FUEL QUALITY ANALYSIS FOR BIOGAS UTILIZATION IN HEAVY DUTY DUAL FUEL ENGINES

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ABSTRACT: Natural gas (NG) and subsequently synthetic natural gas (SNG) are expected to increase their share of the market in the heavy transportation sector. In response to this trend engine suppliers need to develop engines for various fuels of both fossil and renewable origin. One possibility is Dual Fuel engines (DF), which uses a Diesel pilot to ignite a gas mixture. To obtain significant share of biofuels, gasification of raw solid biomass to gas is a key process. The initial gas from the gasification, before it is upgraded to SNG, contains of a blend of various gas components, which are not commonly present in NG. The upgrading takes place in many process steps increasing costs and energy losses. The question raised is if there are more efficient routs to introduce biomass derived gas than refine it all the way to SNG, from a well to wheel perspective? This work investigates how different gas mixtures could meet emission limits, together with the required performance of efficiency and load, in DF engine. Three parameters which are fundamental for a proper combustion in a DF engine have been used to define the quality of the fuel: Lower Heating Value (LHV), Methane Number (MN) and Lower Flammability Limit (LFL). The components available from biomass gasification were evaluated together with those from different NG compositions on the European market.

Keywords: Dual Fuel engine, Biomass Gasification, Synthetic Natural Gas, Methane Number, Fuel Quality

1 INTRODUCTION

Internal combustion engines using oil-derived fuels are dominating the heavy transportation sector today. However, the climate issue and security of supply drive the development towards new fuels and engine technologies.

The fuel's market is expected to migrate towards a mix of oil-based fuels, natural gas (NG) and biofuels both gaseous and liquid. Especially NG will increase its share on the market due to its high availability, low price, existing distribution network and of its favorable H/C ratio which can drop CO_2 emissions from engines. The expansion of the NG in the transportation sector will also be a route for introducing CO_2 neutral gaseous biofuels of second and third generation.

In this scenario the engine suppliers need to develop engines for various fuels of both fossil and renewable origin. One possibility are Dual Fuel engines (DF), which use a Diesel pilot to ignite a gas mixture and can be used for natural gas of various qualities including synthetic natural gas (SNG).

To obtain significant share biofuels, into the transportation sector, gasification of raw solid biomass to gas is a key process, as it can offer high production capacity and high efficiency. One interesting biofuel is SNG and at present there are a number of projects focusing on SNG production through gasification of biomass to be fed to the NG grid. However, this is a rather advanced and several stage process.

The initial gas from the gasification before the gas is upgraded to CH_4 (SNG) contains of a blend of various components such as H_2, CO, CO_2, CH_4 and fractions of C_2H_2, C_2H_4, C_3H_6, and C_3H_8, as well as, longer hydrocarbons. The upgrading takes place in many process steps, where each step involves a cost and loss of efficiency. The question raised is if there are more efficient routs to introduce biomass derived gas than refine it all the way to SNG, from a well to wheel perspective?

2 APPROACH TO THE INVESTIGATION

The SNG production process is rather complex and involves six five steps (Fig.1). After the gasification the gas is cleaned from tar and sulfurs. There is the opportunity to preserve the compounds from the gasification for a more efficient production of fuel for heavy duty engine; before they are converted to syngas (CO and H_2).

During the steps following the gasification and the cleaning, the gas is before cracked to carbon monoxide and hydrogen and then converted to a mixture of methane carbon dioxide and hydrogen. In the last separation step carbon dioxide and hydrogen are removed to meet the required Wobbe index for the injection of SNG in the pipeline.

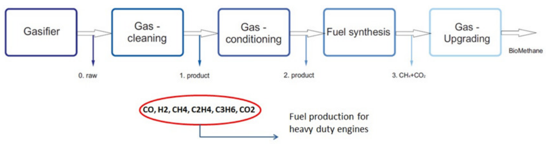

Figure 1: Fuel production from SNG production process

If the gas obtained from gasification will result of interest for utilization in DF engines, it could be used as fuel with eventually minor upgrading steps.

The first step in such an analysis is to investigate the operability of the fuel into the engine depending on the composition. The operability has a key role in the optimization of the WTW efficiency, since it influences both the production process and the combustion in the engine. This issue has been addressed in this work.

The fuel has to be of such a quality to meet the emissions limits, together with the required performance of efficiency and load. This investigation has been carried out with regards to compounds present both in the gasification gas and in the compressed natural gas (CNG) and liquefied natural gas (LNG) on the EU market.

3 INVESTIGATED FUEL QUALITY PARAMETERS

In contrast to the oil-based fuels the quality of gaseous fuels (CNG, LNG or SNG) for utilization in internal combustion engines is not yet properly defined. Standards about NG quality exist mostly to guarantee the interchangeability within the EU network and to operate properly the gas turbines. This involves variations in NG composition larger than those that engine manufacturer would like to have. However, the CNG (and soon LNG and SNG) is no longer considered an alternative fuel and the need for official norms is increasing.

In the last decades a few standards about fuel quality in gas fueled vehicles have been proposed, the most important are: the *SAE common practice J1616 (1994) [1]*, the standard *ISO 15403 (2006) [2]* and the German norm *DIN 51624 (2008) [3].* Among these the DIN norm is the most complete and provides limits and calculation methods for the Methane Number (MN), as well limits on the content of C_2 and C_3 hydrocarbons in the fuel mixture. Besides these limits in the fuel compositions there are others, like the sulfur content or the water dew point, which are important for the safety and operability of the accessory systems (as the fuel tank or the injection circuit). They have to be respected, but they are less relevant for the combustion process itself. However, these standards have been designed for spark ignited engines and they might not be sufficient for DF engines. For instance the DIN norm 51624 set the lower limit for the MN at a value of 70; which is not compatible with the higher compression ratio of DF engine. A proper limit should be set from the engine manufacturers, but value of 80 or more can be assumed. A higher MN value would be also beneficial for conventional spark ignited engines to optimize them for best efficiency, which is rarely done today.

For combustion in DF engines three parameters have been considered significant to rank the quality of gaseous fuel mixtures: the Lower Heating Value, the Methane Number (MN), and the Lower Flammability Limit (LFL). The three parameters investigated have been selected, because they are related to the critical aspects of the combustion in the DF engines; and at the same time they can be calculated with established procedures from the fuel composition.

Combustion in the DF engine becomes critical mainly because of two main reasons: the occurrence of knock at high load and the incomplete fuel combustion at low load. Comparing the two types of DF engines, port-injected and direct-injected, the first is more sensitive to both aspects, especially to the occurrence of knock. For this reason the port-injected type has been used as base case in this investigation. The third parameter LHV, or alternatively Wobbe index, is essential for all engines since it will determine the maximum load and power. With no regulation on LHV there is a risk for e.g. engine overloading and engine breakdown.

Usually for NG fueled spark ignited engines knocking is not considered a big issue, but DF engines represent a more critical application because of the higher compression ratio. Knock in DF engine is of autoignition nature and it has been investigated especially in [4] and [5].

Methane Number is commonly used to express the resistance against knock of gaseous fuels. There are two methods available for the calculation of the MN from the fuel composition: the CARB (California Air Resource Board) [1] and the AVL method [3]. The first is a polynomial calculation which fits the experimental data only in a restrict composition range; this method is used in the SAE J1616. The AVL method instead is based on the utilization of three graphs resuming a large experimental investigation made from AVL in the 70's. Despite a more complex calculation it provides a wider application range and better agreement with experimental results [6]. This method is advised in the norm DIN 51624 and used in this work.

Performance and emissions are negatively influenced when operating the DF engine at light load, as shown in [7], [4], [8]. When the gas-air mixture within the cylinder is particularly lean the result is incomplete combustion and very high emissions of CH_4 and CO. The specific energy consumption is increased and higher amount of diesel injected to stabilize the combustion. The poor gaseous fuel combustion is mainly consequences of the fact that the flame front cannot propagate fast enough to consume all the air-gas mixture within the time available. Good flame propagation is depending on the set of fuel properties and engine parameters. However it has been shown that there is a correlation between the fuel concentration in gas-air mixture, at the lowest operational point of the engine, and the lower flammability limit of the fuel [8]. The two parameters follow the same trend when increasing of the amount of diesel injected which is coupled to the temperature in the in-cylinder gas.. Even if the LFL cannot be used to predict the lower operational point of the engine in absence of experimental data (which will quantitatively correlate them) it can be assumed that fuels with a lower LFL will give a lower operational limit (leaner mixtures) in the same engine.

The lower heating value has been used to indicate the energy content of the fuel.

4 METHOD

The AVL method was followed for the calculation of the MN. It is based on three experimental maps which give the MN for mixtures of methane-propane-butane, methane-ethane butane, and methane-nitrogen-carbon dioxide. The actual fuel mixture is divided in the three sub-mixtures depending on components and MN is obtained by a combination of the MN of each sub-mixture. A limit in this calculation is that all hydrocarbons longer than butane have to be represented by butane.

One interesting aspect of the AVL calculation is the possibility of have the MN of mixture containing inert gases (N_2 and/or CO_2), up to 30 %vol in the mixture.
This gives the possibility to estimate the effect on MN by excess of air/or exhaust gases recirculated (EGR) in the engine. The results will give that the MN varies with a similar behavior but that EGR has a much higher effect on increasing the MN than dilution with air.

It was not possible to find literature for MN calculation which includes the gasification compounds, and they had to be assimilated of the closest hydrocarbons present in NG. Especially C_2H_4, and C_3H_6, which are abundant in the gasification gas, have been treated as C_2H_6 and C_3H_8. Gasification compounds are expected to have a MN slightly lower than those in the natural gas. This simplification has been used only in MN calculation.

The LFL has been estimated by using the Shebeko calculation, illustrated in [9]. It is based on the approximate constant adiabatic flame temperature, experimentally observed [9], for mixtures of gaseous fuel at LFL. For alkanes and alkenes this temperature is around 1600 K with a deviation about ± 60K. From the energy balance, calculated neglecting heat losses, with final temperature equal to the adiabatic flame temperature (set at 1550 K, as average for the hydrocarbons of interest), is possible to obtain the fuel-ratio corresponding at the LFL, for each pure compounds.

This approach has been extended to mixtures of hydrocarbons, air and inert gases from Vidal [10]. Implementing this approach results obtained were compared with the experimental data from [10]. The mean error for mixture of the hydrocarbons of interest is lower than 5% while and for mixture including inert gases is lower than 12 %.

5 RESULTS

5.1 Methane Number analysis

At first the influence of C_2 (Ethane) C_3 (Propane) and longer hydrocarbons on the MN of a mixture with methane was investigated. The line on the top of figure 2 describes mixtures of methane and ethane only, while the bottom line shows mixtures of methane and propane. All the lines in between are mixtures of the three compounds. It is evident that ethane lowers the MN significantly less than the propane. With a total content of ethane plus propane of 6 %vol, the MN can vary more than 10 points depending on the amount of propane. Such a variation is not negligible when considering a minimum MN of 80.

Longer hydrocarbons have stronger influence than C_2 and C_3 and they can drop the MN of the fuel even if present in small fractions. For instance a mixture with 1.25% butane and 3.75% ethane has a MN of 80, while if the mixture contains 5% of ethane only the MN is 87. Fractions of C_4 higher than 1 %vol are not compatible with utilization in DF engines.

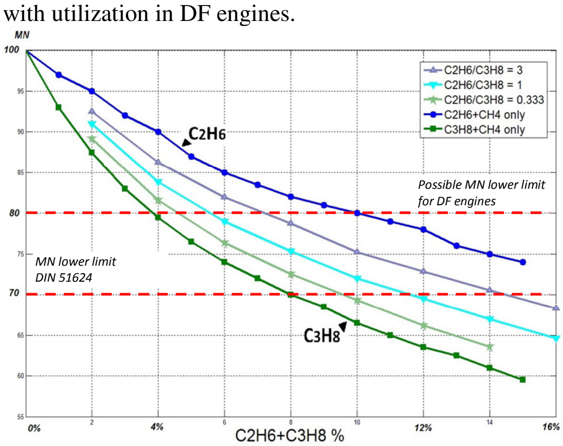

Figure 2: MN of CH_4-C_2H_6-C_3H_8 mixtures

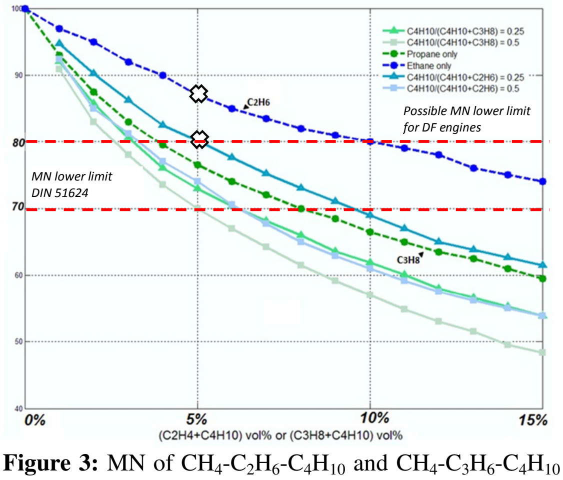

Figure 3: MN of CH_4-C_2H_6-C_4H_{10} and CH_4-C_3H_6-C_4H_{10} mixtures

Nitrogen and carbon dioxide can be present in the fuel mixture, or added to the fuel-air mixture by controlling the excess of air (N_2) and the EGR (CO_2 and N_2). The MN of blends made of methane and/or nitrogen and carbon dioxide are shown in figure 4. MN increases linearly with the fraction of inert gases added. CO_2 and N_2 differ for the slope of the trend line; CO_2 is being more effective than N_2.

This was confirmed experimentally by Karim [11], who shows that EGR has a higher effect than excess of air on controlling knocking in a DF engine. By adding carbon dioxide to methane the MN is increased with one unit per percent rate, a behavior opposite to that of hydrogen which by definition lowers the MN with one unit per percent. Theoretically a mixture of methane-hydrogen-carbon dioxide would achieve high MN (100) with similar fractions of hydrogen and carbon dioxide. This should be proven experimentally, however.

5.2 Lower Flammability Limit analysis

Literature available about flammability limits of methane-air-diluent mixtures shows that nitrogen does not affect the LFL of methane, while CO_2 raises it in a not-linear manner [12].

The main focus of the LFL analysis was on the C_2 (C_2H_4, C_2H_6) and C_3 (C_3H_6, C_3H_8) hydrocarbons. Compounds from gasification lower the LFL slightly more than those in the NG but the difference is not significant.

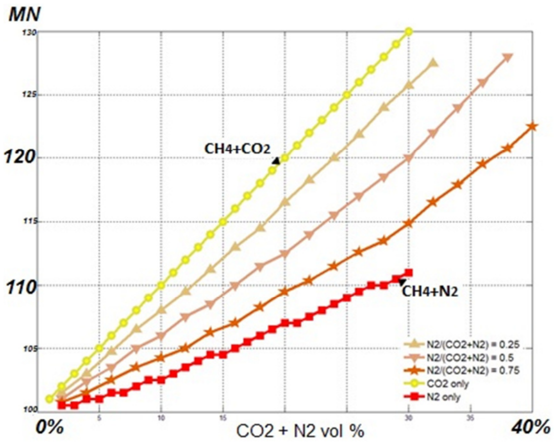

Figure 4: MN of CH_4- CO_2-N_2 mixtures

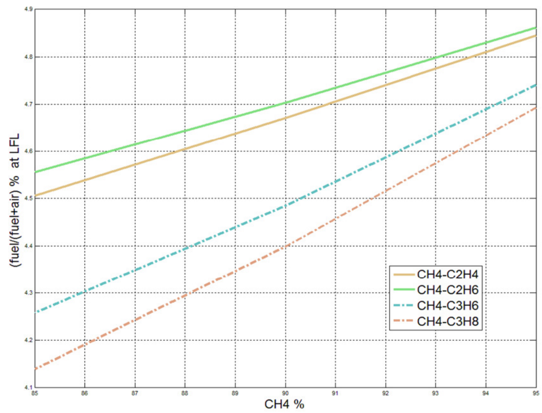

Figure 5: LFL of mixtures of CH_4 and C_2H_4, C_2H_6, C_3H_6, C_3H_8

5.3 Maps for the European market

Twenty-two different compositions of NG from pipeline, LNG and Biogas have selected to represent the European gas market. The three quality parameters investigated have been calculated for all of them and two maps LHV-MN and LFL-MN have been created. The investigated compositions are in table I.

The results of the MN-LHV analysis are shown in figure 6. The studied compositions are distributed along a diagonal line in the map. The general trend indicates that increasing the energy content in the fuel mixture the MN decreases. Excluding biogases with very high content of inert gases, the MN of the other cases vary from 65 to 102; and the LHV from 32 to 42 MJ/m^3. These ranges are probably too wide for the operation of a DF engine. In the map LNG gases are all grouped in the bottom right corners. Their energy value is particularly high due to the high content of C_2, C_3 and longer hydrocarbons, but the MN is too low for utilization in DF engines. Hence, they need to be diluted before the combustion. The gases from the gas fields in the Mediterranean countries and in the North Sea have a MN between 70 and 80, and energy content significantly higher than the methane one.

These gases could be used in the DF engine with moderate utilization of dilution techniques (for example EGR) and only at high load. However operability will depend on the engine itself.

Russian gases fall in the same range as the pure methane, hence good performance at high load are expected while difficulties at low load are probable. Gases containing high fraction of inert gases, like those from Dutch and German gas fields and biogases, will not have knocking issues but their energy content is very low. Since a proper limit for the MN has not been set yet is difficult to say which compositions could be used in the engine. However it is quite evident that gases far from pure methane could have operability limits issue at high load.

Figure 7 shows the result of the MN-LFL analysis. The linear trend of the MN-LHV maps is observed here as well.

Table I: Investigated compositions: pipeline *NG*, * LNG, *"BIO"* biogas, # internal market average gas.

Vol %	*RUS1*	*DNK*	*NLD1*	*NOR1*	*ALG*	*LBY*	*NOR2*
CH_4	98,4	89,8	81,6	92,1	88,3	85,8	86,4
C_2H_6	0,6	5,8	2,7	4,1	6,8	6,9	8,4
C_3H_8	0,2	2,3	0,5	0,9	1,4	1,8	1,9
C_4H_{10}	0,1	0,9	0,2	0,5	0,3	0,7	0,4
C_5H_{12}	0,0	0,2	0,0	0,1	0,1	0,2	0,1
C_6H_{14}	0,0	0,1	0,0	0,1	0,0	0,1	0,0
N_2	0,3	0,4	14,0	1,5	2,4	3,2	0,9
CO_2	0,4	0,5	1,0	0,7	0,7	1,3	1,9
Vol %	*RUS2*	*NLD2*	*AUT*	*GER*	*SWE#*	*GER#*	*ALG**
CH_4	97,8	83,2	85,3	87,6	90	95,0	87,6
C_2H_6	0,9	4,0	3,1	0,7	5,7	2,6	9,4
C_3H_8	0,3	0,8	0,5	0,1	2,2	0,7	2,0
C_4H_{10}	0,1	0,2	0,1	0,0	0,9	0,4	0,2
C_5H_{12}	0,0	0,1	0,1	0,0	0,2	0,2	0,1
C_6H_{14}	0,0	0,00	0,0	0,0	0,1	0,2	0,0
N_2	0,8	10,1	9,2	9,1	0,3	0,4	0,6
CO_2	0,1	1,6	1,7	2,5	0,6	0,5	0,1
Vol %	*NGA**	*QAT**	*OMA**	*BIO1*	*BIO2*	*BIO3*	*CH4*
CH_4	90,4	89,3	86,7	97,5	75,0	80,0	100
C_2H_6	5,1	7,1	8,4	0,0	0,0	0,0	0,0
C_3H_8	3,0	2,5	3,3	0,0	0,0	0,0	0,0
C_4H_{10}	1,5	1,0	1,8	0,0	0,0	0,0	0,0
C_5H_{12}	0,0	0,1	0,1	0,0	0,0	0,0	0,0
C_6H_{14}	0,0	0,0	0,0	0,0	0,0	0,0	0,0
N_2	0,0	0,0	0,0	0,0	1,0	10,0	0,0
CO_2	0,0	0,0	0,0	2,5	24,0	10,0	0,0

As expected other hydrocarbons than methane in the fuel mixture lower the LFL and the MN, hence LNG gases are placed in the bottom left corner while compositions with relevant fractions of inert gases are in the top right. The variation range of the LFL is not so wide and many of the studied mixtures fall within ±0.5% from the LFL of the methane, while MN varies more.

6 DISCUSSION AND CONCLUSIONS

6.1 About Fuel market investigation

The results of the investigation on the EU gas market shows large variations on the MN and LHV and only moderate variations on the LFL.

In the MN-LFL map only few fuels fall in the area with MN higher than 70 (limit for SI engines) and LFL lower than that of methane. No compositions have been found with LFL lower than methane and MN higher than 80 (possible limit for DF engines).

The results indicate that a tradeoff between a high MN and low LFL must be accepted. The operability range of a DF engine depends on the engine type and on the effect of EGR on controlling the knocking. Nevertheless it will be hard to run a DF engine on all the investigated compositions.

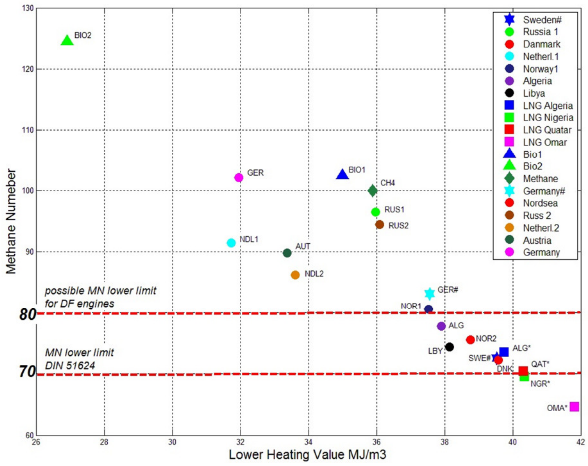

Figure 6: MN-LHV map

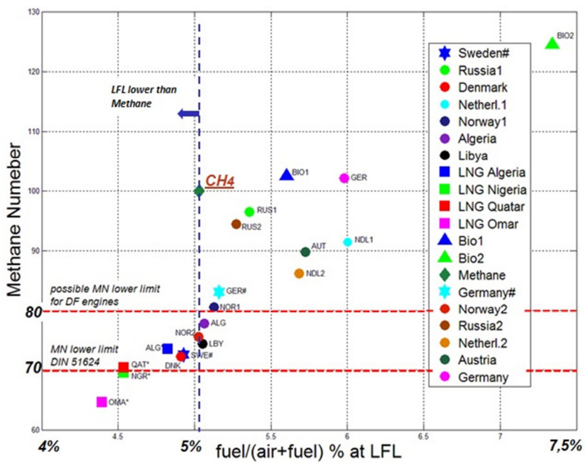

Figure 7: MN-LFL map

EGR can be a good mean to extend the operability range towards fuels with low MN (especially for those vehicles running on LNG). Another mean to control the operability of the engine when low MN fuels are use the cooling of the air charge, this could be combined with the EGR and the total effectiveness enhanced. Fuels with low MN have low LFL as well and they will provide good performance at low load (high gas/diesel substitution ratio, and good efficiency).

For fuels with very high content of methane (many pipeline gases and some biogas, including SNG) the resistance to knock will be higher but some difficulties on combustion at low load will occur.

Fuels with MN higher than 103-105 will probably have too high emissions at low load, but they can be used for stationary engines high compression ratio, to achieve higher efficiency.

6.2 About utilization of gasification gas

The influence of ethylene and propylene on the LFL is not much different from that of ethane and propane. There are not data available to estimate the exact effect on the MN, but it is possible to assume that it will not differ much from that of the corresponding hydrocarbons in the NG. Since the content of hydrocarbons longer than methane is around the 10-15% of the combustible mixture (H_2, CO, CH_4 and other hydrocarbons), the MN of the fuel will be too low for utilization in DF engines. The conclusion is that is not worth to have a production line different from that of SNG. The gas from gasification should be cracked to syngas and from it converted to the final fuel.

A suggestion for utilization of SNG in DF engines comes from this work. In last upgrade step the carbon dioxide and hydrogen removal could be controlled to meet specific values of MN and LFL instead that Wobbe index, to optimize the combustion in the DF engine. However MN values between 85 and 100 are expected for gaseous fuels from biomass gasification, making them suitable for utilization in DF engines.

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