

Compositional Effects of Gasoline Fuels on Combustion, Performance and Emissions in Engine

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ABSTRACT

Commercial gasoline fuels are complex mixtures of numerous hydrocarbons. Their composition differs significantly owing to several factors, source of crude oil being one of them. Because of such inconsistency in composition, there are multiple gasoline fuel compositions with similar octane ratings. It is of interest to comparatively study such fuels with similar octane ratings and different composition, and thus dissimilar physical and chemical properties. Such an investigation is required to interpret differences in combustion behavior of gasoline fuels that show similar knock characteristics in a cooperative fuel research (CFR) engine, but may behave differently in direct injection spark ignition (DISI) engines or any other engine combustion modes. Two FACE (Fuels for Advanced Combustion Engines) gasolines, FACE F and FACE G with similar Research and Motor Octane Numbers but dissimilar physical properties were studied in a DISI engine under two sets of experimental conditions; the first set involved early fuel injection to allow sufficient time for fuel-air mixing hence permitting operation similar to homogenous DISI engines, while the second set consists of advance of spark timings to attain MBT (maximum brake torque) settings. These experimental conditions are repeated across different load points to observe the effect of increasing temperature and pressure on combustion and emission parameters. The differences in various engine-out parameters are discussed and interpreted in terms of physical and thermodynamic properties of the fuels.

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INTRODUCTION

With the evolving trend of engine downsizing and turbocharging to increase efficiency, internal combustion (IC) engine operation practices have advanced significantly from historically prescribed ASTM standards (D2699 [1], D2700 [2]). The evolution of engine technology oversaw extensive modifications in engine geometry and combustion processes. This development also led gasoline fuels to become increasingly complex in composition and properties to meet diverse performance requirements. Such elaborate compositions allow multiple degrees of freedom to achieve desired fuel properties. Consequently, many fuel formulations with diverse compositional details can maintain vital performance targets, such as Research Octane Number (RON) and Motor Octane Number (MON), within a narrow range as seen in FACE gasolines [3]. This variability in composition could lead to differences in fuel's physical and thermodynamic properties, which might have significant effects on various processes in an IC engine, hence a systematic investigation is necessary. Such a study must be conducted in a combustion mode where the fuel's physical properties exhibit evident effects on mixture

formation and combustion. A number of investigations indicate that DISI engine is more sensitive to fuel properties [4, 5, 6, 7]. Furthermore octane requirement studies of direct injection spark ignition (DISI) [8] engines indicate that fuels with high RON and high sensitivity ($S=RON-MON$) are more suited. FACE F and G gasolines [3] differ significantly in composition and have high RON and high sensitivities, thus making DISI mode suitable for this study.

DISI engines offer a flexibility over conventional port fuel injection (PFI) engines [9], enabling higher power to weight ratio by allowing higher compression of air before fuel injection, lean throttle-less operation at low loads [7] and advantages of charge cooling due to spray evaporation. The latter effect suppresses pre-combustion temperatures effectively mitigating thermal NO_x production during combustion. However, the available time for fuel to mix with air can be considerably less in DISI mode as compared to PFI operation, which leads to a greater dependence of combustion processes on fuel properties such as density, volatility, diffusion, and viscosity. [4, 10].

Differences in these factors often lead fuels with similar research and motor octane numbers to demonstrate distinguishable effects on combustion, emission and performance of a DISI engine [5, 11].

Several studies have investigated the effects of fuel composition on various aspects in a DISI engine. Davy et al. [7] conducted an experimental study to explore the effects of fuel composition on mixture formation in a DISI engine and concluded that mean droplet diameter and mixture formation are strong functions of fuel composition, and thereby affects combustion and emissions critically. Carlisle et al. [12] examined the effects of fuel composition and T_{90} on deposit formation on injectors. The role of aromatic contents was found to be significant in promoting injector deposits while the effects of olefins and T_{90} was inconsequential. Zigan et al. [13] experimentally investigated the effects of fuel properties and ambient conditions on spray breakup and evaporation. At higher temperatures, the droplet evaporation rate was governed primarily by composition. Also the heavier fractions in multicomponent fuels were found to increase the spray liquid lengths.

In the present investigation two FACE gasolines [3], FACE F and G with similar anti-knock index (AKI) and different physical and compositional aspects (Table 1) are studied in a single cylinder DISI research engine across a range of experimental conditions. Figure 1 represents the advanced distillation curve (ADC) measurement for FACE F and G, the advantages of ADC over conventional ASTM D-86 are:

- The temperature is measured in kettle which is a thermodynamic point and hence could be modelled using equation of states.
- The experiment doesn't allow volatile fraction to escape the distillation column and minimizes reflux by design.
- The distillate is sampled in level stabilized columns allowing precise measurement.

This study incorporates engine experiments, GT-power simulations and enhanced application of fuel properties to understand how compositional differences of FACE F and G affect various in-cylinder processes and emissions.

Table 1. Properties of gasoline FACE F and FACE G

Properties	FACE F	FACE G
RON	94.4	96.5
MON	88.8	85.4
AKI (RON+MON)/2	91.6	91
S (RON-MON)	5.6	11.1
H/C ratio	2.1	1.83
Density @ 288 K (Kg/m ³)	707	733
LHV(KJ/Kg)	44361	43268
N-paraffins (mol %)	4.9	7.8
Iso-paraffins (mol %)	61	38.2
Cyclo paraffins (mol %)	15.4	14
Aromatics (mol %)	8.8	31.7
Olefins (mol %)	9.7	8
Stoichiometry	14.67	15.10

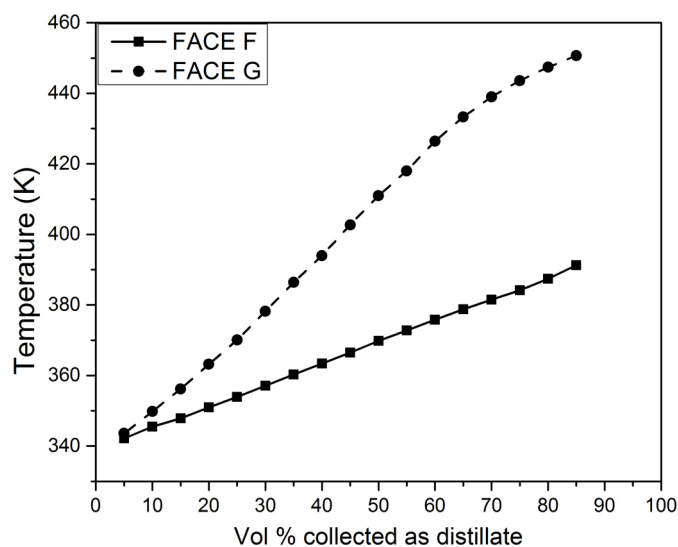


Figure 1. Advanced distillation curve profile for FACE F and FACE G from Burger et al.[14]

2. EXPERIMENT

2.1. Experimental Setup

Engine experiments were conducted in a single cylinder DISI engine (AVL 5405) at 1500 RPM and at different load conditions, i.e., 40, 60, 80 and 100 %. The exhaust gasses were analyzed for concentration of regulated emissions of CO, HC, CO₂ and NO_x with an exhaust gas analyzer (AVL AMA i60) and smoke meter (AVL 415s) to obtain filter smoke number (FSN). Fuel was injected with a centrally mounted piezoelectric gasoline direct injection (GDI) injector at a pressure of 135 bar. The engine pressure traces were acquired with a resolution of 1 CAD and averaged for 330 cycles.

Details of the engine and fuel injection system are provided in Table 2. The engine was operated at two sets of operating conditions; the first set was carried out with early fuel injection timings with spark at TDC (Table 3), while the second set involved early fuel injection with advanced spark timings (Table 4). The first set was intended to simulate homogenous DISI conditions across different loads, however owing to the differences in density and volatility of fuels, the degree of premixing at spark was different. In the second set, spark timing was advanced to attain maximum brake torque (MBT). Along with other factors, MBT depends on fuel burn rates, which is different for both the fuels, and results in difference in cylinder conditions. Throughout the experiments, the engine was operated at $\lambda = 1$. The coolant and oil temperature was maintained at 80 ± 2 °C and intake air was conditioned to maintain 1bar, 25 °C and 6 g/Kg of humidity during the experiments.

Table 2. Engine and fuel injection system specifications

Engine Type	Single cylinder NA engine operated in DISI mode
Cylinder bore	82.00 mm
Stroke	86.00 mm
Swept volume	454.00 cm ³
Injection Pressure	135 Bar
Compression ratio	11.5
Lambda (λ)	1
Engine RPM	1500
Fuel injector	GDI
Fuel injection pressure	135 bar
Coolant temperature	80° C
Lubricant temperature	80° C
IVO: -360 °CA	IVC: -140 °CA
EVO: 140 °CA	EVC: 360 °CA

Table 3. Experimental details of first set of experiments at various load conditions

		FACE F			FACE G		
RPM	Load %	IMEP	Injection Time	Ignition Time	Injection Time	Ignition Time	IMEP
1500	40	8.6	-300	0	-300	0	8.5
1500	60	9	-300	0	-300	0	8.9
1500	80	9.1	-300	0	-300	0	9
1500	100	9.1	-300	0	-300	0	9

Table 4. Experimental details of second set of experiments at various load conditions

		FACE F			FACE G		
RPM	Load %	IMEP	Injection Time	Ignition Time	Injection Time	Ignition Time	IMEP
1500	40	9.8	-300	-16	-300	-12	9.7
1500	60	10.2	-300	-12	-300	-10	10
1500	80	10.3	-300	-12	-300	-10	10.2
1500	100	10.3	-300	-12	-300	-10	10.2

The compositions of FACE F and G gasolines [15] were obtained with detailed hydrocarbon analysis (DHA) in compliance with ASTM standards D6733 and D6730 [16]. Detailed thermodynamic data were also compiled for all the species of FACE F and G to generate NASA [17] polynomials to predict thermodynamic properties of these fuels.

3. ENGINE MODELLING WITH GT-POWER

An engine model (AVL 5405) was created using GT power software, version 7.5.0 build 4 [18]. A closed cycle method (from IVC to EVO) was employed with precise details of engine operation and geometry as mentioned in Table 2. GT power engine simulations were performed using the reverse-run methodology to retrace experimental pressure data with a modeled pressure trace. The reverse run method employs a two-zone model for analysis of the combustion chamber, i.e., burnt and unburned zone, the burnt zone consumes fuel from the unburned zone depending on the burn rate. The burn rate calculations are performed at each time step, as a charge transfer rate from unburned to burnt zone, eventually defining several parameters including heat release rate, combustion phasing and predicted pressure profile. During the simulation, it was assumed that initially all the constituents in the cylinder are in the unburned zone including the residual gases from the previous cycle and EGR (none in this case). The two zones are separated by infinitely thin flame front and no heat exchange is allowed between the two zones. The cylinder pressure is considered spatially uniform during the calculations and all the gasses behave as ideal.

During the course of simulations, the engine model requires various input parameters including experimental pressure profile, emission concentrations, injected fuel quantity and a convective heat transfer coefficient between the in-cylinder media and the walls. Here, heat loss is modelled as forced convection with the heat transfer model proposed by Woshini [19]. These parameters are utilized within the model to predict a pressure trace, which is eventually matched with experimental pressure data by adjusting the convective heat transfer coefficient. The convective heat transfer coefficient (h) is assigned a discretized range of values using the design of experiments (DOE) tool during the simulation. The DOE functionality allows discretized variation of h within this pre-defined range and the value of h enabling closest match of experimental and modeled pressure data is taken as an optimum value for the respective set of experiments. The engine model can then be utilized to predict several in-cylinder crank resolved parameters by means of a tuned modeled pressure profile. This exercise was repeated for both set of experiments to capture actual heat loss characteristics of the engine at its respective experimental state. Furthermore, in cases where MBT conditions were attained by spark advance, mild knock was observed experimentally and hence a knock analysis (*KnockAnalysis*) object was added to the GT power engine model to account for knock in the end gas zone by detecting and characterizing pressure oscillations.

Since this study emphasizes the effect of physical properties on engine combustion, it is imperative to use surrogate fuels which accurately represent physical, thermodynamic and chemical kinetic properties of FACE F and G. A recent study by Sarathy et al. [15] investigated ignition chemistry of FACE F and G, together with multi-component surrogate fuels for each fuel and detailed chemical kinetic modeling simulations. The multi-component surrogates matched multiple physical properties and satisfactorily predict ignition delay over wide ranges of pressure, temperature and equivalence ratio regimes. In this study, the multi-component LLNL surrogates have been utilized for engine modeling and simulation.