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Understanding fuel anti-knock performances in modern SI engines using fundamental HCCI experiments

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Abstract

Modern engine technologies have considerably changed the in-cylinder conditions under which fuel autoignition and engine knock take place. In this paper, fundamental HCCI engine experiments are proposed to characterize the impacts of using these technologies on the knock propensity of different fuels. In particular, the impacts of turbocharging, direct injection, and downspeeding on ethanol and gasoline are investigated. Results earlier reported for the potential of ethanol and gasoline as HCCI fuels are revisited with the new perspective on how their autoignition characteristics fit into the knock reduction requirement in modern SI engines. It is found that ethanol’s weak autoignition sensitivity to pressure boost makes turbocharging barely increase its knock propensity. On the other hand, ethanol’s strong sensitivity to charge temperature makes the charge cooling produced by fuel vaporization (from direct injection) and expansion due to piston motion (for retarded combustion) very effective to inhibit autoignition. However, gasoline’s strong pressure sensitivity allows only marginal pressure boost before knock occurs, and its weak temperature sensitivity is unable to make effective use of the charging cooling available. These arguments comprehensively explain literature results which demonstrate ethanol’s remarkable improvements over gasoline in knock-limited SI engine combustion. These fundamental HCCI experiments can thus be used to diagnose and predict the knock-limited SI engine performance for various fuels. Examples are presented using this method as a screening tool to identify proper biofuels compounds for modern SI engines application.

Keywords: Knock propensity, HCCI, turbocharging, DISI, ethanol

Introduction

The increasing use of biofuels, e.g. ethanol, and gaseous fuels, e.g. natural gas, is considerably changing the fuel composition for spark ignition (SI) engines. Understanding the knock limit of these fuels is essential for engine design and operation. The in-cylinder conditions under which knock occurs have also changed significantly with the adoption of modern engine technologies, e.g. turbocharging, direct injection (DI). These changes substantially affect fuel knock propensity, because the autoignition of the end gas, generally accepted as the mechanism causing engine knock, is controlled by chemical-kinetics and thus depends on the in-cylinder thermodynamic conditions.

Octane number (ON) has been conventionally used to provide quantitative measurement for fuel knock propensity. However, the standard octane test conditions in a CFR engine, e.g. naturally aspirated, carburettor fuelling, etc. are considerably different from that in modern SI engines. As indicated by Kalghatgi, modern SI engines often operate at conditions outside those used to determine the research and motor octane numbers (RON and MON) [1, 2]. The K-factor in the Octane Index, OI = RON – K(RON-MON), which by definition is 0 for RON test conditions and 1 for MON conditions, is often negative in turbocharged DISI engines, and it varies significantly with operating conditions [1-3]. The ONs therefore are limited in their ability to predict fuel anti-knock performance in SI engines, although they are still good for indicative purposes.

Using advanced SI engine technologies generally results in higher pressure, lower temperature conditions inside the cylinder, and more time for autoignition to occur. Although general trends exist, different fuels have shown significantly different responses. For example, ethanol demonstrates superior anti-knock performance to gasoline across a wide range of SI engine conditions [4], but the improvements of ethanol are considerably larger for turbocharged and direct-injection conditions than at non-boosted and port fuel-injection conditions. Such differences have been attributed partly to the larger vaporization cooling effect that ethanol produces from DI fuelling, but more importantly, to the higher knock resistance of ethanol's autoignition chemistry [4, 5]. However, the literature lacks a consistent, detailed understanding as to why the chemistry of one fuel performs better than that of another under these modern in-cylinder conditions, particularly the *in-situ* conditions where autoignition reactions leading to knock occur.

The objective of this paper is to propose fundamental HCCI engine experiments as a tool to study fuel anti-knock properties in modern SI engines. In particular, the impact on the anti-knock properties of different fuels by using three SI engine technologies, turbocharging, direct injection, and downspeeding, are investigated. The HCCI experiments for ethanol and gasoline reported in our previous works are revisited and used to explain the remarkable anti-knock performance of ethanol reported in the literature, which confirms the validity and utility of the proposed method.

Experiment

HCCI experiment for understanding SI knock

The concept of using HCCI engine combustion to understand SI engine knock is for the first time proposed to the authors' knowledge. SI engine knock is generally considered resulting from compression of the end-gas by the propagating flame (and to a lesser extent, by the piston motion); this compression accelerates the autoignition kinetics in the unburned gas, driving the mixture into hot ignition. The process undergone by the end gas can be approximated by a piston compressing a homogeneous fuel/air mixture to hot ignition, i.e. an HCCI combustion. Compared to the standard CFR engine tests, this method allows the engine to operate at similar conditions to those in modern SI engines by independently controlling the temperature, pressure, fuel preparation, engine speed etc. Compared to the knock-limited SI engine experiments [4], this method removes the complexity of turbulent flame propagation and avoids engine-damaging knock, while preserving the reciprocating nature and timescales of engine combustion. Indeed, HCCI combustion process can be considered as being similar to rapid compression machine experiments running in a continuous manner under realistic boundary conditions for engines. In addition, unlike the K-factor in the Octane Index model, results from the autoignition experiments using homogeneous mixtures are less dependent on the engine geometry than those using SI engines, and thus provide a better general understanding of the problem.

The major difference for autoignition in an HCCI engine compared to an SI engine is that the former occurs in considerably diluted mixtures (with air or EGR). To compensate for the lower equivalence ratio or more dilute mixtures, the autoignition in an HCCI engine can require somewhat higher temperatures, higher pressures, or lower engine speeds to achieve autoignition. However, this difference is less a concern because as will be seen, the operating parameters including temperature, pressure, and engine speed can be swept over a wide range of conditions, which would cover the targeted SI engine conditions for most cases (except for the equivalence ratio). More importantly, it is the change of these parameters, rather than their absolute value, that is of primary interest here. The magnitude of these changes characterizes the sensitivity of fuel autoignition (knock propensity) to the variation of these parameters. Therefore, the conditions for the end gas autoignition should be reproduced by the HCCI engine experiments, provided the operation parameters being swept over a proper range.

Engine setup

The engine used for these HCCI experiments was derived from a Cummins B-series diesel engine that has been converted for single-cylinder HCCI operation. The displacement is 0.98 L/cylinder. The active HCCI cylinder is fitted with a custom piston with an open combustion chamber that gives a compression ratio (CR) of 14:1. Air is supplied by a compressor and metered with sonic nozzles to produce the desired intake pressures (P_{in}). Electrical heaters are used to maintain the desired intake temperature (T_{in}). A fully premixed charge is used for all cases via a fuel vaporizer and mixing system upstream of the intake plenum. The engine speed is 1200 rpm for all cases except for the study of the effects of downspeeding. A more complete discussion of the engine, fuelling system, combustion-chamber geometry, experimental setup, data acquisition, and method for heat release calculations can be found in [6].

Test conditions

The HCCI experiments are designed to separately understand the impact of turbocharging, direct injection, and downspeeding on the knock propensity of neat ethanol and a reference gasoline. To simulate the impacts of these technologies, sweeps of three parameters are conducted using fully premixed charge:

1. intake pressure to study the effect of turbocharging;
2. intake temperature to study the charge cooling effects of DI fuelling;
3. engine speed to study the effect of downspeeding.

Two methods are used to indicate the knock propensity. First, while one parameter is swept, the other parameters are kept constant so that the relation between the variation of the sweeping parameter and the knock propensity, indicated by the autoignition timing, can be determined. More advanced autoignition timing indicates higher knock propensity. Second, the autoignition timing is kept constant, and another parameter is adjusted to compensate for the change in autoignition caused by the swept parameter. In this case, the knock propensity is indicated by the adjustment required for the second parameter to maintain the prescribed autoignition timing. For example, during the P_{in} sweep with a constant autoignition timing, a lower required T_{in} indicates an higher knock propensity. Operating conditions for each sweep are reported along the results below.

Most data reported here have been published in our previous papers [6-8]. These studies primarily focussed on the potential use of these fuels for HCCI engines and did not discuss their anti-knock properties in SI engines which is the topic of the present work.

Results and Discussion

Impact of turbocharging (intake pressure sweep)

Turbocharging increases the intake pressure and consequently the pressure and temperature after compression and in the end-gas, which generally enhances the propensity of the fuel to autoignite. However, it is known that different fuels respond to pressure variations in different manners [9]. Figure 1 shows the variation of the BDC temperature (T_{BDC}) with P_{in} for ethanol and gasoline while the autoignition timing, indicated by the 10% burn point (CA10), is held constant. T_{BDC} is essentially a corrected intake temperature [10].

It can be seen that for both ethanol and gasoline, increasing P_{in} reduces the T_{BDC} requirement, indicating that autoignition is enhanced, i.e. higher knock propensity. However, for a given increase in P_{in}, e.g. from 1.0 to 1.6 bar, the temperature reduction with ethanol (~ 20°C) is much smaller than that of gasoline (~35°C). This difference indicates that the knock propensity is much less enhanced for ethanol than for gasoline. For SI engine applications, this result suggests that ethanol will be much more knock resistant than gasoline when turbocharging is used, so its advantage over gasoline becomes greater as boost pressure increases.

Fig. 1

To better understand the reason for these differences in pressure effects for ethanol and gasoline, heat release rates prior to the hot ignition are analysed, as shown in Fig. 2. The data are from the same sweeps as in Fig. 1. These pre-ignition heat release rates, highly zoomed in from the normal heat release rates, are indicative of the fuel autoignition reactivity. Note that these heat release rates are normalized by the total heat release to remove the differences in the input fuel energy at various pressures (since ϕ is kept constant).

Ethanol remains essentially constant for the normalized pre-ignition heat release rates over P_{in} = 100-180 kPa, suggesting that the pressure does not enhance the actual autoignition reaction rates for ethanol: the T_{BDC} reduction in Fig. 1 is thus likely just due to more fuel inside the cylinder at higher boost. However, the pre-ignition heat release rates of gasoline are significantly promoted by pressure, indicating that its autoignition kinetics is accelerated by pressure boost. With the additional pressure-enhanced heat releases, gasoline requires lower temperatures to autoignite, as observed in Fig. 1. These heat release variations with P_{in} explain the P_{in} vs. T_{BDC} trends in Fig. 1 and support the argument that turbocharging enhances the knock propensity of gasoline to a much greater extent than ethanol.

Fig. 2

Impact of direct injection (intake temperature sweep)

The impact of direct injection on knock is generally realized by using early DI fuelling (during the intake stroke), so that vaporization of the DI fuel cools the charge reducing the overall in-cylinder temperature, and thus inhibiting knock. Vaporization cooling also occurs for late DI fuelling, just before the spark timing; however, in this case knock is generally not a concern due to the highly stratified charge.

Ethanol is known to have a considerably larger charge cooling capacity than conventional hydrocarbon-based fuels, due to ethanol's higher heat of vaporization and higher fuel percentage for a given equivalence ratio. This offers great potential for knock reduction with ethanol. However, an important factor often ignored is the fuel autoignition sensitivity to the charge cooling. This is because the autoignition kinetics of different fuels can have different dependences on the charge temperature (as will be shown below); therefore, strong charge cooling will strongly inhibit knock only if the fuel autoignition is sufficiently sensitive to the temperature reduction.

The temperature effect on the knock propensity is shown in Fig. 3, where the dependence of CA10 on T_{in} is shown for naturally aspirated condition (P_{in} = 1.0 bar). Note that for these HCCI data, the fuel is evaporated in the fuel vaporizer and then fully mixed with air before entering the engine. The fuel vaporization cooling is thus absent inside the cylinder, and the impact of temperature on knock propensity can be isolated. Reducing intake temperature slows the autoignition kinetics, thus more time is required to reach the hot ignition, resulting in a later CA10. The slope of these curves indicates the sensitivity of the fuel autoignition to temperature change. Comparing the two fuels, ethanol shows stronger temperature sensitivity, since for a given T_{in} reduction, ethanol's CA10 is retarded more than that of gasoline. This suggests that for the same amount of charge cooling, the autoignition rate will be slowed more for ethanol, i.e., knock will be less likely to occur with ethanol. Thus, not only does ethanol give more vaporization cooling with DI fuelling, but the cooling has a greater effect on autoigntion rates. This combination results in a much greater reduction in the knock propensity than for DI fuelling with gasoline. In short, there is more cooling and the cooling is more effective with ethanol.

Fig. 3

In addition to intensifying the anti-knock effect of charge cooling from DI fuel vaporization, the strong temperature sensitivity of ethanol also enhances the benefit of retarding the spark timing to control knock because the effect of the charge cooling due to piston expansion is greater. This latter effect is particularly important because spark-timing retard is the primary means for knock control in SI engines.

Impact of turbocharging + direct injection

The temperature sensitivity analysis discussed in above is for naturally aspirated conditions (P_{in} = 1.0 bar). When turbocharging is used, the temperature sensitivity can change, and thus the DI effect on knock propensity could be different.

As seen in Fig. 1, the autoignition of ethanol and gasoline show different dependences on pressure. The pre-ignition heat release rates, an indication of fuel autoignition reactivity, are significantly promoted by pressure for gasoline but remain essentially constant for ethanol (Fig. 2). As the reactivity increases with pressure, the autoignition of gasoline tends to become less sensitive to the reduced in-cylinder temperature from DI fuelling because the lower temperatures tend to enhance the pre-ignition heat release, partially counteracting the effect of the temperature change. Figure 4 confirms this, showing that the temperature sensitivity of gasoline is considerably reduced at P_{in} = 2.4 bar compared to P_{in} = 1.0 bar (Fig. 3) (i.e. a given change in T_{in} produces a significantly smaller change in CA10 at P_{in} = 2.4 bar than at P_{in} = 1.0 bar). As a result, the charge cooling produced by various mechanisms, e.g. fuel vaporization or piston expansion, becomes less effective for knock control with gasoline for turbocharged conditions.

Fig. 4

On the other hand, for ethanol, the autoignition reactivity is essentially unchanged by pressure, as evident from Fig. 2a. Ethanol's strong sensitivity to temperature (i.e. charge cooling) is thus largely preserved, as shown in Fig. 4 (a small T_{in} change causes a large CA10 change). As a result, the difference in the knock propensity of ethanol and gasoline is much greater at boosted pressures than at naturally aspirated conditions, as evident from the SI engine experiments discussed below.

Understanding literature data on knock-limited SI engine performance with turbocharging and DI

The insights gained from the fundamental HCCI experiments can be applied to understand the anti-knock performance of ethanol/gasoline blends in a modern SI engine, as reported by Stein et al. [4]. Using direct injection and simulated turbocharging (using an air compressor), Stein et al. reported SI engine performance in terms of knock-limited net mean effective pressure (NMEP) for a wide range of fuel blends.

An example of their results comparing the performance of E50 (gasoline:ethanol = 50:50 by volume) and neat gasoline (E0) are shown in Fig. 5. These two fuels are not the same as those in our HCCI experiments: the gasoline is somewhat more reactive (Research Octane Number, RON = 88 vs. 91 in the HCCI experiments), and the ethanol is blended with the gasoline rather than being neat ethanol. Nevertheless, ethanol should be responsible for any differences observed between the two fuels. Additionally, Anderson et al. [11] have shown that a blend of 50% ethanol with a RON = 88 gasoline gives more than three-fourths of the RON increase that would occur for switching from this gasoline to neat ethanol, which suggests that its autoignition reactivity should shift by a similar amount. Therefore, the general trends obtained from the HCCI experiments with neat ethanol and the RON=91 gasoline, regarding the effects of variations in cylinder pressure and temperature on the knock propensities of the fuels, should still be applicable.

Two different fuelling methods were used by Stein et al., early DI and a so-called upstream fuel injection (UFI) in which fuel is injected well upstream of the intake port. The temperature at the intake port is fixed at 52°C for all the tests, therefore with UFI the fuel vaporization is completed upstream of the intake port, i.e. essentially the same as in our HCCI experiments. The engine speed is fixed at 1500 rpm, and a stoichiometric charge is used except for high loads where enrichment is used to suppress knock to allow a higher NMEP. Intake pressure dictates the load (NMEP), as indicated in the inset in Fig. 5. Spark-timing retard is used to retard the 50% burn point (CA50), and therefore to control knock. In all cases, the combustion occurs with knock-limited spark advance.

Fig. 5

Retarding the combustion timing after TDC utilizes the charge cooling due to the piston expansion to slow the autoignition kinetics and thus prevent knock. Similar to the case of DI charge cooling, the effectiveness of the piston-expansion cooling to control knock depends on the sensitivity of the fuel's autoignition to the temperature drop. The "E0, UFI" case in Fig. 5 shows that for neat gasoline, a large CA50 retard is required for a marginal NMEP increase, indicating that the expansion cooling is not very effective for knock control. This can be explained by the relatively low temperature sensitivity of gasoline autoignition above discussed (Fig. 3). For the same reason, the charge cooling produced by DI fuel vaporization is not very effective for inhibiting knock as can be seen by a comparison of the "E0-UFI" and "E0-DI" data. The NMEP of gasoline therefore appears to be self-constrained due to the strong pressure sensitivity and weak temperature sensitivity of its autoignition.

However, adding ethanol into gasoline substantially changes the trends. With 50% ethanol, E50 should possess ~50% of the charge cooling capacity of pure ethanol, and its autoignition reactivity should be approaching that of ethanol, as discussed above. For a pre-vaporized fuel/air mixture, the “E50-UFI” case shows that the NMEP increases from 5 bar to 27 bar using pressure boost and spark retard. This large increase in load is possible because of the weak pressure sensitivity and strong temperature sensitivity of ethanol autoignition, as discussed above. The weak pressure sensitivity allows high boost for higher load without knocking; more importantly, the strong temperature sensitivity makes the autoignition very sensitive to the piston-expansion cooling, so it is very effective for controlling knock. When DI is used (“E50-DI”), the strong vaporization cooling from ethanol coupled with the high temperature sensitivity (which is not much affected by pressure boost) further increases the anti-knock performance of E50. Even higher NMEP is thus produced and the maximum value reaches 41 bar. Note that the difference between “E0, UFI” and “E50, UFI” is due to the different fuel autoignition sensitivity to pressure boost, which becomes increasingly larger as their autoignition reactivities become increasingly different as higher pressures (Fig. 2). On the other hand, the difference between “E50, UFI” and “E50, DI” is due to the different fuel vaporization cooling capacity and the different fuel autoignition sensitivities to the charge cooling; such differences also becomes larger at higher pressures as more fuel is injected at higher loads. In summary, the weak pressure sensitivity and strong temperature sensitivity of ethanol autoignition provides ideal anti-knock properties for turbocharged DISI engines using spark timing for knock control.

Impact of downspeeding (speed sweep)

Another important engine operating parameter affect knock is the engine speed, which determines the time available for the end gas to undergo autoignition process. Lower engine speeds typically corresponds to higher knock propensity, which represents a problem for the current trend of engine downspeeding.

Autoignition sensitivity to engine speed is again fuel dependent. Figure 6 shows the HCCI experiments at P_{in} = 1.0 bar where the engine speed is plotted against the required intake temperature to reach a fixed CA50 [7]. For both ethanol and gasoline, the required intake temperature drops as engine speed decreases for speeds < 1200 rpm, indicating higher knock propensity at lower speeds, which is consistent with SI engine observations. Gasoline shows a much steeper T_{in} drop at these speeds, primarily because of the onset of low-temperature heat release (LTHR) [7], which substantially reduces the temperature required for autoignition. Ethanol, on the other hand, shows a much smaller T_{in} drop because no LTHR occurs even at low speeds. Therefore, the anti-knock performance of ethanol remains high at these low speeds, which is desired for SI engine downspeeding.

Figure 6 also shows some common trends with the octane numbers of gasoline (RON=91, MON=83) and ethanol (RON=109 , MON=90). It is noted that the RON difference between ethanol and gasoline, 18, is much larger than their MON difference, 7. This is consistent with the T_{in} difference between the two fuels at the speeds where these ONs are measured. At 600 rpm (for RON), the T_{in} difference is much larger than that at 900 rpm (for MON), indicating much larger anti-knock difference at lower speeds than at higher speeds. Similar arguments have been presented in [7]. Note that unlike a RON test where the fuel vaporization cooling and autoignition chemistry both contribute to the anti-knock performance, the HCCI experiments are conducted with pre-vaporized fuel; thus, the T_{in} difference in Fig. 6 essentially reflects the difference in the autoignition chemistry of ethanol and gasoline at 600 rpm.

At the speeds > 1200 rpm, the T_{in} of both fuels become much less sensitive to the engine speed, because more pumping work is required to induct the charge in a shorter amount of time, which causes a stronger dynamic heating effect [10]. This effect raises the temperature of the charge mixture significantly more at higher speeds than at lower speeds. Also, higher engine speeds allow less time for heat transfer. As a result of these two effects, less external heating is required, even though the charge temperature must continue to increase with engine speed to maintain the same CA50, as indicated by the T_{BDC} curves in Fig. 6. Compared to gasoline, ethanol appears more responsive to the increase in dynamic heating with speed, since the T_{in} curve shows a weak trend of decreasing with speed. This can be explained by the stronger temperature sensitivity of ethanol as observed in Fig. 3.

In summary, compared to gasoline, ethanol is more knock resistant at low engine speeds due to the lack of active low temperature combustion chemistry, but could be more knock prone at high speeds due to its high sensitivity to the increase in cylinder temperature. These characteristics make ethanol better suited than gasoline for the general trend of engine downspeeding. In addition, the T_{in} crossover in Fig. 6 indicates that ethanol could become more prone to knock than gasoline as speed increases under this naturally aspirated condition, which is an important anti-knock property that cannot be learned from RON and MON measurements.

<u>Application to other biofuels</u>

This method of using HCCI experiments to characterize fuel anti-knock properties in SI engines can be applied to other fuels. In particular, it can be used a screening tool for evaluating next-generation biofuels for SI engine application. For example, Fig. 7 shows the results of two oxygenated fuels, isopentanol [8] and cyclopentanone [6], which are potential components for advanced cellulosic biofuels. The results indicate that isopentanol has similar anti-knock properties to gasoline, since it shows very similar sensitivities to temperature, pressure, and speed. Cyclopentanone, on the other hand, is similar to ethanol, but with even stronger anti-knock properties, as indicated by the stronger temperature sensitivity, weaker pressure sensitivity, and higher T_{in} requirement than ethanol. These properties suggest that for knock-limited combustion in a turbocharged DISI engine, isopentanol will perform similarly to gasoline and cyclopentanone will perform even better than ethanol. Such predictions obtained from fundamental HCCI experiments are valuable for deciding which new biofuels fuel to select for further development, and they cannot be made by just knowing their octane numbers.

Fig. 7

Conclusion

Fundamental HCCI engine experiments are proposed as means of characterizing the fuel anti-knock properties in modern SI engines where the combustion environment is being substantially changed advanced engine technologies. Knock propensities at varying in-cylinder temperatures, pressures, and engine speeds are reported for ethanol and a conventional gasoline to understand the impacts of turbocharging, direct injection and downspeeding. The major conclusions are:

1. The weak sensitivity of ethanol autoignition to pressure allows considerable pressure boost without a significant increase in knock propensity.
2. The strong sensitivity of ethanol autoignition to temperature makes the charge cooling produced by fuel vaporization (from DI fueling) and piston expansion (from spark retard) very effective for inhibiting knock.
3. These autoignition characteristics give ethanol ideal anti-knock properties for SI engines using turbocharging and direct injection. This advantage is in addition to the commonly recognized large charge cooling capacity for ethanol direction injection.
4. Relative to ethanol, gasoline's strong autoignition sensitivity to pressure boost causes its knock propensity increase rapidly with turbocharging. Further, gasoline's relatively weak sensitivity to temperature, which tends to become even weaker with pressure boost, makes charge cooling increasingly ineffective for knock control.
5. For these reasons, the knock-limited performance of gasoline quickly becomes self-constrained with respect to utilizing the full potential of turbocharging and charging cooling from DI fueling and/or timing retard.
6. Ethanol's weak sensitivity to engine speed, particularly at low speeds, makes it better aligned with the trend of engine downspeeding.

Overall, the fundamental HCCI experiments provide a comprehensive understanding as to why ethanol is a superior fuel for modern SI engines. In addition, this paper demonstrates the validity and utility of the proposal that HCCI experiments can be a useful tool to diagnose and predict fuel anti-knock performance in SI engines, which can be readily extended to other fuels than those investigated here.

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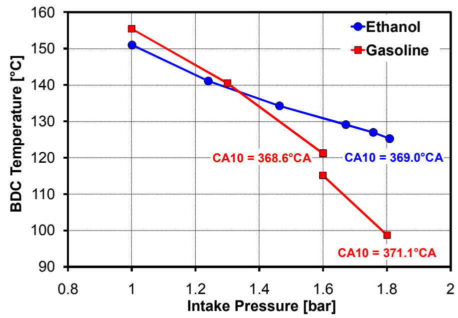

Fig. 1 Pressure sensitivity – T_{BDC} vs. P_{in}. ϕ = 0.38. No EGR except for gasoline at 1.8 bar (23% EGR). 1200 rpm.

Data first reported in [7] for ethanol and in [6] for gasoline.

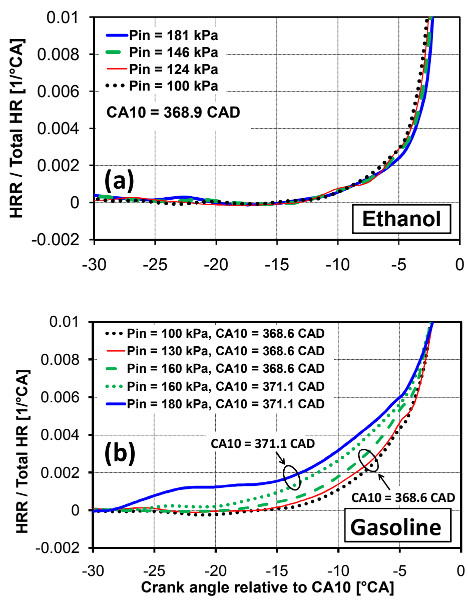

Fig. 2 Pre-ignition heat release rates, normalized by the total heat release, for (a) ethanol (b) gasoline at

P_{in}=1.0-1.8 bar. Same data set as in Fig. 1.

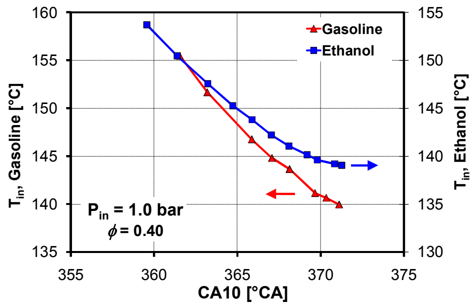

Fig. 3 Temperature sensitivity at naturally aspirated conditions – T_{in} and CA10. No EGR. Data first published in [6].

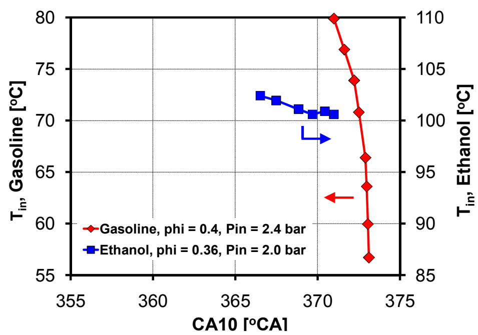

Fig. 4 Temperature sensitivity at boosted conditions – T_{in} vs. CA10. Similar scales to Fig. 3 to facilitate comparison.

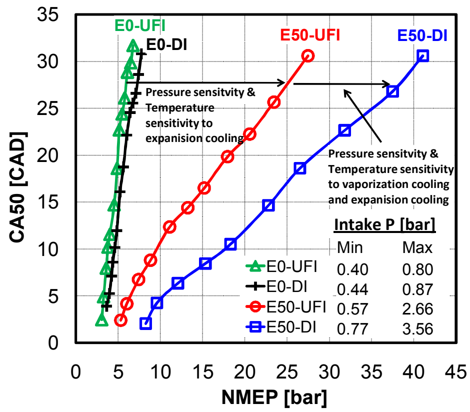

Fig. 5 SI engine performance - NMEP at knock-limited spark advance for gasoline (RON=88) and E50 (gasoline : ethanol = 50:50 by vol.). DI = direction injection, UFI = upstream (of intake port) fuel injection. Changes in NMEP are produced by varying P_{in}, while maintaining a stoichiometric charge. T_{in} fixed at 52°C. Reproduced from [4] with permission.

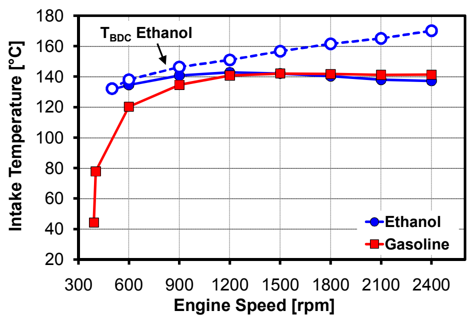

Fig. 6 Speed sensitivity – T_{in} vs. speed. CA50 = 372°CA, P_{in} = 1.0 bar, ϕ = 0.38, no EGR. Data first reported in [7].

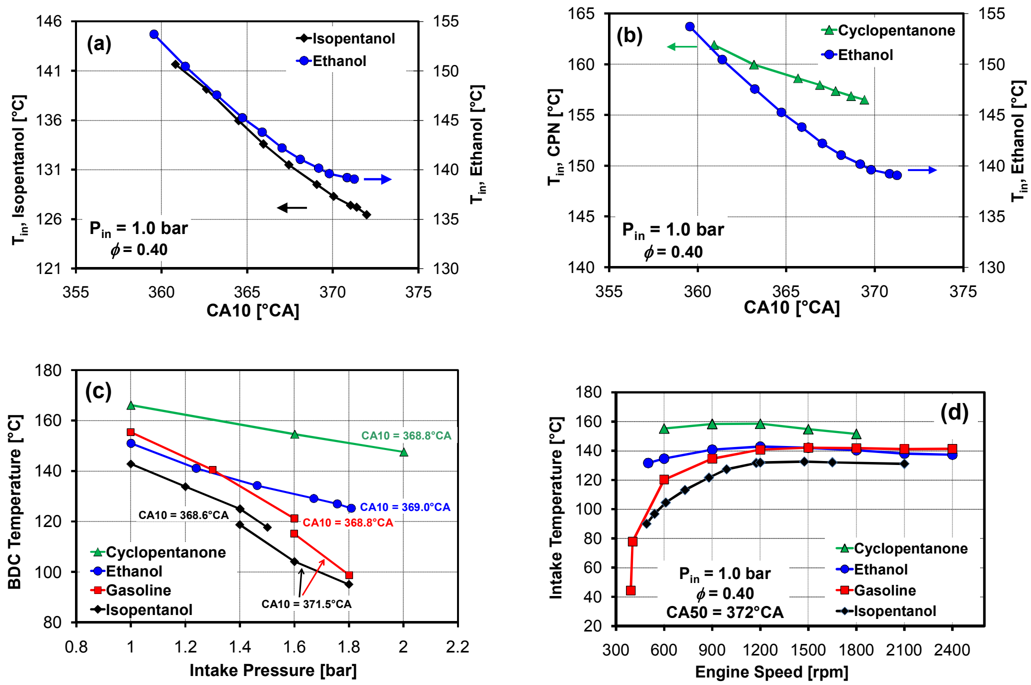

Fig. 7 Anti-knock properties of isopentanol [8] and cyclopentanone [6]. (a) temperature sensitivity – isopentanol and ethanol (b) temperature sensitivity – cyclopentanone (c) pressure sensitivity (d) speed sensitivity. Same conditions as in the respective sweeps.