

The Effect of Charge Cooling on the RON of Ethanol/Gasoline Blends

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ABSTRACT

This paper examines the effect of charge cooling on the Research Octane Number (RON) of ethanol/gasoline blends. While gasoline is fully vaporized prior to entry into the engine in a standard RON test, significant charge cooling is observed for blends with high ethanol content, with the presence of a near-saturated and potentially two-phase air-fuel mixture during induction. Thus, the relative significance of the charge cooling and the autoignition chemistry cannot be determined from the standard RON test.

In order to better delineate the effects of charge cooling and autoignition chemistry, a so-called 'modified RON' test is therefore devised in which the temperature of the air-fuel mixture entering the engine is fixed and representative of that observed for primary reference fuels (PRFs). Thermodynamic modeling of this modified RON test suggests the mixture is always fully vaporized prior to compression, and that the modified RON test maintains much more constant temperatures during compression, regardless of the enthalpy of vaporization. The modified RON test thus appears to be a more practical means of examining the significance of autoignition chemistry of various fuels, particularly gasoline blends with significant alcohol content.

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INTRODUCTION

Ethanol use in transportation has grown significantly in recent years. From 2007 to 2008, estimates show that the percentage of ethanol blended with gasoline globally increased from 3.8% to 5.5% [1]. In the United States, the 2007 Renewable Fuel Standard further requires that the use of biofuels be increased to a total of 36 billion gallons per year by 2022. Ethanol is expected to supply the majority of this mandated fuel volume, and could displace approximately 20% of gasoline demand in the United States by then [2]. Likewise, the European Union has also set a target of 10% of transport fuel to be from renewable sources by 2020 [1]. The reasons for this growth are several, and include environmental, economic and social considerations.

It is already well known that, relative to gasoline, ethanol can raise spark ignition engine efficiency whilst reducing specific emissions. Numerous studies have reported that engines fueled with ethanol had significantly lower carbon monoxide and unburned hydrocarbon emissions, e.g. [3, 4]. Moreover, ethanol does not demonstrate the low-temperature

reactivity of analogous alkanes due to differing autoignition chemistry [5, 6], in addition to a high burning velocity [7], and the enthalpy of vaporization of ethanol is significantly higher than that of conventional gasoline [8], providing additional charge cooling. These effects combine to achieve a high Research Octane Number (RON) and Motor Octane Number (MON) for ethanol, enabling higher compression ratios and providing an explanation for how ethanol increases engine efficiency (e.g. [9, 10, 11]).

Defined in the ASTM standards D2699 and D2700, the RON and MON test methods quantify the propensity of a fuel to knock in a standardized single-cylinder spark-ignition CFR engine [12, 13]. One of the key differences between these two test methods is the charge temperature. In the MON method, the intake air temperature (IAT), which is monitored upstream of the carburetor, is specified to be 38 °C, and the air-fuel mixture temperature entering the engine to be 149 °C [13]. The RON method, however, specifies only the IAT to be 52 °C, leaving the air-fuel mixture temperature entering the engine to vary, particularly due to fuel vaporization [12].

Questions have been raised as to whether the RON and MON methods are appropriate for rating fuel blends with high ethanol content. Originally developed for rating gasoline, use of the standard CFR engine may be problematic for fuels with drastically different physical properties [14, 15]. The two major hardware limitations are the fuel metering jet and the air-fuel mixture heater. The stock fuel metering jet, while providing a sufficient fuel flow rate of gasoline or primary reference fuels (PRFs), may limit the fuel supply when rating ethanol due to its low stoichiometric air-fuel ratio [16]. Hence, careful selection of an appropriate fuel metering jet is required in order to deliver a sufficient fuel flow rate. As a result, the ASTM D2699 and D2700 standards recommend that both test methods may not be applicable to fuels with high oxygenate concentration, although no information about the upper limit of the oxygenate concentration that may be used is provided [12, 13].

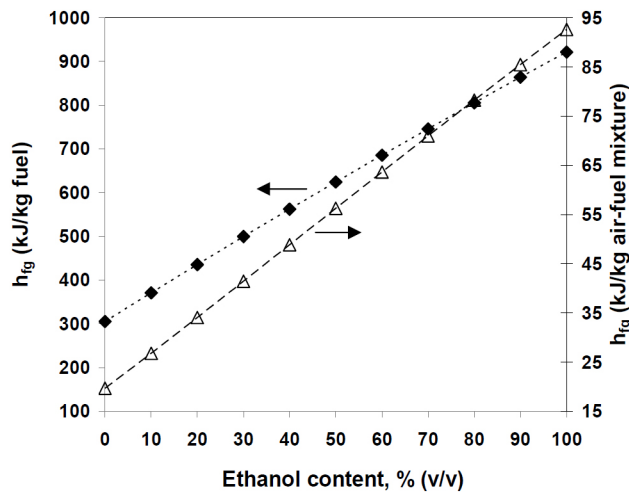


Figure 1. Estimated enthalpy of vaporization, h_{fg} , for ethanol/gasoline blends at 25 °C and 1 atm, where h_{fg} is defined both per kg of fuel and per kg of air-fuel mixture assuming stoichiometric mixtures. The gasoline data was obtained from [19].

Compounding this uncertainty is that the charge cooling effect of ethanol/gasoline blends varies significantly with ethanol content. The enthalpy of vaporization, h_{fg} , of ethanol (per unit fuel mass) is approximately three times that of gasoline at 25 °C and 1 atm. Figure 1 then shows a representative variation of h_{fg} of gasoline/ethanol mixtures when an ideal mixture is assumed. Whilst there is evidence that vaporization of gasoline/ethanol blends may not be closely approximated assuming an ideal mixture [8, 18], the value of h_{fg} for a given gasoline/ethanol mixture depends on the specific composition of the gasoline in question, which can of course vary significantly. Nonetheless, as Figure 1 shows, it is always the case that increasing ethanol content results in a reduced air-fuel ratio which infers a larger relative change in the charge cooling per unit mass of air-fuel mixture.

The knock limits on spark ignition engine operation for different ethanol/gasoline blends are therefore not clear. Indeed, as this paper discusses, the standard RON test itself is sensitive to the fuel's charge cooling and not just its autoignition chemistry.

The specific aims of this paper are therefore two-fold. First, this study will report the charge cooling effects of ethanol/gasoline blends on their RON measurement. It will then propose a modification to the standard RON test, such that the relative significance of the charge cooling and the autoignition chemistry of these blends on the RON measurement can be determined.

EXPERIMENTAL METHODS - RON

CFR Engine and the Test Method

The RON values of ethanol/gasoline blends were measured on a standard Waukesha CFR engine. Standard knock rating instruments, including the detonation meter and the knock meter, were used in this study. An air dehumidifier was installed upstream of the carburetor to control the humidity of the intake air. Critical engine parameters were monitored and maintained within the accepted limits as defined in [12] and [13] during the tests. Table 1 lists the RON test conditions.

Table 1. The RON test conditions [12].

Displaced volume	619 cc
Number of cylinder	1
Stroke	114.3 mm
Bore	83.1 mm
Compression ratio	4 - 18
Engine speed	600 rpm
Inlet Valve Closing	146° bTDC
Exhaust Valve Opening	140° aTDC
Spark timing	13° bTDC
Intake air temperature (IAT)	52 °C

The standard RONs in this study were determined using the Equilibrium Fuel Level Bracketing procedure. This method involves linear interpolation of the knock intensity of two PRFs of known octane number which 'bracket' the sample fuel. During the rating of a fuel, the air-fuel ratio was adjusted such that maximum knock intensity could be attained, as measured by the knock meter.

Fuel Metering Jet

Measurements showed that while the required air-fuel ratio for maximum knock intensity varies from fuel to fuel, overall it was slightly rich in all cases. When rating ethanol, which has a lower stoichiometric air-fuel ratio of roughly 9:1, the stock fuel metering jet fails to provide an adequate fuel flow rate. In order to handle the increased fuel flow, the original jet in the carburetor was replaced by an adjustable

orifice jet, following the recommendations detailed in the standards [12, 13, 17].

Mixture Temperature Monitoring

Figure 2 shows a schematic diagram of the intake system of the CFR engine configured for a RON test. In the standard RON rating, the IAT is set depending on the barometric pressure at the time of rating; at sea level, the IAT is required to be at 52 ± 2 °C. In order to investigate the charge cooling effects of ethanol/gasoline blends in the RON test, the temperature of the air-fuel mixture entering the engine was measured by a T-type thermocouple with an accuracy of ± 1 °C. The thermocouple was installed at the intake port (approximately 6 cm upstream of the intake valve) with the junction in the middle of the gas path. This temperature will be referred to as the ‘mixture temperature’ in this study. It is noted that whilst placement of this thermocouple in the intake port violates the standard RON test method, the ‘fit-for-use’ tests in the RON test standard [12] indicated that the engine still rated within specification.

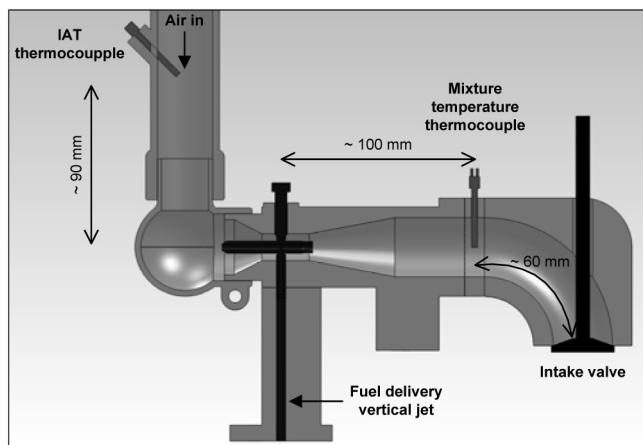


Figure 2. Schematic of the intake system (cross section) of the CFR engine in the RON configuration.

The ‘Modified RON’ Test Method

Since only the IAT upstream of the carburetor is regulated in the standard RON test, variation in the mixture temperature may exist due to different enthalpies of vaporization. In an attempt to minimize the additional charge cooling provided with increasing ethanol content, a modification was made to the standard test by fixing the mixture temperature for all rating. The modified RON tests were then performed with the following procedure.

1. Calibrate the detonation meter system with a reference fuel having a RON close to that of the sample fuel.
2. Run the engine with the sample fuel, with the IAT adjusted such that the mixture temperature is 36 °C. This is the average mixture temperature for the PRF-only cases.
3. Adjust the air-fuel ratio and compression ratio to attain a knock meter reading of 50 ± 2 , at which the standard knock intensity occurs.

4. The modified RON is obtained from the compression ratio at which this occurs, by referring to Table A4.3 in [12]. This table relates the dial indicator reading (compression ratio) to the RON at the standard knock intensity.

5. If the RON of the sample fuel is more than ± 1.5 octane numbers different from that of the calibration fuel (step 1), a new calibration fuel with a closer RON to that of the sample fuel has to be chosen, and steps 2 - 4 have to be repeated.

The modified tests were performed without the bracketing fuels, due to the long running times (up to 30 minutes for a single run) required to obtain an IAT up to 165 °C when rating ethanol/gasoline blends, and then to subsequently cool the IAT down to 52 °C again for rating the bracketing fuels. While the omission of the bracketing procedure may reduce the precision of the RON measurements, it is the authors' experience that a deviation of no more than ± 0.5 octane numbers is normally expected compared to that obtained using bracketing fuels.

Fuels

Regular non-oxygenated unleaded gasoline was obtained from a service station in Melbourne, Australia. Ethanol, iso-octane and *n*-heptane used in the experiments were analytical grade and at least 99% pure.

RESULTS AND DISCUSSION

Mixture Temperatures and Dew Points

Several studies have shown that ethanol can significantly cool the air-fuel charge as it evaporates, e.g. [8, 20]. The two factors that contribute to this charge cooling of ethanol are the enthalpy of vaporization and the fuel stoichiometry (Figure 1). While the stoichiometric air-fuel ratio by mass of gasoline is approximately 15:1, that of neat ethanol is approximately 9:1. Taking into account both the higher enthalpy of vaporization and greater fuel mass required to reach stoichiometry, Figure 1 shows an approximately five-fold increase in the evaporative cooling of the air in a stoichiometric mixture when the fuel is switched from gasoline to neat ethanol.

Given this large variation in the charge cooling of the fuel, it is reasonable to expect that the temperature of the air-fuel mixture entering the engine should vary. Figure 3 shows that this is indeed the case for the standard RON test, even though the air temperature upstream of the carburetor (the IAT defined previously) was controlled to be 52 ± 2 °C for all tests. Of note is that these measured mixture temperatures do not vary monotonically with increasing ethanol content, in contrast with the enthalpies of vaporization shown in Figure 1. In the case of gasoline, the mixture temperature is approximately 38 °C. As ethanol is added to gasoline, the mixture temperature drops, with the lowest mixture temperature being approximately 20 °C for blends containing 40% (v/v) ethanol. Further addition of ethanol beyond 40% (v/v) increases the mixture temperature, eventually reaching