THE PERFORMANCE CHARACTERISTICS OF C_1-C_5 ALCOHOL - GASOLINE BLENDS WITH MATCHED OXYGEN CONTENT IN A SINGLE CYLINDER SI ENGINE

Yasser Yacoub, Reda Bata, Mridul Gautam, Daniel Martin
Department of Mechanical and Aerospace Engineering
West Virginia University
Morgantown, WV 26506

Keywords: alcohol-gasoline blend, engine knock , brake thermal efficiency

ABSTRACT

Alcohols with carbon numbers ranging from C_1 to C_5 were individually blended with unleaded test gasoline (UTG-96). All of the alcohol-gasoline blends had the same oxygen mass content. The performance characteristics of the blends were quantified using a single cylinder spark ignition engine. The knock limiting spark timing was determined by analysis of the third derivative of the measured in-cylinder pressure versus crank angle. The engine operating conditions were optimized for each (C_1-C_5) blend with two different values of matched oxygen content. Adding lower alcohols (C_1,C_2,C_3) to UTG96 improved knock resistance. Further improvement was achieved by increasing the oxygen content of the fuel blend. Blends with higher alcohols (C_4,C_5) showed degraded knock resistance when compared to neat gasoline.

INTRODUCTION

Alcohols are being used as fuel blending components to improve unleaded gasoline octane quality. Normally, methanol and ethanol are the main blending components [1][1]. Addition of small amounts of alcohols, with carbon numbers greater than one, improves fuel blend water tolerance, material compatibility, and volatility characteristics [2-7]. Increasing the alcohol content, which also increases oxygen content, up to a certain concentration (when blended with gasoline) improves the blends' knock resistance. Further increase in alcohol content does not lead to any further improvements in knock resistance [2,8,9].

The global objective of the current study is to examine individual alcohols, when blended with gasoline, with regard to engine knock. The specific objective is to determine whether the improved knock characteristics of an alcohol-gasoline blend is solely dependent on its oxygen content or if other factors are involved.

THE PHYSICAL AND CHEMICAL PROPERTIES

Selected chemical and physical properties of gasoline and alcohols are shown in table 1. When higher alcohols are blended individually with gasoline, larger amounts are needed in the blend in order to match the oxygen content of lower alcohols blends, as shown in figure 1. The changes in properties of blends with oxygen mass contents of 2.5% and 5.0%, relative to neat gasoline, are shown in figures 2 - 5. In general, as the alcohol concentration increases so does the blend's specific gravity, as shown in figure 2. Fuel blends with higher alcohols are slightly denser than those with lower alcohols for given oxygen mass contents of 2.5% and 5.0%. The energy-mass density for each blend is predicted by summing up the mass weighted heating values of the neat components[2]. The higher the oxygen content in the blend, the lower its energy mass-density value, as shown in figure 3. The decrease in the heating value is almost the same for blends with matched oxygen content. The energy-volume density for each blend is computed by multiplying its energy-mass density and its specific gravity. Blends with higher alcohols have larger energy-volume densities, when compared to those with lower alcohols for the given oxygen mass contents of 2.5% and 5.0%, as shown in figure 4. For the same operating conditions, engines burning a stoichiometric mixture need to consume more alcohol-gasoline blend than neat gasoline, as shown in figure 5. It should be noted that other important properties of gasoline-alcohol blends, such as distillation characteristics, reid vapor pressure, and water tolerance, are not discussed.

Table 1. Comparison of selected fuel properties

	Methanol	Ethanol	N-Propanol	N-Butanol	N-Pentanol	Gasoline
Formula	CH_3OH	CH_3CH_2OH	$CH_3CH_2CH_2OH$	$CH_3(CH_2)_2CH_2OH$	$CH_3(CH_2)_3CH_2OH$	—
Oxygen content (mass fraction)	0.50	0.35	0.27	0.22	0.18	0.00
Molecular weight	32.04	46.07	60.10	74.12	88.15	111.21
Specific gravity	0.79	0.79	0.80	0.81	0.81	0.74
Energy-mass density (KJ/gm)	19.93	26.75	30.94	33.22	34.84	42.91
Energy-volume density (KJ/cm^3)	15.78	21.11	24.86	26.90	28.38	31.87
Stoichiometric air/fuel ratio	6.43	8.94	10.28	11.12	11.68	14.51

[1] Numbers in parentheses designate references at end of paper.

EXPERIMENTAL

The engine used is a Waukesha single cylinder spark ignition cooperative fuel research engine with variable compression ratio. The engine bore and stroke are 3.25 and 4.5 in; respectively, giving a displacement of 0.612 L. A DC current General Electric dynamometer is used to motor and load the engine. Unleaded test gasoline (UTG-96) and high purity straight chain (n-) alcohols are used. Table 2 lists the engine conditions which are held constant throughout this investigation.

Table 2. Engine test conditions

Speed (rev./min.)	1000
Equivalence ratio	1.0 ± 0.02
Load	wide open throttle
Coolant temperature (°F)	209
Oil temperature (°F)	153 ± 4
Mixture temperature (°F)	110 ± 3
Air relative humidity (%)	25 ± 4

Alcohols with carbon numbers ranging from C_1 to C_5 are individually blended with unleaded test gasoline (UTG-96). The resulting alcohol-gasoline blends have oxygen mass contents of 2.5% and 5.0%. For each fuel blend, the compression ratio (CR) is changed from a value of 7, to the high knock limiting value in increments of 0.5. The spark timing (ST) is varied from a value of 30 to 5 degrees crank angle (CA) before top dead center (BTDC) in decrements of 5.

ANALYSIS PROCEDURE

For a fixed CR, a polynomial (up to fourth order) in ST is fit to brake thermal efficiency (η) values using the least squares method. The fitted polynomial is used to determine the spark timing for maximum η.

The magnitude of the third derivative of the measured in-cylinder gas pressure is used to quantify the engine knock strength [10]. A value of 50 psia/CA^3 is observed as a maximum threshold to characterize a single pressure trace that does not exhibit any knocking. Figure 6 shows that at low knocking operations, the time-averaged knock strength value is less than the threshold value, over a set of consecutively sampled in-cylinder pressure traces for different operating conditions (CR,ST). It also shows that the percentage of traces that exhibits knocking correlates linearly with the time averaged knock strength over that range. This linear relation is used to calculate values of time averaged knock strength that corresponds to a range of traces that exhibit knock.

For a fixed CR, a polynomial (up to fourth order) in ST is fit to the time-averaged knock strength values using the least squares method. The fitted polynomial is used to determine the spark timing for a range (5-20%) of traces that exhibit knock.

The intersection of the knock limiting spark timing curve ,and that of maximum η, identifies an optimum operating point (ST,CR), as shown in figure 7. The line of maximum BMEP is shown as well. Another operating point of interest is that of the maximum possible CR within the tested range. This is the point of intersection of the 5 CA BTDC spark timing line with the knock limiting spark timing curve.

RESULTS AND DISCUSSION

For the investigated CR range, all blends with 2.5% and 5.0% oxygen content have higher maximum η values as compared to neat gasoline, with the exception of ethanol-gasoline blend with a 2.5% oxygen content, as shown in figures 8 and 9. The increase in brake thermal efficiency with increased alcohol content is attributed to the faster burning rate, and higher cylinder pressure, than those of neat gasoline [2,11]. Detailed thermodynamic analysis of the power cycle is required to explain the improvement in η values for all blends and, specifically, the degradation for the ethanol-gasoline blend with 2.5% oxygen.

Figures 10 and 11 show the knock limiting spark timing at different compression ratios for 5% traces exhibit knocking. The C_1 to C_3 alcohol-gasoline blends show a wider range of operation relative to neat gasoline. On the other hand, higher alcohol (C_4,C_5)-gasoline blends show degraded knock resistance when compared with neat gasoline. These trends are common for the 2.5% and 5.0 % oxygen blends.

In order to quantify each blend's knock resistance characteristics, the areas under the curve in figures 10 and 11 are computed and compared to that of neat gasoline, as shown in figure 12. Adding lower alcohols (C_1,C_2,C_3) to gasoline has improved knock resistance. Ethanol-gasoline blends show the highest knock resistance improvement (~ 20%-35 %). On the other hand, blends with higher alcohols (C_4,C_5) show degraded knock resistance, when compared to gasoline. The pentanol-gasoline blend shows the highest knock tendency (~30%-60%). For the 5.0% oxygen blends, both the improvement and degradation trends of knock resistance are more pronounced when compared with the 2.5% oxygen blends.

For an engine operating at optimum conditions, the improvement in the values for η and CR for different blends, relative to neat gasoline, are shown in figures 13 and 14 respectively. For the 2.5% oxygen blends, the methanol-gasoline blend shows the highest improvement in η (~2%). The ethanol-gasoline blend, however, has the highest improvement (~6.0%) for η when compared with the 5.0% oxygen blends. Blends with higher alcohols (C4,C5) have degraded η values, with the exception of butanol-gasoline blend with 2.5% oxygen. For the 5.0% oxygen blends, both the improvement and the degradation trends for the η values are more pronounced, when compared with the 2.5% oxygen blends with the exception of 2.5% oxygen butanol-gasoline blend. The slight improvement in η value for the butanol-gasoline blend with 2.5% oxygen, is attributed to the blend's higher η value when compared to gasoline at the same CR value. Both 2.5% and 5.0% oxygen ethanol-gasoline blends show the highest improvement (~ 2.5% and 10.0%, respectively) in optimum CR value, when compared with matched oxygen content blends.

For an engine operating at the maximum possible CR and ST of five degrees BTDC, all blends (with the exception of pentanol-gasoline blends) show improvement for the values of η and CR relative to neat gasoline, as shown in figures 15 and 16 respectively. For the 2.5% oxygen blends, methanol-gasoline blends show the highest improvement in η (~4%). On the other hand, the propanol-gasoline blend has the highest improvement in η (~7.5%), when compared with the 5.0% oxygen blends. For the 2.5% oxygen blends, the ethanol-gasoline blend operates at the highest (~15%) CR value and the methanol-gasoline blend operates at the highest (~20%) CR value among the 5.0% oxygen blends.

CONCLUSIONS

Adding lower alcohols (C_1,C_2,C_3) to unleaded test gasoline improves its knock resistance from 8% to 20% for blends with a 2.5% oxygen mass content, when compared to neat gasoline. The knock resistance is further improved (20% - 35% compared to gasoline) by increasing the oxygen content of the blend to 5.0%. Ethanol-gasoline blends show the highest knock resistance improvement (~ 20% - 35 %) among all tested blends.

Blends with higher alcohols (C_4,C_5) show degraded knock resistance when compared to gasoline. Pentanol-gasoline blend exhibits the highest knock tendency, ~ 30% more, than gasoline for 2.5% oxygen blends. The knock tendency is further promoted (~60% more than gasoline) by increasing the oxygen mass content in the blend to 5.0%.

All tested alcohol-gasoline blends have a higher brake thermal efficiency than neat gasoline operating, when compared at the same compression ratio, with the exception of ethanol-gasoline blend with 2.5% oxygen mass content.

For an engine optimized for maximum brake thermal efficiency and knock limiting operating conditions, (C_1,C_2,C_3) alcohol-gasoline blends operate at higher efficiency (~ 2% for C_1-UTG 2.5% O_2 and ~6% C_2-UTG 5.0% O_2) when compared to neat gasoline, due to its higher optimum compression ratio. Ethanol-gasoline blends show the highest improvement in optimum compression ratio (~2.5% for 2.5% O_2 and ~10.0% for 5.0% O_2).

For an engine optimized for knock limiting operating conditions and five degress BTDC spark timing, (C_1,C_2,C_3) alcohol-gasoline blends operate at higher efficiency (~ 4% for C_1-UTG 2.5% O_2 and ~7.5% C_3-UTG 5.0% O_2), when compared to neat gasoline, due to their higher compression ratios (15-20%).

Detailed thermodynamic analysis of the power-gas exchange cycle is required to explain the improved/degraded trend of different blends.

ACKNOWLEDGMENTS

The authors wish to thank the US-DOE Pittsburgh Technology Center, especially Gary Stiegel, Project Manager, for funding this project, Contract No. DE-AC22-91PC91034. Thanks are also due to the National Research Center for Coal and Energy (NRCCE), specifically, Dr. Caulton Irwin, Project Coordinator. Thanks are also due to our project team colleges at WVU Chemical Engineering Department and Union Carbide Company, Charleston, West Virginia.

REFERENCES

1. N. E. Gallopoulos, "Alcohols for Use as Motors Fuels and Motor Fuel Components", Presented at the Coordinating European Council Second International Symposium, Wolfsburg, West Germany, 1985.
2. K. S. Patel , S. Kuma, and O.Y.Kwo, " The Performance Characteristics of Indolene-MPHA Blends in a Spark Ignition Engine", SAE 872069.
3. M. Sposini, R. Pea, et al., Proceedings of the Fifth International Alcohol Fuel Technology Symposium, Vol. II, Auckland, NZ, May 1982.
4. "Alcohols and Ethers A Technical Assessment of Their Application as Fuels and Fuel Components", API Publication 4261, Second Edition, July 1988.

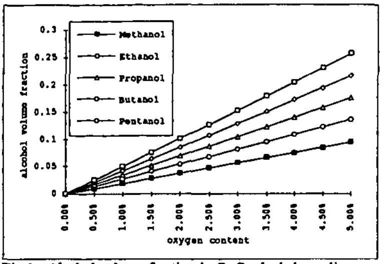

Fig.1 Alcohol volume fraction in C_1-C_5 alcohol-gasoline blends with matched oxygen content.

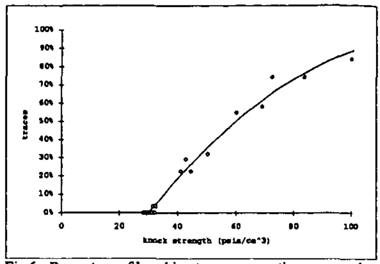

Fig.6 Percentage of knocking traces versus time averaged knock strength for different operating conditions.

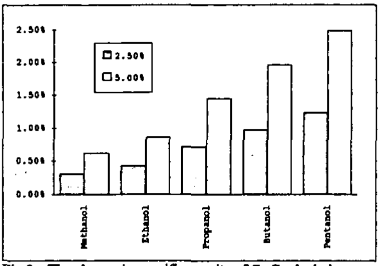

Fig.2 The change in specific gravity of C_1-C_5 alcohol-gasoline blends relative to neat gasoline.

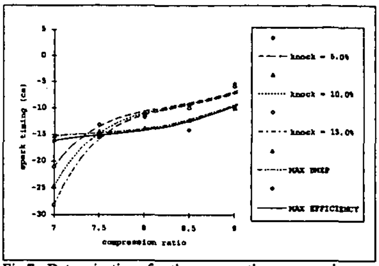

Fig.7 Determination of optimum operating compression ratio and spark timing.

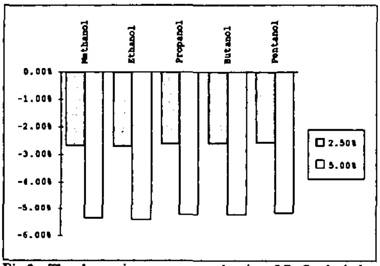

Fig.3 The change in energy-mass density of C_1-C_5 alcohol-gasoline blends relative to neat gasoline.

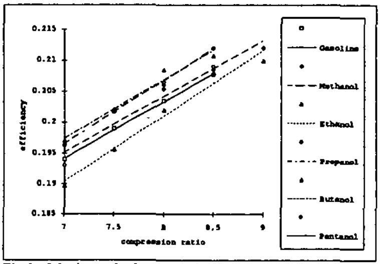

Fig.8 Maximum brake thermal efficiency at different compression ratios for blends with 2.5% oxygen.

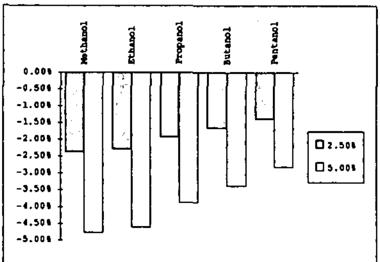

Fig.4 The change in energy-volume density of C_1-C_5 alcohol-gasoline blends relative to neat gasoline.

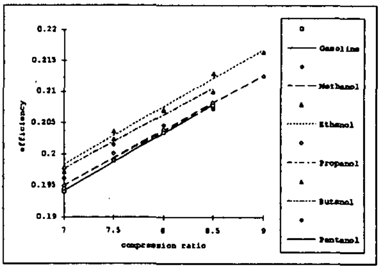

Fig.9 Maximum brake thermal efficiency at different compression ratios for blends with 5.0% oxygen.

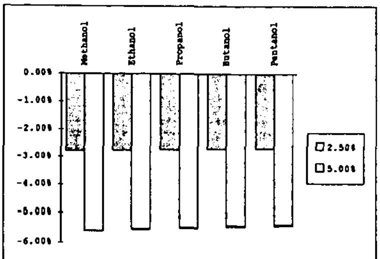

Fig.5 The change in stoichiometric air to fuel ratio of C_1-C_5 alcohol-gasoline blends relative to neat gasoline.

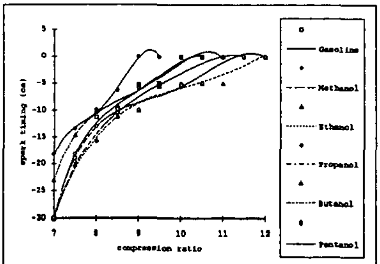

Fig.10 Knock limiting spark timing at different compression ratios for blends with 2.5% oxygen content.

5. E. I. Dupont De Nemours and Company, Inc., "Clean Air Act Waiver Application Section 211(f)", Application to the US. Environmental Protection Agency, Vol. 3, Sect. XIII, 1984.
6. R. L. Furey, "Volatility Characteristics of Gasoline-Alcohol and Gasoline-Ether Fuel Blends", SAE 852116.
7. K. Owen and T.Coley, "Automotive Fuels Reference Book", Second Edition, Society of Automotive Engineers, Inc., 1995
8. K. S. Patel and N.A.Henein, "Burning velocities in Methanol-Indolene Air Mixtures in a CFR Engine", SAE 850111.
9. A. R. Sapre, "Properties, Performance and Emissions of Medium Concentration Methanol-Gasoline Blends in a Single-Cylinder, Spark-Ignition Engine", Paper 881679, Presented at The International Fuels and Lubricants Meeting and Exposition, Portland, Oregon, Oct, 1988.
10. M. D. Checkel and J.D. Dale, "Computerized Knock Detection from Engine Pressure Record", SAE 860028
11. N. D. Brinkman, "Ethanol Fuel - A Single-Cylinder Engine Study of Efficiency and Exhaust Emissions", SAE 810345

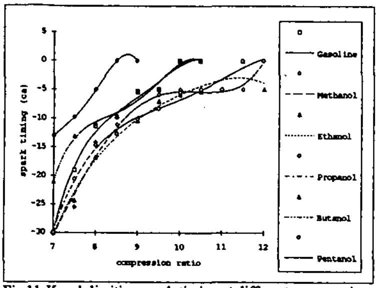

Fig.11 Knock limiting spark timing at different compression ratios for blends with 5.0% oxygen content.

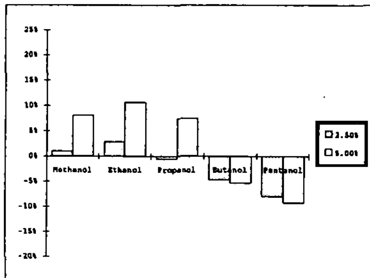

Fig.14 Comparison of alcohol-gasoline blends (2.5% and 5% oxygen mass content)compression ratio to neat gasoline at optimum operation.

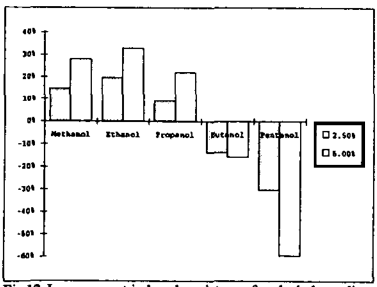

Fig.12 Improvement in knock resistance for alcohol-gasoline blends (2.5% and 5% oxygen mass content) relative to neat gasoline.

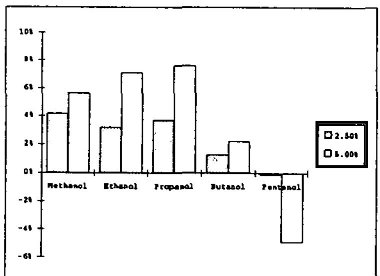

Fig.15 Comparison of alcohol-gasoline blends (2.5% and 5% oxygen mass content) brake thermal efficiency to neat gasoline at maximum compression ratio.

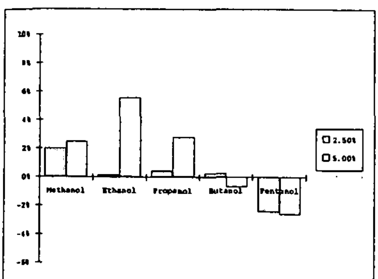

Fig.13 Comparison of alcohol-gasoline blends (2.5% and 5% oxygen mass content)brake thermal efficiency to neat gasoline at optimum operation.

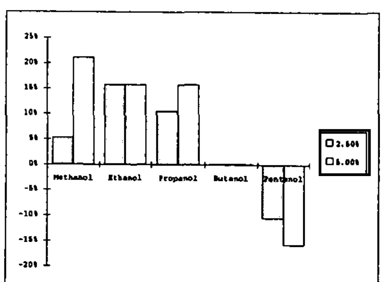

Fig.16 Comparison of alcohol-gasoline blends (2.5% and 5% oxygen mass content) maximum compression ratio to neat gasoline.