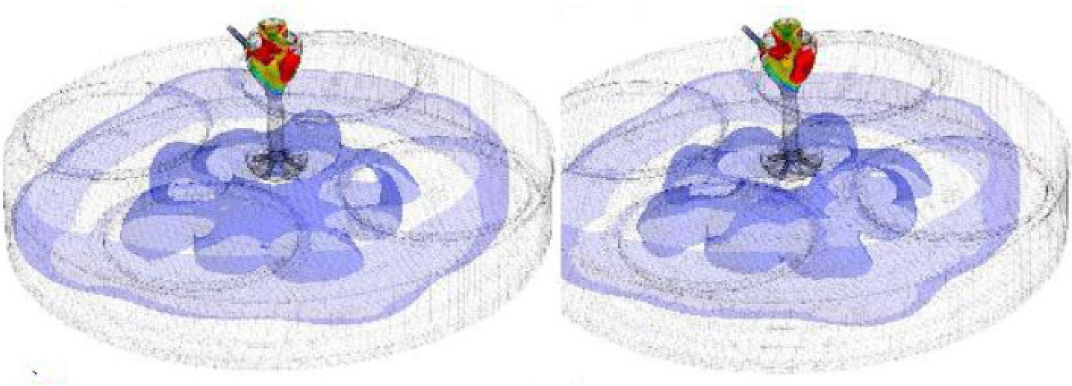
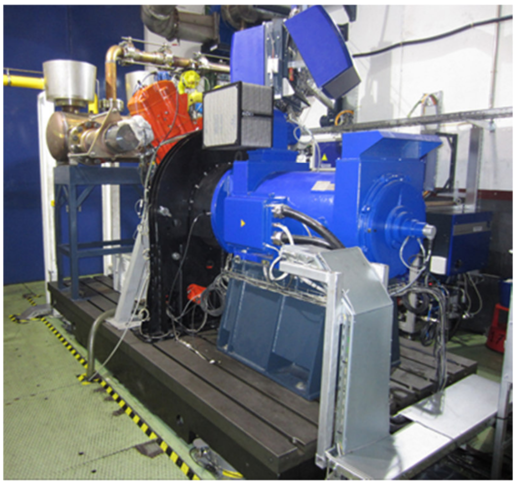


Figure 10. CFD simulation of a gas-fed pre-chamber combustion process

As a second step, the new pre-chamber designs were tested on the SCE. Single-cylinder engine research reduces development time and cost and offers greater flexibility to operate the engine under different boundary conditions. The primary goal of the SCE test was to validate the simulation results and to obtain the most suitable operation parameters of the engine. As a result of the SCE testing, the best solution regarding pre-chamber shape, ignition timing, injected gas flow, and main chamber lambda was identified. Finally, the selected pre-chamber design was tested on the MCE.



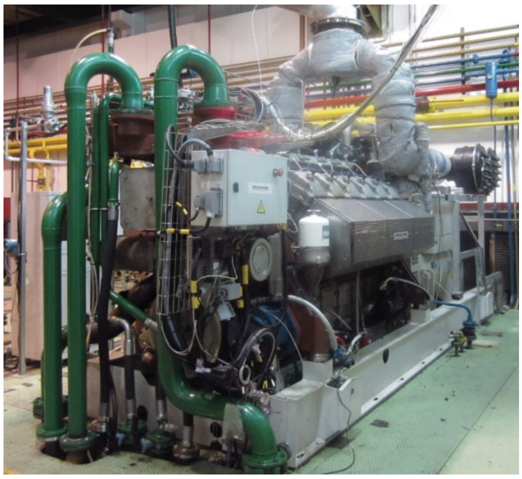


Figure 11. SCE and MCE engine test beds in Siemens Engine Business R&D facility in Miñano, Spain.

Advantages of the lean-burn combustion systems compared to the rich-burn combustion systems were addressed in chapter 2 of this paper. The lean-burn pre-chamber concept consists of applying these benefits to the pre-chamber itself and trying to operate it with leaner lambdas, thus improving the BTE/NOx trade-off of the pre-chamber. However, the conversion from a rich-burn pre-chamber to a lean-burn pre-chamber requires several modifications in the pre-chamber tip design. The main objective is to increase the mechanical energy inside the pre-chamber to compensate for the reduced chemical energy caused by the leaner lambda. For the main chamber, the piston compression ratio is increased to augment the mechanical energy, whereas in the pre-chamber, the following design parameters need to be optimized:

- Pre-chamber volume
- Pre-chamber nozzle size
- Pre-chamber nozzle orientation
- Pre-chamber neck

After designing the new pre-chamber with the support of CFD simulation, the following improvements in the SCE and MCE tests conducted in the SEB R&D facility were observed when compared to the rich-burn pre-chamber test results:

- Improved BTE/NOx trade-off
- Improved combustion stability at low NOx emissions (COV of IMEP)
- Capability to operate with a lower amount of gas injected into the pre-chamber without running into cylinder misfire
- Capability to operate with richer lambdas in the main chamber and thus lower boost pressure

This optimized combustion process has improved the performance of the SGE-EM engine regarding engine efficiency and combustion stability, not only for 500 and 250 mg NOx/Nm3 but also for 200 mg NOx/Nm3. Furthermore, the efficiency drop from 500 mg NOx/Nm3 to 250 and 250 mg NOx/Nm3 is also lower compared to the rich-burn solution. Figure 12 shows the improved engine efficiency for the different emission levels compared to the rich-burn solution.

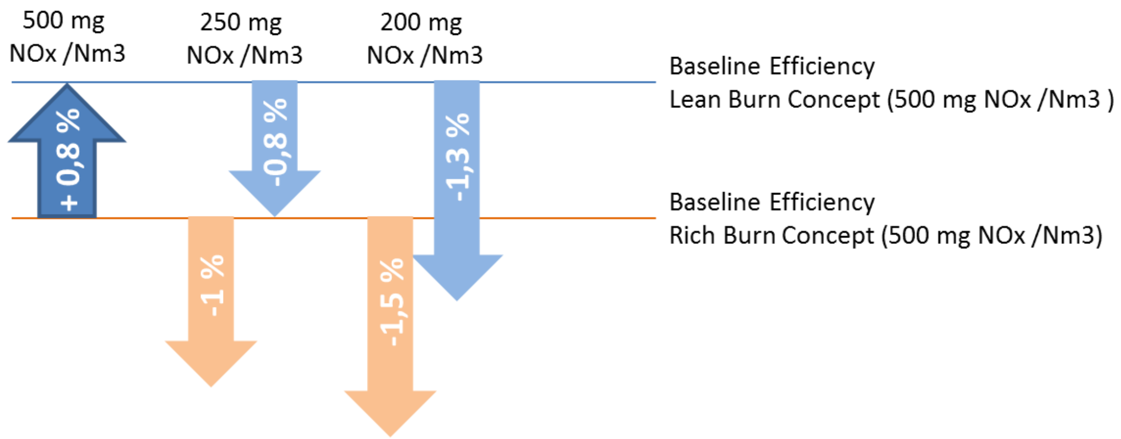


Figure 12. Engine efficiency comparison between rich-burn and lean-burn pre-chamber concepts for different NOx emission levels.

Based on the results obtained in the SCE and MCE, the new combustion technology sets the perfect scenario for further reduction of the NOx emissions below 200 mg NOx/Nm3.

3.3 Operation at 100 mg NOx/Nm3

With the engine running at constant 200 mg NOx/Nm3 and before increasing the air excess ratio to look for lower NOx levels, several engine operation parameters were modified. This parameter tuning is focused on increasing the potential for further NOx emission reduction without considering the penalties on engine efficiency:

- The amount of gas injected into the pre-chamber was reduced leading to lower NOx generation inside the pre-chamber (leaner operation inside the pre-chamber). This affects the power of the flame jets reducing engine efficiency, but on the other hand, allows the engine to operate with richer lambda and therefore lower boost pressure.
- The ignition timing has been retarded. The effect is similar to the reduction of the gas, whereas the engine efficiency is reduced while the boost pressure is also reduced.
- Ignition energy on the spark plug was increased to ensure the ignitability of the leaner mixture inside the pre-chamber [5].

As a result of the three measures explained above, the engine can operate with a lower boost pressure for the same NOx emission level (200 mg NOx/Nm3). These new operating conditions are less demanding for the turbocharger and enable the potential to increase the air excess ratio. For the SGE-EM, the air excess ratio was increased until the limit of the turbocharger was found to achieve less than 100 mg NOx/Nm3. No cylinder misfire events were observed under these operating conditions and the obtained electrical efficiency value was still 41.2%.

It was proven that combustion stability and cylinder misfire are not the limiting factors to operate the SGE-EM engine at low emission levels.

4. Customer value of a low-emissions solution versus a high-emissions solution with an after-treatment system

The real market applicability of a low-emission generator set (gen-set) is often challenged by the possibility of using a high-emission but more efficient gen-set together with an after-treatment system. The use of SCR for NOx emissions reduction is a common practice in the market today for generation units of this size. The technology has significantly evolved, and prices have decreased over the last years.

The final decision for the customer regarding whether to use one solution or the other is determined by calculating if the savings in fuel, obtained by using a more efficient engine compensates for the extra investment and maintenance cost of an SCR system. The result will depend on several factors, such as fuel costs and expected number of operating hours per year of the generation unit.

By comparing a solution with the SGE-86EM gen-set at 500 mg/Nm3 NOx and adding an SCR to reduce it to 100 mg/Nm3 with the SGE-86EM gen-set directly giving 100 mg/Nm3 NOx, but with the efficiency not fully optimized yet, we can obtain the annual operating hours at which NPV of fuel cost savings offset the additional price and maintenance cost of a solution with SCR (depending on natural gas price):

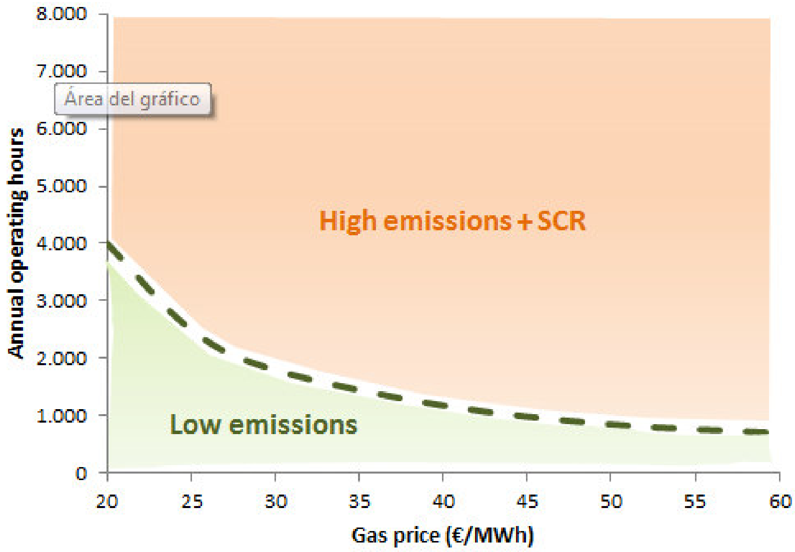


Figure15. SGE-86EM at 500 mg/Nm3 plus SCR versus SGE-86EM at 100 mg/Nm3 NOx.

For a gas price scenario of 50 €/MWh a solution with a higher efficiency plus SCR starts becoming profitable for annual operating hours above 800 h whereas for a gas price of 20 €/MWh the customer will only start seeing value above 4.000 h a year.

Comparing now a solution with the SGE-86EM gen-set at 500 mg/Nm3 NOx and adding an SCR to reduce it to 200 mg/Nm3 with the SGE-86EM gen-set directly giving 200 mg/Nm3 NOx with the efficiency already optimized, the result is:

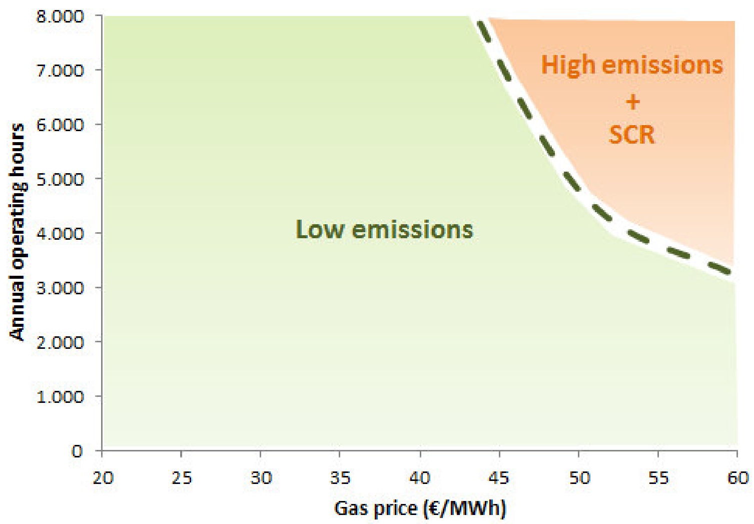


Figure16. SGE-86EM at 500 mg/Nm3 plus SCR versus SGE-86EM at 200 mg/Nm3 NOx.

In this case, for a gas price scenario of 50 €/MWh a solution with a higher efficiency plus SCR starts becoming profitable for annual operating hours above 4800 h.

These comparisons show that there are conditions under which a low-emissions solution generates customer value versus a high-emissions solution plus after treatment.

If the efficiency of the low-emissions solution is increased the conditions under which there is customer value for it will be wider.

5. Conclusions

The SGE-EM is a lean-burn gas engine that uses a gas-fed pre-chamber to achieve high efficiency and power density at low NOx emission levels. During the project execution, Siemens took advantage of the latest technology trends regarding pre-chamber development to achieve the highest BTE/NOx ratio possible. As a result of this development effort, the SGE-EM engine series show "best-in-class" efficiency for operation at 250 and 500 mg NOx/Nm3 @ 5%O_2. Furthermore, the engine can operate at 200 mg NOx/Nm3 @ 5%O_2 fulfilling the requirements of the EU Directive for plants with rated thermal input power higher than 50 MWth.

Performance tests on the MCE showed that with fine tuning the engine operating parameters, 100 mg NOx/Nm3 could be achieved without cylinder misfire. These results confirm the robustness of the combustion system when operating at very low emissions and they also point out that the combustion system is no longer the limiting factor.

6. References

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