The Quality of Gaseous Fuels and Consequences for Gas Engines

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Abstract:

Over the last few decades, natural gas in Europe has been categorized as either H-Gas (high caloric value) with a methane content of 87 to 99.1 vol% or L-Gas (low calorific gas) with a methane content of 79.8 to 87 vol%. The quality of heating value, the Wobbe Index and other gas components have been standardized in EU legislation and the legislation of certain member states while in the U.S., the natural gas industry rates natural gas on the basis of heating value.

Around the globe, different countries have different specifications for LNG. The composition of LNG depends on its source of production and on the requirement of the customers. LNG composition also varies with time in transportation due to natural boil-off of low boiling LNG composites (Nitrogen and Methane).

The composition of the fuel gas determines the limits of power density and controllability in spark ignited gas engines. In specific the limit to knocking combustion is of great importance. While higher hydrocarbons and hydrogen increase the knock tendency, inert gases lower it. A comparison of the most commonly used methods for calculation are given. Also the LEC-GPN method [1] performs best for the special application of a lean-burn gas engine, generally recommendable is the calculation method according to MWM [2] which was proposed as a standard by CIMAC; EuroMot and European Union.

The calculations on the characteristic values and the Methane number show under which conditions the mixing of pure methane with different gas components can reach the limits of the latest European standards (EASEE [3] and EN 16726:2015 [4]). The mixing of pure methane and H2 poses more of a problem; however, with natural gas it is possible to reach the required limits up to a content of 10 vol% H2.

Different real compositions of LNG from 2014 with their respective combustion related properties (i.e. calculated Methane number, calculated Wobbe index) are also given.

The fossil gas market has delivered less natural gas in EU in the last years due to rather warm weather but also due to an increasing share of renewables and to the low price of coal that results in a continued presence of coal in the power sector [5]. Based on the investigations of this project we conclude that

- Emission standards could have an impact on future gas demand. In specific GHG-emissions can be cut by fuel switch from coal to gas.

- The future wide range of possible natural gas compositions makes it necessary to invest into new engine technologies in order to reliably provide power at high engine efficiency and low pollutant emissions using large gas engines.

Keywords: Energy market, gas engines, gaseous fuels, LNG, standardization

1 Introduction

The energy demand is escalating with growing population and per capita consumption. Governments around the world are contending to meet energy demand, affordability and climate change. Fossil fuels have been the blood for the industrial sector for many centuries. With the new emissions policies in place, search for efficient alternative fuels have been progressing. Natural gas is proved to be an efficient fossil fuel to bridge the gap for energy demand. The years from 2013-2030 are considered to be the years of golden age for gas. Although, natural gas being a fossil fuel in nature, it is much cleaner than most predominantly used fossil fuels in terms of emissions.

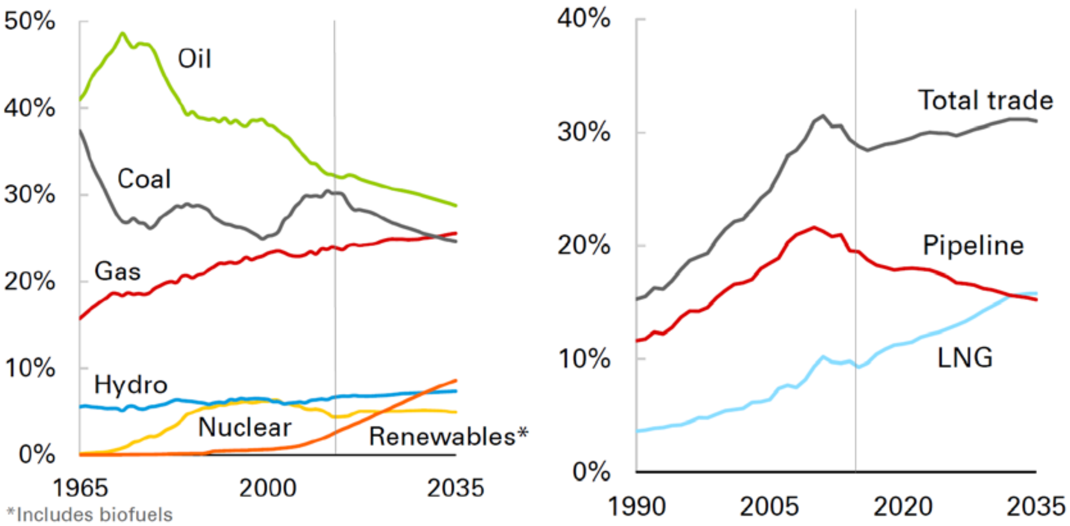

Figure 1: Share of different sources in the production of primary energy (left) & Trade as share of global consumption comparing pipeline gas and LNG (right) [6]

Over the last few decades, natural gas in Europe has been categorized as either H-Gas (high caloric value) with a methane content of 87 to 99.1 vol% or L-Gas (low calorific gas) with a methane content of 79.8 to 87 vol%. The quality of heating value, the Wobbe Index and other gas components have been standardized in EU legislation and the legislation of certain member states while in the U.S., the natural gas industry rates natural gas on the basis of heating value. Standard natural gas has an average heating value of at least 1,000 British thermal units per cubic foot of gas. With the liberalization of the gas market in Europe, the extraction of shale gas in the US and the “greening” of energy systems, gas quality issues have recently come high on the agenda. Nevertheless, the debate on gas quality issues is intensifying due to imports from a growing number of sources including LNG and biogas. Power-to-gas technologies contribute to increasing amounts of H2 and SNG (synthetic natural gas) components in pipeline gas.

In the future, natural gas will play a major role in stationary applications as well as in the mobility sector with NGV (natural gas vehicles) based on CNG (compressed natural gas) for private cars and LNG (liquefied natural gas) for trucks, ships and off-road applications. Fluctuating gas quality represents a major challenge in the development of combustion concepts for gas engines. Dynamic gas properties must be taken into consideration during the optimization process, which requires the establishment of new technologies and new concepts.

2 EU emission policies and trends for the use of gaseous fuels

EU climate action sets goals for GHG emissions, for the share of renewables and for energy efficiency. In a short-term perspective, by 2020, the goals are 20-20-20, i.e. a reduction in GHG emissions of 20% (compared to 1990), a 20% total energy consumption from renewable energy and a 20% increase of energy efficiency. The EU countries are well on track to meet their climate and energy targets for 2020 [7].

But long-term goals are very ambitious, only to be met if Europe turns into a highly energy efficient and low-carbon economy by 2050. As for GHGs, they have to be cut by 40% until 2030 and by 80 – 95% until 2050. This will contribute a necessary effort to keep the increase of global average temperature to well below 2°C above pre-industrial levels as was demanded in the COP21 (21st Conference of the Parties) in Paris, 2015.

In its World Energy Outlook 2016, the IEA has analysed the national pledges for Paris and found that these are not yet enough to keep global warming below 2°C. Goals that are even more ambitious would have to be set. In fact, it is required that the global economy becomes carbon neutral by the end of the century. This needs a fossil exit strategy with a promotion of all renewables and employing technological decarbonisation solutions (e.g. CCS technologies) for remaining fossil capacities.

At the same time, natural gas is predicted to boom in the next decades. The most important reasons that can be put forward are:

1. among fossil fuels natural gas is the “greenest” option, apt to substitute coal most notably in the energy generation sector,
2. gas power plants are highly flexible and serve best to stabilize a power grid with a large share of intermittent renewables (wind and solar PV).

Various institutions have outlined the role of gas for a way towards decarbonisation, stating that natural gas has a big potential to be a fuel to bridge the gap. [8][9][10]

Although, natural gas being a fossil fuel, it is much cleaner than most predominantly used fossil fuels in terms of emissions. It has lower Sulphur dioxide and nitrogen oxides emissions, lower particulate matter emissions and lower carbon dioxide emissions when burned. The hydrogen-to-carbon ratio of natural gas, whose main component is methane (CH4), is about 4:1, compared to 0:1 for solid coal and 2:1 for Diesel or gasoline. Hence, the combustion of natural gas produces less CO2 per unit of energy than either coal or gasoline. The last step in a pathway of decarbonisation is to use pure hydrogen for combustion.

Natural gas in Europe is consumed for a multitude of purposes [5]. The residential and commercial sector is the biggest consumer (more than 40%) for space heating and hot water. In the industrial sector (more than 30%) it is used for process heat and electiricity generation as well as ingredient for varied products, like fertilizers, plastics and so on. More than 20% of the deliveries of is going to the power plants (including heat plants). Today's gas turbines have an efficiency rating of up to 61% (e.g. GE H class turbines). Also gas engines have increased their efficiency up to 48%. In combined heat and power plants the overall efficiency already reaches up to 95% (in combination with heat pumps).

In the power sector gas fired plants are an attractive alternative to coal fired plants, being easy and fast to construct, having low capital costs and meeting emission goals better. Renewable sources are often preferred for the energy transition but they still need baseload backup by conventional power plants until large-scale storage technologies become economic. Gas turbines and gas engines will enhance their flexibility and serve as a bridge to a renewable energy system.

As for gas engines three pathways [11] for the use of gas in a sustainable energy future can be outlined:

1.) A classic path that uses natural gas, as a "companion"/complement for a strong expansion of renewables, improving further the efficiency of gas uses and filling in any dents of renewable supply.

2.) A "waste gas" path that utilizes waste gases from industrial processes like blast furnace gas from steel industry or flare gases that would be burned or worse: vented off without further use of their energy content.

3.) A renewable gas path, exploiting (excess) renewable energy sources like solar or wind energy to produce hydrogen or synthetic methane, or biogas from biomass by gasification. These renewable gases can be stored or fed into an existing gas grid.

Except the first pathway, the other two options imply that the gas grid is used for gas qualities that will vary to a larger extent in future than it is now the case. This is the background for the in depth analysis of gas qualities and implications for gas engines in the following chapters.

3 Standards and regulations for gas compositions

In the EU, there are intensive efforts to liberalize the intra-European gas market and to harmonize national gas quality standards. In 2005 the "European Association for the Streamlining of Energy Exchange" (EASEE) published the CBP 2005-001/02 "Harmonisation of Natural Gas Quality". The specification applies only to high-calorific value (H-gas) gas without added odorants. Building on this, the European Committee for Standardization (CEN) finalized the standard EN 16726 "Gas infrastructure – Quality of gas - Group H" in March 2015. Requirements for gas quality are set in this European standard with the aim to allow the free flow of gas between the CEN member states [4].

Although on most issues compromise and agreement could be achieved, some topics are still controversial. So for the latest standard EN 16726 no agreement regarding the Wobbe-index could be reached. This is the reason why the European Commission releases the standard without limits for the Wobbe index. Nevertheless, a lower limit for methane number is set to 65. Furthermore, no limit for hydrogen is defined. The Wobbe index is a value that evaluates the interchangeability of gases. It describes the heat stress imposed onto a burner or furnace. The methane number is a criterion to determine the knock tendency of a gas in a combustion engine. Methods to determine this value will be described in the following chapter in detail.

Initialized by the mandate M/475, the European Committee for Standardization published the standard EN16723 in November 2017. The scope of the standard is the "Standardization of specifications for natural gas and biomethane as vehicle fuel and of biomethane for injection in the natural gas grid", including any necessary related methods of analysis and testing. This standard considers and refers to parameters which are published in the European standard EN16726 [12].

As mentioned above, the so called "greening" of the European energy market takes place. One problem of this new renewable energy is the high fluctuation of production e.g. by the use of wind. One technology to fix this problem is "power to gas". Here the waste energy is used in electrolysis to produce hydrogen. The H_2 can be used directly or stored. Because of the great storage capacity of the natural gas pipelines and the connected gas storages, power to gas offers a high potential for storage of a large amount of energy. But, as also mentioned above, at the moment there are no limits for the adding of Hydrogen in the pipeline network defined in the European standard EN16723.

In the US the Federal Energy Regulatory Commission (FERC) regulates the interstate transmission of electricity, natural gas, and oil. The FERC reviews applications for the construction and operation of natural gas pipelines. The agency also reviews proposals to build liquefied natural gas (LNG) terminals and interstate natural gas pipelines, as well as licensing hydropower projects. FERC has the jurisdiction over the regulation of interstate pipelines and is concerned with overseeing the implementation and operation of the natural gas transportation infrastructure. Since FERC Order 636, the pipeline and distribution companies must separate their transportation and sales services. Thereby pipeline customers have the choice to select their gas sales, transportation, and storage services from all providers, in any quantity. Each pipeline or distribution company has to submit their FERC NGA Gas Tariff defined by the Natural Gas Act to FERC for filing. Among other things, the specifications of gas qualities that are transported in the pipeline are defined in these tariffs [13].

LNG has been a major medium of transport for natural gas. The LNG trade has also shown considerable progress during the last couple of decades. The quality of LNG varies from location to location due to different technologies and different composition of natural gas raw sources. Many countries import LNG based on the pricing and the national regulations detailed for the quality control. With increase in demand and more stringent emission regulations, the need for managing the quality of LNG and safety measures while handling LNG had also increased. The regulations are meant to modulate effective bunkering and safely handling LNG at ports. There are not any proper set of guidelines that enable LNG to be used as a fuel in bunkering. There is a need to establish international guidelines in order to bridge the gap for using LNG as a fuel. The technology that is meant to use LNG as fuel is already available and the standards for these technologies can be imposed based on the available standards meant for liquefaction plants and import terminals.

As mentioned above, in EN 16726 limits for gas properties are provided. Depending on composition, gas mixtures may lie within the limits or not. In the following diagrams, these limits are shown as dashed lines. The upper limit of the relative density is at 0.7 and the lower limit as 0.555. The relative density of a gas is calculated as the density of the gas divided by the density of air at the reference conditions of 0°C and 101.3kPa. However, the methane number has only a lower limit at 65. The calculation of the methane number is more complex and will be described in the next chapter. The left picture in *Figure 2* shows how much of a single component can be added to pure methane to exceed the limits. It is possible for example to mix 25% of ethane before the limit is reached. The other picture shows, that it is almost unlimited to dilute methane with carbon dioxide or nitrogen because there is no upper limit of the methane number. However, if we want to mix hydrogen to pure methane this is not possible. If we change the starting gas composition, as we can see it in the left picture in *Figure 3*, to e.g. North Sea gas, a mixing of up to 10% hydrogen is possible.

The right side of the diagram shows the distribution of different LNG compositions within the given limits. Methane (CH_4) is the major component of LNG with little amounts of heavier hydrocarbons and inert gases. The composition of LNG highly depends on its source of production and by the requirement at the customer end. LNG composition also varies with time in transportation due to natural boil-off of low boiling LNG components (Nitrogen and Methane). LNG form Libya lies at the lower limit for methane number, because of a high content of heavier hydrocarbons. On the other side LNG from USA consist nearly of 100% methane and so the MN is also nearly 100 [14].

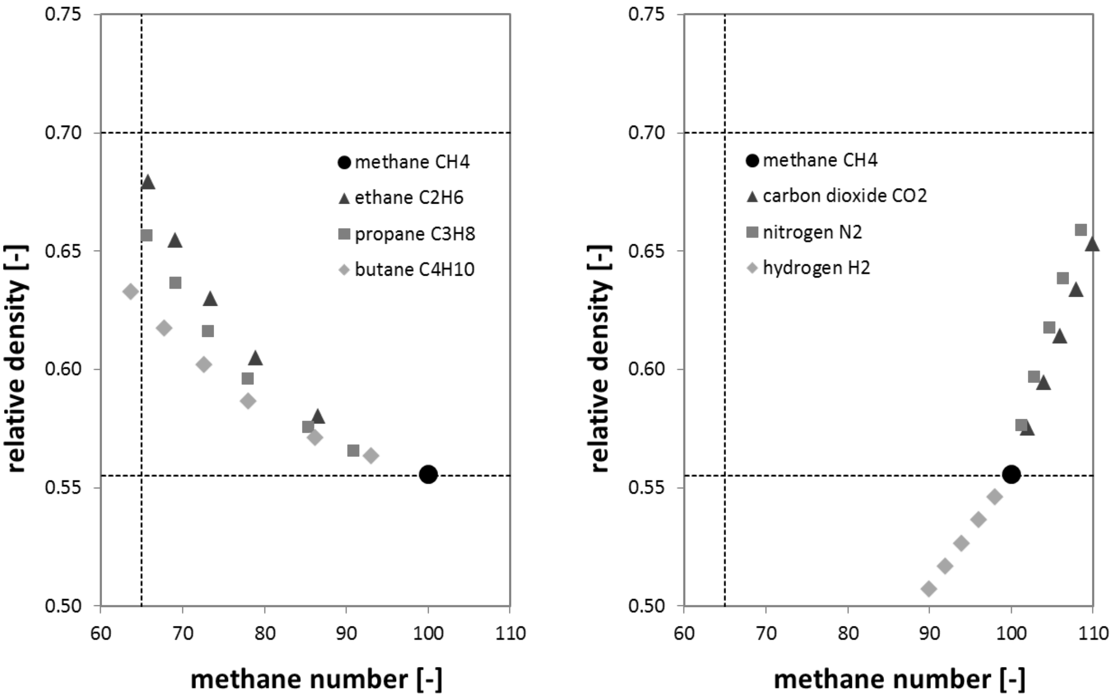

Figure 2: Mixing of selected gas components with methane and limits according to EN 16726

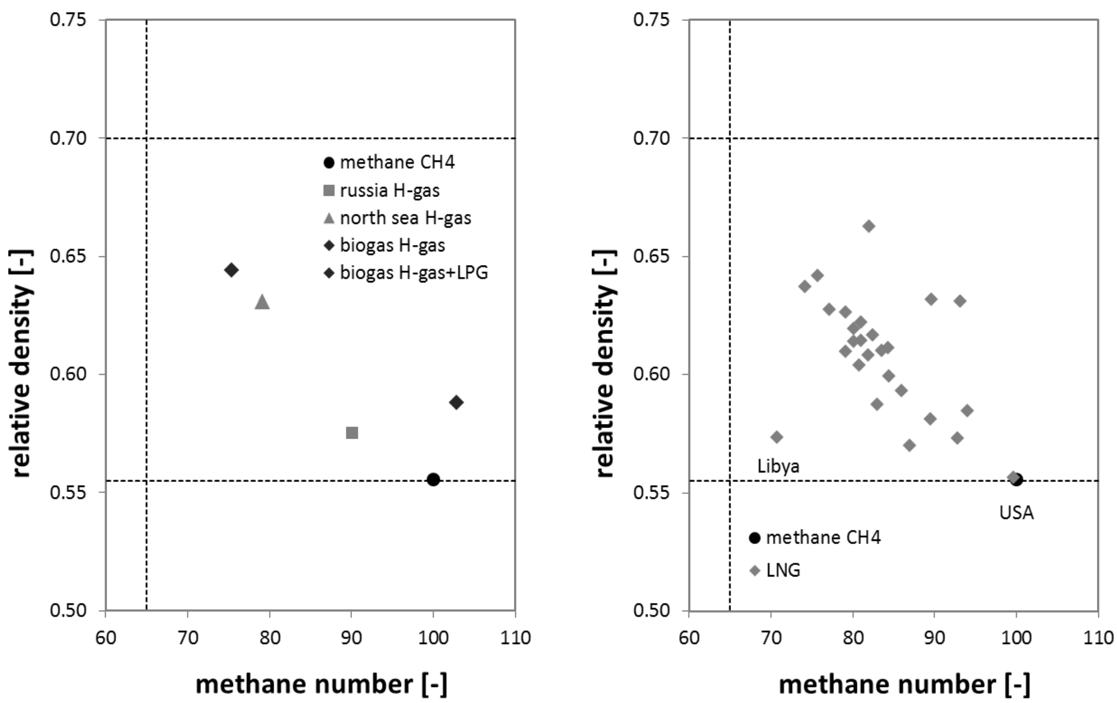

Figure 3: Different real pipeline gases and LNG compositions and limits according to EN 16726

4 Effects on the gas engine

For large bore gas engines, the most common combustion concept is the lean burn concept. This combustion concept uses high air-to-fuel ratios (lambda), making it possible to fulfill the current emission limits without any exhaust gas aftertreatment systems. However, very lean mixtures are difficult to be ignited and also burn rates are reduced, compared to stoichiometric combustion. This can be compensated either by high charge movements resulting in a high level of turbulence in the combustion chamber, or the use of a prechamber.

Due to the high lambda of the lean combustion engine, the use of high compression ratios (ε) is possible. In addition, a high amount of excess-air increases the isentropic exponent (κ) of the mixture, making it possible to increase the thermodynamic efficiency of the ideal engine process. This relationship can be seen in the following formula:

$$\eta_{th,v} = 1 - \frac{1}{\varepsilon^{\kappa-1}}$$

The usable area for a stable engine operation is shown in *Figure 4*. The diagram shows engine load versus excess-air ratio (lambda). The range for stable engine operation is limited by the knock and misfire limits. With increasing excess-air ratio the misfiring area is getting bigger because the mixture is to lean for a stabile ignition. On the other hand the knock tendency increases towards higher loads. The operating range is getting narrower with high lambda and increasing load, as well as with higher compression ratio, which is necessary for increased efficiency [15].

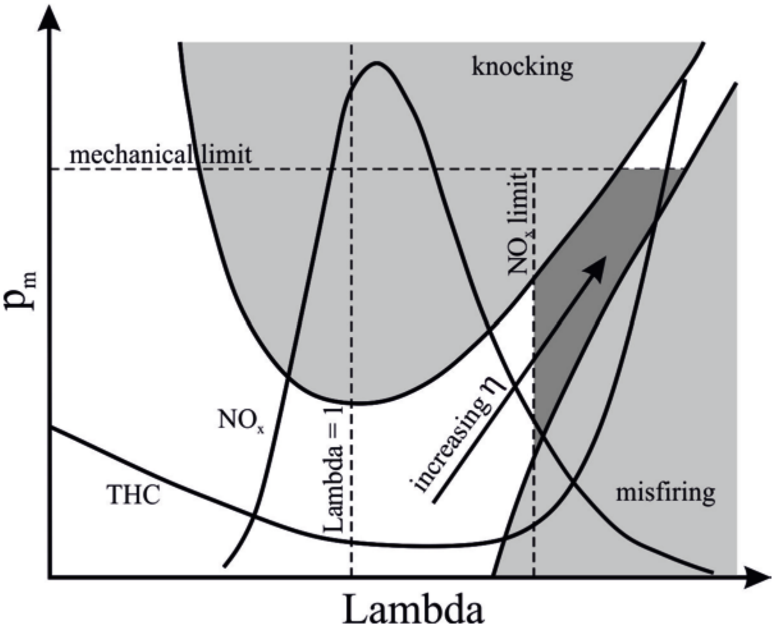

Figure 4: Operating range of gas engines [16]

4.1 What is detonation and knocking

A detonation is a shock wave that is generated by a chemical reaction and the related heat release. Detonations have high flame speeds of above 1000 m/s. In combustion engine processes, these detonations are called knocking. This knocking combustion arises by self-ignition of the unburned gas, which was not reached by the flame front. Due to the sudden release of a high level of chemical energy, there is a strong increase of the pressure as well as the temperature and so a propagation of pressure waves with large amplitudes occurs. This causes the high frequency noise, which is referred to as knocking and leads to material damage, that can destroy the engine in a short time. *Figure 5* shows the pressure curves of normal *(a)* and knocking combustion *(c)*, provoked by advancing the ignition timing.

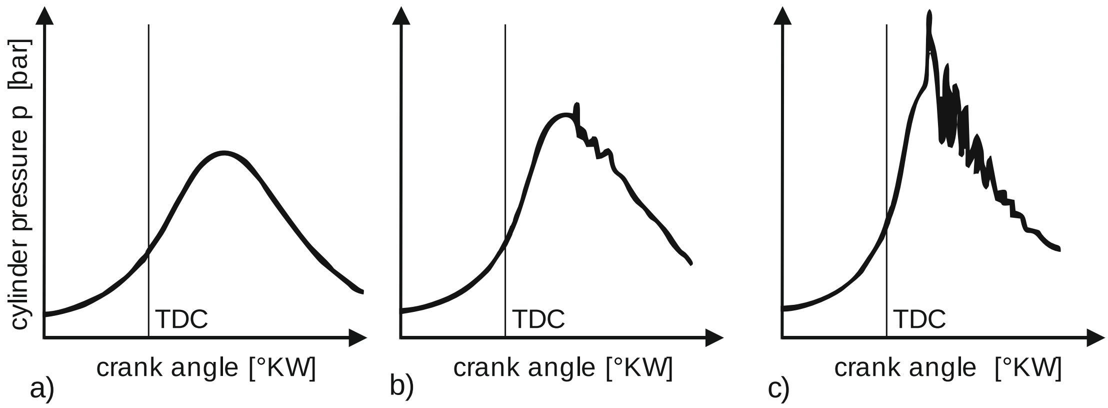

Figure 5: Comparing regular and knocking combustion [15][16]

Due to the local inhomogeneity in distribution of pressure, temperature and air-to-fuel ratio, the pre-reactions of the combustion are at a different level. After completion of the pre-reaction, self-ignition occurs, mostly in very hot regions of the combustion chamber. If the temperature in the unburned mixture is very low, the pressure wave from the self-ignition is in the range of a normal combustion. This so-called deflagration can be seen in picture ***b*** in

Figure 5. However, if the temperature and pressure are very high, the chemical reaction happens much faster. This detonation is presented in picture *(c)* in *Figure 5*. [15]

Furthermore, each composition of the fuel gas has its own knock tendency and this tendency determines the limits of power density, controllability and efficiency in spark ignited gas engines.

4.2 Existing criteria to determine knock

There are several criteria to determine the knock resistance of different fuel gas compositions. Most of the described criteria aim on determining a methane number. The methane number is similar to the well-known octane number used for gasoline fuels. The methane number is determined like the octane number on a specifically designed single cylinder engine. On this engine, defined knocking combustion is first realized with the fuel to be evaluated. With the same engine settings, a reference fuel mixture is adjusted in a way to reach the same knocking engine behavior [16].

Based on a literature research, some of the existing evaluation criteria regarding the influence of gas composition on knock tendency are screened. The criteria will be evaluated regarding their applicability for different gas compositions.

4.2.1 AVL method

Whereas for determination of the octane number, a mixture of iso-octane and n-heptane is used as a reference, a gas-mixture was chosen for the determination of the methane number. One main reason is the fact, that the MON index (Motor Octane Number) is limited at 120, so most of the existing fuel gas mixtures cannot be covered herewith. Methane number describes the relation of a very knock resistant gas and a gas very prone to knocking. Methane is chosen to be the knock resistant gas. The knock sensitive gas is represented by hydrogen. Following this definition, a gas consisting of pure methane has a methane number of 100. A mixture of 80% by volume methane and 20% by volume hydrogen has a methane number of 80 [16]. Extending the methane number to values above 100 is realized by admixing carbon dioxide with methane. In this area, methane number is defined by 100 plus the CO_2-precentage in the reference mixture (MN of 120 is 80%v methane and 20%v CO_2). By evaluating different gas compositions including higher hydrocarbons and inert gases (nitrogen and carbon dioxide), a series of ternary diagrams were derived to estimate methane number by a patented technique. The calculation method includes also carbon monoxide, ethylene and propylene. Higher hydrocarbons as pentane and higher are treated as butanes.

4.2.2 CWI

Cummins Westport offer a so called fuel quality calculator on their website. This Methane Number calculation method is based on the SAE 922359 Eqn 4 and was released in Nov. 2015 [17].

4.2.3 Caterpillar GERP

Caterpillar's GERP method provides similar results to those produced with AVL method [18]. The algorithm for determining methane number is not publicized. The list of gas components for determination of methane number also includes propylene and ethylene.

4.2.4 MWM

MWM method is based on the AVL method but includes amendments by MWM GmbH made in 2005 and 2011 [4]. The procedure for determination of the methane number consists of several steps:

- Simplification: removing inert components
- Division into partial ternary mixtures
- Adjustment of composition and selection of partial mixtures to minimize difference in resulting methane numbers
- Calculation of methane number by taking inerts into account

The calculation method is valid for mixtures containing carbon monoxide, butadiene, butylene, ethylene, propylene, hydrogen sulfide, hydrogen, propane, ethane, butane, methane, nitrogen and carbon dioxide.

4.2.5 WKI

The Waukesha Knock Index was derived to overcome the inadequacy of classical methane number calculations to predict the knock tendency of fuel gas mixtures containing significant amounts of higher hydrocarbons. The development is based on a predictive regression equation for methane number (SwRI) implementing several procedures to cover the specific properties of higher hydrocarbons, as well as non-hydrocarbon combustibles (e.g. H_2, CO) and inert gases. For example, all C6, C7 and C7+ hydrocarbons, as well as ethene and propene are added to heptane. Isomers of butane and pentane are separated first and added to the fractions of propane, butane end pentane. Methane number calculated from the combustible components is then adjusted according to the carbon dioxide and nitrogen content.

4.2.6 LEC-GPN

As Wimmer et al. pointed out, the maximum achievable IMEP at the knock border can vary several bar depending on composition, even if they have the same methane number [1].

A knock index has been introduced that overcomes the drawbacks of methane number by taking real combustion behavior into account. With the LEC-GPN (LEC Gas Performance Number) the knock limited maximum achievable engine load can be determined. One significant advantage of this index is its suitability for different engine configurations, making this method universally applicable. No specially equipped research engine is required.

The procedure to determine the LEC-GPN compares the knock-limited IMEP of a fuel gas under specified engine operating conditions with the test result obtained using pure natural gas with a predefined methane number. The cylinder pressure trace is measured and the apparent rate of heat release is calculated and normalized with the rate of heat release integral. The normalized rate of heat release curve of the natural gas operating point serves as reference for the later assessment of the LEC-GPN of other fuel gases. The normalized rate of heat release curve of the gas-mixture being tested is matched with the reference curve by adjusting spark timing and excess air ratio. The equality of the normalized rate of heat release curves ensures an equal history of the unburned zone for each measurement point with a specific engine configuration. Methane number for determination of the knock limited IMEP is calculated using a predictive regression equation using the combustible components (methane, propane) of the gas mixture.

4.3 Comparison of different knock ratings

Due to of the fact, that the AVL method is the foundation of almost all chosen methods, this methane number calculation is the basis of the examination. Also the MWM method is important in this comparison. This method is defined as the standard MN calculation, which was decided by the European committee for standardization (CEN). Because of this reason, the numerical gas compositions which are described in the EN 16726:2016 were chosen for the comparison. The gas compositions of the 16 gases and the calculated methane number are listed in *Table 1*.

The deviation of the different calculation methods are graphically shown in the *Figure 6*. The AVL, MWM, CWI and GERP are nearly on the same level for the first seven mixtures. A difference, however, can be seen at the first and second composition, where the CWI results have a lover value. At mixture seven, only MWM and GERP are nearly at the same value. For the WKI method a constantly higher methane number for the first seven compositions compared to the others can be seen.

At the gas compositions with addition of H_2, the calculation methods have some problems. For example, the WKI and GERP method cannot calculate a methane number of a mixture with a high percentage of H_2. The MN of GERP is zero and with WKI the value is even negative. Also, the AVL method has some problems which can be seen in the result of mixture eleven. At a H_2 content of 65% the calculation of the MN is far away form the result of the MWM and CWI method. The MN calculation with the ternary diagrams shows that the value should be in the region of the result from MWM and CWI.

Table 1: Gas compositions and comparison of different knock ratings

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Gas composition																
CH4	83.5	82.4	94.7	86.3	87.3	84.6	85.6	15	80	70	10	65	5	75	55	4
C2H4																
C2H6	3.5	3	3.2	8.7	7	8	5.7	5	5	5	5	5	5	5	5	2
C3H6										5	5	5	5			
C3H8		0.2	1.1	1.6	2.2	1.7	2.1	5	5	5	5	5	5		5	2
C4H8										5	5	5	5	5		
C4H10		0.3	0.5	0.3	0.4	1.5	0.9	5	5	5	5	5	5	5	5	2
C5H12		0.1	0.2		0.1	0.5	0.8									
C6+					0.2		0.6									
O2																
N2	13	13	0.2	0.8	0.7	3.7	0.4									
H2								70	5	5	65	5	50	5	20	90
CO													20			
CO2		1	0.2	2.3	2		3.9									
H2S												5		5	10	
Methane number [-]																
MWM	90.0	85.0	80.0	75.0	70.0	65.0	56.0	21.6	53.2	41.3	19.6	35.0	23.9	44.2	30.5	10.0
AVL	92.4	89.7	80.7	77.0	74.8	67.8	70.3	29.3	52.8	43.2	56.3	36	26.5	42.3	31.4	10.6
CWI	81.1	81.3	82.6	78.3	77.3	70.0	76.5	18.6	58.2	52.3	15.5	51.5	15.1	57.3	53.4	6.3
GERP	89.2	86.9	83.2	74.6	71.1	68.8	61.2	0.0	55.6	51.7	0.0	13.7	0.0	17.5	0.0	0.0
WKI	98.7	98.0	89.3	82.7	81.1	77.5	76.7	0.0	60.5	49.4	0.0	43.3	0.0	54.2	27.9	0.0

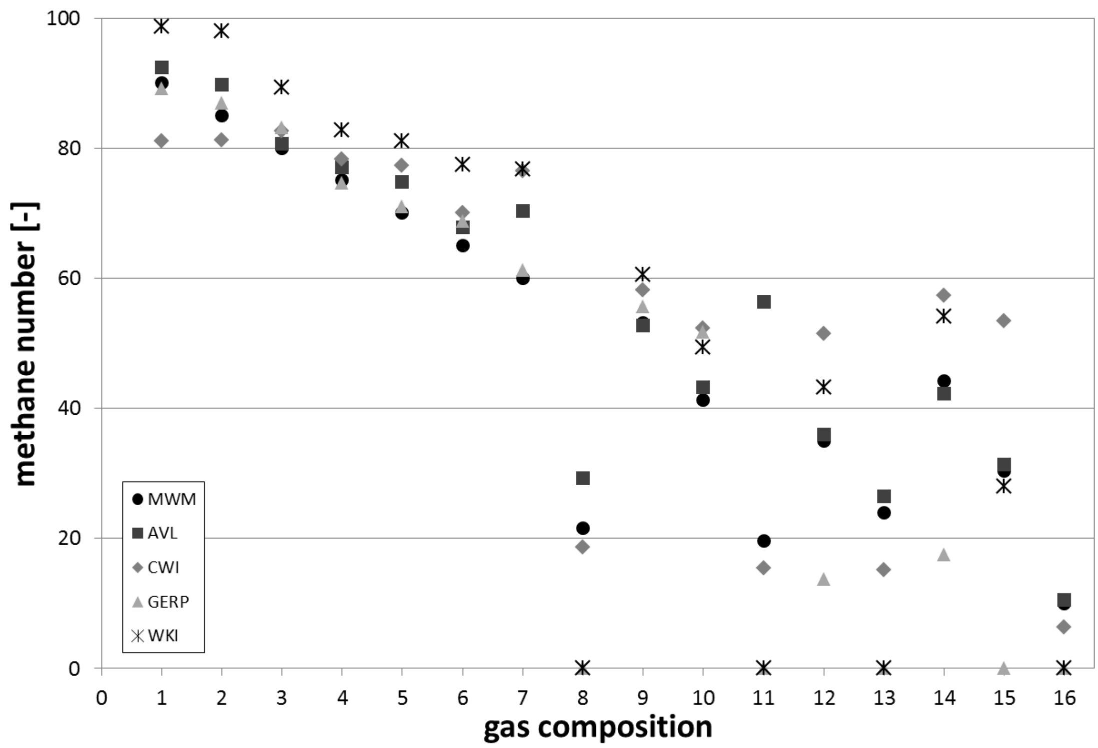

Figure 6: Methane number results of different calculation methods

4.4 Additional criteria that influence knocking

There are many factors that have an influence on the knocking of a gas engine. However, the compression ratio, the laminar flame speed and the ignition delay have the most important effects on knocking.

As already described before, a high compression ratio is necessary for a high efficiency. But the possibility of increasing the compression ratio and therefore the efficiency has a disadvantage. With a higher compression ratio, the combustion temperature and the process peak temperature increase, the exhaust gas temperature instead is reduced. Due to this high peak temperature the danger of knocking becomes stronger. Nevertheless, to allow a high compression ratio, turbocharger, intercooler and the miller process are useful. The least wanted possible method is to reduce the compression ratio.

The ignition delay time is defined as the difference in time between the beginning of the fuel injection and the start of ignition. During this time high complex physical and chemical processes are running. The ignition delay time depends very much on temperature

When ignition has started in an ignitable mixture, the flame front spreads from this point. The so-called flame speed of this flame front is of great importance for the pressure rise in the cylinder. One distinguishes between laminar and turbulent flame speed. The laminar flame speed describes the speed of a thin premixed flame front in a non-turbulent fuel air mixture [19].

The left picture in *Figure 7* shows the laminar flame speed of different gas blends. The black dot to the left represents pure methane, which is the starting point of all following mixtures. If methane is mixed with 20% of ethane or propane, the flame speed is increasing only a little bit. However, if methane is mixed with hydrogen the flame speed increases very much stronger, up to about 210cm/s for pure hydrogen. On the other side, if methane is diluted with inert gases like nitrogen or carbon dioxide, the laminar flame speed decreases. The values shown left in *Figure 7* are calculated with different chemical reaction software packages and measured from different experiments [20][21].

The ignition delay time of methane, hydrogen and a mixture of these two gases can be seen in the right picture in *Figure 7*. As previously explained the ignition delay time changes a lot with changes in temperature. *Figure 7* also shows, that with higher hydrogen content, the ignition delay time strongly decreases. To provide a more simple presentation of the results, the temperature on the abscissa is shown as a reciprocal value and because of the wide range of the ignition delay the ordinates in *Figure 7* and *Figure 8* are in a logarithmic form.

The ignition delay of ethane and propane as well as the mixture of these gases with methane is illustrated in the left picture in *Figure 8*. In comparison to hydrogen, the ignition delay is not reduced that much. The opposite happens by mixing methane with nitrogen or carbon dioxide. In *Figure 8* right, the increase of the ignition delay time can be seen. All the values of the ignition delay were measured in different experiments [22][23][24].

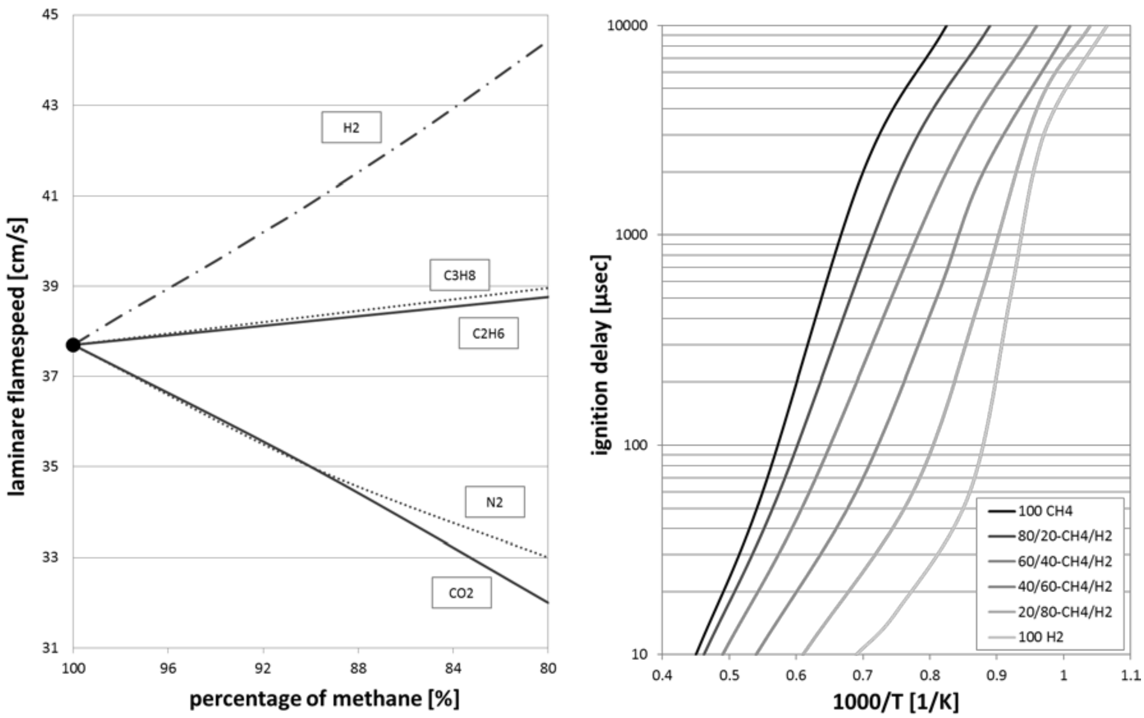

Figure 7: Laminar flame speeds of different gas compositions (left) & ignition delay of CH_4 and H_2 blends (right)

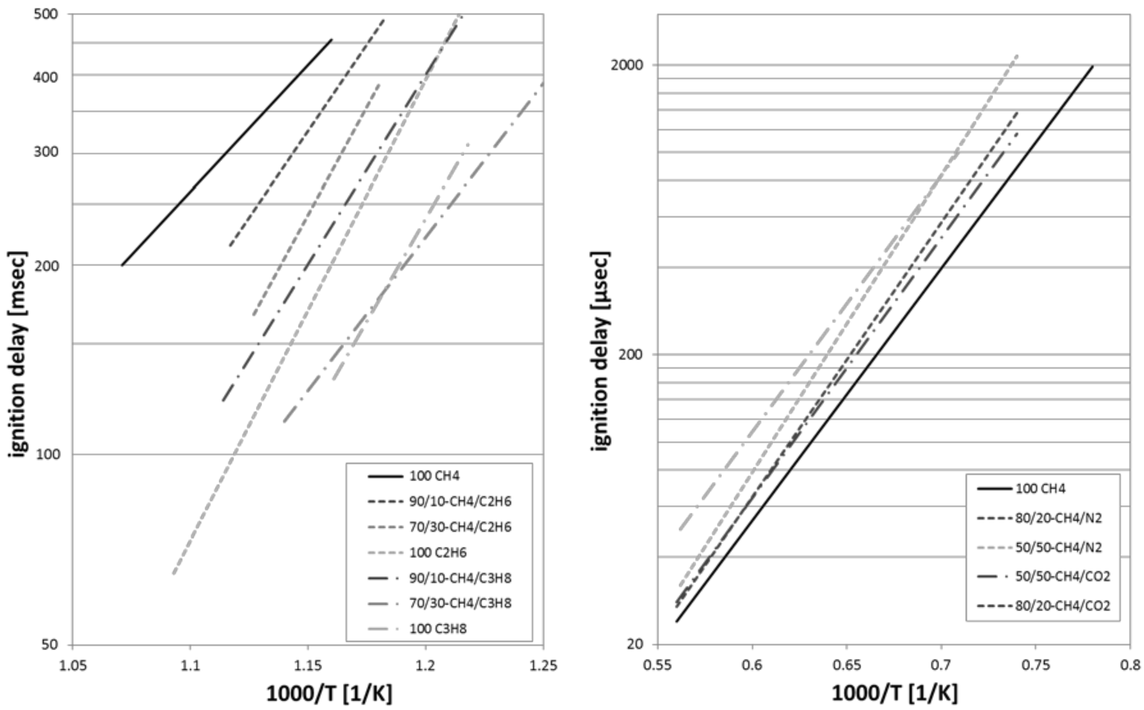

Figure 8: Ignition delay of CH_4 and C_2H_6/C_3H_8 blends (left) & ignition delay of CH_4 and N_2/CO_2 blends (right)

5 Consequences on the gas engine performance

The standards and regulations that were mentioned in chapter 2 specify the boundary conditions for the operation of gas engines. Because of the intensive efforts of the EU to liberalize the intra-European gas market and to harmonize national gas quality standards, a very conservative standard was created. The fact alone that no limit for the Wobbe-index is included, shows the big problem to find a regulation, which meets every requirement. However, the Wobbe-index is not an appropriate index to characterize the suitability for a gas engine. This index shows interchangeability but is not suitable for complex reaction kinetic effects like the combustion in a gas engine. The auto ignition time can be much different for two different gases with the same Wobbe-index. In the current standards and regulations, the main index which is important for combustion in a gas engine is the methane number. Nevertheless, it also has to be said that the range in methane down to MN 65 is a very big challenge for efficient engine operation. Traditionally, the exact gas composition has to be measured in a first step, when installing a gas engine. Based on this, the most efficient combustion process with the highest efficiency and power in compliance with the current emission limits is developed. The engine manufacturer normally specifies a detailed area in which the engine has to be operated and therefore guarantees the safe operation if these set boundaries are respected. Efficiency and emissions that are produced by the system are contractually guaranteed. An operation of the gas engine outside of this range is not economically viable on the one hand and can damage or even destroy the engine on the other hand.

6 Conclusion

Today, the gas engine is facing great challenges because gas compositions in the pipeline network that used to be stable in the last decades now start to fluctuate. Feeding the pipeline network with gases form different sources like biomethane or LNG and fast temporal changes of the compositions are a new fact. In this situation, not only the individual gas compositions but also the temporary changes of these have to be coped with. The most important factor that limits the combustion process in a gas engine is knocking. Significant criteria that have a main influence on knocking were explained. For high methane numbers and long ignition delays, the knock tendency of the gas will decrease. However, the influence of the laminar flame speed is much more complex and the knock tendency depends on many different effects. Generally, one can say, with higher hydrocarbons and hydrogen the knock tendency increases, whereas inert gases lower it.

If the new standards and regulations stay in this wide range, it can be helpful to expand the gas supply information system. One solution might be daily information about the current gas composition in the pipeline or the integration of gas chromatographs. Another possibility is the installation of a gas conditioning to supply a constant gas composition. It is also important to improve the communication between the gas provider and the system operator. If not all these factors can be aligned, high engine efficiency and safe engine operation cannot be guaranteed for all gas compositions.

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