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Methane number testing of alternative gaseous fuels

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ABSTRACT

Alternative gaseous fuels, like syn-gas and bio-gas, are attractive fuels for internal combustion engines due to energy and environmental concerns. Although the worldwide use of alternative gaseous fuels has increased, the knock properties of these fuels are not well understood. The methane number (MN) knock rating technique was selected based on its range and sensitivity. Eight alternative gaseous fuel compositions were simulated with a gas blending system and tested for MN in a Cooperative Fuel Research (CFR) F-2 engine. The alternative gaseous fuels ranged from 24 to 140 MN (natural gas typical range 75–95).

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1. Introduction

1.1. Background

Currently, there is a growing concern about the future of energy supply as well as climate change caused by unsustainable energy usage. For these reasons, alternative fuels are being used and developed to replace traditional fuels. One application of these fuels is in a spark-ignited gaseous-fueled internal combustion engines (ICE). These alternative gaseous fuels are derived from a variety of feedstock such as biomass, waste products, and coal. Different feed stocks introduce variation in fuel composition, properties, and performance, the effects of which have not been fully investigated. One key property yet to be explored for these fuels is knock tendency. This body of work describes the development of an experimental apparatus capable of blending simulated alternative gaseous fuels and measuring their MN. The apparatus is validated using results of Leiker et al. [1] and then used to determine the MN of eight alternative gaseous fuels.

1.2. Knock

Knock is an abnormal combustion phenomenon that adversely affects performance, emissions, and service life of spark-ignited (SI) internal combustion engines. The normal combustion event in a spark-ignited ICE can be described as a turbulent flame front, originating at the spark plug, moving through the fuel air mixture in a controlled fashion dictated by the chemical kinetics of the oxidation reaction. The unburned portion of the fuel air mixture ahead of the flame front is termed "end gas". During normal engine operation the flame propagates through the end gas, consuming the fuel and air mixture in a controlled fashion. In contrast, the term "knock" describes an abnormal combustion phenomenon which produces an audible sound. During knock the end gas auto ignites and combusts before the arrival of the flame front and produces a rapid pressure rise and extremely high localized temperatures. The combination of the high temperature and high pressure degrade the materials and erosion occurs [2]. For these reasons, engine manufactures strive to design engines that operate knock-free. The occurrence of knock is dependent on many variables, including combustion chamber design, equivalence ratio, intake air temperature and pressure, and fuel properties.

1.3. Previous work

Knock tendency is one of the critical fuel properties for spark-ignited internal combustion engines, as well as one of the most difficult to measure or model. While knock measurement for gasoline was standardized in the 1930s, even today, there is no such standard for gaseous fuel knock rating. During the 1960s, interest in gaseous fuels prompted ASTM to establish a standard for gaseous fuel knock testing. This standard used the F-2 Cooperative Fuel Research (CFR) engine and the Motor Octane Number (MON) method to test liquefied petroleum gas (LPG). The MON method has an upper limit of 120, and therefore is suitable for knock testing of LPG [3]. However, given that the MON of methane is beyond 120, this ASTM standard is limited for testing of gaseous fuel knock tendency. The next major step in gaseous fuel knock rating took place in 1972 by Leiker et al. [1]. It not only consisted of a comprehensive evaluation of gaseous

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fuels, but extensive method development, attempting to standardize gaseous fuel knock rating based on gaseous reference fuels. This contrasted the ASTM MON method of rating gaseous fuels which used liquid reference fuels. Due to the available range, as well as sufficient sensitivity, Leiker et al. [1] concluded that a mixture of hydrogen and methane should be the standard gaseous reference fuel. This rating system extends the measurable range beyond the MON and was termed "Methane Number" defined as:

> The percentage by volume of methane blended with hydrogen that exactly matches the knock intensity of the unknown gas mixture under specified operating conditions in a knock testing engine. For the range beyond 100 MN, methane-carbon dioxide mixtures were used as reference mixtures. In this case, in accordance with the definition, the MN is 100 plus the percent CO_2 by volume in the reference methane-carbon dioxide mixture. [1]

For example, a blend of 20% hydrogen and 80% methane constituted a methane number (MN) of 80. To achieve a 120 MN reference fuel 20% carbon dioxide was blended with 80% methane. Through this testing a correlation was developed to compute MN based on fuel composition. The work presented in [1] was the first viable solution for knock characterization of gaseous fuels.

In 1993, Ryan et al. [4] replicated the MN work done in [1] with the goal of increasing the understanding of the method and instrumentation. Correlations were presented to calculate MN based on composition. These correlations described fuels composed of C_1–C_5 hydrocarbons and carbon dioxide with methane concentrations between 60% and 100%. The work in [4] also investigated the effect of changing equivalence ratio on MN. Further use of the MN method was presented by Callahan et al. [5] in which tests of fuel representing wellhead gas were evaluated. A correlation was developed and referred to as the Waukesha knock index (WKI), but the specific equations were not published.

While there are many published works dedicated to gaseous fuel knock testing, little of it pertains to alternative gaseous fuels. Sewage or digester gas, an alternative gaseous fuel, has been investigated for knock properties [6–8]. Work by Neyeloff and Gunkel [8] evaluated the performance of digester gas in a CFR engine. The work determined the optimum compression ratio to be 15:1 when running a CFR engine on digester gas. However the knock rating of digester gas was not determined in these published works. Recently a group of Canadian researchers began characterizing the combustion and knock properties of alternative gaseous fuels [9]. Their work is directed at reformed product gas ($2H_2$ + CO). While the work completed in [9] provides detailed information on the effects of varying compositions of reformed product gas on knock, it does not characterize other alternative gaseous fuels or assign a MN to the fuels tested.

In summary, numerous methods of gaseous fuel knock rating have been proposed over the last fifty years. While each approach has it merits, the use of the Methane Number method has been found to be appropriate for the knock rating of alternative gaseous fuels. This is primarily due to its combination of range and sensitivity. It is further supported by a 1999 publication produced by a consortium of European natural gas industry leaders with the consensus that the Methane Number method is preferred [10]. Previous MN testing investigated natural gas compositions. While alternative gaseous fuel research has not measured MN.

2. Test setup

2.1. Engine

The engine used is a 1957 Cooperative Fuel Research (CFR) F-2 engine. An engine of this type has been used for gaseous fuel research by other researchers [1,8,9,11,12]. As manufactured, the F-2 model is used to determine the MON. It is a single cylinder, four stroke, spark-ignited engine. It is belt driven by an AC synchronous motor which serves to start and load the engine, as well as maintain speed at 900 rpm. The engine has a stroke of 114.3 mm (4.5 in.) and a bore 82.55 mm (3.25 in.). The design of the cylinder assembly allows the compression ratio to be changed while the engine is running, from 4:1 to 18:1.

A number of modifications and additions were made to the engine in order to assist in operation and monitoring of the engine. Thermocouples were installed for monitoring the temperature of the intake air, exhaust gas, and cooling water. A solid state Altronic CD200 electronic ignition system was also installed. Due to the heavy dependency of knock on air fuel ratio (AFR) a EGC-2 from Continental Controls Corporation was installed, which provides automated control of the AFR based on a feedback signal from a wide band oxygen sensor.

2.2. Knock detection

The cylinder is fitted with a port for the knock detection system which consists of a detonation pickup, detonation meter (sensitivity adjustment), and knock meter (readout). The pickup consists of a core rod of magnetostrictive alloy. As pressure rises in the combustion chamber, the diaphragm transmits this force to the core rod which in turn produces a magnetic field. The copper wire coil around the core converts the magnetic field to a voltage that is proportional to the rate of change of the combustion pressure [13]. This voltage signal is sent to the detonation meter which serves to:

- Capture the portion of the signal that is due to knock and remove the portion due to normal combustion.
- Output a DC voltage proportional to the integrated knock signal which is displayed on the knockmeter as Knock Intensity (KI).
- Allow the operator to adjust the zero point, integration time, and sensitivity [13].

2.3. Gas blending system

A computer controlled gas blending system was developed to simulate alternative gas fuels and blend binary reference blends of 0–140 MN. Electronic mass flow controllers (MFCs) from Omega Engineering were chosen to control gas composition. The system pressure is monitored by the control software and cycles the MFCs to meet engine fuel requirements. The blending system schematic is shown in Fig. 1. A Varian CP-4900 MicroGC gas chromatograph (GC) is employed to verify the gas composition.

3. Test procedure

One of the major difficulties when testing fuels for knock resistance is the measurement and quantification of knock. In the ASTM knock rating methods for gasoline, unknown fuels are directly compared to reference blends. When testing gaseous fuels this approach is more difficult. Therefore, previous MN testing used an indirect test method [1,4]. A map of reference fuel MN versus compression ratio at light knock was created, termed "MN guide line". Then an unknown fuel was tested in the engine and the compression ratio required to produce light knock was compared to the MN guide line, thereby producing a MN. In contrast, the method developed in this body of work directly compares unknown fuels to reference blends. While this increases test time and fuel consumption, it removes many of the inherent variables present in indirect method. If a test fuel produces the same knock intensity

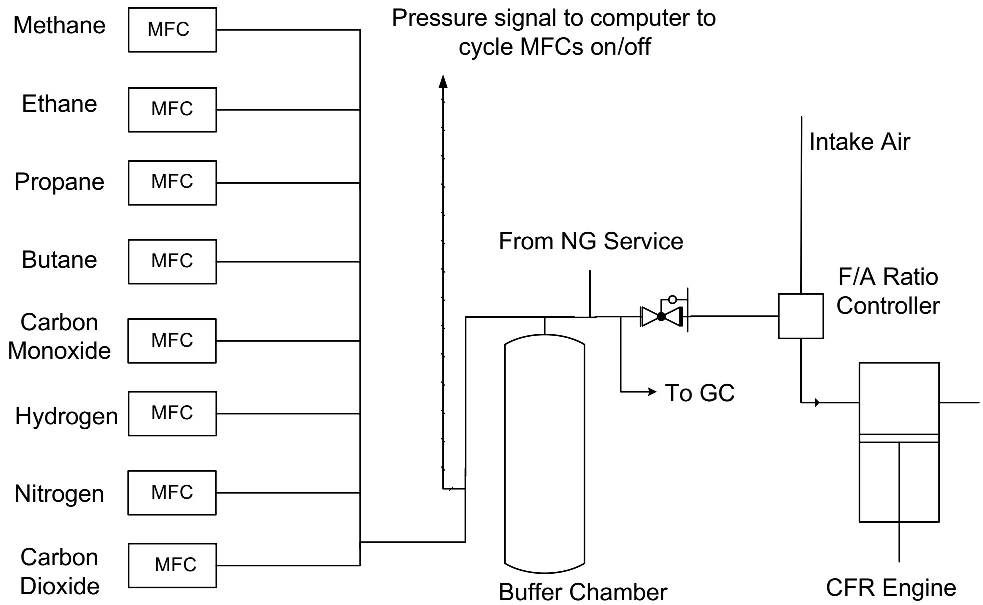

Fig. 1. Schematic of gas blending system.

Table 1
Engine operating parameters

Speed	900 rpm
Oil temperature	54–60 °C
Coolant temperature	95 °C
Spark timing	15 °C ABTDC

as a reference fuel at the same compression ratio, the MN of the test fuel is known regardless of ambient temperature, atmospheric pressure, and other uncontrolled variables. The direct comparison method was preferred to the indirect approach because the impact of uncontrolled variables was minimized.

Another significant variation in test methods is the AFR. In previous work the equivalence ratio was maintained at $\phi = 1$ [1,4]. In order to improve the MN test method and also replicate the ASTM MON method, testing is conducted at the AFR that produced maximum knock. This removes any error associated with AFR measurement. The test procedure is outlined below:

1. Run engine on natural gas and bring to operating conditions in Table 1.
2. Change engine fuel supply to test gas.
3. Adjust compression ratio for light audible knock.
4. Sweep AFR for maximum knock.
5. Adjust detonation meter to obtain a KI of 50.
6. Record engine and GC data.
7. Begin running engine on reference blend.
8. Once stabilized, observe KI; adjust blend until KI = 50; if less than 50 increase concentration of hydrogen in reference blend; if above 50 decrease hydrogen concentration.
9. Record engine and GC data.
10. Once the proper reference blend has been determined, the MN is equal to the percent methane in the reference blend.

4. Discussion of error

4.1. Validation error

The error is categorized into three sources: method, test gas blend, and reference gas blend. During the validation a target composition is being tested and compared to previous work; therefore variation in the validation gas composition causes uncertainty in the measured MN. However, when testing simulated alternative gaseous fuels, the published compositions are representative compositions for a given fuel type, rather than a specific composition. Therefore, the effect of composition variation for the alternative fuel test gases is not included in the given uncertainty.

The gas blends contain uncertainty associated with the MFCs and the GC. Since the GC error is smaller than the MFC error and all results are based on GC measurements, the MFC uncertainly is not relevant. In order to find the error in the test method, the validation gas "VAL #6" was tested ten times. The method standard deviation was determined to be 0.3 MN.

The validation of the experimental setup consists of testing gas mixtures from [1] and comparing results. The four validation gas compositions selected are shown in Table 2 along with the Methane Number measured in [1]. In order to determine the MN range a test gas could encompass, the Leiker, et al. MN model is used to calculate the MN of the possible extremes. This is accomplished by varying the composition within the known GC uncertainty that would produce the lowest and highest MN. The difference of these two MNs provides the error associated with the test gas. The uncertainty of the reference blend is dependent on the GC's measurement of methane composition in the reference fuel. This is based on the uncertainly of the calibration gases used to calibrate the GC. This error is computed for each reference blend at the composition required for each validation gas. This reference gas uncertainty is added to the uncertainty of the test gas blend. Each test gas has a different amount of error depending on the composition

Table 2
Validation gas composition [1]

Validation gas	$\%CH_4$	$\%C_2H_6$	$\%C_3H_8$	$\%C_4H_{10}$	Leiker et al. measured MN (±1.5)
VAL 6	69	20	11	*	54.8
VAL 9	93	4.3	2.7	*	75
VAL 10	91	4.2	2.7	2.1	65.6
VAL 11	49	19	32	*	43.8

The '*' denotes '0' i.e. the gas was not present in the mixture.

and the measured methane number. Therefore, the error is individually computed for each validation gas.

4.2. Experimental error

The error analysis for this portion of the experiment includes the uncertainty of the reference blend and the standard deviation of the method. The variation due to test fuel composition is neglected because each test fuel only aims to represent an alternative gaseous fuel type and not a specific composition. As an example, assume a test gas is measured to have a MN of 70. This means that the reference fuel contains 70% methane, at this composition, the GC's methane measurement has an uncertainly of ±2%, calculated to be 1.4 MN. This uncertainly is then combined with the standard deviation of the method, 0.3, to produce a total error of ±1.7 MN. Since the uncertainly is dependent on the measured MN it must be calculated for each test gas.

5. Validation

This experimental setup closely resembles the one used by Leiker et al. [1]. Consequently, four gases selected from [1] are used as validation gases for this system and method, shown in Table 2. Three tests of each gas were conducted and the average is the reported value for "Current Work" in Fig. 2. The error for this experimental system is based on variation in gas composition and its effect on the methane number measurement. The calculated error for [1] is solely based on the variation in the measurement of the engine compression pressure determined to be ±0.5 kg /cm^2. This pressure uncertainty is then equated to a MN uncertainty by means of the MN guide plot, and found to be ±1.5 MN [1]. This does not take into account the compositional variation of the test gas or the reference gas. The results of validation testing are shown in Fig. 2 and are plotted with the MN values published in [1]; there is good agreement. This indicates that the experimental setup and testing method produce acceptable MN measurements.

6. Alternative gaseous fuel testing

6.1. Selection of test gases

Test gases were selected from technical papers containing documented gas compositions including wood gas, bio-gas, and syngas, shown in Table 3. It is assumed a moisture separator would be placed in the fuel supply line when operating an engine on any of these gases; therefore, any published water content was removed and the remaining constituents normalized. Test gas three is the reported composition of gas produced by fluidized bed steam gasification of wood [14], while test gas four is produced when using two-stage gasification [15]. Test gas two represents the coal gas composition produced using an integrated coal gasification/ molten carbonate fuel cell (IG/MCFC) [16]. Using a fixed bed reactor for coal gasification, a variety of gas compositions are presented in [17] depending on operating parameters and location within the reactor. Test gas eight is a composition representative of the aggregate compositions. Test gas one is a composition of steam reformed natural gas using a thermo-chemical recuperation (TCR) system [18]. In contrast, test gas seven is the reformed gas composition produced when using a partial oxidation of methane (POM) catalyst operated at a catalyst equivalence ratio of 2.8 [19]. Gas produced by decomposition at landfills is referred to as landfill gas (LFG). It is comprised of 40–60% methane, 40–55% carbon dioxide,

Table 3
Test gases

#	Test gas	%CH_4	%H_2	%N_2	%CO	%CO_2
1	Reformed natural gas	39.7	46.7	0.8	0.9	11.9
2	Coal gas	*	24.8	16.3	58	1
3	Wood gas	10	40	3	24	23
4	Wood gas	1	31	35	18	15
5	Digester gas	60	*	2	*	38
6	Landfill gas	60	*	*	*	40
7	Reformed natural gas	1.2	30.8	49	15.6	3.4
8	Coal gas	7	44	*	43	6

The '*' denotes '0' i.e. the gas was not present in the mixture.

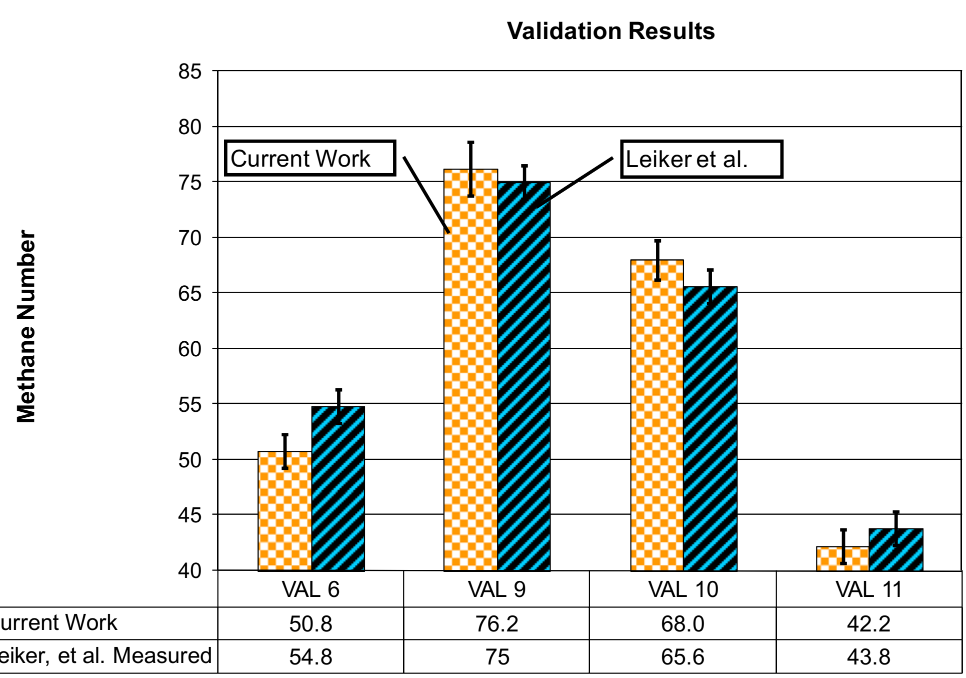

Fig. 2. Results of validation gases.

0–13% nitrogen, and 0–3% oxygen [20]. Test gas six was selected to represent LFG. The composition of LFG is similar to the composition of digester gas. Digester gas composition is comprised of 35–65% methane, 30–40% carbon dioxide, 1–2% nitrogen, and 0–1% oxygen [21]. Test gas five represents digester gas. The composition of test gas six is the definition of a 140 MN reference blend.

6.2. Results and discussion

Each gas was tested three times. The composition and measured Methane Number for each run is shown in Table 4. Significant variation in measured MN between runs can be attributed to the variation in the composition. Due to this variation, the averaging of MN from the three runs was not done. The results from the second run were arbitrarily selected for display in graphical format in Fig. 3.

Test gas one, representative of reformed natural gas produced through TCR, has a MN of 62 which is below typical natural gas due to the high concentration of hydrogen, 45%. The 12% carbon dioxide decreases the knock tendency thereby increasing the MN. Test gas two, the coal gas composition found in IG/MCFC, has a MN of 30. This extremely low value can be attributed to the high concentration of carbon monoxide and a significant amount of hydrogen. Test gases three and four both represent wood gas compositions with MN of 62 and 70, respectively. The lower MN of test gas three may be attributed to the higher concentrations of hydrogen and carbon monoxide as well as the lower concentration of inert gases. Test gases five and six are very similar in composition and, consequently, have about the same MN. The high measured MN of these two gases is caused by the high concentration of inert gases, 40%. The slightly higher MN for test gas six is due to the higher specific heat of carbon dioxide over nitrogen. This reduces the temperature of the end gas which reduces knock. Test gas seven, with a MN of 66, represents reformed natural gas from a POM catalyst. Its MN may be due to the high concentration of hydrogen with respect to other combustibles. The significant concentration of nitrogen decreases knock tendency. Test gas eight represents coal gas produced by coal gasification in a fixed bed reactor. Both test gas two and eight have very low MN values. The lower value of test gas eight is due to higher hydrogen concentration and lower inert gas content.

Table 4
Methane number test results

#	Test gas	Run	%CH_4	%H_2	%N_2	%CO	%CO_2	Methane number
1	Reformed natural gas		39.7	46.7	0.8	0.9	11.9	
		1	35.9	46.8	2.5	2.4	12.4	59.3
		2	38.1	44.5	2.1	2.3	13.0	62.4
		3	37.8	45.0	2.1	2.3	12.9	59.7
2	Coal gas		*	24.8	16.3	58	1	
		1	*	21.1	13.5	64.0	1.4	30.2
		2	*	22.3	13.3	63.1	1.3	30.0
		3	*	22.6	13.3	62.7	1.4	29.2
3	Wood gas		10	40	3	24	23	
		1	8.3	39.8	2.7	24.2	25.1	61.3
		2	8.3	39.7	2.4	24.3	25.3	61.5
		3	8.5	39.2	2.4	23.5	26.4	61.4
4	Wood gas		1	31	35	18	15	
		1	1.5	31.4	33.3	17.6	16.3	69.6
		2	1.6	30.9	33.8	17.4	16.2	70.2
		3	1.5	30.9	33.9	17.6	16.0	69.9
5	Digester gas		60	*	2	*	38	
		1	59.7	*	2.3	*	38.0	139.7
		2	60.8	*	1.5	*	37.8	139.1
		3	60.5	*	1.5	*	38.0	138.5
6	Landfill gas		60	*	*	*	40	
		1	60.3	*	*	*	39.7	139.7
		2	60.5	*	*	*	39.5	139.6
		3	60.5	*	*	*	39.5	139.5
7	Reformed natural gas		1.2	30.8	49.0	15.6	3.4	
		1	1.8	30.8	50.4	13.7	3.3	57.3
		2	1.4	30.2	47.4	13.9	7.1	66.3
		3	1.6	30.1	47.1	14.0	7.3	65.6
8	Coal gas		7	44	*	43	6	
		1	6.3	44.5	*	43.2	6.0	24.8
		2	6.6	44.4	*	42.9	6.1	23.9
		3	6.3	44.7	*	42.9	6.1	23.3

The '*' denotes '0' i.e. the gas was not present in the mixture.

These results illustrate the significant MN difference between the gases and stress the importance of fuel quality with regard to SI engine design limitations. For example, if all things are set equal, an engine optimized to operate on natural gas (≈90 MN) will experience knock when operated on test gases 1–4, 7 or 8. However, it will not knock for test gases five and six due to their higher MN. Fuels with a lower MN will knock at lower compression ratios.

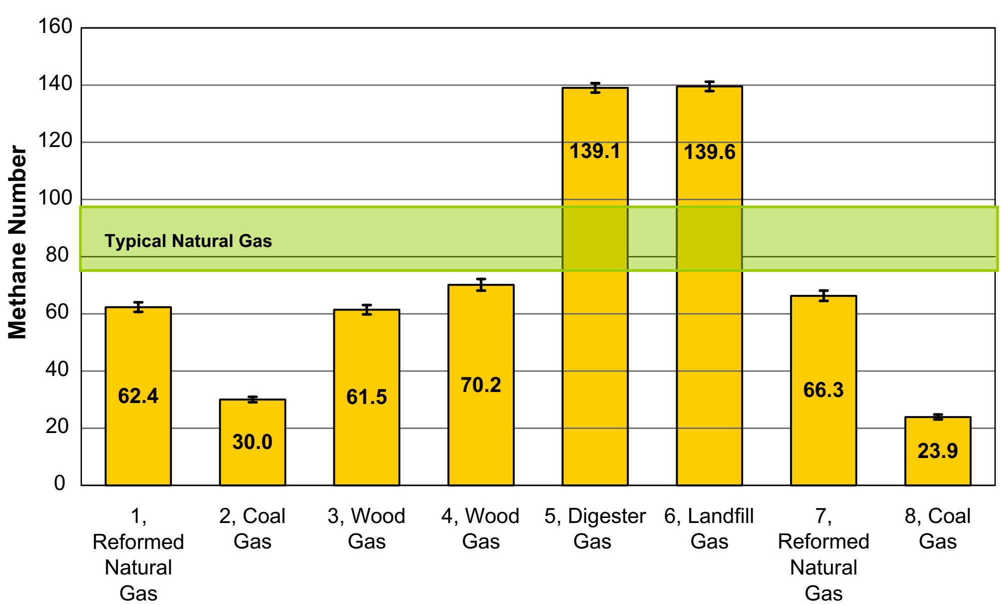

Fig. 3. Methane number results for simulated fuels, for run 2.

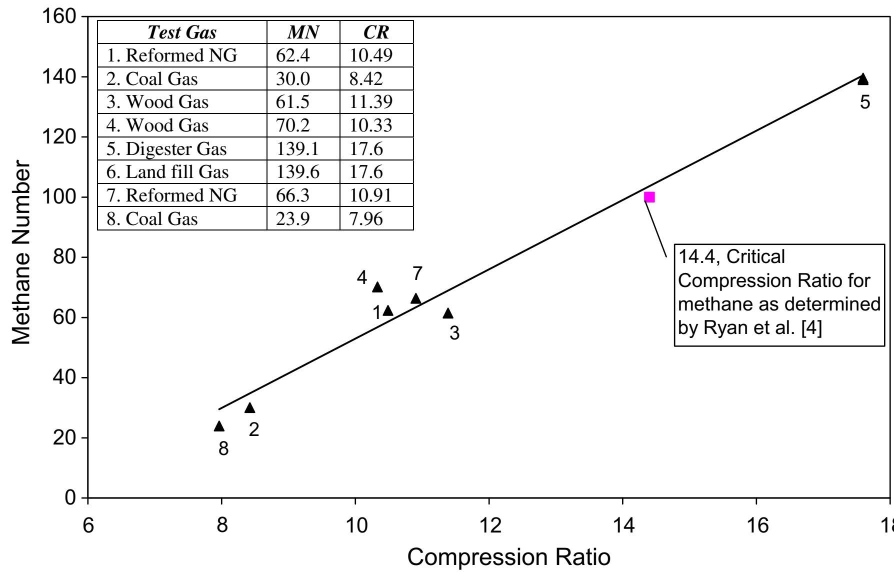

Fig. 4. Test gas compression ratio vs. measured methane number.

The compression ratio at which each gas was tested, implying the occurrence of light knock, is plotted against the MN in Fig. 4. A linear relationship is found between MN and compression ratio. For comparison, a point for pure methane is also shown at a compression ratio of 14:4 as determined in [4]. While there is data scatter in Fig. 4, this does not discount the validity of the results. Test gases one, three, four, and seven are closely grouped and appear not to follow the relationship that higher MN gases knock at higher compression ratios. This variation is likely due to the human ear detecting light knock and the narrow MN range of these gases. Since the test method directly compares test gases to reference blends, such variations do not affect the measured MN. However, the variability in detecting light knock with the human ear does affect the specific compression ratio at which the MN measurement takes place.

A fuel's MN limits the compression ratio and ultimately the efficiency. This concept is further developed by evaluating the fuel conversion efficiency for the ideal Otto cycle with constant specific heats. The equation, which is a function of compression ratio, is written as [2]:

$$\eta = 1 - \frac{1}{r_c^{\gamma-1}}$$

Where η = fuel conversion efficiency, r_c = compression ratio, γ = specific heat ratio.

Compression ratio versus fuel conversion efficiency is shown in Fig. 5, for $\gamma = 1.4$. While the calculated fuel conversion efficiencies are significantly higher than they are for real engines, the plot provides an estimate of the change in fuel conversion efficiency corresponding to a change in compression ratio. The theoretical efficiencies for test gases five and eight, based on the compression ratios at which they were tested, are also shown in Fig. 5. This graph shows the importance of proper SI engine design with respect to alternative gaseous fuels. For example, assuming an en-

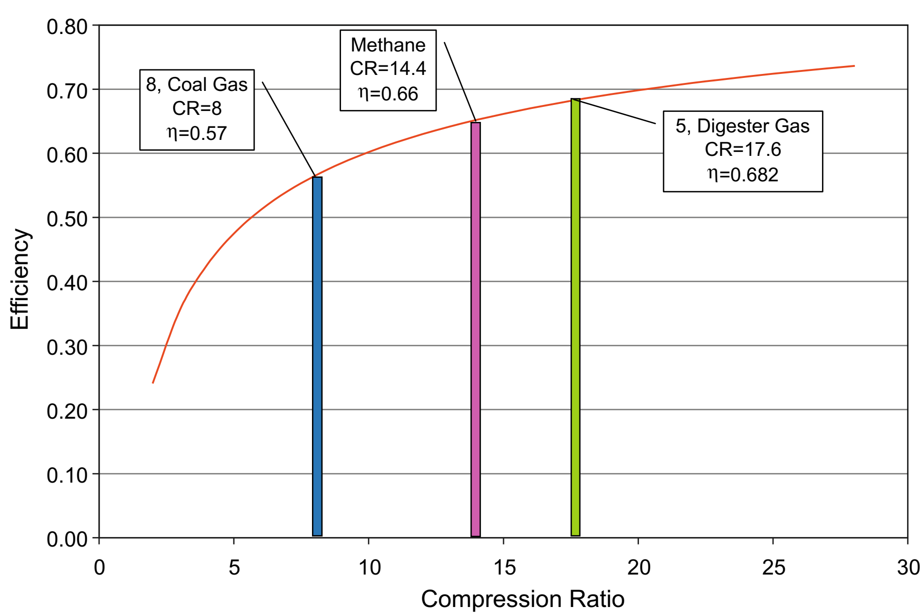

Fig. 5. Theoretical efficiency of simulated alternative gaseous fuels.

gine is operated on test gas five, an 11% improvement in theoretical fuel conversion efficiency is achieved by optimizing the compression ratio for test gas five rather than a compression ratio that provides knock-free operation on test gas eight. This example illustrates the effect of MN on engine design and efficiency.

7. Summary and conclusions

The successful and widespread use of alternative fuels in SI engines is greatly dependent on the compatibility of the two, which is not fully known. One of the most important parameters for SI engine fuels is knock tendency. Knock is detrimental to SI engine operation and should be avoided. Since compression ratio and efficiency are directly related, the knock tendency of a fuel limits the efficiency. Knowledge of the knock characteristics for alternative gaseous fuels is crucial for engine suppliers to provide reliable and efficient products.

An experimental apparatus was developed consisting of a gaseous-fueled CFR F-2 engine, a gas blending system, control system, data acquisition, and gas chromatograph. The apparatus and method were validated by testing four gas compositions with published MNs. Alternative gaseous fuels encompass many different fuel sources and compositions. In order to capture the breadth and diversity of these fuels, eight test gases were selected from literature to represent wood gas, coal gas, reformed natural gas, digester gas, and landfill gas. The methane numbers for these fuels were measured and compared to each other.

This work has added value to the Methane Number knock rating system by improving the test method and expanding the database. The test method was improved by:

- Directly comparing reference fuel blends to test blends, rather than relying on a previously generated curve relating critical compression ratio to MN.
- Testing fuel at the AFR of maximum knock, with electronic control of AFR.
- Incorporating an error analysis which includes gas composition uncertainty.

The test results show:

- There is extreme variation in the knock tendency of alternative gaseous fuels.
- The measured methane numbers of landfill and digester gas (140 MN) are above those of typical natural gas (75–97 MN).
- The measured methane numbers for wood gas are below those of typical natural gas (61–70 MN).
- The measured methane numbers of coal gas (24–30 MN) are much lower than natural gas.
- Maximizing efficiency and reliability of engines operating on the alternative fuels tested will require fuel-specific engine designs due to the effect of MN on knock limited compression ratio.

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