1.3 An Advanced Ignition System for High Efficiency Engines

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Abstract

A pragmatic approach to meeting future CO_2 regulations while delivering vehicles that customers want and can afford will require the synergistic integration of advanced tech-nologies that enhance engine efficiency by minimizing loss mechanisms and maximi-zing work recovery. Aggressive downsizing, higher compression ratios, increased le-vels of charge dilution, and homogeneous stoichiometric operation at wide open throttle with acceptable peak pressure levels are essential technologies to meet these challenging objectives. Many of these enabling technologies pose significant challen-ges for the conventional spark ignition system. To maximize gasoline engine efficiency, the ignition system should enhance early flame kernel development to support robust spark ignition combustion, should be able to enhance mixture reactivity to support part-load lean low-temperature combustion, and should tolerate high heat fluxes to support high speed and load operation without compromise. In this paper, we demonstrate a single, passive, low-temperature plasma ignition concept that simultaneously addres-ses all these challenges. The groundless barrier discharge igniter (GBDI) can enhance early flame kernel development through the local deposition of high energy reactants, enable lean low-temperature combustion control through the generation of pre-com-bustion ozone, enhance knock tolerance by reducing early flame kernel variability, and enhance overall engine robustness through the elimination of ground straps, spark gaps, and heat ranges.

1 Introduction

In the pursuit of high efficiency gasoline engines, conventional inductive ignition systems face severe challenges. As engines are downsized and boosted, to maximize engine efficiency we must focus on minimizing loss mechanisms and maximizing work recovery. In these next-generation engines, the ignition system must handle multiple operating conditions. Future high efficiency engines will aim to have compression ratios between 13 & 14 to maximize work extraction without incurring major parasitic losses. These engines will also utilize elevated levels of charge dilution at part-load to minimize heat losses and maximize work extraction. This implies that the ignition system must enable increased EGR tolerance and/or enable lean low- temperature combustion (LTC) with robust phasing control. Also, the engine must support homogeneous stoichiometric operation at higher loads and wide-open-throttle (WOT) operation with rated speed above 6000 rpm while maintaining modest peak pressure levels. At such operation, ignition systems must not only handle increased breakdown voltages but also withstand significant thermal loading and avoid overheating.

The higher in-cylinder pressure with downsizing and boosting demands higher breakdown voltages and one way to overcome the problem is to reduce the spark gap size on conventional inductive spark ignition systems. The smaller gap size can worsen combustion stability, especially with EGR dilution and/or lean operation. Advanced ignition systems are being investigated as an enabling technology for downsize boost dilute combustion engines [1-3]. Among these advanced ignition systems, low-temperature plasma based systems are gaining in importance. Several alternatives to conventional spark plug systems are considered and the most prominent among them are the radio frequency based systems like the corona ignition system and the barrier discharge ignition system. Other technologies include multi-charge ignition, dual-coil offset/ignition system, passive and active jet ignition systems, microwave high-frequency ignition system and laser ignition. While many of these systems were evaluated for dilute stoichiometric combustion and lean homogeneous applications, low-temperature plasma systems were explored for achieving advanced combustion strategies like lean stratified-charge combustion and lean homogeneous charge compression ignition (HCCI) [4-6].

Figure 1 shows a schematic of engine speed and load operating regimes for a lean LTC high-efficiency engine. As shown in the schematic, the engine operation is differentiated by low- mid- and high-load operating regimes that support different combustion modes. In the low-load regime, negative valve overlap (NVO) may be utilized to trap hot-residuals that is necessary to support flameless and flame-assisted controlled lean LTC. In the mid-load regime, positive valve overlap (PVO) operation and advanced injection strategies may be utilized to achieve flame-assisted controlled lean LTC. At even higher speed and load operation, the engine is required to support stochiometric combustion with significant dilution and knock tolerance. There are several advanced technologies that need to be synergistically integrated to achieve these objectives and the ignition system plays a key role. For example, the capability of the ignition system to enable robust control of lean LTC, as well as increase dilution and knock tolerance at high-load stoichiometric operation are critical. An advanced ignition system may outperform a conventional inductive ignition system while taking into consideration the desired engine operation. Table 1 shows a comparison between different ignition systems and their pros and cons while considering its capability to meet the desired results. In this paper, we present results for a groundless barrier discharge ignition (GBDI) system that enables all the challenges to be addressed.

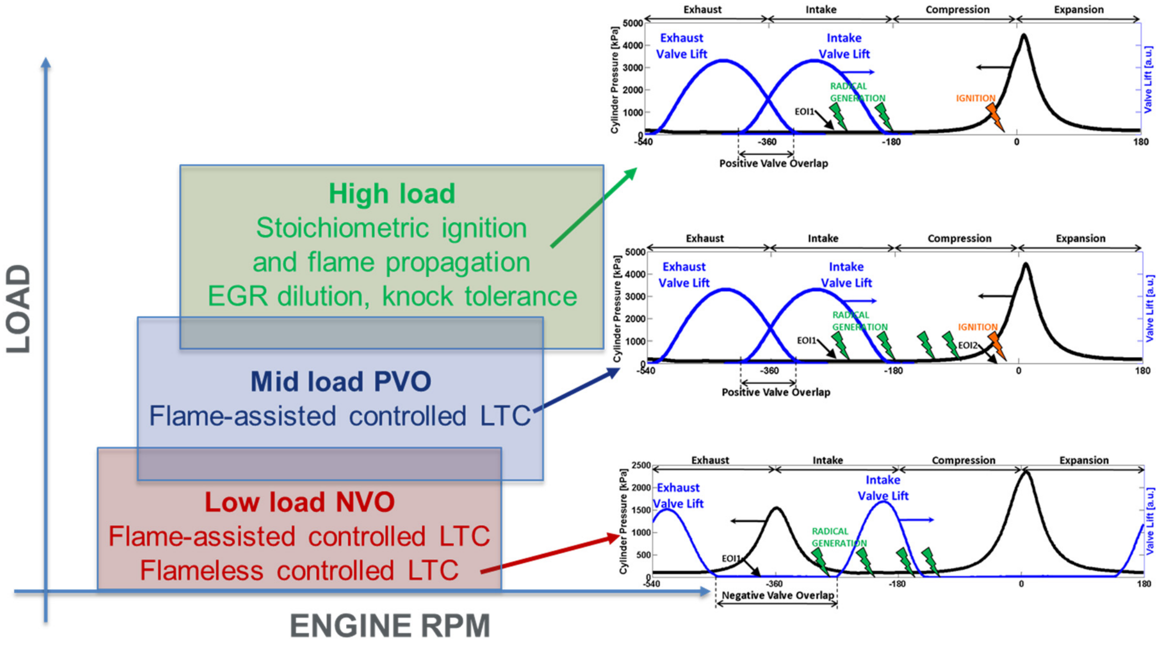

Figure 1: Schematic show engine speed load operating regimes and different combustion modes that needs to be supported by the ignition system

Table 1: Alternate ignition systems and their pros and cons.

Ignition Concept	Low Temperature Plasma	Low Temperature Plasma	Low Temperature Plasma	Capacitive Discharge	Inductive Discharge	Inductive Discharge
Type	Corona	GBDI	Passive Jet ignition	Passive Jet ignition	Passive jet ignition	Active Jet ignition
Pros						
	Supports lean combustion	Supports lean combustion	Potential to support lean combustion			Supports lean combustion
	Supports high EGR	Supports high EGR	Supports high EGR			Supports high EGR
	Increases knock tolerance	Increases knock tolerance	Increases knock tolerance	Increases knock tolerance	Increases knock tolerance	Increases knock tolerance
	Reduced erosion concerns	Eliminates erosion concerns	Eliminates erosion concerns			
	Reduced fouling concerns	Eliminates fouling concerns	Reduces fouling concerns	Reduces fouling concerns		
		Simplified control strategy				
Cons						
	Arc detection and control necessary		Poor light load combustion stability	Poor light load combustion stability	Poor light load combustion stability	Complexity with additional injector
			Poor cold performance	Poor cold performance	Poor cold performance	Poor cold performance
				Gap erosion	Fouling/heat range issues	Fouling/heat range issues
Cost	+++	++	++	+	+	++

1.1 Low-temperature plasma ignition system

From Table 1 it is evident that low-temperature plasma based ignition systems offer significant advantages when compared to alternate ignition systems. Figure 2 shows a comparison between two radio frequency low-temperature plasma ignition systems. On the left column is the corona discharge based plug and the right column is the GBDI plug. It is important to illustrate the difference between the two systems and understand why one may be preferred over the other. The more traditional corona system has a power electrode (the example in Figure 2 has four prongs), from which multiple low-temperature plasma streamers emanate. The propensity for these streamers to transition to a single high-temperature plasma (arc) discharge is well understood and is dependent primarily on the driving voltage, duration, the proximity of the power electrode prongs to any ground surface (e.g. opening valves, piston surface, cylinder head), and the in-cylinder conditions (e.g. pressure at time of ignition). The advantage of the corona system is its capability to promote near-simultaneous and closely located multiple ignition points, thereby reducing the 0-10 burn duration (ignition delay). Also, the absence of a prominent ground electrode reduces potential heat losses suffered by the early flame kernel. This is in addition to the widely accepted difference in the underlying ignition process between low-temperature plasma and high-temperature plasma (e.g. inductive spark plug) ignition systems. In contrast, the barrier discharge system has a power electrode that is fully enclosed in the dielectric casing and does not have a prominent ground electrode. As shown in Figure 2, multiple streamers propagate on the surface of the dielectric. The streamers originate at the base of the plug shell and reach the tip of the dielectric, depending on the ambient pressure, voltage and duration settings. The images in the bottom row of Figure 2 shows multiple events in a single exposure. It shows that while the corona streamer discharges emanate from the prongs, they largely seem to repeat their spatial location from discharge to discharge, in this quiescent environment. On the other hand, for the barrier discharge, in a similar environment, the streamers move and form all around the dielectric surface.

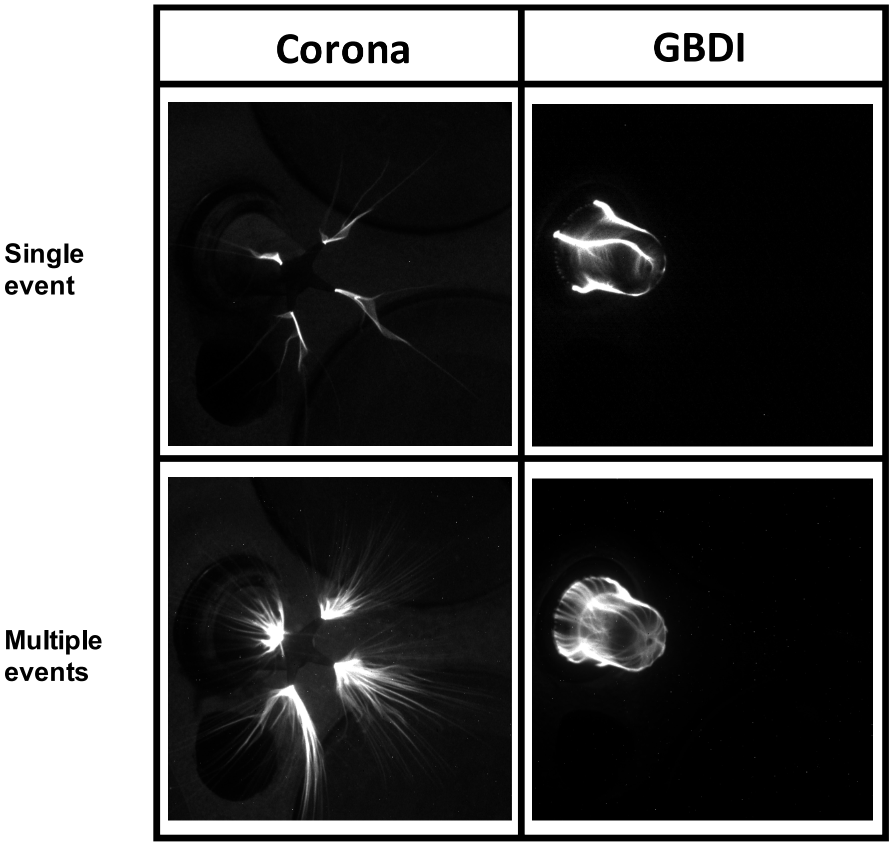

Figure 2: Visualization of corona ignition system and GBDI system. The top row shows a single discharge event and the bottom row shows multiple discharge events visualized in the same exposure.

2 Results

In this section, we will present results from single- and multi-cylinder engine testing. Results are presented for engine operating regimes and combustion modes as illustrated in Figure 1.

2.1 Lean LTC NVO operation

This section presents the voltage based reactivity control achieved by using a barrier discharge ignition system for NVO operation. The engine speed is 1000 rpm and the fueling rate for the single-cylinder engine experiment is approximately 9 mg/cycle with an NVO duration of 156 CAD and intake temperature set to 125 C. As shown in Figure 1, for this flameless controlled LTC mode, the fuel is injected after TDC of the recompression process, thereby limiting the amount of fuel reforming. The plasma igniter is actuated multiple times after fuel injection to generate radicals that assist with the combustion. For this example, an additional plasma igniter was also added in the intake plenum and actuated multiple times. Figure 3 shows the cycle averaged (200 cycles) heat release rate for multiple operating strategies. When the igniter in the intake and cylinder are turned off, the heat release rate is delayed and combustion is unstable and unacceptable. However, activating the intake and in-cylinder igniters and increasing the driving voltage, the combustion phasing is advanced and the combustion stability is improved as well. In Figure 3, the effect of increasing the driving voltage from 30 V to 40 V to 50 V is evident as COV of IMEP improves to 2% and combustion is phased more favorably. It should be emphasized that there is no propagating flame in this combustion mode, and the plasma igniter is enhancing the flameless low-temperature combustion. For this lean operating condition, the low-temperature plasma igniter supports generation of ozone that enhances the reactivity of the fuel-ambient mixture and supports controlled low-temperature combustion.

The corona based system can also support generation of ozone to enhance LTC as shown for the barrier discharge system. However, active control of the voltage and duration of the corona discharge is required to ensure that the discharge is in low-temperature plasma mode. For example, for these light-load operating conditions, when the discharge events are occurring at ambient pressure conditions, the sensitivity for the corona discharge to transition to a high-temperature plasma that does not produce any ozone is increased. On the other hand, the barrier discharge system never transitions to a high-temperature plasma with increasing voltage and therefore the voltage is the most important control parameter to achieve distinct levels of combustion enhancement and phasing control by varying the amount of ozone that is generated.

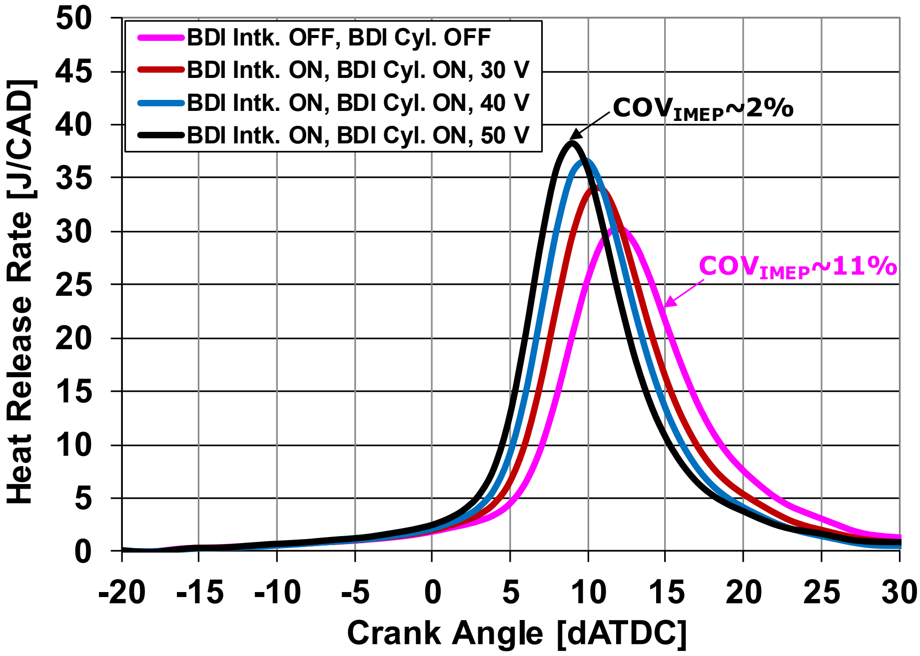

Figure 3: Voltage based reactivity control achieved by using barrier discharge ignition system for flameless low-temperature combustion at NVO operation.

Figure 4 shows results from cylinder #1 of multi-cylinder engine testing depicting the lean operation limit with different ignition systems. For these tests, a single GBDI igniter is used per cylinder and only a single ignition event was utilized, unlike the results obtained in Figure 3. The engine is operated at 2000 rpm with a fueling rate of 10 mg/cycle/cylinder (nominally 250 kPa IMEP) and intake temperature of 40 C. The change in air-fuel ratio (AF ratio) was achieved by changing the amount of NVO, while maintaining the injection timing and spark timing. As the mixture gets leaner, the combustion phasing is delayed and combustion instability increases as indicated in Figure 4 by the COV of IMEP. This flameless combustion mode can be achieved without any ignition and the maximum achievable AF ratio is a little over 21 with COV of IMEP < 3%. If a traditional high energy spark ignition system is used, the lean limit can be extended to a little over 22. Further enhancement of the lean limit to 23.5 can be achieved by using the GBDI system. It is the unique voltage based reactivity enhancement of the GBDI system that enables reliable combustion performance at lean condition. The higher voltage that is required for the GBDI system at the leaner condition is labeled in Figure 4. The system that was evaluated in this study was limited to peak voltage setting of 70 V. Beyond this voltage, the potential for dielectric puncture failures was high for the GBDI system.

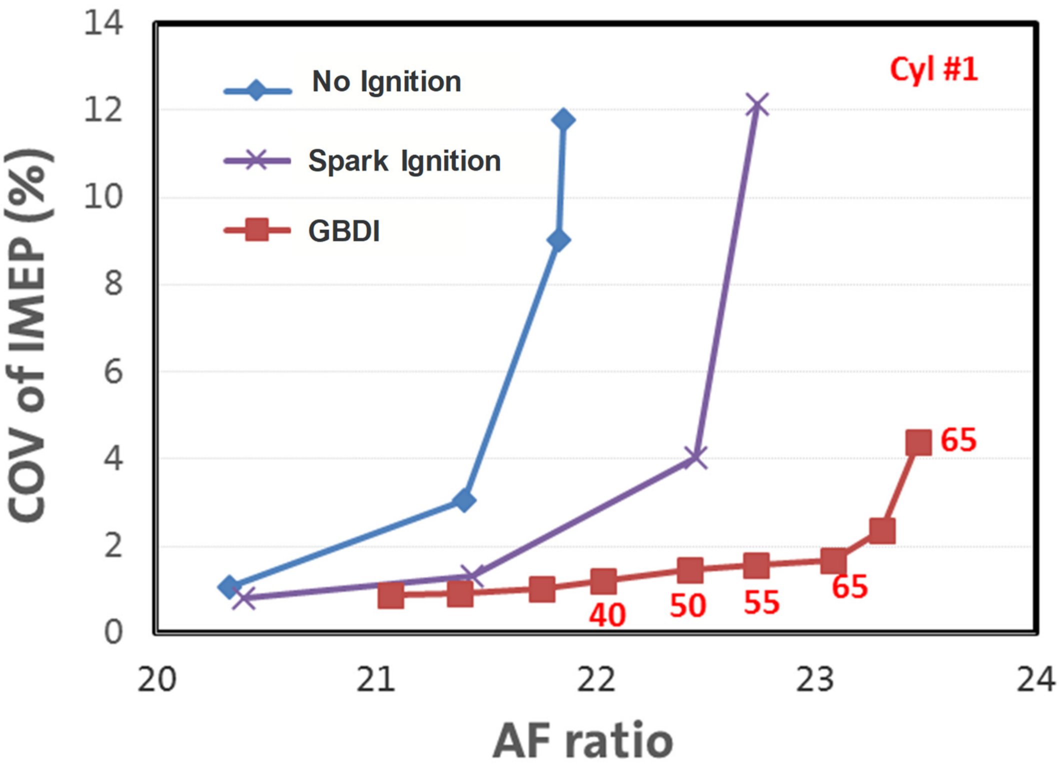

Figure 4: Voltage based reactivity control achieved by using GBDI system for flameless low-temperature combustion at NVO operation.

2.2 Lean LTC PVO operation

This section presents the voltage and number of events based reactivity control achieved by using a GBDI system for PVO operation. The combustion mode in this operating regime is flame-assisted controlled LTC. The engine speed is 1000 rpm and the fueling rate for the single-cylinder engine experiment is approximately 12 mg/cycle with a PVO duration of 100 CAD and intake temperature set to 40 C. As shown in Figure 1, the fuel is injected in two parts with an early injection event that delivers majority of the fuel (10 mg) during the intake stroke, and a second smaller quantity of fuel (2 mg) during the compression stroke that is ignited with a closely coupled ignition event. Also, there are multiple actuations of the igniter (referred to as radical generation in Figure 1 or pre-strikes in Figure 5 and 6) during the intake and early compression stroke, to generate ozone or reactants that enhance the reactivity of the mixture. The small quantity second injection is ignited (referred to as ignition in Figure 1) that initiates the combustion of the stratified mixture with a turbulent flame propagation. This is followed by a controlled LTC (autoignition) of the remaining mixture. This mixed mode of combustion is clearly shown in Figure 5 and Figure 6. The unique capability of the GBDI igniter to enable controllability of LTC with voltage and number of pre-strikes is shown in Figure 5 and Figure 6, respectively.

Figure 5 presents cycle averaged (200 cycles) heat release rates for flame-assisted controlled LTC at PVO operation. Three different cases are shown, with radical generation or pre-strikes turned off or two pre-strikes events at 40 V and 50 V. With the pre-strikes turned off, the heat release shows a robust flame initiation event of the stratified mixture, followed by a weak low-temperature combustion that leads to combustion instability and poor COV of IMEP. For the same condition, when the pre-strikes are turned on with a setting of 40 V, the flame initiation portion remains relatively the same, but significant enhancement of low-temperature combustion and improvement in combustion stability is achieved. As the voltage is increased further to 50 V, continued enhancement of LTC and combustion stability is obtained.

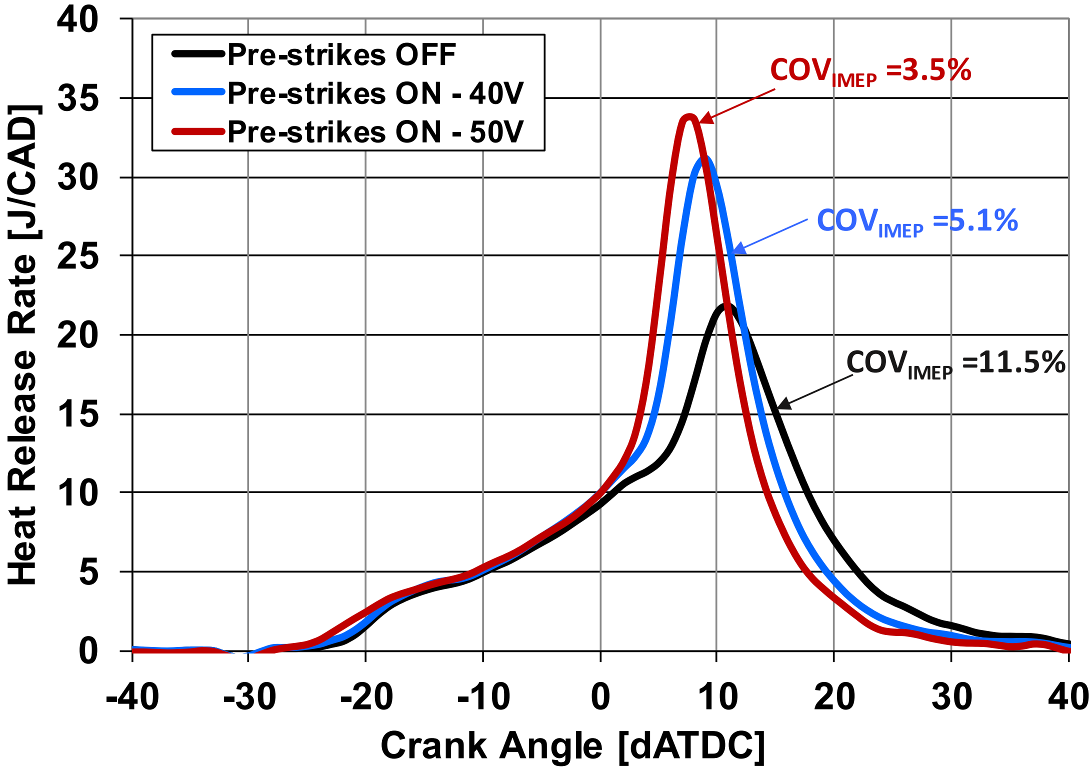

Figure 5: Robust ignition and voltage based control achieved by using GBDI system for flame-assisted LTC at PVO operation.

Figure 6 presents cycle averaged (200 cycles) heat release rates for a similar condition as in Figure 5. Four different cases are shown, with radical generation or pre-strikes turned off and varying the number of pre-strikes at a fixed 50 V. With the pre-strikes turned off, the heat release shows a robust flame initiation event, followed by a weak low-temperature combustion that leads to combustion instability and poor COV of IMEP. As the number of pre-strikes is increased from 2 to 3 to 4, increasing levels of low-temperature combustion enhancement is achieved with improving combustion stability. The results shown in Figure 5 and Figure 6 together indicates that the applied voltage and number of pre-strikes are effective controls for enhancing and controlling low-temperature combustion for flame-assisted LTC with PVO.

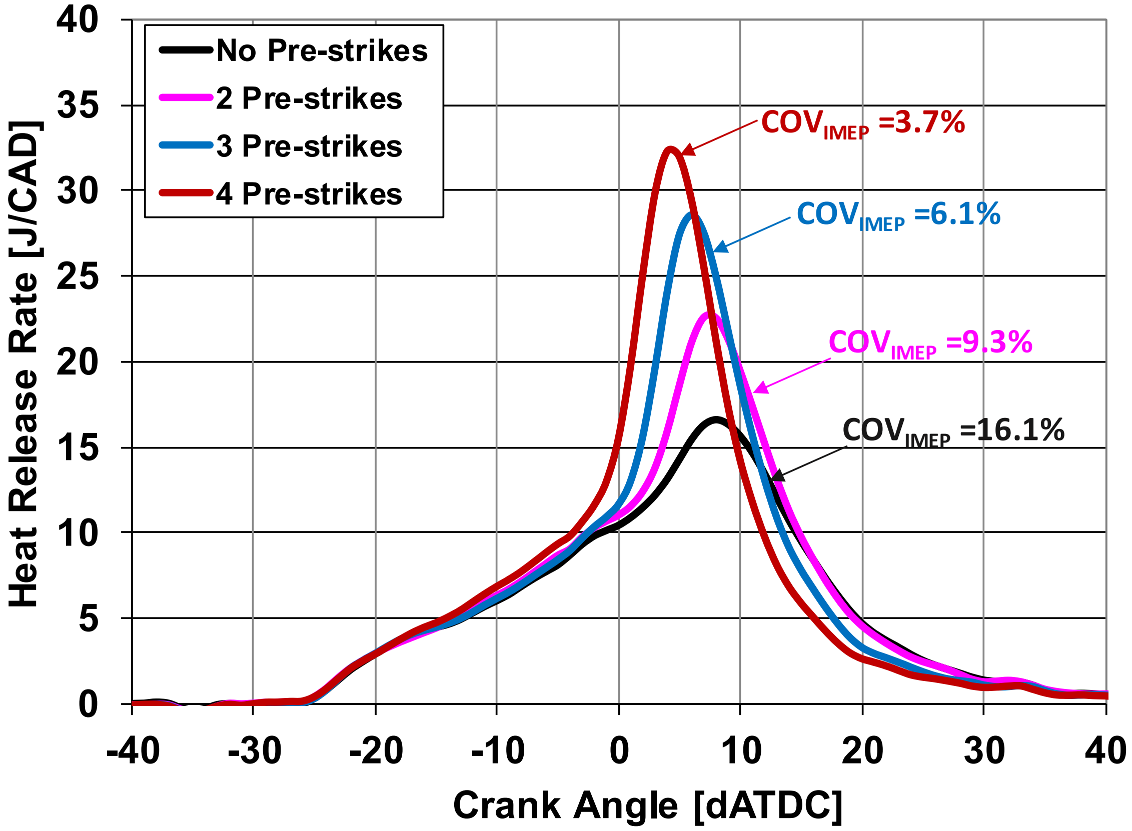

Figure 6: Robust ignition and number of pre-strikes based control achieved by using GBDI system for flame-assisted LTC at PVO operation.

2.3 Stoichiometric part-load operation (dilution tolerance)

This section presents the unique capability of GBDI system for dilute stoichiometric part-load operation. As shown in Figure 1, the impact of using pre-strikes to improve exhaust gas residual (EGR) dilution tolerance is demonstrated, followed by EGR dilution tolerance improvement by using only a single ignition event.

Figure 7 shows indicated mean effective pressure (IMEP) plotted for 200 cycles from single-cylinder engine tests with an engine speed of 1000 rpm and fueling of 12 mg/cycle (nominally 325 kPa IMEP) at stoichiometric condition. The EGR is simulated in this operating condition by adding excess nitrogen to the intake air, and is estimated to be at 32%. Minimal amount of trapped internal residuals is present at this condition and the dilution is primarily due to simulated EGR. In the absence of pre-strikes, the best attainable COV of IMEP is 9% with a spark advance of -34 aTDC, and misfire and partial burn cycles are present. Adding one pre-strike while maintaining the same spark timing improves the combustion stability with COV of IMEP of 3%, but there are several cycles with less than optimal IMEP. With two pre-strikes added during the early part of compression stroke, the combustion stability is further improved and COV of IMEP is less than 2%. This clearly shows that by adding pre-strikes the EGR tolerance for this engine can be enhanced with the unique capability of GBDI. It should also be emphasized that for this operating regime, the combustion is purely ignition and flame propagation dominated with no LTC. The improvement in combustion with the pre-strikes is therefore because of enhancement of the propagating flame speed.

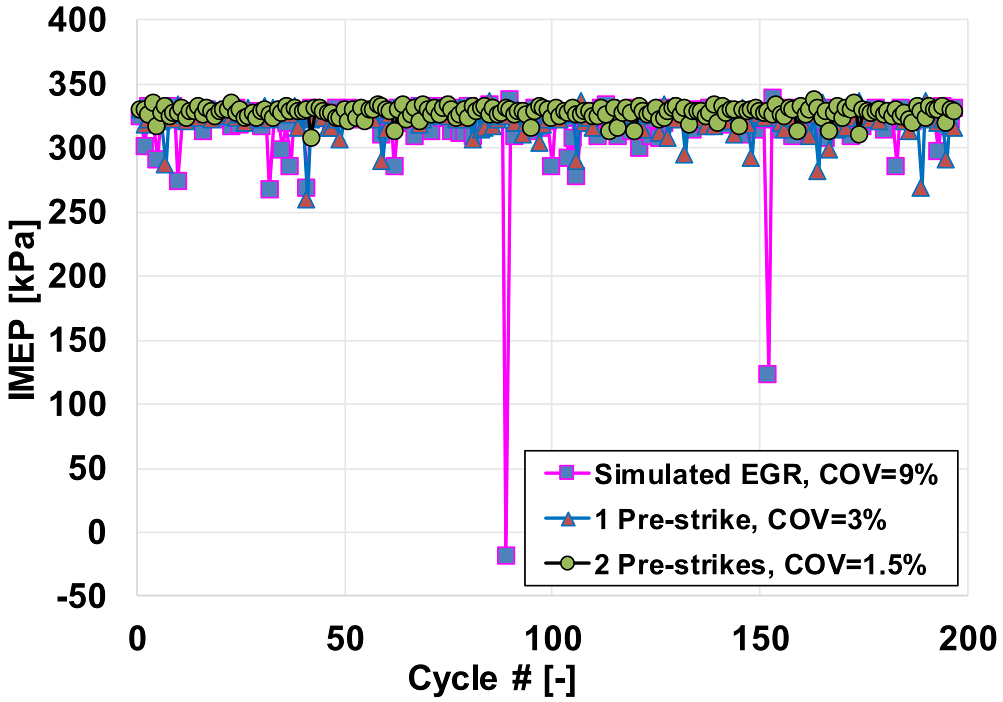

Figure 7: Improvement in simulated external EGR tolerance with GBDI by implementing pre-strikes.

The results shown in Figure 8 and Figure 9 are from a single-cylinder metal engine testing with an engine speed of 2000 rpm and fueling rate of 12 mg/cycle at stoichiometric condition. The sensitivity of the ignition system to real EGR dilution is presented in this section. It should be noted that the relative improvement in EGR rate between ignition systems is of most significance than the absolute dilution rate achieved.

Figure 8 shows the COV of IMEP as a function of EGR rate for three different ignition systems. For these EGR sweeps, the spark timing was chosen such that the combustion phasing was matched between the ignition systems (CA50 ~ 8° aTDC). For the spark plug system, two different energy levels are examined (60 mJ and 100 mJ) and compared to corona ignition and GBDI. The target COV of IMEP is 3% and is shown as a red dashed line. Figure 8 shows that at this operating condition, the GBDI system has the maximum tolerance to EGR dilution with rates of up to 25% with COV of IMEP < 3%. The unique capability of the GBDI system is its potential to deliver a wide range of ignition energy while maintaining its discharge in low-temperature plasma mode. The loss in combustion stability at the high EGR rates is also more gradual for the GDBI when compared to the other ignition system, thereby allowing for a more effective calibration.

From Figure 8, corona ignition is shown to be least tolerant to EGR dilution with onset of combustion instability as EGR is increased from 20% to 21%. For corona ignition, as EGR is increased, an advanced spark timing is demanded for achieving the target combustion phasing, to compensate for the slower combustion burn rates with increasing EGR. However, the advanced spark timing decreases the pressure at time of corona discharge and requires a reduction in driving voltage to prevent the transition to

arcing. Also, an increased duration of the discharge event is desired as EGR dilution is increased, which is a further challenge for the corona ignition system to prevent a transition to arcing. Therefore, the corona ignition system is more constrained by transition from low-temperature plasma discharge mode to high-temperature plasma discharge mode (arcing) at this part-load stoichiometric operation with EGR dilution.
For the spark plug system, the increase in ignition energy supports an improvement in EGR dilution tolerance by 1% for an acceptable combustion stability.

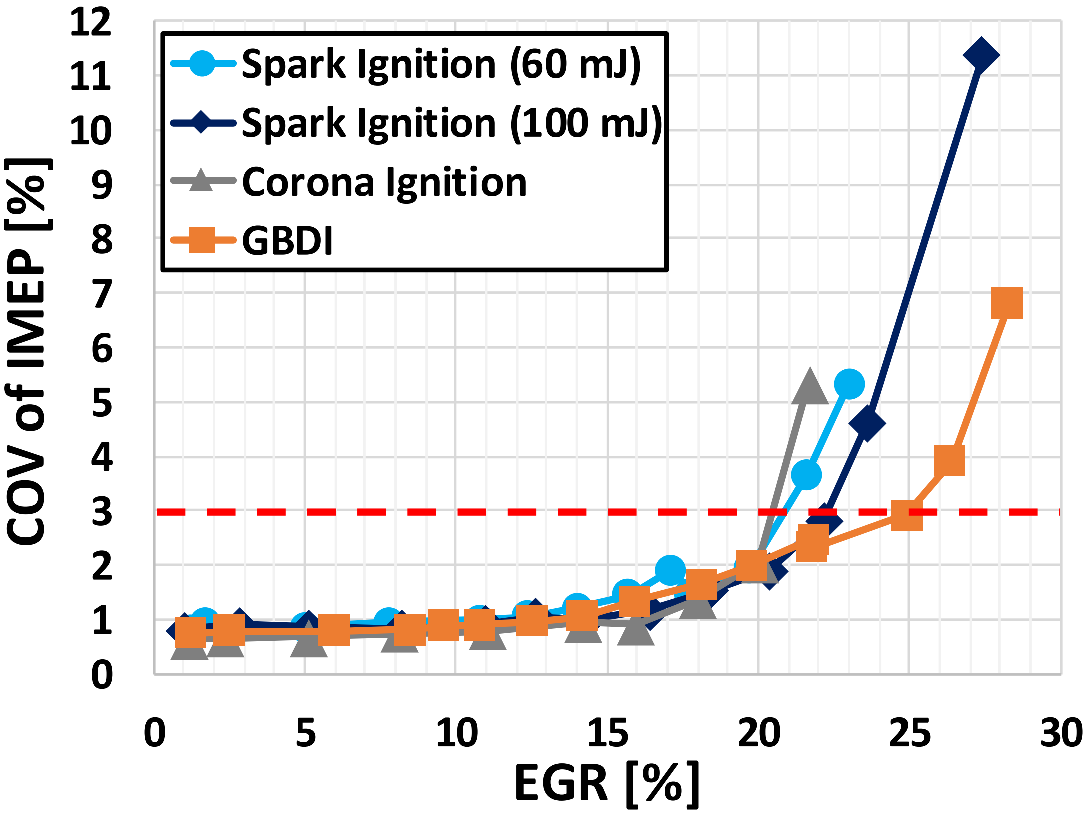

Figure 8: Improvement in external EGR tolerance with different ignition systems.

Figure 9 shows the improvement in net specific fuel consumption (NSFC) for the same operating condition as Figure 8. The data in Figure 9 is plotted as a relative improvement (negative values) in NSFC as a function of EGR rate. For the data shown in Figure 9, the NSFC at the lowest EGR rate for the 60 mJ spark plug case is chosen as the baseline and relative difference is shown for the different ignition systems. From Figure 9, adding EGR lowers the NSFC, implying an improvement in fuel consumption, and most of this benefit is from reducing pumping losses and improving thermodynamic properties. The data also shows that as the ignition energy is increased for the spark plug, there is no significant improvement in NSFC. However, for the corona ignition and GBDI, there is improvement in NSFC for the same EGR rate when compared to the spark ignition system. The most benefit is seen for the corona ignition system (~1%-2% improvement) and the GBDI system in between the spark ignition and corona ignition systems. As mentioned previously, the tendency for the corona ignition system to transition to arcing is a challenge at lighter load conditions. Therefore, the GBDI system is a good alternate that offers a much simpler and passive control of maintaining the low-temperature plasma discharge, while delivering efficiency benefits.

The improvement in NSFC for the same EGR level can be attributed to several reasons. The low-temperature plasma ignition systems provide consistent ignition from cycle to cycle and reduces the 0-10 burn duration significantly when compared to the spark ignition system. The overall reduction in burn duration these systems offer over the spark ignition system translates to an improvement in combustion efficiency as well as less cumulative heat release prior to TDC of firing, which may support reduced heat losses. Additionally, the GBDI system has demonstrated an impact on the later burn (50-90 burn duration), but the reason for this improvement is not well understood. Taken together, the low-temperature plasma ignition systems improve the combustion performance, potentially reduce heat losses and hence provide efficiency improvement.

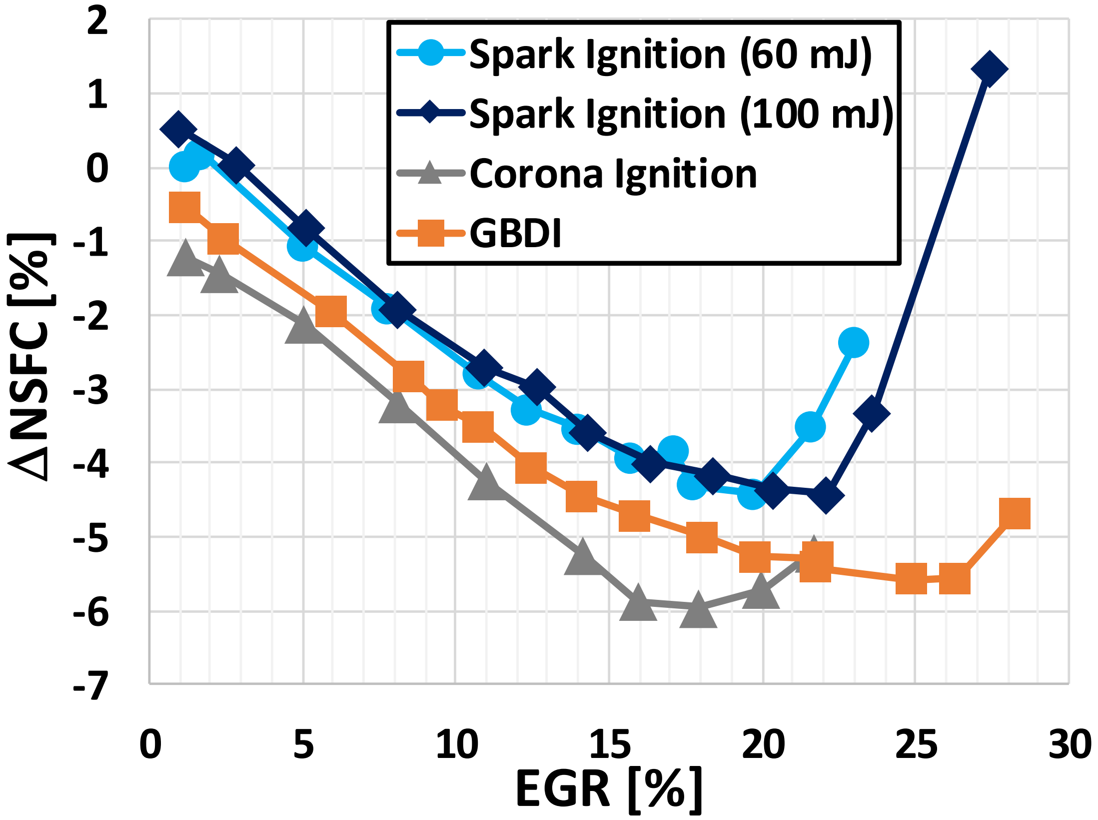

Figure 9: Improvement in net specific fuel consumption with different ignition systems for part-load stoichiometric operation with EGR dilution.

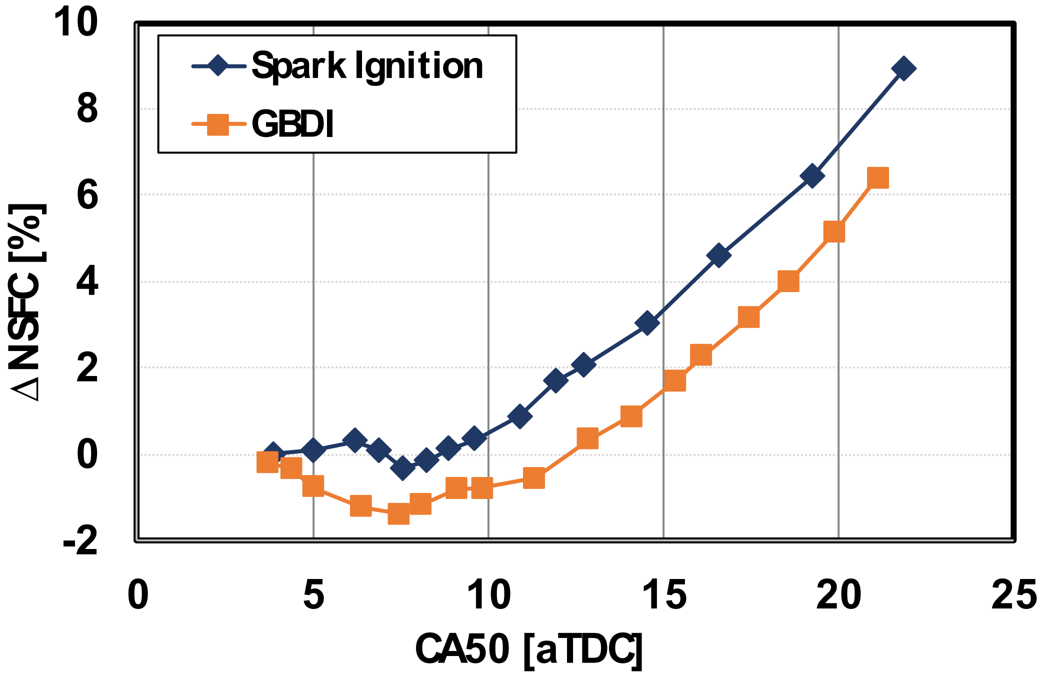

Figure 10: Comparison of net specific fuel consumption between spark ignition and GBDI for higher load stoichiometric operation.

Figure 10 shows multi-cylinder engine data for stoichiometric operation at 2000 rpm, 26 mg/cycle/cylinder fueling rate (nominally 800 kPa IMEP) with a fixed EGR of 10%. A spark advance sweep is conducted for this operating condition and the relative improvement in NSFC is shown for spark ignition and GBDI. For the data shown in Figure 10, the NSFC value at the most advanced combustion phasing for the spark ignition system is the baseline. At the most advanced combustion phasing, the NSFC of the GBDI is very similar to the spark ignition. As the combustion phasing is delayed, the spark ignition system does not show any significant improvement in NSFC, but the GBDI system shows an improvement by 1.5% as the phasing is more optimally placed at 7° CAD aTDC. When comparing spark ignition and GBDI, it is also evident that there is a wider range of combustion phasing where the GBDI can operate without significant loss in efficiency. NSFC increase with further delay of combustion phasing for both ignition systems, but the 1%-2% efficiency gain with the GBDI continues even with the delayed phasing.

2.4 Wide open throttle operation (knock tolerance)

This section presents the capability of improving the knock tolerance with GBDI for wide open throttle operation in a multi-cylinder engine. The results are from a 1.0 L, 3-cylinder turbocharged engine opearting at wide open throttle at 4000 RPM. Figure 11 presents the crank angle at mass burned fraction of 5% (MBF5%) plotted against mass burned fraction of 50% (MBF50%) for three different ignition systems. The corona igntion system and GBDI were operated at a voltage and duration of 50 V and 150 µs, respectively. The scatter plot includes data from all the three cylinders. The engine is knock limited at this opearting condition and the maximum combustion advance that can be achieved for the spark ignition system is at an average of 26° aTDC. It is also noticable that there are several late burning cycles and several early burning cycles for the spark ignition system that largely limits the average combustion phasing. With the corona ignition system, the scatter plot indicates a tighter spread than spark ignition,

but the average combustion phasing is the same or marginally better by 0.5°. In contrast, the GBDI system shows a tighter grouping of the individual cycles and offer an improvement in combustion phasing advance by almost 3°.
The advantage of the GBDI system to mitigate knock is in its ability to provide consistent and reliable igntion and combustion from cycle to cycle while reducing the overall burn duration. The tigther scatter of individual cycles in Figure 11 is indicative of such consistency and is an important feature of the GBDI system.

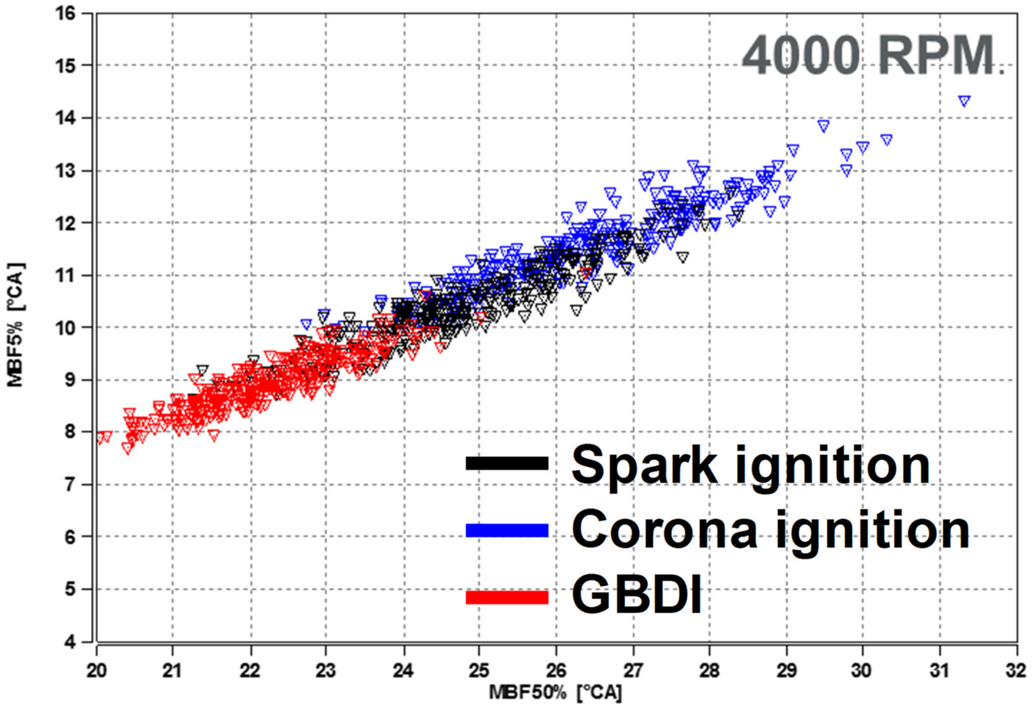

Figure 11: Improvement in knock tolerance for GBDI system at WOT operation.

3 Summary

The paper demonstrates the potential of low-temperature plasma ignition system, specifically groundless barrier discharge ignition (GBDI) system in enabling multiple combustion modes that are of importance for future high efficiency engines. To summarize, GBDI offers unique capabilities that make it a very compelling alternative to conventional inductive spark ignition systems.

- GBDI can enable flameless and flame-assisted controlled LTC in part-load lean operation and offers a simple and passive control with voltage, duration and number of pre-strikes as the primary control parameters.
- GBDI can enable significant improvement in dilution tolerance for part-load stoichiometric operation with and without the use of pre-strikes. The GBDI system also provides efficiency improvement potential due to better combustion performance and potential reduction in heat losses.
- At WOT operation, GBDI demonstrates the potential to improve knock tolerance when compared to corona and spark ignition systems, primarily due to shorter burn duration and reduced cycle to cycle variability.

- The inherent design of the GBDI lacks a ground electrode that helps with reducing heat losses and removes a potential hot-spot for pre-ignition.
- The GBDI is also not dependent on a gap and thus gap erosion is not a concern. It has the potential to be a plug for the life of the engine.
- The GBDI is in an active state of development with plug to plug variability and dielectric issues to be addressed. The primary failure mode of the plug is through puncture of the dielectric. These concerns need to be addressed as future development of this promising system continues.

4 Acknowledgements

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