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Trends in the Development of Large Gas Engines for Power Generation

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Abstract

Numerous studies verify that the global significance of natural gas for combined heat and power generation (CHP) and mobility will greatly increase in the future. In its World Energy Outlook (WEO) 2012, the IEA (International Energy Agency) predicts that the use of natural gas for power generation will double in the next 20 years. Due to great improvements in efficiency and power output in recent years, large gas engines for stationary power generation have registered significant growth. To make gas engines more competitive in areas currently dominated by diesel engines, intensive research is required to overcome the disadvantages that still exist. This primarily entails improving dynamic behaviour and robustness. Further challenges will result from the great fluctuations in gas quality to be expected of grid gas and LNG. The trend to use special gas engines which make use of many gases that would otherwise not be exploited will continue to increase. The previous research focus of the LEC was on thermodynamically oriented optimization of combustion concepts for large engines. Developed at the LEC over the course of many years, LEC Development Methodology (LDM) is based on the intensive interaction between simulation of the engine cycle and experimental investigations of single cylinder research engines. LDM has been applied successfully to a wide variety of combustion concepts. A methodology which allows optimization of the overall system has also been created: LDM Advanced. Using a multidisciplinary approach which includes mechanics, material sciences, chemistry, and tribology in addition to thermodynamics, its main focus is on extensive physical modeling of all combustion related subsystems and effects. This paper indicates future trends in engine performance and describes the LEC development methodology.

Keywords:	Internal combustion engines; Development methodology; Single cylinder research engines; Gas engine; Power generation

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1. Introduction

Numerous studies verify that the global significance of natural gas for power generation and mobility will greatly increase. Figure 1 presents a prognosis made by the International Energy Agency (IEA) about the development of global power generation as divided into shares of the individual areas (World Energy Outlook 2012) [1]. According to this prognosis, the share of natural gas will increase significantly in the next 20 years and even double.

The main impetus for this development comes from the large natural gas resources in conventional and unconventional deposits (shale gas, tight gas and CBM), the trend in the price of natural gas (especially in the U.S.), the discussion about how to stop using nuclear energy in various countries (e.g., Germany and Japan) and the fact that natural gas technology can be used to bridge the gap between carbon-based and "carbon-free" energy supply and mobility since natural gas has less carbon than other fossil fuels.

Currently, one of the most important areas of gas engine application is in combined heat and power plants (CHPP), where engines are used to produce electricity and heat. Gas engines are also used to produce power independent of the grid in generator sets (gen-sets) and in mechanical drive applications for pumps and compressors (e.g., petrochemistry, oil and gas production, wastewater treatment). As future emission regulations for marine applications are becoming more stringent, manufacturers and shipping companies are increasingly interested in using gas and dual fuel (DF) engines for ship propulsion. In addition, the use of gas engines for the exploitation of special gases such as landfill gas, waste gas from industry, and flare gas is also gaining in importance [2], [3].

On the whole, there is a clear trend toward increased use of gaseous fuels for engine operation. Figure 2

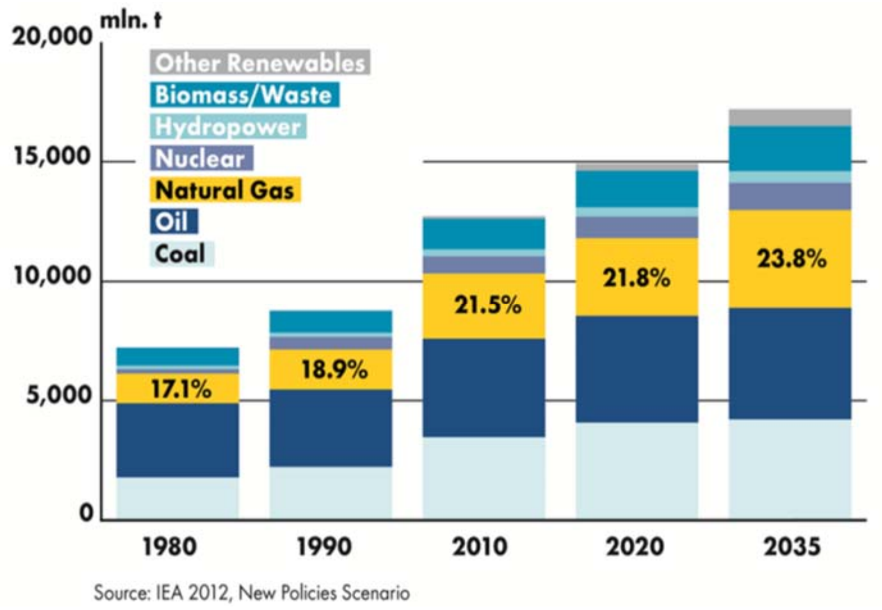

Figure 1. Development of resources for global power generation [1]

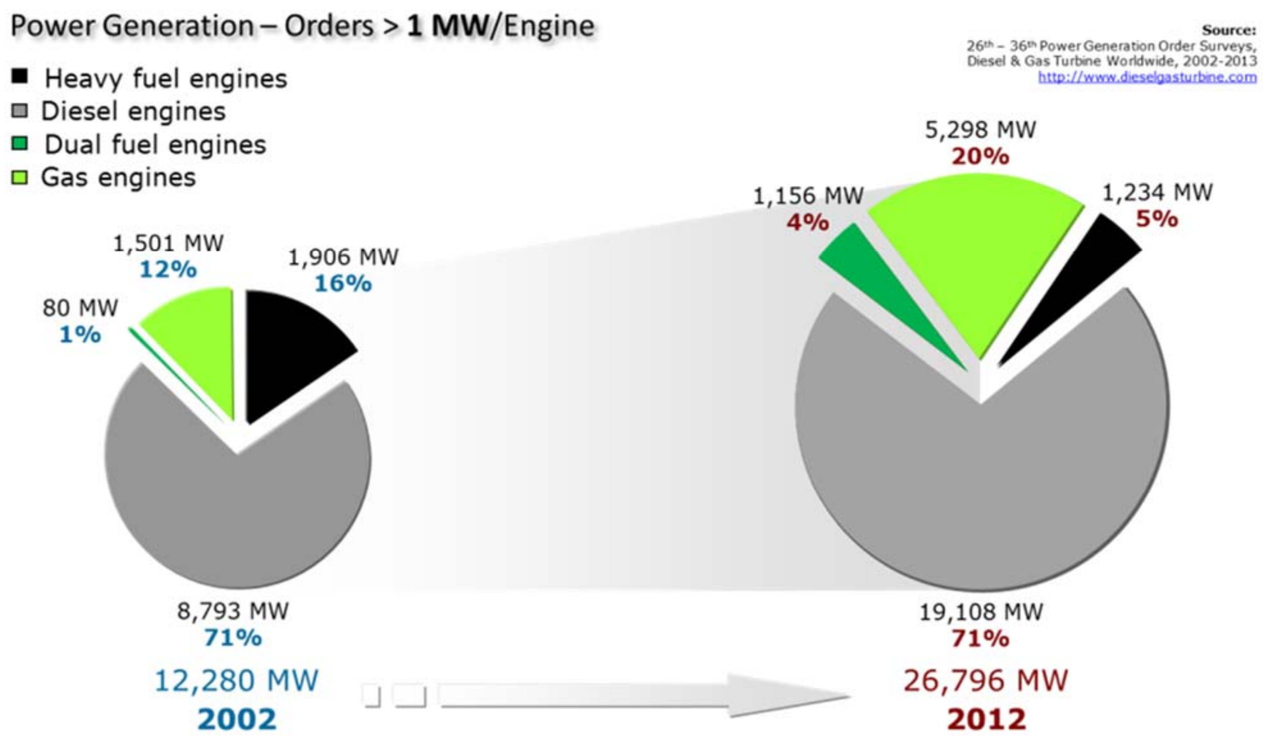

Figure 2. Orders received worldwide for large engines > 1 MW/engine

shows global development of orders for large engines for power generation with an output greater than 1 MW. It can be seen that the share of gas and DF engines nearly doubled from 2002 to 2012, achieving a share of almost 25%. Since it offers advantages in certain situations, however, the diesel engine still dominates. Any significant gains by gas engines will thus require further improvements in gas engine technology.

2. State of the art performance of Large Gas and DF Engines

To describe state-of-the-art technology for large engines and to identify potential areas in gas and DF engines that require development, it is first necessary to determine the evaluation criteria. Figure 3 shows selected features in the areas of performance and robustness.

Performance is characterized by load response, power output, emissions and efficiency while robustness consists of long-term stability, fuel flexibility and maintenance.

The current state of diesel, gas and dual fuel engines have been evaluated according to these criteria. As shown in Figure 3, the diesel engine has more shortcomings than a modern gas engine with regard to PM, NOx and CO_2 emissions (the over 30% advantage in CO_2 of the gas engine is mainly due to the higher energy content in terms of mass and the lower carbon content of natural gas). In contrast, the Otto gas engine shows inherent advantages in emissions except for methane slip due to incomplete combustion and the loss of unburned gas during the scavenging phase. In recent years, the efficiency of the gas engine has improved significantly, and in this respect it has outperformed the diesel engine.

To confirm this statement, Figure 4 presents the efficiencies that can be obtained with modern high-speed and medium-speed large gas and diesel engines in relation to NO_X emissions. The limit of TA Luft is given in g/kWh to allow comparison with diesel engines. Typical emission limits for large diesel engines are the 7.4 g/kWh limit for locomotive engines corresponding to U.S. EPA Tier 2 and the 9.0 g/kWh limit for marine engines (calculated for an engine speed of 1000 rpm) corresponding to IMO Tier 2. The disadvantage of the diesel engine arises in particular from the considerably higher NO_X emissions from the diesel process caused by the high temperatures in the burned zone of non-premixed combustion that proceeds near the stoichiometric air/fuel ratio. However, the diesel engine exhibits higher losses not only from losses from incomplete combustion but also from increased wall heat transfer due to the higher compression ratio as well as higher mechanical losses. Since measures such as EGR, increased injection pressure and post-injection have a negative effect on efficiency, improvements in emissions are presumably possible only on account of fuel efficiency, see [4].

The specific power output of the modern gas engine is nearly that of a diesel engine. However, there are still significant disadvantages in the areas of load response and robustness. A compromise between a diesel engine and a gas engine, the dual fuel engine has drawbacks mainly in diesel mode. As compared to the Otto gas engine, it has disadvantages in terms of particulate emission and fuel efficiency. On the other hand, load response behaviour is superior because during load changes, the gas mode is switched to pure diesel mode while accepting the Diesel specific disadvantages during these short periods of time (e.g. smoke).

		Efficiency	Emissions				Power density	Load response	Maintenance	Long Term Stability	Fuel Flexibility
			NO_x	PM	CO_2	CH_4					
Diesel Engine		o	-	--	-	++	++	++	++	+	+
Gas Engine		+	+	++	+	-	+	-	-	-	-
Dual Fuel Engine	Gas Mode	o	+	o	+	-	+	o	+	-	-
	Diesel Mode	--	-	--	--	++	+	++	+	o	+

Figure 3. Evaluating engine technologies

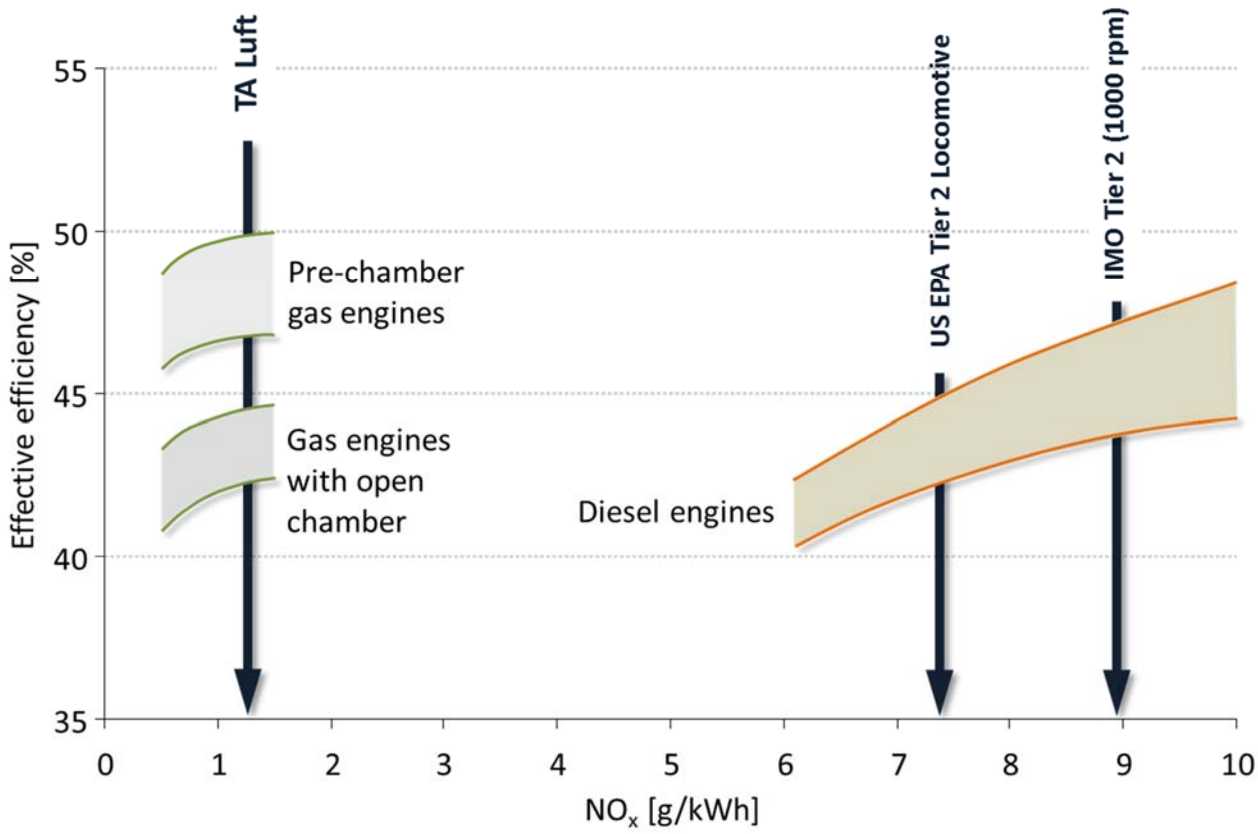

Figure 4. Efficiencies of current high-speed and medium-speed large gas and diesel engines

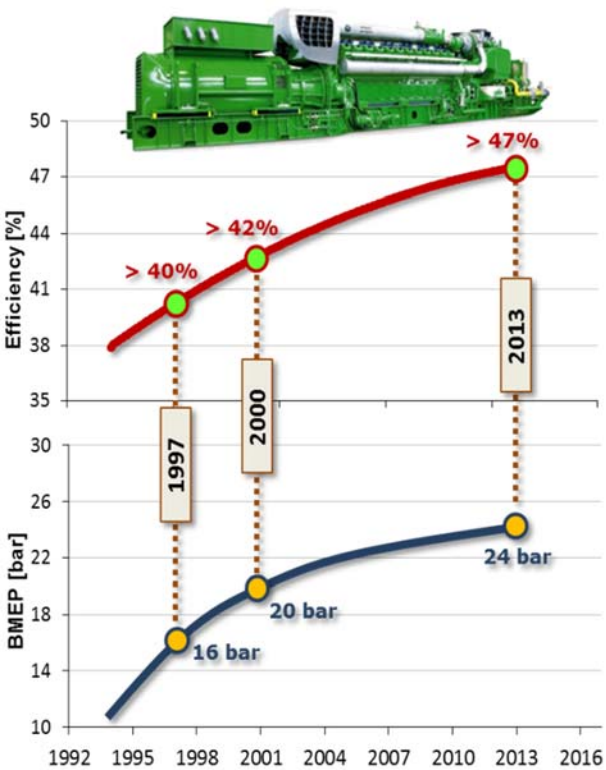

Figure 5. Increase in output and efficiency of the type 6 engine (GE Jenbacher)

3. Main challenges in the future development of Gas Engines

Due to great increases in efficiency and power output in recent years, large gas engines for stationary power generation have registered significant growth, thereby obtaining a considerable boost. Figure 5 provides one example of such a gain, charting the development of the GE type 6 engine over the years. Starting with a value of 38% (1994), efficiency increased to over 47% (2013). Over the same time period, BMEP increased from 12 to 24 bar.

In addition, low emission gas engines are favoured to solve the problem of how to meet the very stringent emission requirements for marine applications. Along with pure SI operation, dual fuel (DF) technology (from gas operation with diesel pilot injection to pure diesel operation) is a promising approach. In the meantime, DF technology is being intensively discussed for many other applications (such as locomotives). All in all, the inference is that gas and DF engines have great potential. To promote the use of environmentally sound gas and DF engine technology, the following challenges must be met:

3.1. Dynamic behaviour

Significant improvements in transient behaviour are necessary for gas engines to be used in areas currently dominated by diesel engines (e.g., mobile applications) and increasingly strict future requirements for stationary operation (island mode, grid parallel operation). The dynamic behaviour of the gas engine is inferior to that of a conventional diesel engine because the load acceptance of the gas engine is greatly limited by the knock limit, cf. [5]. This is especially true for high performance gas engines, which achieve a high level of efficiency and BMEP when operated with a very high compression ratio, extreme Miller valve timing and thus a high level of boost pressure as well as low turbocharger reserve. Dynamic behaviour can be improved through more robust engine design (e.g., lower BMEP, moderate Miller valve timing, lower boost pressure). However, this results in poorer efficiency and emission values. Thus one major goal must be to provide high performance gas engines with sufficiently transient behaviour.

Dual fuel engines exploit the advantages of the diesel mode for transient operation. However, here too new strategies for more favourable transient behaviour must be developed in parallel to desired improvements in efficiency and emissions. The considerably higher number of degrees of freedom that resulting from operation with two fuels also represents a great challenge.

3.2. Robustness

Along with worse dynamic behaviour, the gas engine also has the disadvantage that engine behaviour changes over runtime. This change is mainly caused by the formation of deposits on the combustion chamber walls and wear on the components involved in combustion. The limited service life of the spark plug shortens the maintenance interval for gas engines and represents a further drawback. Higher demands are also placed on high performance engines. Thus it is critical to design robust combustion concepts, and this design should be based on a profound understanding of wear mechanisms so that components can be optimized when appropriate.

3.3. Fuel sources

Gas and dual fuel concepts face the additional challenge of great fluctuations in the quality of grid gas and liquefied natural gas (LNG). The quality of grid gas will fluctuate in the future because of the diversification of its sources and more importantly the more extensive feeding of biogas and hydrogen as well as synthetic natural gas (SNG) from power to gas facilities, cf. Figure 6. Current regulations make reference to either the calorific value or the Wobbe Index, each of which must be maintained within a narrow range. No specific requirements exist for the change in knock resistance (methane number), which is a deciding factor for gas engines. Currently the lowest methane number being discussed is 65 (+/-2), cf. [6].

Figure 6. Causes of fluctuating quality of grid gas

Table 1: LNG composition with geographic variation [Mole Percent]

Source	Methane	Ethane	Propane	Butane	Nitrogen
Alaska	99.72	0.06	0.0005	0.0005	0.20
Algeria	86.98	9.35	2.33	0.63	0.71
Baltimore Gas & Electric	93.32	4.65	0.84	0.18	1.01
New York City	98.00	1.40	0.40	0.10	0.10
San Diego Gas & Electric	92.00	6.00	1.00	--	1.00

Source: Liquid Methane Fuel Characterization and Safety Assessment Report: Cryogenic Fuels Inc. Report No CFI-1600, Dec. 1991

Figure 7. Flare gas

The composition and thus the quality of LNG are by nature highly dependent on the source, cf. Table 1. The different fractions of methane have a great impact on knock resistance. However, methane number is influenced not only by its source but also by the liquefaction process and the storage system, which can lead to different shares in heavier hydrocarbons.

More and more large engines are being run on biogas and special gases. Special gas engines permit environmentally sound and energy efficient use of gases which would otherwise not be exploited, for example landfill gas, industrial waste gas and flare gas. There is clearly great potential for using flare gas to power engines. According to one estimate by GE, around 5% of global flare gas production is wasted annually, cf. Figure 7. Furthermore, gases with a very low calorific value (for example gases from steel production processes) are interesting as a future source of fuel for engines. In this context, dual fuel technology could be advantageous. However, gas composition has an impact on the different engine components, which must be designed accordingly.

3.4. Future emission limits

Research and development expenditure is very heavily influenced by the development of the emission limits. Very different emission regulations for large engines exist around the globe. These regulations define limits depending on the region and the application. Due to this variety, this paper will not described this legislation in detail. Since the permissible level of NOx emissions has a great influence on achievable efficiency and engine technology, Figure 8 provides an example of the future development of NOx limits in the EU for stationary lean burn gas, diesel and dual fuel engines. It shows the development of limits in the Gothenburg Protocol [7] and EU directive 2010/75/EU [8] in comparison to TA Luft. With the exception of a few regions, the EU limit of 200 mg/mn³ (with a 5% O_2 concentration in the exhaust gas) is the strictest limit for lean burn gas engines. This limit can be considered to be the basic goal for stationary applications, yet it is imperative to achieve this limit without losses in efficiency.

Gas engines are faced with yet another series of challenges due to the recent discussion of formaldehyde emissions. According to TA Luft, the emission of formaldehyde is limited to 60 mg/mn³. As soon as a substance is proven to be a carcinogen, TA Luft stipulates that its emissions must be reduced. In theory, formaldehyde emissions should be limited to 1 mg/mn³. Gas engines regularly emit significantly higher amounts of formaldehyde. This is true in particular of biogas engines, which can only be used after the gas has undergone an extensive purification procedure to

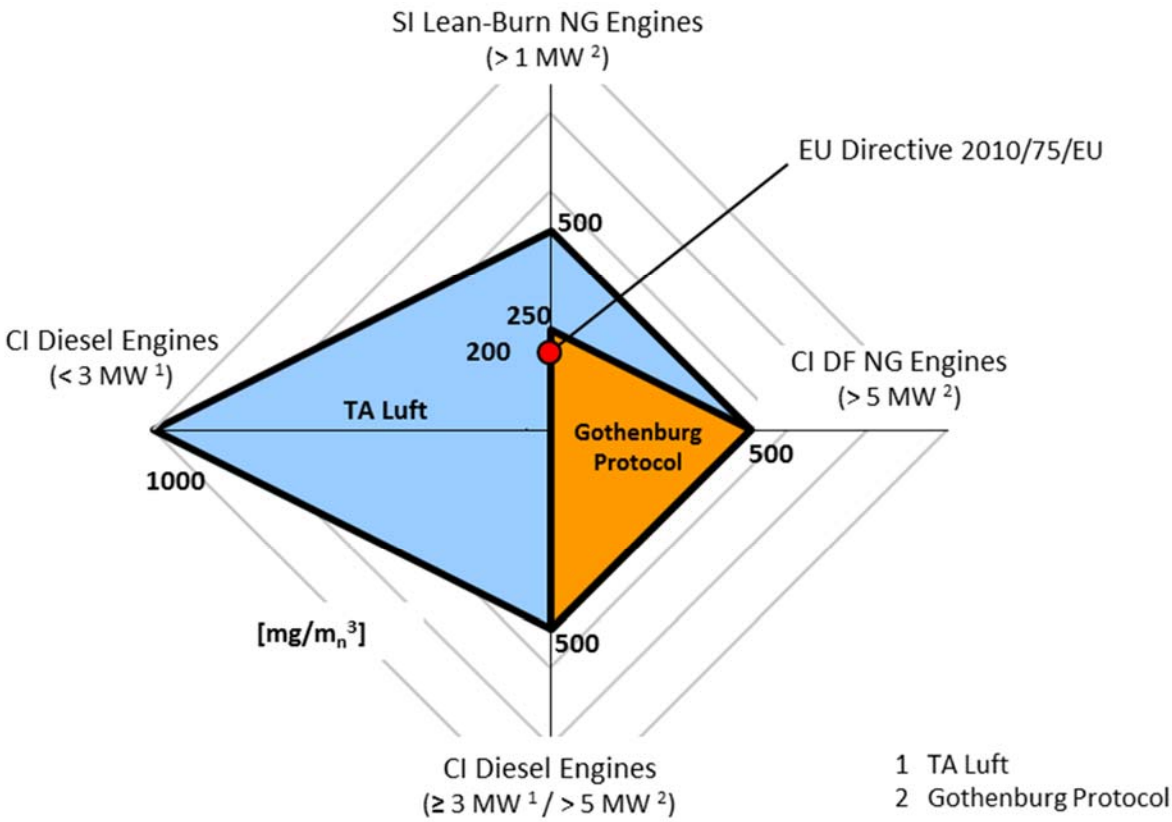

Figure 8. Limits for stationary gas engines proposed by the EU

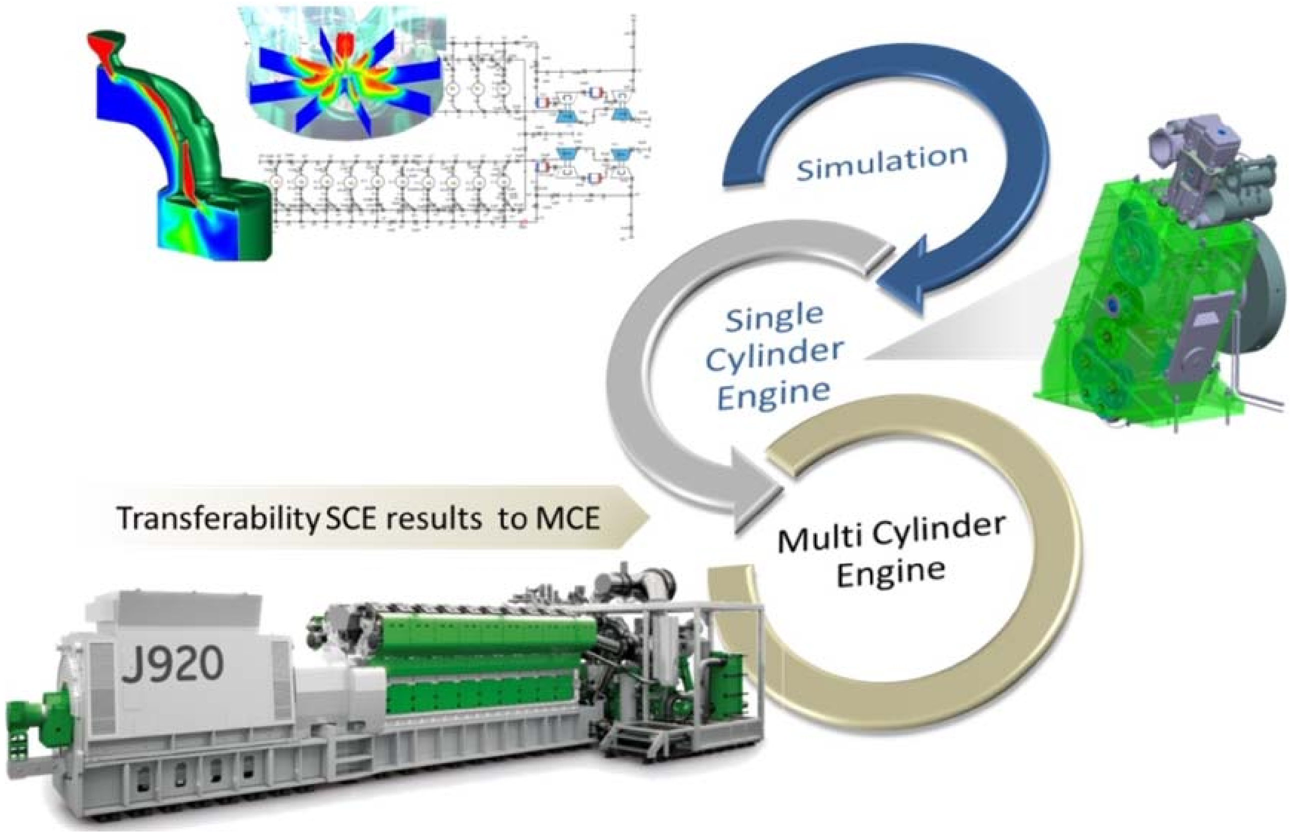

Figure 9. State-of-the-art development methodology (LDM)

remove catalyst poisons. In the future, it will become increasingly important to avoid the formation of this pollutant within the engine.

Like formaldehyde, the topic of methane slip has also stimulated much discussion in recent years in terms of its environmental impact [9]. The main component of natural gas, methane makes up the largest amount of THC emissions and has an impact on the greenhouse effect around 25 times greater than that of CO_2. Greater legal regulation can be expected in this area. From the standpoint of total greenhouse gas emissions as well as efficiency, it is essential to reduce the level of THC emissions from the engine to a minimum; this reduction is thus an important research objective.

3.5. Increased output and efficiency

Gas engines have already achieved a very high state of development in terms of efficiency and power. From a thermodynamic perspective, it is possible to improve the efficiency of gas engines by increasing the compression ratio even more. Dual fuel engines represent a compromise between gas engine and diesel engine technology. Introduced relatively recently, they are still in the initial stages of development. Further improvements in efficiency can be achieved in both modes of operation (gas mode and diesel mode) through intelligent combustion concept design. In general, any further increase in performance will be heavily influenced not only by thermodynamics but also by wear and durability, areas of particular importance.

To sum up, the main challenges for the future development of gas engines are to improve robustness (higher fuel flexibility, long-term stability and maintenance), dynamic behaviour and methane slip. Fuel efficiency remains an issue in both operating modes of the dual fuel engine but is particularly challenging in diesel mode due to PM and NOx emissions; as with the conventional gas engine, robustness is one of the main issues in gas mode.

4. Development methodology

4.1. State-of-the-Art-Methodology

LEC Development Methodology (LDM) can be regarded as the state-of-the-art in development methodology [10], [11], [12]. Since its creation, many manufacturers and research institutions have come to rely on this method, which has established itself as the standard in the area of large engines (albeit under different names) [13], [14], [15]. LDM is used to develop and optimize combustion concepts and is based on the intensive interaction between simulation and experimental investigations on single-cylinder research engines (SCE), see Figure 9. The methodology makes use of three-dimensional CFD simulation as well as zero- and one-dimensional engine cycle simulation. While 3D CFD simulation is employed above all to optimize the details of relevant processes (e.g., mixture formation and combustion in the pre-chamber and main combustion chamber, determination of the location of knock), 0D/1D engine cycle simulation is applied to pre-optimize significant engine parameters (e.g., compression ratio, valve timing). Statistical methods such as the DoE method are used in both simulation and experiments, see [11], [12]. For this methodology to be applied, it must be guaranteed that the results from single cylinder tests can be transferred to the multicylinder engine (MCE). To this end, it is necessary to achieve boundary conditions comparable to those of the multicylinder engine, not only the thermal boundary conditions but also the conditions at the beginning of the intake stroke (temperature, pressure, and working gas composition). These conditions are determined in an iterative process based on 1D engine cycle simulation of the multicylinder engine and the single cylinder set-up.

Simulation is conducted using commercially available tools (e.g., AVL FIRE, Converge, GT Power, AVL Boost). Research institutions and OEMs also develop and use simulation tools of their own. The LEC has developed its own software suite to describe relevant procedures. All in all, LDM is excellently suited to steady state combustion concept development (CCD) and has already been implemented to accomplish a variety of research and development tasks. New challenges have arisen from the transition to transient CCD and the expansion of a thermodynamically oriented approach to a multidisciplinary and much more comprehensive approach.

In analysis and simulation, it is not yet possible to describe the highly complex processes in dual fuel combustion with sufficient precision; the general validity of the models is not fully known. In the experimental evaluation of combustion concepts on the single cylinder research engine, the limits of measuring techniques have been reached since the changes possible when developing new concepts have become extremely small.

4.2. Advanced Methodology

New paths must be taken to improve applied technologies and development methodology for gas and dual fuel engines. This will require a transition to holistic treatment of all combustion-related processes. While LDM is currently focused on stationary development of combustion concepts, a significantly more comprehensive approach will be required in the future.

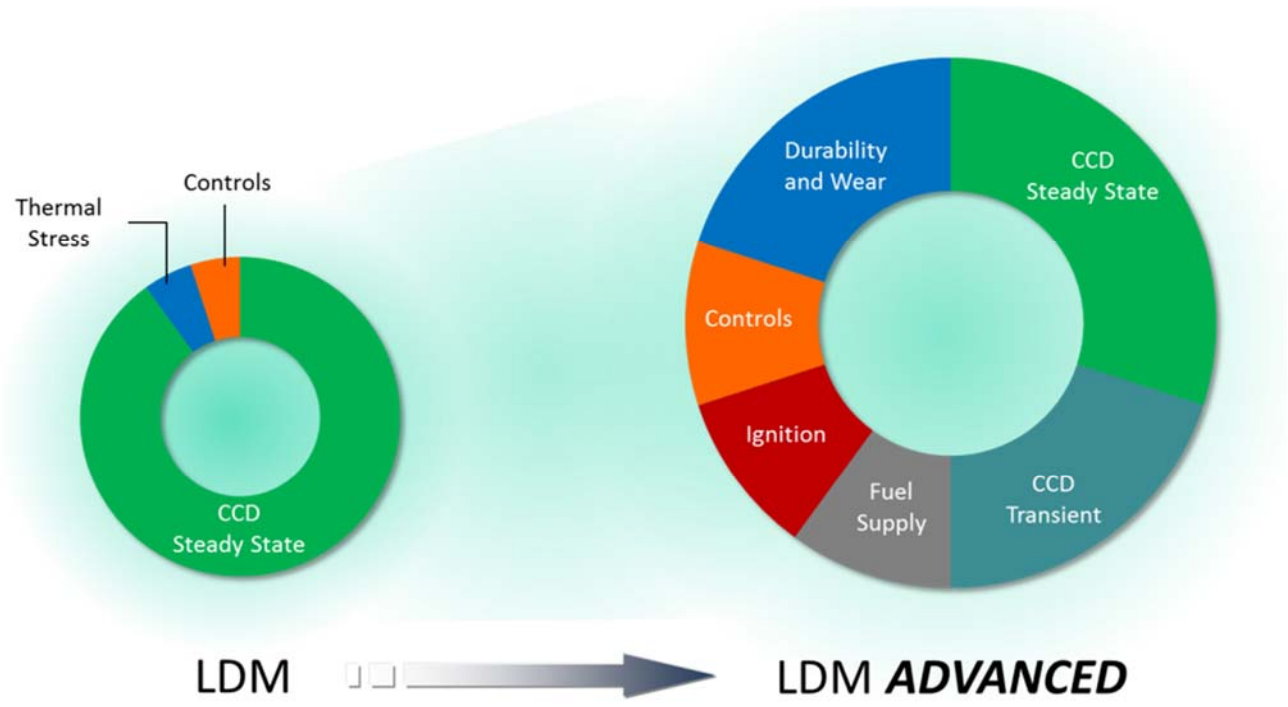

Figure 10. Transition from LDM to LDM Advanced

As indicated in Figure 10, LDM Advanced, the latest version of LDM currently in use at the LEC, incorporates combustion-related aspects such as durability, wear, ignition, and fuel supply into the transient development of combustion concepts and controls. This necessitates detailed physical modelling of all effects and their suitable connection to the appropriate models. In the area of spark plug wear, for example, detailed models to describe spark initiation and removal of material along with parameters derived from thermodynamic simulation (e.g., heat transfer, gas composition, velocity, turbulence) must be made available and linked to an overall model. To accomplish this, integration of expertise from a variety of disciplines will be required. This comprehensive approach is used for all systems under consideration. Further examples of systems are controls (from the control concept itself to the optimal integration of the sensor into the cylinder head to durability and the algorithms for recognizing sensor errors) and ignition (from ignition initiation to flame kernel propagation and subsequent combustion).

5. Conclusions

An increase in achievable efficiency will not be the sole target of future development of gas engines. Further reduction of NOx emissions will be a considerable challenge. Very strict legislation is expected that will limit NOx and HC and make the use of exhaust gas after treatment imperative in many cases. In addition, development work will focus on measures to improve the robustness, dynamic behavior and fuel flexibility. The consideration and optimization of the entire system will become more and more important, thereby making the use of a comprehensive development methodology absolutely essential.

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References

[1] Warnecke, W., Karanikas, J., Levell, B., Mesters, C., Schreckenberg, J., Adolf, J., "Gas – Eine Brückentechnologie für zukünftige Mobilität?", 34 Internationales Wiener Motorensymposium, 25–26 April 2013.

[2] Zauner, S., Arnold, G., Kopecek, H., Kumar, C.,Spreitzer, C., Trapp, C., Schneßl, E., Wimmer, A., „Nutzung von Gichtgas im Großgasmotor mit

Hilfe zylinderdruckbasierter Motorregelung und Zweigasbetrieb“, 3 Rostocker Großmotorentagung „Die Zukunft der Großmotoren III – Großmotoren im Spannungsfeld von Emissionen, Kraftstoffen und Kosten“ 18–19 September 2014.

[3] Wimmer, A., Schneßl, E., Simon N., “HyWood – Nachhaltige Strom- und Wärmeerzeugung mit wasserstoffreichem Synthesegas aus Biomasse“, Submission and nomination for the Energy Globe Styria Award, Graz 2016.

[4] Wimmer, A., Pirker, G., Engelmayer, M., Schnessl, E., “Gas Engine Versus Diesel Engine: A Comparison of Efficiency”, MTZ Industrial 11:2-6, 2011.

[5] CIMAC Working Group "Gas Engines": Position Paper "Transient Response Behaviour of Gas Engines", Conseil International des Machines a Combustion, April 2011.

[6] EUROMOT 2013: "Gas Quality Harmonisation", The European Association of Internal Combustion Engine Manufacturers – EUROMOT, 18 September 2013.

[7] Gothenburg Protocol 2010: "Protocol to the 1979 convention on long-range transboundary air pollution to abate acidification, eutrophication and ground-level ozone", Gothenburg, 1999, available in the internet, URL: http://www.unece.org/env/lrtap/multi_h1.htm, Status: 30.07.2010.

[8] Council of the European Union: Interinstitutional File: 2007/0286 (COD), Brussels, 2009, Annex V S. 14.

[9] EUROMOT 2012: Euromot Position "Methane Slip from Internal Combustion Gas Engines", The European Association of Internal Combustion Engine Manufacturers – EUROMOT, 27. April 2012.

[10] Kogler, G., Wimmer, A., Eichlseder, H., Schnessl, E., Winter, H., "Methodology in the Development Process of Large Gaseous Fuelled Engines". – ICE 2003-0575 (2003), S. 547 – 557. Spring Technical Conference of the ASME Internal Combustion Engine Division; 2003.

[11] Wimmer, A., Winter, H., Schnessl, E., Pirker, G., Dimitrov, D., “Brennverfahrensentwicklung für die nächste Gasmotorengeneration von GE Jenbacher,” 7th Dessau Gas Engine Conference, Dessau, Germany, March 24–25, 2011.

[12] Wimmer, A., Pirker, G., Schnessl, E., Trapp, C., Schaumberger, H., Klinkner, M., “Bewertung von Simulationsmodellen zur Brennverfahrensauslegung für die neue Generation von Großgasmotoren,” 10th International Symposium on Combustion Diagnostics, Baden-Baden, Germany, May 22–23, 2012.

[13] Auer, M., Friedrich, C., Waldenmaier, U., Knafl, A., Stiesch, G., "Combustion Development Methodology for MAN Diesel & Turbo Large Bore Gas Engines", 14th Conference "The Working Cycle of the Internal Combustion Engine", Graz 2013.

[14] Schlemmer-Kelling, U., Hamm, T., Reichert, E., Struckmeier, D., "FEV Single Cylinder Engine Family for large engine applications of MAN", 22nd Aachen Colloquium Automobile and Engine Technology 2013.

[15] Trapp, Ch., „The Future of Gas Engines – A Technology Comparison with Diesel Engines in the Light of Legislation and Market“, 14th Conference "The Working Cycle of the Internal Combustion Engine", Graz, 2013.

[16] Krenn, M., Pirker, G., Mühlberger, M., Wimmer, A., “Einsatz der DoE-Methode zur simulationsbasierten Optimierung von Großgasmotoren,” 14th Working Process of the Internal Combustion Engine Conference, Graz, 2013.