Cetane Number Effects on HCCI Combustion and Emissions

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ABSTRACT

The purpose of this study was to investigate cetane number effects on HCCI combustion performance and emissions.

In this study, a CFR engine was modified to operate in HCCI combustion mode. The base fuel was a minimally-processed, low cetane number refining stream derived from oil sands sources. Three different methods were employed to increase the cetane number of the base fuel, namely hydroprocessing the base fuel, cetane improver addition, and blending with a high cetane number renewable diesel blending component derived from mustard seed oil.

Results show that increasing the fuel cetane number shifted the AFR-EGR operating region for HCCI combustion towards leaner mixtures and reduced the cyclic variations for controlled input conditions. At fixed speed-load conditions, higher EGR rates were required to operate the higher cetane number fuels at lower AFR (richer mixtures). This led to a significant decrease in the maximum engine power produced for the higher cetane number fuels with a fixed boost pressure. Also, The hydroprocessed fuels had more stable and complete HCCI combustion than the base fuel, which resulted in reduced CO, HC, and NOx emissions and lower ISFC.

EXPERIMENTAL SETUP

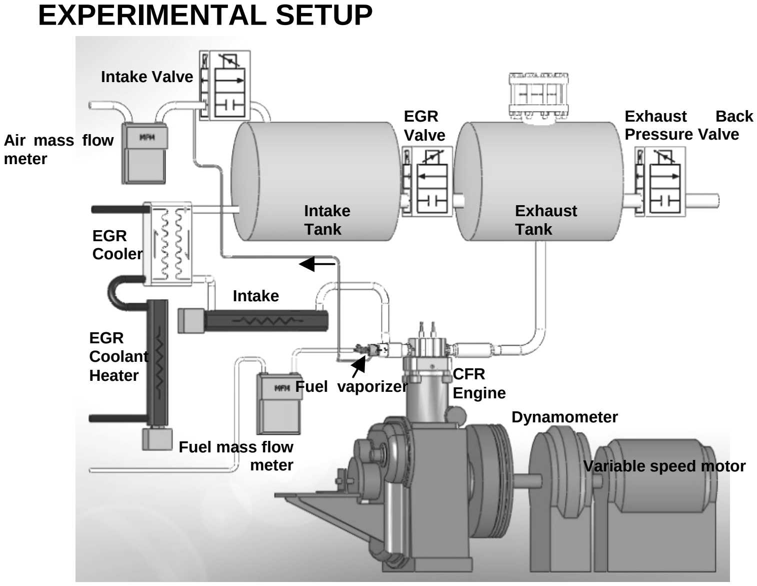

Figure 1: HCCI Engine Research Facility

Figure 1 is a schematic diagram of the HCCI combustion research facility. The Cooperative Fuels Research (CFR) engine used for this study is a single-cylinder, four-stroke, variable compression ratio engine.

A port fuel injector was used to atomize the fuels just upstream of the intake port. Compressed air was used as blast air to improve the atomization process. An in-house fuel vaporizer was added downstream of the fuel injector to vaporize part of the diesel fuel components.

Exhaust gas composition (NO_x, HC, CO, CO_2, O_2) was measured using an emission analyzer (California Analytical Instruments, 600 series). A water-cooled pressure transducer (Kistler Corp., model 6041A) flush-mounted in the cylinder head was used to measure cylinder pressure. The cylinder pressure data was acquired for 300 consecutive engine cycles with 0.2°CA resolution using a real-time combustion analysis system (AVL LIST GmbH, IndiModule).

FUELS

The base fuel for this study was a minimally-processed refinery stream derived from oil sands sources with a 36.6 cetane number (OS-CN36).

Three different methods were used to increase the cetane number (CN) of the base fuel, namely hydroprocessing, cetane improver addition, and blending with a renewable diesel blending component.

In this study, the base fuel was subjected to two hydroprocessing severities using a commercial CoMo ULSD hydro-treating catalyst at the National Centre for Upgrading Technology (NCUT), Devon, Alberta, Canada. The cetane number of the resultant fuels were 39.4 (OS-CN39) and 41.4 (OS-CN41).

The second method used to increase the CN was the addition of 2-ethyl-hexyl-nitrate (2EHN), a commercial cetane improver. Two fuels with 40.0 (2EHN-CN40) and 44.6 CN (2EHN-CN44) were produced by adding 0.05% and 0.23% by volume of 2EHN to the base fuel, respectively.

The third method was to blend Supercetane™ renewable diesel blending component with the base fuel. The Supercetane™ fuel was produced by hydrotreating mustard seed oil at CanmetENERGY, a Centre of Natural Resources Canada. This renewable fuel consisted primarily of C_{15} to C_{20} normal alkanes and had a DCN of 109.

RESULTS AND DISCUSSION

Experiments with controlled input conditions

AFR and EGR were changed and the resultant engine combustion behavior was measured. Other initial conditions were fixed for this experiment, as shown Table 1. No control was placed on the engine output.

Table 1: Initial conditions for engine experiments with controlled input conditions

Fuel vaporizer temperature (T_{vap}, °C)	220
Intake mixture temperature (T_{mix}, °C)	75
Compression ratio	13:1
Engine speed (rpm)	900
MAP (kPa)	200

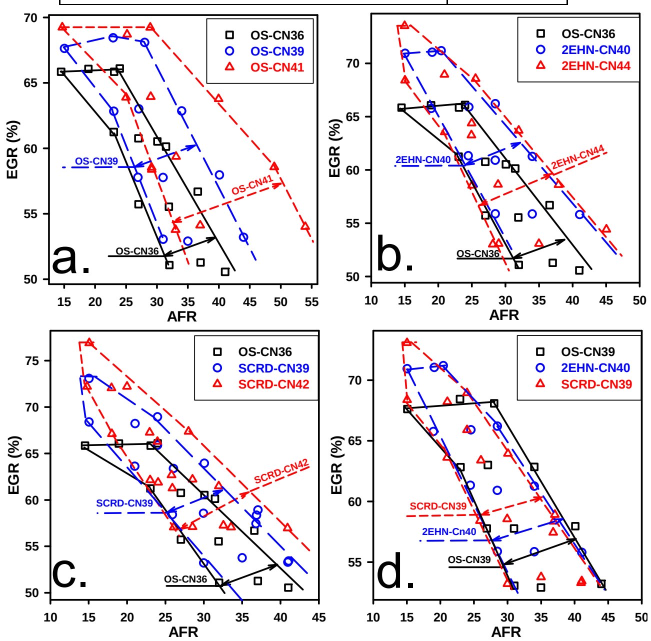

Figure 2: AFR-EGR operating regions, a. hydroprocessing, b. cetane improver addition, c. blending with renewable diesel, and d. similar cetane number fuels obtained by different methods.

The maximum EGR was determined with the aforementioned initial conditions for each fuel. AFR conditions were bounded by the rich and lean limits, denoted by maximum rate of pressure rise ≤ 10 bar/^{o}CA and COVIMEP ≤ 5%, respectively. The EGR rate was reduced in four steps of 5% each from the maximum EGR rate, and various AFR conditions were examined at each EGR rate. Increasing CN in all cases expanded the operating region on the fuel lean side and limited the operating region on the fuel rich side. Figure 2 shows that CN is indicative of AFR-EGR operating window. In Figure 2.d, similar CN fuels exhibited identical AFR-EGR operating regions despite of different chemistries.

Figures 3 and 4 show IMEP and ISFC as functions of AFR for different fuels at constant EGR ratios (EGR=59.6%±1.5%). Hydroprocessing increased IMEP while the two other methods decreased IMEP. The decrease in IMEP for SCRD-CN39 and SCRD-CN42 was due to the slower combustion rate.

Figure 5 shows effects of CN on combustion cyclic variation. With an exception of one case, increasing CN decreased combustion cyclic variation. The most stable combustion belonged to hydroprocessed fuels.

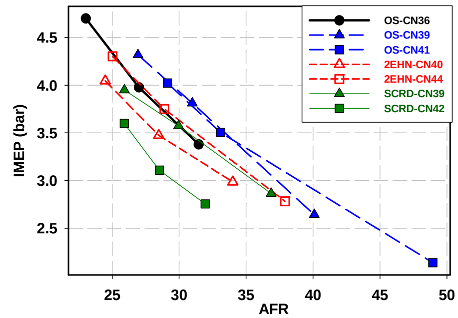

Figure 3: Effect of CN on indicated mean effective pressure (IMEP) at selected operating points.

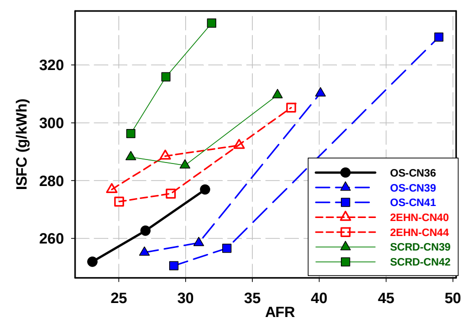

Figure 4: Effect of CN on indicated specific fuel consumption (ISFC)

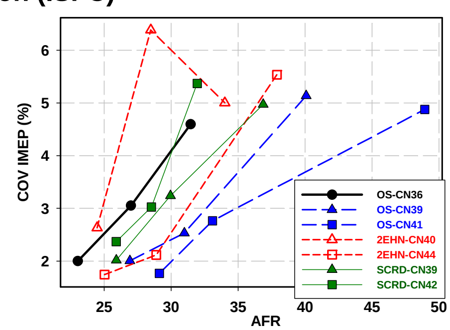

Figure 5: Effect of CN the coefficient of variation of IMEP (COV IMEP)

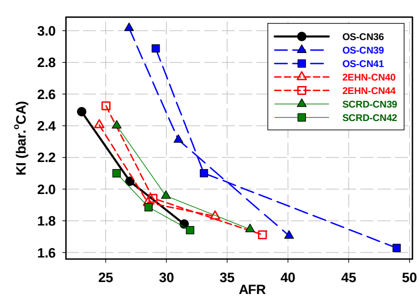

Figure 6: Effect of CN on knocking intensity (KI).

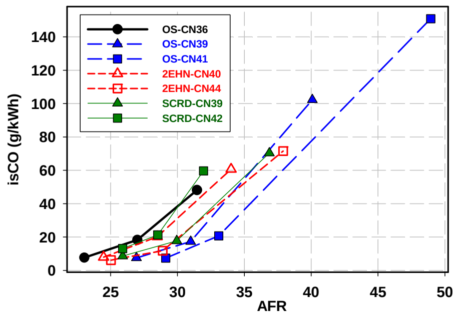

Figure 7: Effect of CN on indicated specific CO emissions (isCO).

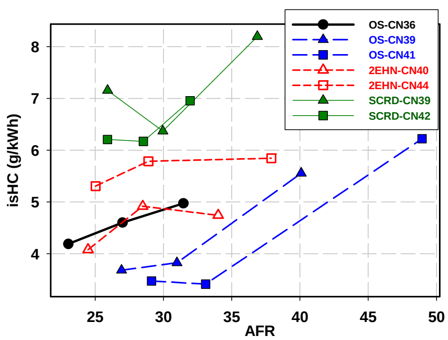

Figure 8: Effect of CN on indicated specific HC emissions (isHC).

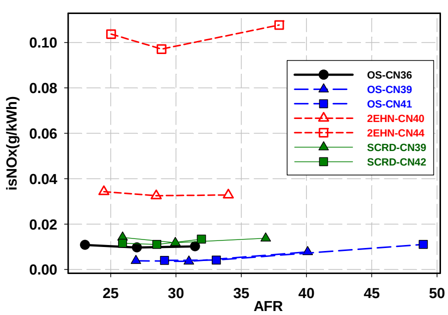

Figure 9: Effect of CN on indicated specific NOx emissions (isNOx).

Figure 6 shows the combustion noise quantified by knocking intensity integral (KI). KI was increased by increasing CN independent of the upgrading method. Hydrprocessing method exhibited the larger increase in knocking intensity.

Figure 7, illustrates that all methods of increasing the base fuel CN reduced CO emissions. In Figure 8, blending with Supercetane™ increased isHC emissions, while adding cetane improver did not clearly affect isHC. Hydroprocessing reduced isHC emissions. Figure 9 shows indicated specific NOx emissions (isNOx). The only method that improved NOx emissions was hydroprocessing.

Experiments with controlled-output conditions

While the experiments with controlled inputs are useful to compare the AFR-EGR operating range for various fuels, other results are difficult to compare because the engine power and combustion timings were not fixed for each test fuel. A matrix of 3 IMEP levels and 3 speed levels were defined for the experiments. Figure 10 gives the details of the controlled engine outputs experimental matrix.

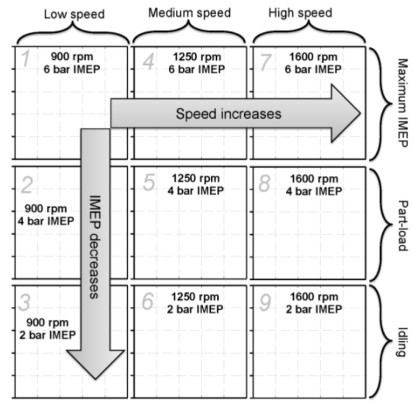

Figure 10: Graphical representation of the operating conditions for controlled engine output experiments.

Intake manifold absolute pressure (MAP) was fixed for each IMEP. At each mode, EGR was set at its maximum such that the combustion timing (CA50) was at TDC. Then, AFR was adjusted to the required IMEP. The rate of pressure rise was also monitored and controlled at each mode ($(dP/d\theta)_{max}$) ≤ 10 bar/^{o}CA). Applying above constraints, the following constant initial conditions were obtained.

Table 2: Initial conditions for engine experiments with controlled output conditions

Fuel vaporizer temperature (T_{vap}, °C)	220
Intake mixture temperature (T_{mix}, °C)	75
Compression ratio	13:1

Figure 11 shows the EGR fraction required to meet the operating conditions for all fuels and Figure 12 demonstrates the adjusted AFR to satisfy the required power level indicated in Figure 10. The number in each box corresponds to the mode in Figure 10.

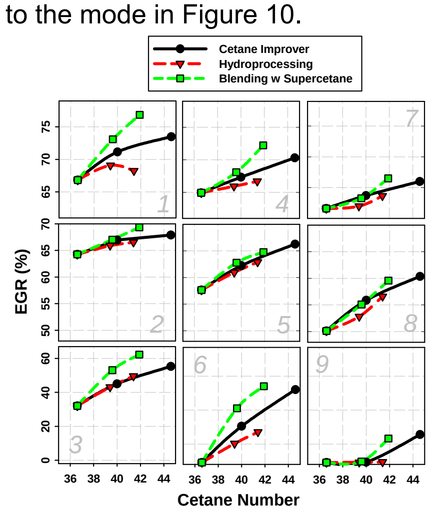

Figure 11 : Effect of CN and improving method on required level of EGR fraction.

Higher cetane fuels, in general, produce more advanced combustion timing that required higher EGR fractions to maintain the combustion timing at TDC. However, this EGR requirement was different based on the method that was used to increase CN. The trend shows that volatility became important in establishing EGR levels.

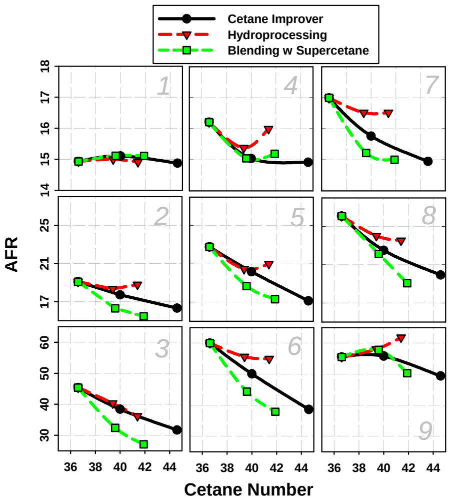

Figure 12: Adjusted AFR to satisfy engine output conditions while changing the cetane number.

Not all of conditions of output-driven experiments were met. As indicated in Figure 13, it was impossible to achieve the target IMEP of 6 bar for some cases. Among examined fuels, fuels blended with Supercetane™ renewable diesel (SCRD-CN39 and SCRD-CN42) exhibited the greatest IMEP shortfall followed by fuels blended with cetane improver (2EHN-CN40 and 2EHN-CN44).

Figure 14 illustrates the fuel conversion efficiency by showing ISFC data. Generally, the effect of speed on ISFC was related to the power. Each of the three methods used to increase CN affected the ISFC differently. Blending with Supercetane™ fuel deteriorated efficiency for most operating modes.

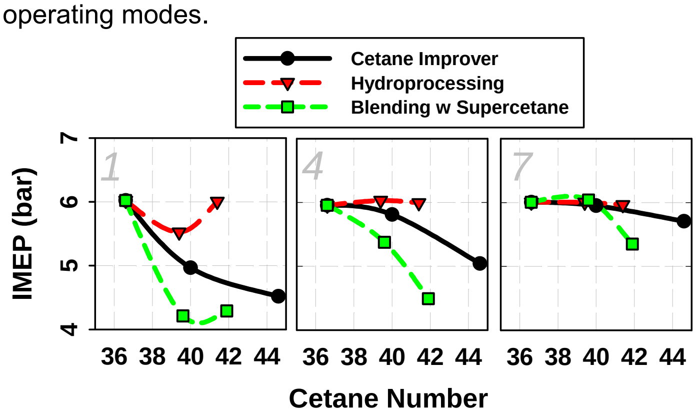

Figure 13: Maximum power achievable with each fuel at controlled engine outputs experiments modes 1, 4, 7.

ISFC variation depended on the operating mode for fuels blended with the cetane improver. However, hydroprocessing improved efficiency considerably for almost all modes. It is obvious that combustion efficiency is a function of the method that was used to increase CN. Note that the differences in efficiencies at each mode are caused solely by fuel chemistry as combustion timing was constant and all other initial conditions were identical.

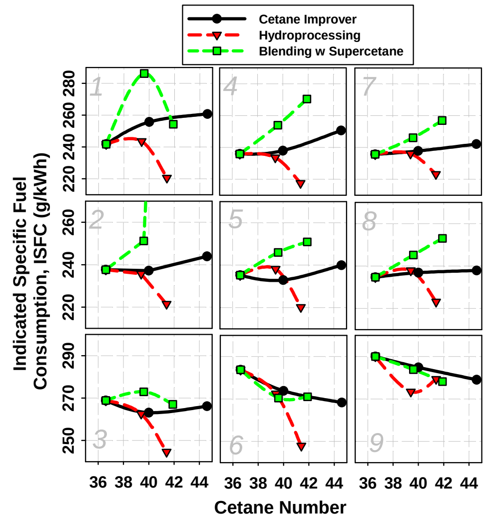

Figure 14: Indicated specific fuel consumption for controlled engine outputs experiments in Figure 10.

It seems that HCCI combustion efficiency is correlated with fuel volatility. The higher volatility of the hydroprocessed fuels improved ISFC while the unchanged volatility of fuels with cetane improver did not affect ISFC. The reduced volatility of fuels blended with Supercetane™ renewable diesel had high ISFC due to high HC emissions.

CONCLUSIONS

Increasing the fuel cetane number shifted the AFR-EGR operating window for HCCI combustion towards higher AFR (leaner mixtures) and reduced the cyclic variations.

Higher EGR rates were required to operate the higher cetane number fuels at lower AFR (richer mixtures). This led to a significant decrease in the maximum engine power produced for the higher cetane number fuels with a fixed boost pressure.

The hydroprocessed fuels had more stable and complete HCCI combustion than the base fuel, which resulted in reduced CO, HC, and NOx emissions and lower ISFC.

The addition of a nitrate cetane improver increased ISFC and led to substantially higher NOx emissions on a relative basis, but the absolute emissions were still very low. Blending a renewable diesel component increased the ISFC and HC emissions.

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