METHANE NUMBER: A KEY PARAMETER FOR LNG USE AS VEHICLE FUEL

Martijn van Essen, Sander Gersen, Gerco van Dijk, Howard Levinsky

DNV GL Oil and Gas, Groningen

Introduction

Liquefied natural gas (LNG) is growing as an alternative for diesel fuel in heavy-duty vehicles. The major advantages in terms of pollutant and noise emissions make LNG an attractive for on- and off-road vehicles. LNG is produced at different locations around the world. The composition of the LNG (the 'quality') varies substantially with the geographical origin due to differences in natural gas sources, production technologies and target markets for the LNG. This results in a range of LNG compositions as summarized in Table 1. Furthermore, the "boil-off" of the volatile components during LNG transport, transfer and storage leads to a change in composition, also known as LNG "aging" or "weathering" [1]. LNG quality aspects must be considered in billing and in assessing the fitness for purpose of the LNG for the end user.

Table 1. Range of imported LNG compositions (based on LNG compositions from GIIGNL 2017 [2])

CH_4	82.6 - 99.7 mole%
C_2H_6	0 - 12.1 mole%
C_3H_8	0 - 3.6 mole%
C_4H_{10}	0 - 1.5 mole%
N_2	0 - 0.7 mole%

Variations in LNG composition influence the so-called knock resistance of the fuel. A fuel knock resistance that is too low for the engine for which it is intended causes engine knock, which can severely compromise engine performance, varying from increased pollutant emissions and reduced fuel efficiency to engine failure. There is a wide variety of engine types used in LNG-fueled trucks. Different engine designs and/or adjustments translate into different sensitivities to knock with variations in fuel composition. Both engine manufacturers and end users must be certain that the engines chosen can accept the range of LNG qualities that will be provided during refueling.

Knock characterization of LNG: methane number methodologies

The knock resistance of LNG is characterized by a methane number, which is similar to the octane number used to qualify gasoline. Several methods have been developed to classify gaseous fuels for their knock sensitivity such as the AVL, MWM, CARB, GRI, Cummins, Waukesha Knock Index method, Wärtsilä and PKI MN. These methane number methods give different outcomes for the same fuel composition, which results in confusion for end users and fuel suppliers in the LNG value chain. To provide transparency in the LNG market, it is first necessary to determine which methane number method provides the most accurate results for gas engines used in LNG vehicles. Once the methane number method is selected, it can serve as an international (ISO) standard which allows unambiguous agreement on the range of compositions accepted in the market, without unnecessarily excluding individual LNGs or unnecessarily derating gas engines. Below, each methodology will be described briefly.

AVL and MWM method

The methods most often used to calculate the methane number are derived from the AVL methodology [3], based on experimental work performed on a stochiometric engine. AVL uses a methane-hydrogen scale; pure methane is a knock resistant fuel and is assigned a value of 100, while hydrogen is knock sensitive and is given the value of 0. The ALV methodology includes hydrocarbons up to butane (higher hydrocarbons are treated as butane), CO_2, CO, H_2, O_2, H_2S and N_2. Engine manufactures developed their own method based on the data of the AVL work [3] and some modifications to fit the methodology to their engines.

The MWM method (published in the standard EN 16726, 2015) is based on the same data as the AVL methodology. In contrast to AVL, the MWM method ignores the effect of nitrogen, stating that nitrogen has no impact on the knock resistance of lean-burn engines [4]. Also, MWM extended the tool to include a maximum of 3% of higher hydrocarbons (n-pentane, hexane and heptane). Both MWM and AVL use complex relations to iteratively find the methane number for a given gas composition.

Traditionally used methods, such as MWM and AVL suffer from a number of shortcomings [5,6]. For example, the suitability of hydrogen as a reference gas has been disputed [5, 7], as has been the method of accounting for butane and higher hydrocarbons [8]. Also, both MWM and AVL do not discriminate between isomers of higher hydrocarbons (butanes, pentanes, etc.) which are known to show different knocking behavior [8].

CARB and GRI method [9,10]

Both CARB and GRI/ISO methods are based on a relation between the reactive H/C ratio and the motor octane number (MON) [9,10]. The MON scale is used as octane number for gasoline engines and ranges from 100 corresponding to iso-octane to 0, which is assigned to n-heptane.

The CARB method uses two correlations to calculate the methane number based on the relation between the reactive H/C ratio and the motor octane number (MON) [9]:

$$MON = -406.14 + 508.04 \cdot \frac{H}{C} - 173.55 \cdot \left(\frac{H}{C}\right)^2 + 20.170 \cdot \left(\frac{H}{C}\right)^3 \quad (1)$$

$$\text{CARB MN} = 1.624 \cdot \text{MON} - 119.1 \quad (2)$$

The CARB method is not valid for H/C ratios below 2.5 or inert concentrations above 5%. The method does not appear to be accurate enough for many gas compositions [10].

The GRI method also uses equation (1) to calculate the MON and the following equation to calculate the methane number (following ISO15403-1; 2006):

$$\text{GRI MN} = 1.445 \cdot \text{MON} - 103.42 \quad (3)$$

There is no information available on the limits of using the GRI method (e.g. limiting H/C ratio).

Waukesha Knock Index (WKI) [11,12]

The Waukesha Knock Index (WKI) to characterize the knock resistance of a gaseous fuel is described by Sorge et al. [11]. The method for calculating the methane number uses either a polynomial equation or a C/H ratio method similar to the method used by GRI and CARB. The polynomial equation is used in case the species concentrations meet the following criteria:

- Methane : 60 – 100 vol%
- Ethane : 0 – 20 vol%
- Propane : 0 – 40 vol%
- N-Butane : 0 – 10 vol%
- N- Pentane : 0 – 3vol%
- Hexane+ : 0 – 2vol%
- Nitrogen : 0 – 15 vol%
- Carbon dioxide : 0 – 10 vol%

As can be seen in Table 1, LNGs typically fall within this concentration range, which means that in most cases the polynomial equation is used to calculate the methane number.

For gas compositions that fall outside this range of concentrations, a C/H ratio method is used, where the C/H ratio can be converted into a methane number using a given calibration curve [11,12]. Adjustments are made for inert gases when using the C/H ratio method.

The method also includes the effect of iso-butane by assigning 58% of the iso-butane concentration to propane and 42% of the iso-butane to normal butane. A similar approach is used to include the effect of iso-pentane (68% to n-butane and 30% to n-pentane) [11]. The method also enables calculation of the methane number calculation for gaseous fuels that contain hydrogen, carbon monoxide and H_2S.

Cummins Methane Number (CMN) [13]

In November 2015, Cummins Westport launched their fuel quality calculator [13], which calculates the methane number and lower heating value for a given gas composition. The online tool uses a traffic light to indicate if the fuel meets the required specification for a number of Cummins Westport Engines. The online tool includes the effect of iso-butane and iso-pentane, higher hydrocarbons including n-hexane, n-heptane, n-octane, n-nonaan and n-decaan, hydrogen (up to 0.03 mole%), oxygen, nitrogen, carbon monoxide, carbon dioxide and H_2S.

Wärtsilä Methane Number (WMN) [14]

On the Wärtsilä website the methane number for gaseous fuels can be calculated. Similar to the Cummins Methane number, the tool provides information whether the fuel can be used in Wärtsilä engines. The tool calculates the methane number for hydrocarbons (up to octane), including iso-butane and iso-pentane, carbon monoxide, carbon dioxide, hydrogen, nitrogen and H_2S.

PKI MN method

DNV GL developed a methane number method (“PKI MN”) that characterizes gases for their knock resistance based on the combustion properties of the fuel mixtures themselves. In contrast to the methods described above, which use a methane-hydrogen scale, the PKI MN method is based on a methane-propane scale (PKI, Propane Knock Index).

Additionally, while AVL and MWM use complex relations to iteratively calculate the methane number, the PKI MN method uses a polynomial equation:

$$PKI = \sum \alpha_{i,n} x_i^n + \sum \beta_{i,n} x_i^n x_j^m \tag{4}$$

Herein i= CH_4, C_2H_6, C_3H_8, i-C_4H_{10}, n-C_4H_{10}, n-C_5H_{12}, i-C_5H_{12}, neo-C_5H_{12}, CO_2, CO, H_2 and N_2, n = 1-4 and m =1,2. The α and β coefficients depend on the engine platform studied [15]. To put the method on a scale analogous to the currently used Methane Number methods, the propane based scale (PKI) has been converted to a 0-100 scale, referred to as PKI MN.

In 2016 DNV GL, launched their online methane number calculator for LNG [16] and in 2017 for pipeline [17] gases, both developed and verified for a high-speed, lean-burn, spark-ignited CHP engine [6,15]. In 2017, the PKI MN methodology was also applied to develop dedicated methane number algorithms for a mono-gas variable-speed, stoichiometric, spark-ignited gas engine typically used in heavy-duty road transportation and a dual-fuel, ultra-lean-burn medium-speed engine used on ships [15]. The results show that the ranking of the knock resistance of fuel compositions differs among the different engine platforms [13]. For the engines tested, the method has shown superior performance as compared to AVL and MWM methods [6, 15].

WHAT IS THE IMPACT OF THE DIFFERENT METHANE NUMBER METHODS FOR DIFFERENT STAKEHOLDERS?

As described above, several methane number calculation methods are available and the challenge at hand for standardization committees is to select the “correct” method. To illustrate what the outcomes of the different methods to determine the methane number described above means in practice, we performed two case studies described in detail below.

In these case studies we used the prediction of the dedicated methane number algorithm for the heavy-duty LNG truck engine studied in detail in Ref [15] as a reference. This methane number algorithm shows excellent predictive power (±1 MN) for the knock resistance measured in the truck engine (characterizing the knock resistance using the Knock Limited Spark Timing; see Ref. [15] for more details).

In the case studies discussed below, we assume that the required minimum methane number for the engine is experimentally determined by adding propane to the reference gas until the engine just shows light knock. This propane fraction is then used to calculate the minimum methane number for the engine. Following this reasoning, if an engine is fueled with a gaseous fuel having a methane number below the minimum value, it will result in engine knock.

For the two cases discussed below, we assume that the truck engine manufacturer has experimentally determined that the maximum percentage of propane in methane that maximizes knock-free performance is 5%. Based on the PKI MN method, the truck engine manufacturer calculated that 5% propane in methane corresponds to a methane number of 74.5. This means that all gaseous fuels having a PKI MN below 74.5 are will cause knock unless the truck engine is derated to avoid it, with the concomitant loss of performance. In one case, we consider the case in which the engine is not derated to accommodate compositions with lower knock resistance, that is, the composition is excluded from use. In the other case, we consider how much an engine must be derated to accommodate a given fuel with lower knock resistance without knock.

Case study 1: acceptance/exclusion GIIGNL LNG compositions

In this case study the gas compositions of the GIIGNL LNGs are used as an example to examine which LNGs would be allowed or excluded based on the minimum methane number calculated for the truck engine (see above and Ref. [15]). In the second column of Table 2 ("Truck engine"), the methane numbers using the PKI MN algorithm for the truck engine are shown for each LNG composition. Assuming that the engine is not derated, then any LNG composition with methane number below 74.5 will be excluded. This is shown in Table 2 with a red background, while the green background denotes the compositions that are allowed (PKI MN $\geq$ 74.5). As can be seen in the Table, 17 out of 23 LNG compositions shown are "allowed" for this truck. Under the assumption that a maximum of 5% propane in methane gives the minimum knock resistance of the fuel for this engine, this is a realistic reflection of the situation, since the PKI MN is an accurate predictor of knock for this truck engine [15].

Now suppose that the truck manufacturer chooses a different method to calculate the methane number; how many LNG compositions in this list will be allowed or excluded for this engine? In Table 2, the minimum required methane number, taken at 5% propane in methane, is shown for each of the 8 methods described above in the top row of Table 2. In the rest of the Table, the methane numbers for the LNG compositions are shown for each of these methods. (Note: the second column "DNV GL" is also a PKI MN, but calculated using the algorithm for the lean-burn spark-ignited engine [16]).

Because of the different approaches to calculating the methane number, the minimum methane number differs from method to method. Nevertheless, depending on the methodology used, the number of allowed LNG compositions in this list varies. Whereas, in practice, 17 out of 23 compositions will be allowed for this engine, choosing a different methodology results in as low as only 7 LNG compositions being allowed, meaning that 10 compositions would be excluded unnecessarily!

Table 2. Calculated Methane Numbers for LNG compositions from GIIGNL 2017 [2], using different methodologies. The red blocks denote gases that are excluded while the green blocks denote gases that are allowed (AVL version 3.2 and MWM version 2.0.1 were used).

	MN≥74.5	MN≥74.5	MN≥75.6	MN≥80	MN≥86	MN≥79.1	MN≥75	MN≥79.2	MN≥86.7
	PKI MN								
GIIGNL LNG	**Truck engine**	**DNV GL**	**AVL**	**MWM**	**CARB**	**GERG**	**WMN**	**CMN**	**WKI**
Australia NWS	70.7	68.6	69.1	68	74.5	68.8	69	70.1	75.2
Australia Darwin	74.6	72.7	73.1	71	78.4	72.3	74	73.6	77.9
Algeria Skikda	82.3	80.3	80.7	79	88.3	81.1	82	80.5	86.1
Algeria Bethioua	77.5	75.5	76.2	75	83	76.4	77	76.6	82.1
Algeria Arzew	76.3	74.3	75.1	73	81.4	75	75	75.5	81
Brunei	70.3	68.6	69.6	69	77.1	71.1	68	71.2	78.2
Egypt Idku	83.4	82.7	83.6	83	93.5	85.7	83	83.9	90.4
Eqypt Damietta	90.9	90.8	90	90	100.3	91.8	91	88.8	94.9
Equatorial Guinea	85.7	84.2	83.8	85	92.3	84.7	86	83.5	88.6
Indonesia Arun	75.8	74.5	75.6	75	83.9	77.2	74	76.8	83.3
Indonesia Badak	70.6	68.9	69.8	70	77.4	71.4	69	71.5	78.4
Indonesia Tangguh	88.7	88.5	88.5	88	98.8	90.5	89	87.7	94.2
Libya	69.6	67.3	67	65	70.1	64.9	68	67.5	70.7
Malaysia	73.5	72.2	73.5	73	81.6	75.2	72	74.9	82.1
Nigeria	75.6	74.3	75.5	75	83.3	76.7	74	76.6	82.9
Norway	78.5	77	78.3	77	86.4	79.4	77	78.8	85.2
Oman	72.7	71.1	72.1	72	80	73.7	71	73.5	80.5
Peru	80.8	78.4	78.5	76	85	78.2	81	78.4	83
Qatar	75.5	74	75	74	82.6	76.1	74	76	82.3
Russia Sakhalin	74.8	73.6	75.1	75	83.8	77.1	73	76.5	83.7
Trinidad	89.5	89.2	88.8	88	98.8	90.5	90	87.9	93.9
USA Alaska	99.3	99.2	99.2	99	107.9	98.6	99	94	100.1
Yemen	82.4	81	81.6	80	90	82.6	82	81.8	87.3
Number of LNGs allowed	17	12	12	7	9	9	12	8	7

Case study 2: derating of the engine

An engine manufacturer wants to ensure that the engine delivered to the customer matches the expected variations in LNG composition. As mentioned above, the engine needs to be derated if the methane number of the gaseous fuel is lower than the required minimum value. In this case study, we assume that the customer wishes to fuel the truck engine with the LNG designated in [2] as Algeria Arzew. If the engine needs to be derated, we assume here the rule-of-thumb that the engine power is derated by 1% for each methane number point below the required minimum.

First, as can be seen in Table 2, Algeria Arzew is allowed in the truck engine (green box), so in practice no derating is necessary. Is this also the case when using different methane number methods?

Table 3 shows the impact of using the different methods on the power derating “needed” to avoid the occurrence of engine knock when using Algeria Arzew. Except for the Wärtsilä methane number (WMN), in all other cases the engine needs to be unnecessarily derated (albeit for DNV GL and AVL by only a small amount), since in reality the engine can accept this composition without any problems.

Table 3. Calculated Methane Numbers for Alegria Arzew [2] and the attendant power deration. The required minimum methane number corresponds to 5 mole% propane in methane (see Table 2 and text for details).

Method	Minimum Methane number requirement	Algeria Arzew Methane number	Engine power derating (%)
PKI-MN Truck engine	74.5	76.3	No derating
DNV GL	74.5	74.3	0.2
AVL	75.6	75.1	0.5
MWM	80	73	7
CARB	86	81.4	4.6
ISO/GERG	79.1	75	4.1
WMN	75	75	No derating
CMN	79.2	75.5	3.7
WKI	86.1	81	5.1

Future trend: feed-forward engine control system for optimization of engine performance

As described above, when confronted with a wider range of fuel compositions than normally specified, engine manufacturers ordinarily must either derate the engine or restrict the range of fuels that can be supplied to the engine. Restricting the range of fuels results in either a limitation of the supply options for the end user or increased processing cost for the fuel supplier, or in (structural) reduction in engine performance [6, 15]. While manufacturers offer knock-protection systems that safeguard the engine for variations in operating conditions, such as by altering spark-timing and/or derating, these methods are generally not intended for large excursions in gas quality below the nominal specification.

For this purpose, manufacturers typically choose to derate the engine to the fuel with the expected lowest knock resistance. As a rule, the resulting engine settings are fixed, i.e. independent of fuel composition and knock resistance, and will yield a structural penalty in engine performance for the fuels with a higher knock resistance than this ‘worst-case’ fuel. While systems for engine protection and control based on cylinder pressure monitoring provide real-time knock protection and on-the-fly performance optimization [18], these systems require the (undesired) occurrence of (light) knock and expert supervision during operation [19].

A better solution for both fuel suppliers and end users is the real-time adjustment of the engine settings based on the measured composition of the fuel that enters the engine. The advantage of such a feed-forward fuel-adaptive engine control system is that the engine only will be adjusted from its optimal setting (maximum power and efficiency) when the methane number is lower than specified.

Shell Global Solutions and DNV GL have tested a feed-forward fuel-adaptive control system, which combines a gas composition sensor located upstream of the engine and the DNV GL methane number algorithm to provide real-time engine performance optimization in response to changes in gas composition.

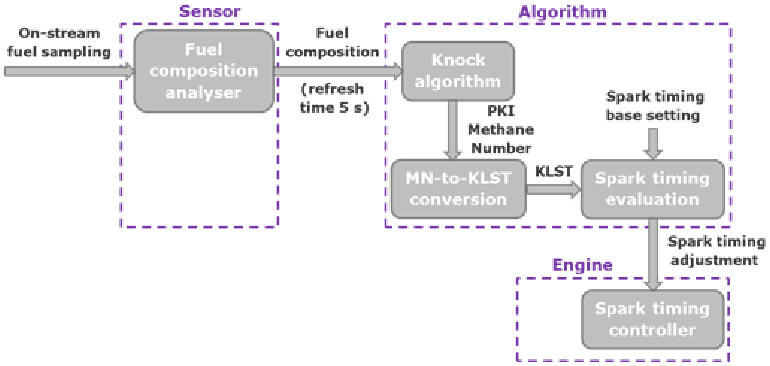

Figure 1. Schematic overview of feed-forward fuel-adaptive control system as tested at DNV GL [20].

The results revealed substantial fuel savings when demonstrating this concept on a lean-burn gas engine [20]. Furthermore, a feed-forward fuel-adaptive control system maximizes the range of gas compositions for this market.

Conclusions

The composition of LNG can differ strongly depending on the origin of the LNG and possible changes during storage arising from the boil-off of lighter components. To ensure that the engines used in LNG-fueled trucks are matched with the variations in LNG composition, the knock resistance of the fuel must be characterized and specified unambiguously.

The knock resistance of LNG is characterized by a methane number. The acceptable range of methane numbers depend on the fuels being supplied and the engine(s) installed. To illustrate this, two case studies were prepared in which nine different methodologies for methane number calculations were compared for the number of LNG compositions they would exclude or for which derating would be required for a stoichiometric spark-ignited truck engine, given a minimum acceptable methane number. The results clearly show that using the wrong method will lead to unnecessary exclusion of LNGs from the market and unnecessarily derating of the engine to prevent the occurrence of knock. Therefore, before choosing an acceptable methane number range in the specification, it is necessary to choose which methane number method should be used in the specification.

Future developments such as fuel-adaptive engine control systems may offer an increase in flexibility, and minimized loss of performance, regarding the range of LNG compositions being supplied. Tests at DNV GL together with Shell Global Solutions on a newly developed control system showed substantial fuel savings.

The information in the paper can be used to decide which methane number method to be used as an international specification and to choose a reasonable minimum methane number that is acceptable for both engine manufacturers and fuel suppliers.

REFERENCES

1. Essen, Martijn van, Gersen, Sander, Dijk, Gerco van, Levinsky, Howard, Mundt, Torsten, Dimopoulos, George and Kakalis, Nikolaos, “The Effect of Boil-off on the Knock Resistance of LNG gases”, CIMAC paper 123, presented during CIMAC congress in Helsinki, June 6-10, 2016
2. The LNG industry GIIGNL Annual Report 2017, http://www.giignl.org/
3. Leiker, M., Cartelliere, W., Christoph, H., Pfeifer, U., Rankl, M., “Evaluation of Anti-Knock Property of Gaseous Fuels by Means of the Methane Number and Its Practical Application”, ASME paper 72-DGP-4, April 1972.
4. Gas Methane Number Calculation MWM method presentation, april 2013 (documentation Euromot MWM tool);
5. Attar, A.A. and Karim, G.A., “Knock rating of Gaseous fuels”, Trans. ASME 125: 500-504, 2003.
6. Gersen, S., Rotink, M.H., van Dijk, G.H.J., Levinsky, H.B., “a New Experimentally Tested Method to classify Gaseous fuels for Knock Resistance Based on the Chemical and Physical Properties of the Gas”, IGRC, Paper No., P3-18:2011.
7. Gersen, S., Essen, M., Levinsky, H., and Dijk, G., "Characterizing Gaseous Fuels for Their Knock Resistance based on the Chemical and Physical Properties of the Fuel," SAE Int. J. Fuels Lubr. 9(1):2016, doi:10.4271/2015-01-9077
8. Callahan, T.J., Ryan III, T.W., Buckingham, J.P., Kakockzi, R.J. and Sorge, G., ICE-Vol. 27-4, 1996, Fall Technical Conference Vol. 4, pp. 59-64, ASME.
9. California Air Resources Board, LNG/CNG Rulemaking 2002 Appendix D [online] 2002, https://www.arb.ca.gov/regact/cng-lpg/appd.pdf
10. Choquette, Gary, “Analysis and estimation of stoichiometric air-fuel ratio and methane number for natural gas”, 23rd Gas Machinery Conference, October 5-8, 2014, Nashville, USA
11. Sorge, Gregory W., Kakoczki, Richard J., and Peffer, John E., “Method for determining knock resistance rating for non-commercial grade natural gas”, US Patent 6,061,637, May 9, 2000
12. Smith, Ryan Thomas, Sorge, Gergory Walker and Zurlo, James Richerd, “Systems and Methods for Engine Control Incorporating Fuel Properties”, European Patent EP 2 963 270 A1, 25th May 2015
13. http://www.cumminswestport.com/fuel-quality-calculator
14. https://www.wartsila.com/products/marine-oil-gas/gas-solutions/methane-number-calculator
15. Gersen, Sander and Essen, Martijn van,” A correct ‘octane number’ for LNG”, DNV GL Report, OGNL.113944, 2017
16. https://www.dnvgl.com/oilgas/natural-gas/fitness-for-purpose-of-lng-pki-methane-number-calculator.html
17. https://www.dnvgl.com/oilgas/natural-gas/fitness-for-purpose-for-pipeline-gas.html
18. Kopecek, H., Spyra, N., Birgel, A., Spreitzer, K., Trapp, C., Cylinder pressure based controls for robust operation of gas engines of high power density, Proceedings 9th Dessau Gas Engine Conference, 301-313, 2015
19. Barta J., Hockett A., Suhre B., Hampson G.J., ”Practical cylinder pressure monitoring for production IC engines combustion control using real-time combustion diagnostics and control (RT-CDC) module”, Proceedings 9th Dessau Gas Engine Conference, 111-120, 2015
20. Dijk, G. van, Essen, M. van, Gersen, S. and Levinsky, H.,“A feed-forward fuel-adaptive gas engine control based on a knock prediction model”, SAE SAE International Journal of Engines, to be published