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A COMPARISON OF HCCI COMBUSTION THERMAL EFFICIENCIES BETWEEN TRANSPORTATION FUELS AND PRIMARY REFERENCE FUELS

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ABSTRACT - Homogeneous Charge Compression Ignition (HCCI) is an advanced combustion process that exhibits sensitivity to differing fuel properties. Often research conducted on HCCI uses research grade fuels to study combustion. The goal of this paper is to investigate the effects of partially refined and transportation fuels on HCCI combustion. Tested fuels include partially refined gasoline and Jet B. An experimental comparison of the fuels is conducted on a single cylinder test engine operating at a compression ratio of 12:1. Each fuel is tested in HCCI operation and compared to the same tests done with a primary reference fuel blend of comparable octane number. The resulting data is useful in characterizing the differences between the transportation grade fuels and the primary reference fuels.

INTRODUCTION

Homogeneous Charge Compression Ignition (HCCI) is a promising new combustion process which allows for an increase in partial load fuel efficiency compared to a Spark Ignition (SI) engine [1]. HCCI technology reduces Particulate Matter (PM) exhaust emissions substantially when compared to Compression Ignition (CI) engines because of the homogenous mixture of cylinder contents [2]. HCCI combustion also reduces Oxides of Nitrogen (NOx) emissions compared to both Compression Ignition (CI) engines, and SI engines due to low temperature combustion [2,3]. Unlike spark timing for a SI engine, or fuel injection timing for a CI engine, HCCI has no direct control over ignition timing [2]. Ignition timing is affected by many parameters including fuel properties [2].

Many studies of HCCI combustion use pure research grade fuels such as Primary Reference Fuels (PRFs) [4, 5, 6]. PRFs are the standard in determining a sample fuel's octane number (ON), and consist of volumetric blends of iso-Octane (100 ON) and n-Heptane (0 ON). Current refining methods do not produce PRFs in the quantity needed for the transportation industry. For this reasons it is important to understand the changes on HCCI combustion when PRFs are replaced with Transportation Type Fuels (TFF). This research examines the differences in combustion efficiency and exhaust emissions of two TTFs and compares them to PRFs.

TRANSPORTATION TYPE FUELS (TTF)

The two TTFs selected for this study are Jet B kerosene and synthetic naphtha. These fuels are selected for their relatively low octane numbers as compared to gasoline and also their high volatility. The naphtha fuel sample is an intermediate to the production of gasoline at Petro-Canada's refinery located in Edmonton, Alberta, Canada. The fuel is refined to a stage where the majority of sulfur has been removed from synthetic crude oil, but before octane increasing processes are undertaken.

Octane Number, although demonstrated to be a relatively effective method of describing a fuel's suitability for SI combustion, has been shown to be a poor indicator of HCCI combustion phasing [7]. For this reason, the sample fuels are not only compared against a PRF mixture of comparable octane, but also against a PRF mixture of comparable combustion phasing and Indicated Mean Effective Pressure (IMEP). The selection process of the later PRF blend ON is discussed in the next section.

To compare the fuels it is essential to characterize both the octane number and lower heating value. The properties of the sample fuels and of the PRF blends studied are found below in Table 1. The Motor Octane Numbers (MON) for the Jet B and Synthetic Naphtha are experimentally derived using a cooperative fuels research engine. The lower heating values are determined using an oxygen bomb calorimeter experiment [8] conducted in house. The fuels are divided into two groups. Group A consists of: Jet B; ON51, a PRF blend with comparable motor octane number to Jet B; and ON20, a PRF blend of similar IMEP and CA50 (timing at which 50% mass fraction of fuel burned). Group B consisted of the naphtha fuel sample and two PRF blends arrived at by the same means as Group A (ON57 and ON28 respectively).

Table 1: Fuel Properties

	Group A			Group B		
Fuel	Jet B	ON51	ON20	Synthetic Naphtha	ON57	ON28
Motor Octane Number	51.4	51	20	57.6	57	28
Lower Heating Value (MJ/kg)	43.2	44.8	44.9	43.7	44.8	44.8
Composition	Mixture of: -heavy naphtha -light naphtha -C5 and C6 hydrocarbons	51% Iso-Octane 49% n-Heptane	20% Iso-Octane 80% n-Heptane	>85% Complex mixture of aliphatic and aromatic hydrocarbons (C4-C12) <7% Toluene <6% Xylene (mixed isomers) <2% Benzene	57% Iso-Octane 43% n-Heptane	28% Iso-Octane 72% n-Heptane

EXPERIMENTAL SETUP

The experiment is conducted on a single cylinder gasoline HCCI test engine with parameters seen below in Table 2. The engine is equipped with camshaft phasing variable valve timing and the intake of the engine is outfitted with an externally driven supercharger and air heater. A detailed description of the engine can be found in [6]. The variables listed in Table 2 are held constant in order to study the effects of the fuel properties on HCCI combustion.

Table 2: Engine Parameters and Control Variables

Engine Parameter	Value	Control Variables	Value
Cylinder Bore (cm)	9.7	Intake Valve Open (CAD)	11° Before TDC
Cylinder Stroke (cm)	8.89	Intake Valve Close (CAD)	199° After TDC
Displacement Volume (L)	0.657	Engine Speed (RPM)	1000
Compression Ratio	12:1	Coolant Temperature (°C)	70

Experimental Procedure

To compare the combustion efficiency and exhaust emissions of the TTF of each of the two groups with an appropriate PRF blend the engine is run at steady state operating conditions. These engine operating conditions, listed below in Table 3, are used to encourage stable HCCI combustion over a broad range of fuel loads. The minimum fuel load is dictated by engine misfire (IMEP Coefficient of Variance >10%), and the maximum fuel load is determined by audible engine knock. The earlier exhaust valve event timing of the Group B conditions produce the larger amount of internal Exhaust Gas Recirculation (EGR) by increasing the negative valve overlap of the cycle.

Table 3: Engine Operating Conditions

Jet B (Group A):		Naphtha (Group B):	
Operating Condition	**Value**	**Operating Condition**	**Value**
Intake Air Temperature (°C)	60	Intake Air Temperature (°C)	76
Intake Air Pressure (kPa)	110	Intake Air Pressure (kPa)	112
Exhaust Valve Open (CAD)	118° ATDC	Exhaust Valve Open (CAD)	108° ATDC
Exhaust Valve Close (CAD)	32° BTDC	Exhaust Valve Close (CAD)	42° BTDC

The experimental fuel load sweeps at the above operating conditions are analyzed to determine the equivalence ratio at which the highest thermal efficiency is achieved. The thermal efficiency is calculated by Equation 1. The IMEP and CA50 timing is determined at the highest thermal efficiency test point for both of the sample fuels. This result is then used to determine what PRF blend would produce similar IMEP and CA50 to the sample fuel. Fuel load sweeps are then recorded for: (1) the PRF blend of similar MON to the sample fuel; and (2) for the PRF blend which demonstrated similar combustion characteristics in terms of IMEP and CA50.

Equation 1: Thermal Efficiency

$$\eta_{th} = \frac{IMEP \cdot V_d \cdot N}{2 \cdot \dot{m}_f \cdot Q_{HV}}$$

η_{th} = Indicated Thermal Efficiency
IMEP = Indicated Mean Effective Pressure (kPa)
V_d = Displacement Volume (m^3)
N = Engine Speed (Revolutions/s)
$\dot{m}_f$ = Fuel Mass Flow Rate (kg/s)
Q_{HV} = Fuel Lower Heating Value (kJ/kg)

RESULTS

Both the thermodynamic efficiency and the Heat Release Rate (HRR) for both Group A and Group B are described in this section.

Group A Results

The thermodynamic efficiency of each fuel as a function of engine power is plotted in Figure 1. Although the Jet B and ON51 have the same Motor Octane Number, it is evident that the two fuels behave very differently at the same operating conditions. To achieve combustion ON51 requires larger amounts of fuel be injected, and is more prone to audible knock which limits the operating range. ON20 achieved HCCI combustion over a similar load range as the Jet B, but consistently has higher thermodynamic efficiency.

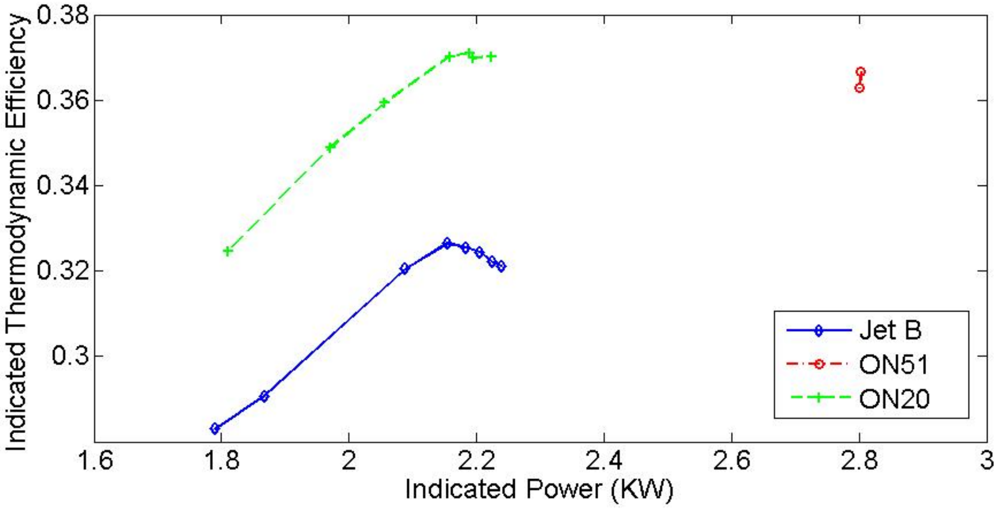

Figure 1: Indicated Thermodynamic Efficiency versus Indicated Power Output of Group A Fuels

To investigate the trends stated above, the in-cylinder pressure trace (recorded every 0.1 Crank Angle Degrees) of the most efficient point for each of the fuels is analyzed. The normalized Heat Release Rate is calculated [9] averaged for 30 consecutive engine cycles, and plotted in Figure 2. Two interesting phenomena are noted. First, the Low Temperature Reaction (LTR) for the Jet B sample and ON51 occur within 0.2 Crank

Angle Degrees (CAD) of each other. However this similarity in LTR timing does not produce a similar High Temperature Reaction (HTR) timing. Paraffinic fuels, such as PRFs, exhibit long ignition delay between LTR and HTR, known as the negative-temperature coefficient (NTC) region. This delay is induced by pressure increase in the cylinder
[10].

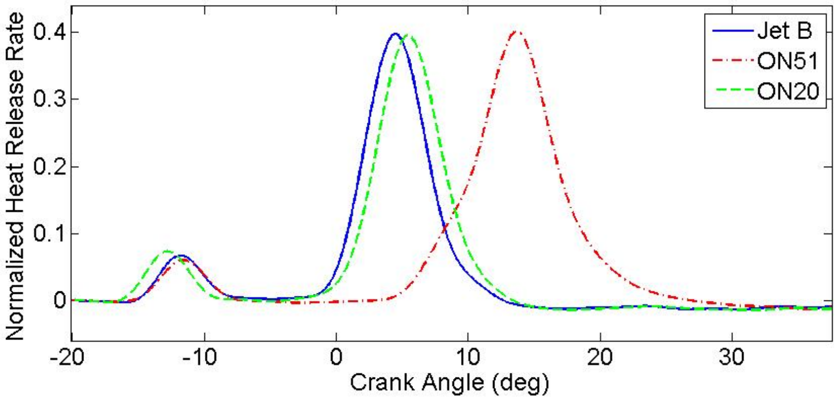

Figure 2: Normalized Heat Release Rate of Group A Fuels at Maximum Efficiency

Second, the CA50 of Jet B is shifted 1.0 CAD later in the engine cycle. The ON20 fuel produced a maximum thermodynamic efficiency of 37.1%, while Jet B produced a maximum thermodynamic efficiency of only 32.7% with a resulting difference of 4.4%. Jet B may have had reduced thermodynamic efficiency due to slightly early CA50 phasing.

To further understand the discrepancy in thermodynamic efficiency between Jet B and ON20, the exhaust emissions are plotted in Figure 3. At the most efficient point of combustion, the Jet B sample produced 3552 ppm Total Hydro-Carbons (THC), while the ON20 sample produced only 2720 ppm THC. The slightly higher amount of THC present in the exhaust of the Jet B combustion indicates higher incomplete combustion and is one possible contributor to the difference in peak thermodynamic efficiencies.

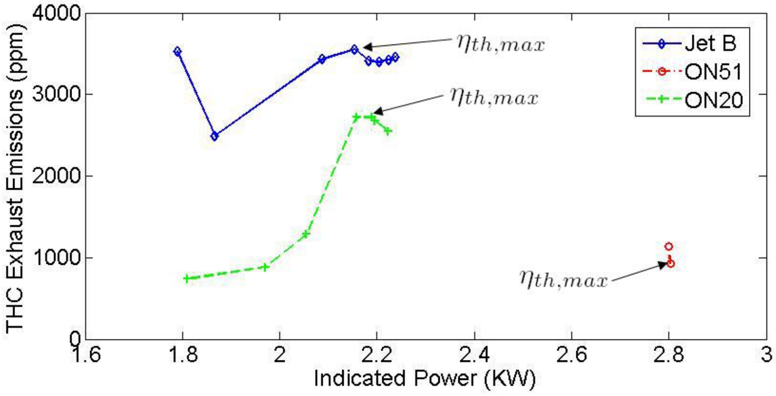

Figure 3: Total Hydro-Carbon Exhaust Emissions versus Indicated Power Output for Group A Fuels

Group B Results

Similarly, a plot of the thermodynamic efficiency was produced below in Figure 4 for the Synthetic Naphtha, ON57, and ON29 fuels. The maximum thermodynamic efficiency is 36.6% for ON57, and 34.2% for Jet B. These values are different by 2.4%, which is less then the difference for the Group A fuels (4.4%). To investigate the difference in thermodynamic efficiency, heat release rate analysis and exhaust emission analysis are performed and are displayed in Figure 5 and Figure 6 respectively.

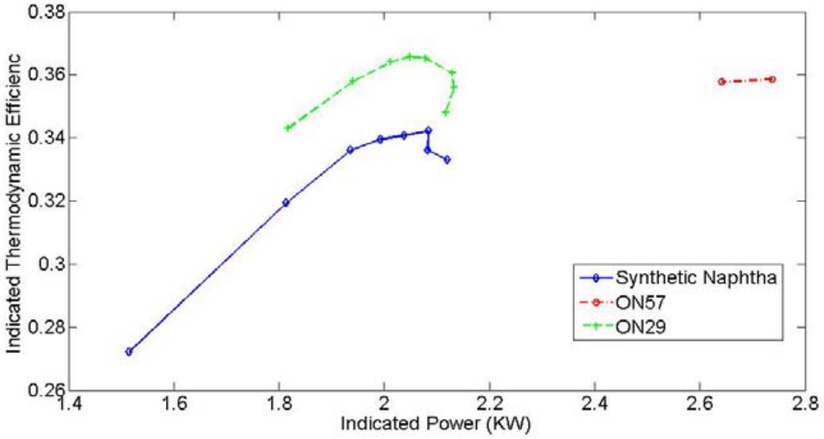

Figure 4: Indicated Thermodynamic Efficiency vs. Indicated Power Output of Group B Fuels

Figure 5 illustrates the same two relationships for Group B fuels as Figure 2 did for Group A fuels. The HTR of ON57 occurs at a much later timing then the HTR of Synthetic Naphtha and ON29. The HTR of ON29 and Synthetic Naphtha occur at close phasing with Synthetic Naphtha having a CA50 timing of 0.9 CAD earlier then ON29. This slightly earlier phasing could have contributed to the Naphtha's lower thermodynamic efficiency. The LTR phasing of the Synthetic Naphtha and ON57 are similar, with ON57's LTR occurring 0.8 CAD before that of Synthetic Naphtha.

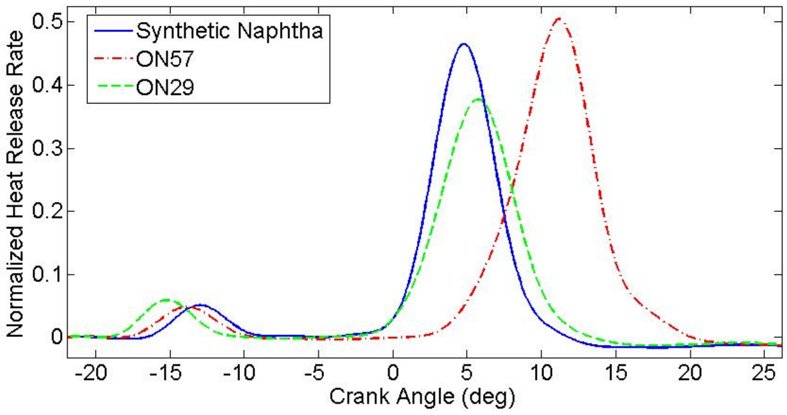

Figure 5: Normalized Heat Release Rate of Group B Fuels at Maximum Efficiency

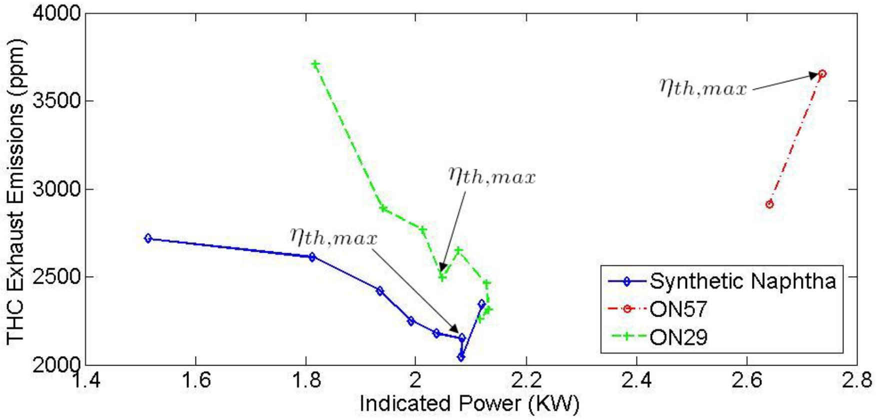

Figure 6: Total Hydro-Carbon Exhaust Emissions versus Indicated Power Output for Group B Fuels

Figure 6 shows the Synthetic Naphtha producing on average less THC exhaust emissions then the ON29 fuel, which is the opposite of what was noted in Figure 3, where Jet B produced consistently more THC emissions then ON20. At their respective highest thermodynamic efficiency points, the Synthetic Naphtha produced 2152ppm THC emissions and the ON29 mixture produced 2497ppm THC emissions. It is likely that the comparable THC emissions generated by the combustion of the Synthetic Naphtha and ON29 indicate a comparable level of incomplete combustion. This result shows that the difference in maximum thermodynamic efficiency is likely due to the slightly earlier combustion phasing of the Synthetic Naphtha compared to the ON29 fuel, which decreases indicated work.

CONCLUSION

The HCCI combustion characteristics of PRF mixtures are compared with Jet B and Synthetic Naphtha. In both cases the PRF blends exhibited higher maximum thermal efficiencies of approximately 4 and 2% respectively.

Since the fuels tested exhibit both a Low Temperature Reaction (LRT) and a High Temperature Reaction (HTR) it is important to distinguish between them when discussing ignition timing. The combustion phasing of the HTR of ON51 was retarded compared to that of Jet B, even though each fuel had a similar Motor Octane Number. The same phenomenon was true with the combustion phasing of the HTR of ON57 occurring later then that of Synthetic Naphtha. This indicates that when comparing Jet B and Synthetic Naphtha to PRFs with corresponding octane numbers, the octane number is a poor predictor of the HTR timing.

The phasing of the LTR was very similar for the Jet B and Synthetic Naphtha, and their respective Motor Octane Number matched PRF blends. Further investigation is required to understand whether Motor Octane Number is a good predictor of the LTR for HCCI combustion.

Jet B and partially refined gasoline fuels show promise for HCCI applications, achieving wide power output ranges under near ambient conditions with internal exhaust gas recirculation.

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