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ON COMBUSTION ENGINES

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CIMAC Position Paper

Gas Engine Aftertreatment Systems

By CIMAC WG 17, Gas Engines

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Content

1 Summary

This position paper describes the potential impact of stricter exhaust emission standards on engine performance, engine design and the requirements for exhaust aftertreatment systems for stationary, 4-stroke natural gas engines. In order to protect air quality and the environment for future generations, increasingly stringent exhaust emissions limits for natural gas fueled engines are under consideration throughout the world. Over the last fifteen years there have been large advances in natural gas engine technology that have simultaneously increased efficiency while also reducing emissions. Reducing engine emissions further while maintaining or improving efficiency will be a large challenge.

2 Combustion Fundamentals of Natural Gas Engines

To understand the impact of requiring lower exhaust emissions for natural gas fueled engines the characteristics of exhaust emission formation in these engines have to be considered. In the context of this paper natural gas is considered to be generally available pipeline gas or LNG which has undergone processing in order to hold its combustion characteristics relatively constant. This paper does not address engines that operate on lower quality gas pulled directly from oil and gas wellheads nor does it address engine technologies that are not currently available in the marketplace. Generally speaking, reciprocating combustion engines fueled with natural gas have the potential to lower carbon dioxide (CO_2) emissions due to the lower carbon/hydrogen ratio of natural gas as compared to diesel fuel as long as methane emissions can be held in check. The achievable nitric oxide (NOx) emission level without exhaust aftertreatment can be 80-90% lower than for a comparable diesel engine and the soot emissions from natural gas engines are negligible.

In general, natural gas engines are operated in one of two regimes as shown in Figure 1: Key exhaust gas emissions as a function of relative AFR (lambda). The two operating spaces are defined by the relative air/fuel ratio (commonly referred to as *lambda*) at which the engine may operate. Engines running at lambda greater than about 1.6 are called “lean burn” combustion systems while those that operate at lambda equal to 1.0 are called “stoichiometric”. At the higher lambda values used in lean burn operation, the formation of NOx is much lower and as a result lean burn engines are typically able to meet many emissions standards without aftertreatment. In many applications engines that can meet emissions targets without aftertreatment systems or with simple aftertreatment systems (i.e. oxidation catalysts). These engine systems are preferred due to lower first costs, lower maintenance costs and better reliability.

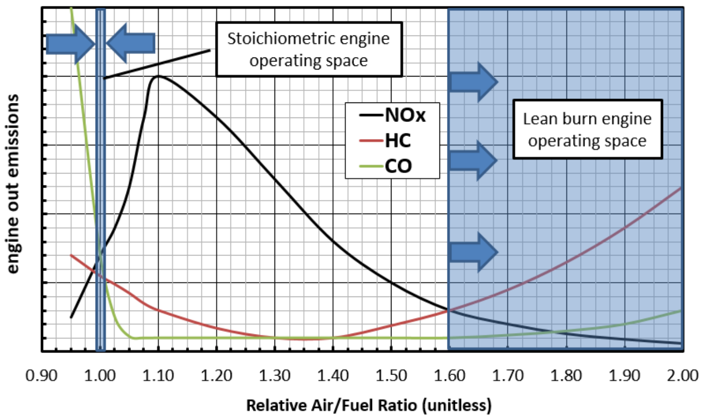


Figure 1: Key exhaust gas emissions as a function of relative AFR (lambda).

As shown in 1, the stoichiometric engine operates in a very tight air/fuel-ratio window where the generation of NOx, carbon monoxide (CO) and hydrocarbons (HC) is relatively high, but where the NOx and CO emissions are balanced. When these emissions species are tightly controlled, they can be passed through a three-way catalyst (TWC). The catalyst helps to encourage reactions that oxidize the CO and HC and reduce the NOx. The resulting emissions from these catalytic reactions are CO_2, nitrogen (N2) and water. Further details regarding both combustion systems can be found in references such as Internal Combustion Engine Fundamentals by Heywood [1].

After decades of research and development directed toward optimizing the lean burn combustion system, today's power generation and marine markets are dominated by this technology. Figure 2 shows engine efficiency versus engine load for a range of products from many different manufacturers. In the power generation market a primary consideration is the engine efficiency due to fuel operating costs. The data in Figure 2 show that lean burn engines perform better than stoichiometric gas engines in this regard.

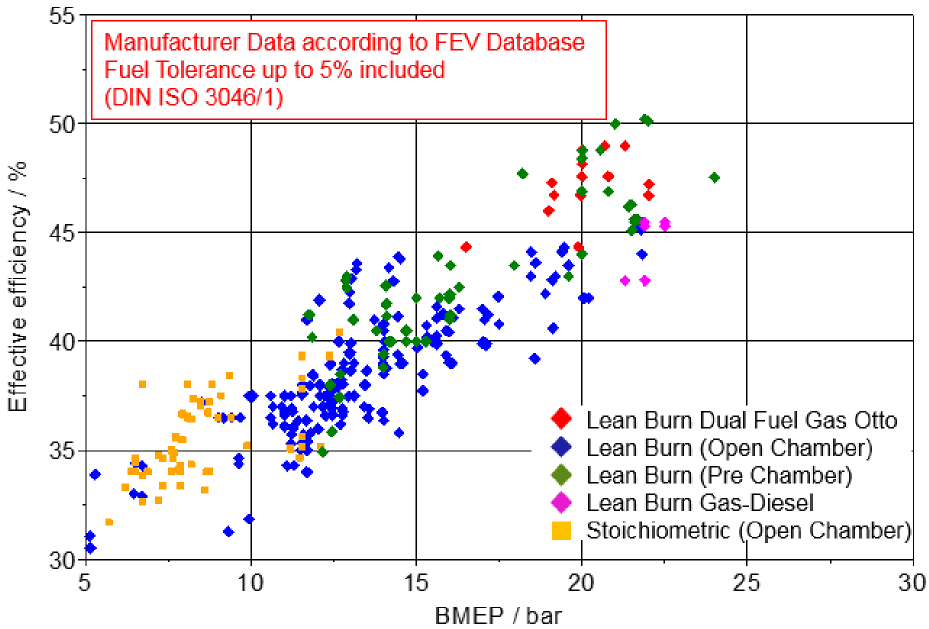
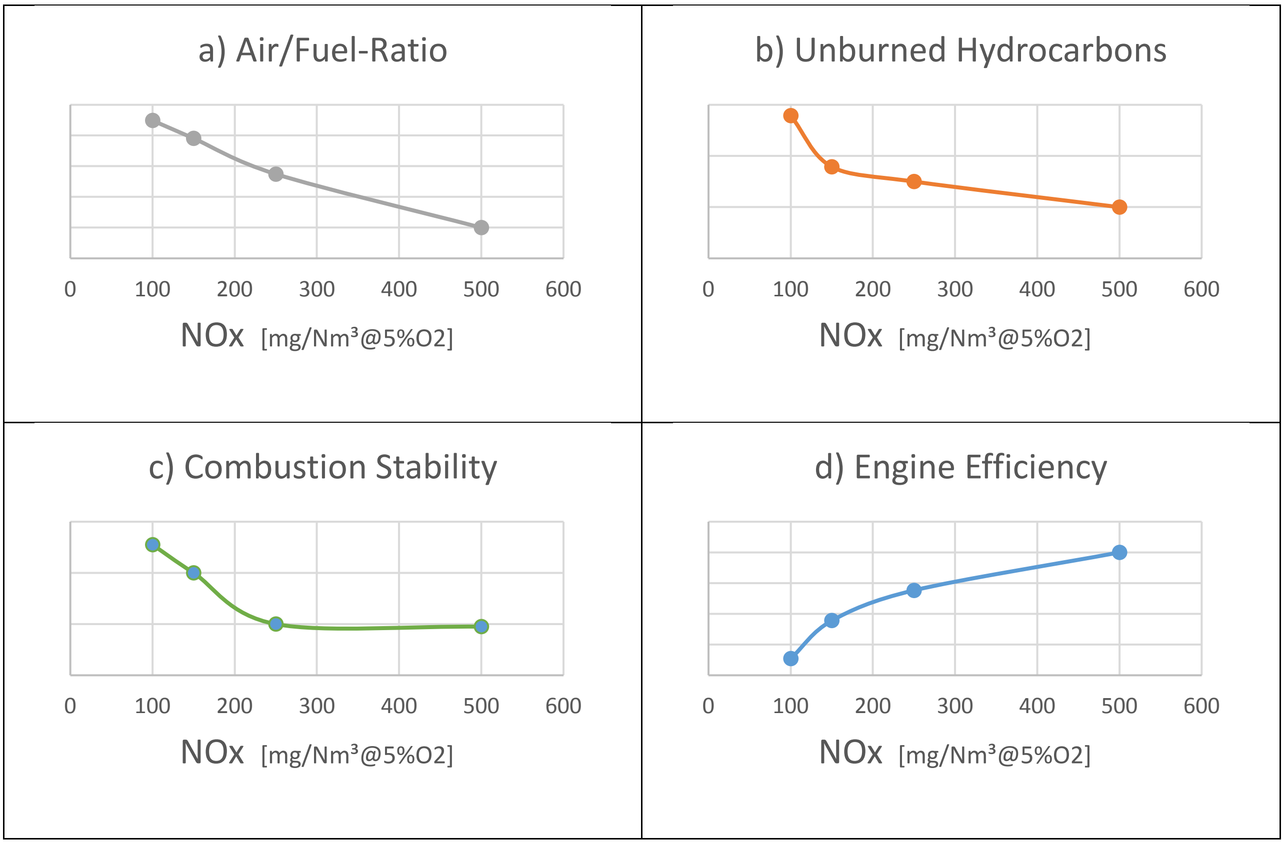


Figure 2: Engine efficiency as a function of load (BMEP) for different combustion systems.

3 Exhaust Emissions of Lean Burn Engines

Lean-burn combustion systems use air dilution in order to achieve low NOx emissions. NOx formation is highly dependent on temperature and higher combustion temperatures will generate more NOx emissions. The addition of excess air reduces the rate of combustion and mixture temperatures during combustion and thereby lowers the amount of NOx formed in the combustion chamber. Figure 3a shows the resulting NOx trend against a normalized air/fuel ratio. Extrapolating this trend it might be expected that continuing to lean out the combustion charge would result in ever decreasing levels of NOx. However, diluting the combustion charge with air also inhibits the propagation of the combustion flame and this results in higher HC and CO emissions (see Figure 3b) as well as generally lower exhaust temperatures. An increase in CO and HC emissions at higher air/fuel ratios (lower NOx levels) is a sign of incomplete combustion and contributes to a loss of combustion stability and a decrease in the overall efficiency of the engine as shown in Figures 3c and 3d. Lower exhaust temperatures make it difficult to add aftertreatment to the engine because all aftertreatment systems have a minimum temperature threshold. If the exhaust temperatures drop below that threshold, the reactions occurring within the catalysts will be reduced or even cease.

Oxidation catalysts use noble metals which are prone to deactivation/poisoning from any amount of sulfur in the fuel and/or elements in the lubricating oil such as zinc or phosphorus. More information on aftertreatment systems can be found in Critical Topics in Exhaust Gas Aftertreatment [2]. Today's state-of-the-art systems struggle to achieve high conversion efficiencies at low operating temperatures. Please refer to CIMAC Working Group 17 position paper from 2014 titled "Methane and Formaldehyde Emissions of Gas Engines" which can be downloaded from the CIMAC website. There is a trade-off between lower NOx emissions, complete combustion and high thermal efficiency. Over the past 20 years' significant effort has been put into optimizing ignition systems, mixture formation, charge motion and combustion chamber geometry in order to meet stability requirements at low NOx levels while continuing to improve engine efficiency. To realize significantly lower exhaust emissions through combustion improvements will likely require compromises with respect to engine efficiency and combustion stability. For high performance natural gas engines, the potential for internal engine changes to address these challenges is quite limited.



Figures 3a-d: Qualitative impacts of lower NOx-emission at higher air/fuel ratios.

4 Aftertreatment for Lean Burn Engines

Efficiency Impacts

For NOx emissions reduction, the main lean burn engine aftertreatment option is the Selective Catalytic Reduction (SCR) system. Typically, the addition of a SCR aftertreatment system does not affect the thermal efficiency of a given engine at fixed operating conditions. High engine efficiency can be maintained when a lean burn engine is coupled with a modern SCR system because the SCR is very effective at reducing NOx. When using a SCR catalyst, a reducing agent (urea/ammonia) must be added to the exhaust stream. This additional fluid adds a measure of cost and complexity to the system. Another disadvantage of SCR systems is that ammonia catalysts are often required to treat any unreacted SCR reductant. Regulated ammonia limits can have a significant impact on system cost and expected catalyst life. Other aftertreatment components for lean burn engines can include oxidation catalysts or a regenerative thermal oxidizer to reduce CO and some amount of unburned hydrocarbons as well as formaldehyde emissions. As discussed in the previous section, lower NOx levels may be achievable through increasing the air/fuel ratio (adding more diluent) but there are challenges to this approach. Increasing the air diluent level beyond today's lean burn engines will likely result in higher HC (mainly methane), CO and formaldehyde emissions. The reduction of these exhaust emissions by oxidation catalysts will become more challenging due to lower exhaust temperatures at higher air/fuel ratios. As regards the potential for methane catalysts, current formulations typically have high initial effectiveness but then performance declines at unacceptably fast rates. Any sulfur present in the fuel or elements in the lubricating oil can have a particularly detrimental effect on catalyst performance. If there is a drive toward lower exhaust temperatures this will only compound the challenge of developing a market viable methane catalyst.

Combustion Air System

The most advanced lean burn engines typically have a high-performance turbocharging system with two stages of compression and associated inter/aftercoolers in order to perform more of the compression work outside the combustion chamber. These two stage turbocharging systems present a dilemma in that while higher boost levels and intercooling enable higher thermal efficiencies, they result in lower exhaust gas temperatures at the aftertreatment system inlet. These exhaust temperatures can be so low that they fall below the operating range of many aftertreatment systems. In that case, additional devices/functionalities with alternative engine operating modes must be used in order to increase the exhaust temperatures. These devices must be placed in higher pressure/higher temperature environments further upstream in the exhaust and therefore are more expensive, require a high level of integration and can reduce the transient response of the engine thereby limiting its application and flexibility. In general, the air systems for lean burn engines must have higher levels of performance than their stoichiometric engine counterparts. The combustion system of a modern lean burn engine usually operates at much higher loads and this requires much more air flow for a given amount of fuel relative to a stoichiometric engine. Turbocharging systems capable of providing air dilution for the next generation of lean burn engines will require higher levels of complexity and cost.

Durability

Natural gas engine durability and component life is tied to operating temperatures within the engine. As mentioned previously, lean burn engines have the advantage of lower operating temperatures as compared to stoichiometric engines currently offered in the market. This means that less expensive materials can be used in their design and that a well-designed lean burn engine will last longer and be more durable. With respect to lean burn aftertreatment, the addition of an SCR system has little to no impact on the base engine durability if the engine operating mode remains unchanged. However, the SCR system does introduce complexity and significant additional cost.

Controls

The addition of any aftertreatment system requires additional control system hardware and software. In the case of SCR systems this requires careful control of the flow of reductant (urea/ammonia) to the SCR catalyst. The SCR system temperatures will have an influence on the NOx conversion performance and needed reductant flow rates and therefore must be monitored and controlled. The use of a NOx sensor for monitoring and feedback control is needed to maintain optimal performance over the system lifetime.

System Schematic

Figure 4 shows examples of lean burn engine exhaust gas aftertreatment systems and their relative sizes. The schematics show the relative footprints of each of the systems in relation to the base footprint of the engine and generator. In the case of the SCR systems, which are required for NOx low emissions, the aftertreatment systems double the size of the space required for a given genset installation. Future systems would likely have to increase significantly in size which would drive additional cost.

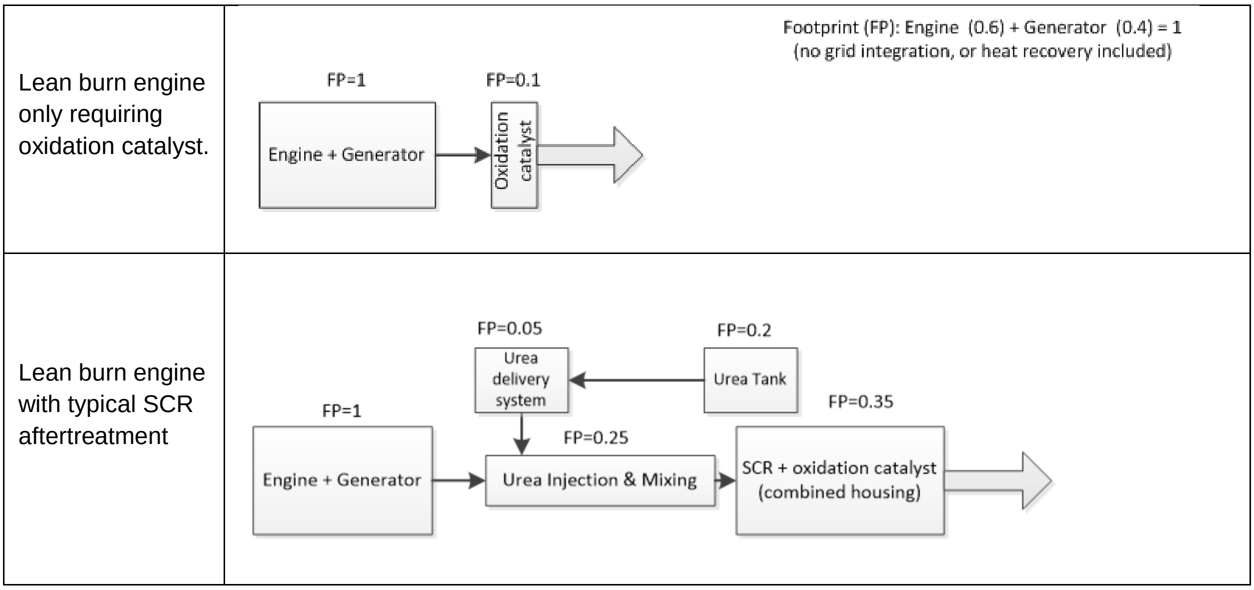


Figure 4: Examples of footprints for two state-of-the-art lean burn engine aftertreatment systems (0.5-3 MW engine output).

5 Exhaust Emissions of Stoichiometric Gas Engines

To achieve low exhaust emissions, the stoichiometric gas engine needs to control lambda within a very tight window so that the three-way catalyst can convert CO, NOx and non-methane HC emissions into CO_2, N_2 and water as previously described. High emissions conversion rates are only possible in a small window close to lambda equal to 1.0. In this lambda region catalyst conversion rates of up to 99% are possible and result in very low exhaust emissions. Stoichiometric combustion is quite fast relative to lean burn combustion and occurs at higher temperatures. This fast, robust combustion results in a very complete burning of the cylinder charge and low levels of engine out unburned hydrocarbons. Despite achieving low emissions levels with TWC aftertreatment this combustion concept is not common for applications where the engine is operated for long periods at high loads such as electrical power generation and marine main propulsion. These markets are currently dominated by lean burn engines because of their higher power density, higher efficiency and minimal aftertreatment requirements.

6 Aftertreatment for Stoichiometric Gas Engines

Efficiency Impacts

Engine out emissions of NOx and CO for stoichiometric engines are quite high as compared to their lean burn counterparts, however by pairing these combustion systems with three-way catalysts the engine/catalyst system is able to achieve very low emission levels. In general, stoichiometric engines are at least 7-8 points lower in efficiency than their lean burn counterparts (refer back to figure 2). There are ways to increase the performance of stoichiometric engines by making them more like a lean burn engine. The main approach would be to recirculate cooled exhaust gas (EGR) back to the intake of the engine. EGR does not participate in the combustion process and thereby acts as a diluent similar to air in a lean burn engine but, unlike air dilution, EGR allows the use of a catalyst. Using EGR would lower the engine out NOx levels and help to reduce the engine component temperatures but currently there are no high load natural gas engines utilizing this technology. The use of EGR presents large challenges with respect to system integration, combustion stability, hydrocarbon emissions and component durability and therefore the current customer must be willing to accept large efficiency and durability penalties when considering the purchase of a stoichiometric engine.

Combustion Air System

In general today's stoichiometric engines require lower levels of turbomachinery performance as compared to their lean burn counterparts. The reason for this is that the combustion charge is not diluted with excess air and therefore the compressor work is lowered for a given engine power level. However, the turbocharging systems on stoichiometric engines must be able to tolerate the higher exhaust temperatures of these engines. As an example, comparing a lean burn and stoichiometric engine at their respective rated load conditions the lean burn engine is producing 60% more power, but it's exhaust temperatures will be roughly 150 deg C lower than the stoichiometric engine.

Durability

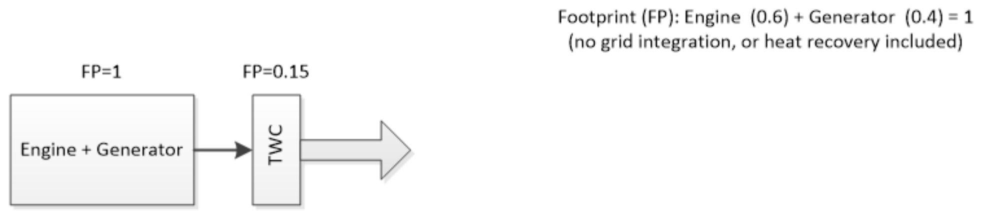
Higher temperatures put more stress on critical engine components and drive higher component costs and shorter life. If future stoichiometric combustion systems move toward using EGR to reduce engine emissions, there could be significant durability impacts for the turbo compressor depending on where the EGR is introduced. While the addition of EGR helps to improve stoichiometric engine efficiency and load capability, it introduces significant additional system cost and complexity. For example, unless the water formed during combustion is removed from the exhaust gas prior to being reintroduced into the engine, significant amounts of water can condense inside the engine if not take into consideration during the system design. If allowed to condense, the water combines with NOx to form nitric acid which can damage engine components. With respect to aftertreatment systems the main durability issue is any sulfur contained in the fuel. Sulfur passing through the engine will contaminate catalyst reaction sites and reduce the catalyst conversion efficiency. When this happens, the catalyst must either be cleaned, regenerated in-situ or replaced in order to restore high catalyst conversion efficiency and regulatory compliance. Lastly, in the case where the engine might misfire (air and fuel pass through the engine unburned) the unburned mixture can quickly cause the catalyst to exceed its maximum operating temperature and pressure which can either damage or destroy the catalyst.

Controls

Similar to SCR systems, the TWC aftertreatment system requires careful control and monitoring. In a typical system oxygen sensors are used to control and monitor the system performance. Three-way catalysts are susceptible to damage from engine misfire so misfire detection must be added to the engine control architecture. For stoichiometric engine solutions that elect to use EGR, accurately measuring or estimating EGR flow rates and controlling EGR levels are also significant challenges.

Schematic

Figure 5 shows the relatively compact footprint of a stoichiometric generator set with a three-way catalyst. As can be seen in the graphic the overall installation is much smaller than for a similarly sized lean burn engine, however for today's stoichiometric engines there is the large efficiency and power penalty for the same footprint which leads to significantly higher operating costs. On an installed power-per-square-meter metric, the lean burn engine package holds a significant advantage over the stoichiometric engine package.

<table>
<tr><td>Base stoichiometric engine TWC</td><td>
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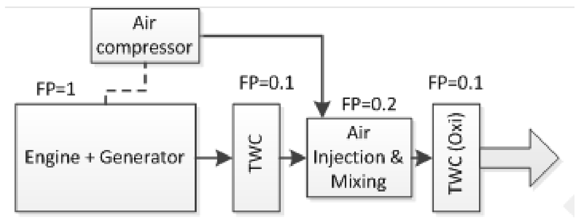
<tr><td>TWC with second stage air injection</td><td>
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Figure 5: Examples of typical stoichiometric engine installations with approximate footprint of engine and aftertreatment (0.5-3 MW engine output).

7 Aftertreatment Systems Cost Comparison

In addition to the performance comparisons between lean burn and stoichiometric engines the relative costs of each system must be considered. Table 1 shows relative costs of different aftertreatment systems for both lean burn and stoichiometric engines. Options 1-3 are the most common types of installations for lean burn engines. The most common installation for stoichiometric engines is Option 1. At first glance it would appear that the SCR system is much more expensive than the TWC system, but this table does not include the efficiency penalty associated with running a stoichiometric engine. In the case of the stoichiometric engine, the annual fuel costs for the customer would be approximately 30% higher and this is what drives the majority of the electrical power generation market to choose the lean burn solution over the stoichiometric option. In applications where the engines are being used to generate power the annual cost of fuel soon eclipses the capital cost of the engine and aftertreatment system.

Table 1: Relative cost - Normalized aftertreatment cost based on engine cost (engine size: 0.5 - 3MW)

Lean burn	Aftertreatment component costs	Aftertreatment installation costs *	Additional OPEX (Service, op. fluid) OH=operating hours	Additional information
Option 1: Oxidation catalyst only	5 - 10%	1 - 3%	Catalyst cleaning / replacement every 10 – 20,000 OH	Catalyst and housing and insulation
Option 2: SCR only	25 -35%	10 - 50 %	Catalyst cleaning / replacement 10 – 20,000 OH; Urea consumption (1-2% of fuel)	Including insulation and urea tank w/ simple urea supply system (no trace heating, etc)
Option 3: SCR and Oxidation catalyst	30 - 40%	10 - 50 %	Catalyst cleaning / replacement 10 – 20,000 OH; Urea consumption (1-2% of fuel consumption)	Including insulation and urea tank w/ simple urea supply system (no trace heating, etc)
Option 4: CO Oxidation catalyst + SCR + Ammonia Oxidation catalyst	35 - 45%	15 - 50 %	Catalyst cleaning / replacement 10 – 20,000 OH; Urea consumption (1-2% of fuel consumption)	Including insulation and urea tank w/ simple urea supply system (no trace heating, etc)
Option 5: Thermo-reactor	35 - 60%	10 - 20%	Supplementary fuel (~1-2%)	Including auxiliaries
Stoichiometric				
Option 1: TWC only	10 - 15%	1 - 3%	Catalyst cleaning / replacement every 10 – 20,000 OH	Catalyst and housing and insulation
Option 2: 2-stage TWC (secondary air injection)	15 - 25%	3 - 10%	Catalyst cleaning / replacement every 10 – 20,000 OH Compressed air	Catalyst and housing + air compressor

* Installation costs for large aftertreatment systems are very dependent on the application and available space. For special applications (e.g. less available space) costs can be even higher.

8 Conclusions

After decades of development and refinement, natural gas engines offer lower emissions at comparable or better efficiencies than their diesel fueled counterparts. Pushing emissions limits further with current lean burn technology will force trade-offs between lower emissions and engine efficiency. Leaner combustion results in lower exhaust temperatures which makes catalyst operation difficult. Lower exhaust temperatures would mean sacrificing catalyst efficiency or significantly increasing costs due to more exotic catalyst formulations and shorten life. Stoichiometric engines are a viable option to meet more stringent emissions, however, with a significant detriment to fuel efficiency. Due to the efficiency advantage and controls simplicity, the current market heavily favors lean burn technology. Using exhaust gases for dilution in natural gas engines would combine the benefits of lean burn combustion with the low emissions capability of three-way catalysts, but this configuration adds significant cost and durability concerns. It is important that industry and regulators work together to arrive at the best possible solution for gas engine stakeholders.

9 Sources

[1] Heywood, J. (1988). *Internal Combustion Engine Fundamentals.* New York: McGraw-Hill.

[2] Eastwood, P. (2000). *Critical Topics in Exhaust Gas Aftertreatment.* Hertfordshire, England: Research Studies Press Ltd.

Information on the following topics can be found in other CIMAC Working Group 17 position papers:

■ Guideline on Methane and Formaldehyde Emissions of Gas Engines [PDF] (April 2014)

Information concerning the application of gas engines in the marine industry [PDF] (December 2013)

■ Transient response behavior of gas engines. [PDF] (April 2011)

■ The influence of ambient conditions on the performance of gas engines. [PDF] (March 2009)

■ Information about the influence of ammonia in the fuel gas on NOx emissions. [PDF] (December 2008)

■ Information about the use of liquefied natural gas as an engine fuel. [PDF] (December 2008)

■ Impact of gas quality on gas engine performance. [PDF] (July 2015)

Imprint

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