

# A Continuous Discharge Ignition System for EGR Limit Extension in SI Engines

2011-01-0661

Published  
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doi:10.4271/2011-01-0661

## ABSTRACT

A novel continuous inductive discharge ignition system has been developed that allows for variable duration ignition events in SI engines. The system uses a dual-coil design, where two coils are connected by a diode, combined with the multi-striking coil concept, to generate a continuous current flow through the spark plug. The current level and duration can be regulated by controlling the number of re-strikes that each coil performs or the energy density the primary coils are charged to. Compared to other extended duration systems, this system allows for fairly high current levels during the entire discharge event while avoiding the extremely high discharge levels associated with other, shorter duration, high energy ignition systems (e.g. the plasma jet [ 1 , 2 ], railplug [ 3 ] or laser ignition systems [ 4 , 5 , 6 , 7 , 8 ]).

Tests on a single cylinder of a 4-cylinder engine indicated that the addition of the continuous discharge mode resulted in a larger improvement in burn rate and stability than was achieved by either one coil in multi-strike mode or both coils in multi-strike mode with simultaneous discharge. The improvement in burn rate and stability translated into improved fuel consumption, particularly at low specific power levels and at high engine speeds. Finally, the improvement in EGR tolerance at low load conditions is seen as an important enabler for high dilution engines, as the requirement for engine stability during throttle tip-out is an important limiting factor in the ultimate EGR levels targeted by engine designers.

## INTRODUCTION

With fuel economy becoming the dominant concern of regulators and many consumers, increased pressure is being placed on engine and vehicle OEMs to continue to improve

the efficiency of spark ignition (SI) engines. Even in the case of hybrid vehicles, regulatory pressure and consumer sentiment will combine to require increased efficiency at a reasonable cost. The SI engine offers considerable benefits over the compression ignition (CI) engine in terms of cost and tailpipe emissions but suffers in terms of efficiency. Compared to compression ignition engines, spark ignited engines have lower efficiency at both low and high loads, despite the inherent efficiency advantage of the Otto-cycle over either the Diesel-cycle or combined cycle [9]. A large reason for the disconnect between ideal and real-world efficiency is that the three-way catalyst, which is the best-available technology to meet the current, ultra-low emissions standards, requires stoichiometric conditions in the exhaust stream to operate properly. This requirement fixes the engine's air/fuel ratio (AFR) and to control torque the engine must therefore be throttled, which results in pumping work at low- and mid-load. Even if the aftertreatment system and emissions regulations allow the engine to run at a lean AFR, which significantly reduces pumping work, the lean limit of gasoline is such that pumping losses would still be incurred at the lightest loads. To overcome the lean limit, several alternative forms of combustion, such as HCCI or stratified charge, are used [10]. However, each new combustion mode offers different challenges and the market penetration of stratified charge engines is low (near zero in the US) while there are no HCCI engines in production for light duty applications.

Given the reality of pumping losses in stoichiometric gasoline engines at low loads, a common proposed solution is to reduce engine displacement and use a turbocharger to increase the power output. Since the vehicle power requirements will not change, the reduced engine displacement will lead to a shift in the typical engine operating range to higher levels of specific power output,

greatly reducing the need to operate the engine at the lowest loads [11] and therefore reducing pumping losses. In addition, shrinking the engine size and operating at higher specific power levels also reduces the relative penalty of frictional losses, especially when the change in engine displacement is accompanied by a reduction in the number of cylinders. If turbocharging and downsizing are not used, an alternative option to reduce pumping work is to employ variable valvetrain configurations, including cam phasing [12, 13] or, in some situations, variable valve lift and/or duration [14, 15].

Pumping losses, however, are not the only, or even the largest, impediment to high-efficiency gasoline engines. Knock and the measures required to overcome it have a significant effect on efficiency. The first step in addressing knock in a boosted engine is to reduce compression ratio. Even the most advanced gasoline engines reduce the compression ratio by at least 1.5 points when going from a naturally aspirated (NA) to boosted application [16], with many modern boosted GDI engines having a compression ratio of less than 10:1 (e.g. [17]). While it is possible to achieve good fuel consumption results at high power levels and reduced compression ratios [18], the fuel consumption at low to part load in these engines is often compromised from their high compression ratio, NA counterparts [19]. Additionally, the fuel economy advantages of the downsized, reduced compression ratio engine at high load conditions are often limited [20], particularly at engine speeds less than 2000 rpm and greater than 4000 rpm. At low engine speeds, knock is reduced with spark retard, which leads to sub-optimal combustion phasing and increases specific fuel consumption. At high engine speeds, knock presents less of a problem, but any spark retard at high power levels results in excessive exhaust temperatures, which require enrichment. Enrichment may also be necessary even at optimum combustion phasing to improve the durability of engine hardware at high specific power levels. The presence of the enrichment region presents two problems for LD manufacturers. First, the enrichment region results in poor fuel consumption, since much of the fuel passes through the engine unburned or only partially burned. Second, the high CO and HC emissions, which result from enrichment, mean that a vehicle whose engine operates in the enrichment region during a test - say on a highly loaded cycle like the US-06 or the SC-03 - will have considerable difficulties passing the CO or HC emissions standards. For consumers, downsizing has the potential for a large improvement in CO<sub>2</sub> emissions reduction, but low fuel consumption and good emissions at higher specific powers are necessary to fully implement a downsizing strategy.

Many researchers have proposed cooled EGR as a potential source of fuel consumption and emissions improvement in engines that operate at high specific power levels [21, 22, 23,

24, 25, 26]. However, the results of many of these studies, e.g. [21, 24, 25, 26], have shown that the level of improvement in fuel consumption decreases at higher EGR levels, primarily as a result of reduced engine stability due to a limit in the dilution tolerance of the engine. Similarly, the same fuel economy limit has been noted in lean-burn engines (e.g. [27]). The presence of the lean limit is a significant driving force in stratified charge engine development, as the stratified mode of operation significantly extends the lean limit of gasoline engines [28, 29, 30]. Besides stratified charge operation, which is less useful the closer one gets to stoichiometric operation, other researchers have used ignition system improvements or ignition enhancers to improve the dilution tolerance of gasoline engines.

There has been a significant amount of work performed to investigate the ability of the ignition system to improve the lean limit / dilution tolerance of gasoline engines. Many researchers have considered using jet-style combustion systems to improve the dilution tolerance of engines. These devices range from very high power devices like the plasma jet [1, 2] or railplug [3], which use very short discharges of extremely high energy. In the case of the plasma jet, the discharge ionizes all the matter in a small volume, expelling ionized gases at high velocity into the combustion chamber. The railplug, on the other hand, creates a moving arc that travels down a set of electrodes. This arc is typically enclosed in a cylinder and results in the expulsion of hot gases into the combustion chamber. In each case, the lean limit of the engine was extended considerably, but the high energy and short duration of the systems often result in significant durability problems and high levels of electronic noise. Other devices of this type are pre-chamber systems, where the spark plug is enclosed in a chamber with one or more exits, which result in high velocity jets when combustion occurs in the chamber. These jets, in turn, promote fast burn rates in the main combustion chamber and improve the lean limit. Examples of these systems include various types of fuelled pre-chambers [31, 32, 33, 34]. These systems do an excellent job of increasing the initial flame kernel volume through their jet development. Earlier, non-fuelled systems suffered from difficulties in gas exchange, but the fuelled pre-chamber designs have overcome that problem by adding a fuel system to the pre-chamber. However, this only works for lean-burn cases, where there is excess air in the charge. When the engine is stoichiometric, the addition of fuel to the pre-chamber serves less purpose, as there is no excess air to make use of the fuel. In these cases, the problem with gas exchange results in high levels of internal residual in the pre-chamber, which causes misfire at even low EGR levels.

Besides the igniters discussed above, there have been numerous other unique ignition system configurations that have tried to address various versions of the problem of extending the lean limit. These solutions range from multi-striking systems, using inductive systems [35, 36, 37], or

other, novel, short duration discharge systems (e.g. [38]), which improve the dilution tolerance by multiple discharges over a significant period of time. In many cases, the repetitive discharge increases the probability of an ignitable mixture being located in the spark gap and also increases the amount of energy released to the spark gap, helping overcome losses and increasing the propagation rate. In addition to these systems, there have been numerous other configurations, including higher energy systems (e.g. [27]) and those with unique electrical systems, many of which use RF electronics or microwaves [39, 40, 41, 42]. In addition, laser ignition has also been applied with a significant degree of success (see e.g. [8, 43, 44]). Laser ignition benefits ignition by moving the flame kernel away from potential heat sinks such as the cylinder head or electrodes. In all of these cases, the systems all provide a benefit in terms of lean limit extension, often a significant lean limit extension. However, in most cases there has been a considerable impediment to production implementation of the device, whether due to hardware cost, device durability or device energy consumption. The common theme among all systems was that an increase in either the length scale of the ignition event, through jet style devices (e.g. [1, 3, 33]) or volumetric ignition systems (e.g. [26, 42]), or the time scale, through repetitive discharge or continuous systems [35, 36, 37, 38], will result in a significant extension of the dilution tolerance. Since volumetric ignition sources often require unique, unproven hardware and a significant amount of power consumption or are impractical for high EGR applications (e.g. fuelled pre-chamber systems), the focus becomes on the extended duration systems, which, when taken to their limit, imply that a continuous discharge system will offer a significant improvement in the dilution tolerance of an engine. The purpose of the current study was to develop a system that has the durability characteristics of standard ignition systems while achieving the goal of a near-constant current in the spark gap. As presented here, SwRI has a new, patent-pending system that intends to achieve a near-constant current in the spark gap.

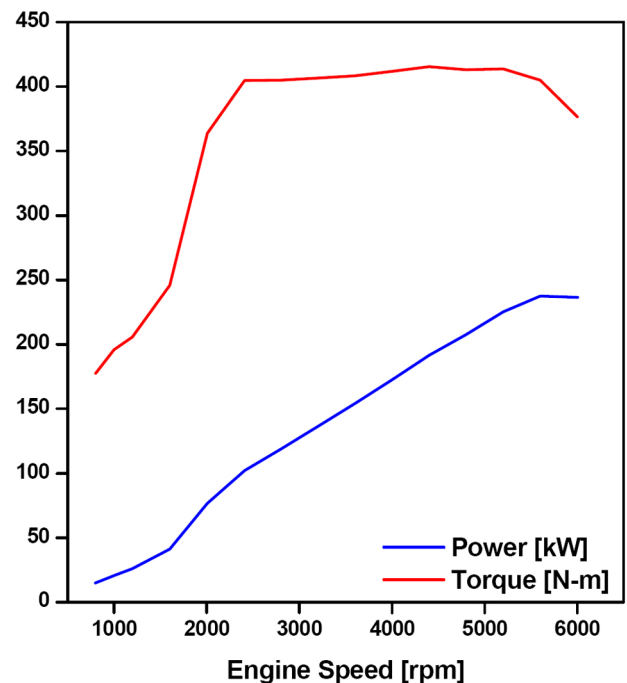


Figure 1. 2.4L engine (top: image; bottom: stock torque and power curves)

## EXPERIMENTAL SETUP

The engine used in this study was a 2.4L PFI engine (Figure 1) and has been used in previous studies at Southwest Research Institute [21, 22, 45]. The 2.4L engine has a peak torque of 400 N-m @ 2400 rpm and a peak power of 240 kW @ 5600 rpm (Figure 1). The engine was port fuel injected and also employed variable camshaft phasing on both the intake and exhaust cams. In stock form, the engine operates at 8.6:1 compression ratio. The initial work on this ignition system was performed at the stock CR, although previous tests have reported CR from 11.4:1 [22] to as high as 14:1 on this engine [45].

The ignition system for these tests was SwRI's Dual Coil Offset® (DCO®) ignition system, which will be further

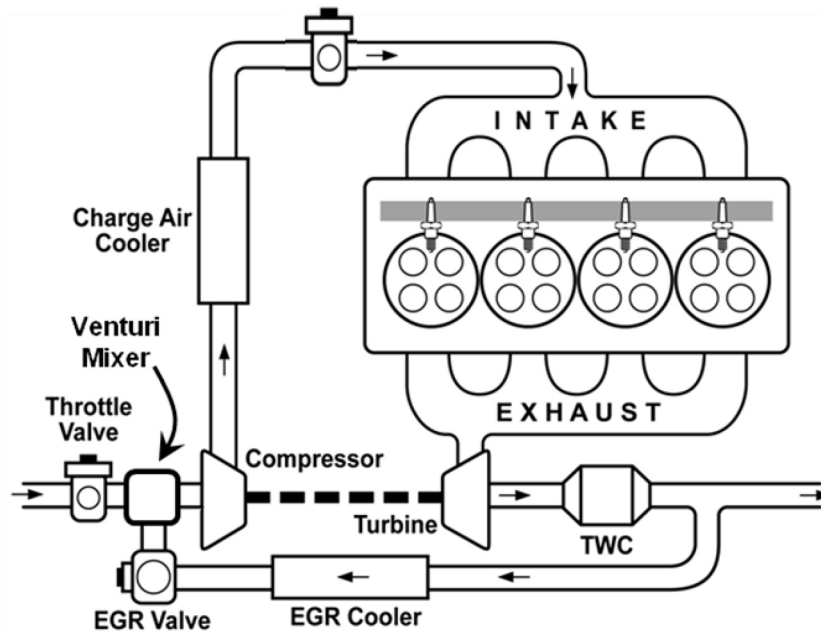


*Figure 2. EGR system layout for the 2.4L engine*

described in a separate section below. The spark plugs in the engine were upgraded from the stock plugs, which had relatively large, nickel-coated copper center electrodes, small gaps and traditional ground straps. The new plugs had a very fine ( $< 0.6$  mm) iridium center electrode and a similar, precious metal electrode on the ground strap. To promote dilution tolerance, the plugs were deployed with a very large gap of 1.65 mm.

A prototype EGR system was installed on the test engine, as shown in [Figure 2](#). The system consisted of an EGR cooler and valve, installed in a Low-Pressure Loop (LPL) configuration. A cooler was installed in the EGR loop, upstream of the EGR valve, to reduce the EGR temperature to  $\sim 100$ - $120^{\circ}$  C. The LPL EGR design was chosen to limit backpressure on the engine at high loads, reducing the amount of hot internal residual and knock at these conditions. At low loads, the engine has limited tolerance for cooled EGR and a bypass valve was employed to maximize the manifold temperature and improve EGR tolerance.

A Horiba 5 gas exhaust analyzer was used to measure carbon dioxide ( $\text{CO}_2$ ), carbon monoxide ( $\text{CO}$ ), oxygen ( $\text{O}_2$ ), total hydrocarbons (THC), nitric oxide and nitrogen dioxide ( $\text{NO}_x$ ) in undiluted engine exhaust.  $\text{CO}_2$  was also measured in the intake manifold. The EGR rate was calculated as the ratio between the  $\text{CO}_2$  level in the intake and the  $\text{CO}_2$  in the exhaust, correcting for ambient  $\text{CO}_2$  levels. Engine operating conditions (engine speed and load) varied during the course of the work and will be detailed in the appropriate discussion section. MBT spark timing and stoichiometric AFR were maintained unless specifically noted. MBT spark timing was

assumed when the location of 50% mass fraction burned (50% MFB) was located 6-8 degrees after top dead center (aTDC). Intake and exhaust cam phasing were optimized at each condition for best brake specific fuel consumption (BSFC). Intake manifold temperature was allowed to vary depending on operating condition, but not allowed to exceed  $50^{\circ}$  C. Fuel injection timing was on a closed intake valve and held constant for all test points at TDC of the compression stroke. All burn rate data was based on a  $720^{\circ}$  crank encoder and was calculated using the method for net heat release found in [46].

## IGNITION SYSTEM CONFIGURATION

Previous testing at SwRI has indicated that the primary factors that influence the engine's EGR tolerance are the amount of energy delivered by the ignition circuit and the discharge duration. In the initial efforts, a multi-striking ignition system was fabricated based on the principles outlined in [35]. In general, the principle of operation is that the ignition coil is initially charged completely for the first strike. Unlike normal, single-strike operation, the discharge of the coil is interrupted at approximately  $\frac{1}{3} - \frac{1}{2}$  of its nominal discharge duration and re-charged to full capacity. The cycle of partial discharge can be repeated several times, depending on the requirements of the operating condition for adequate stability until, on the final spark event, the coil is completely discharged. A plot showing the primary and secondary currents from a multi-sparking coil is shown below in [Figure 3](#) to illustrate this mode of operation.

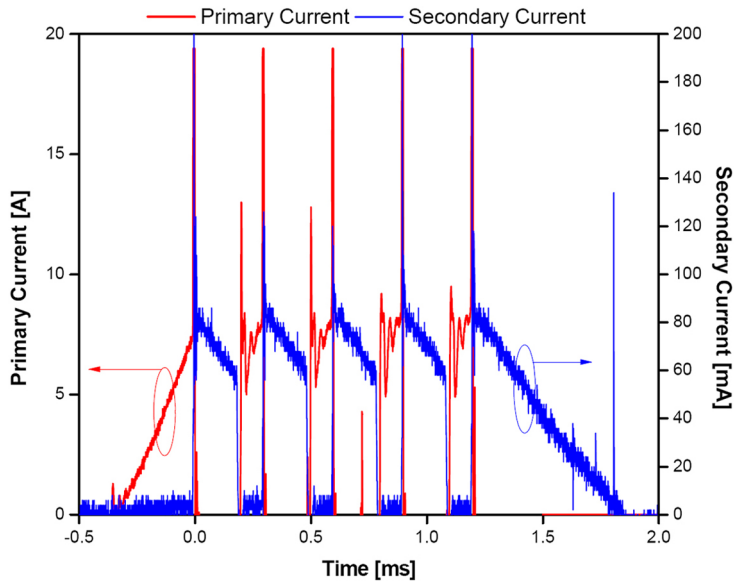


**Figure 3. Typical current traces (primary and secondary) from a multi-strike spark system operated at high primary voltages**

In this case, the OEM ignition coils are typical of modern, MPI applications -  $\sim 75$  mJ of energy per strike, 8 A primary current and  $\sim 90$  mA peak secondary current. Unlike the coils used in the early work on this discharge method, or in subsequent, more recent work [36], the dwell time for these coils at typical vehicle voltages was quite long ( $\sim 3$ -4 ms at 12 V). This duration was too long to provide adequate multi-strike potential and reducing the energy delivery was not considered a feasible option due to the relationship between secondary energy delivery and EGR tolerance described above. Instead, the coils were operated at elevated primary voltages to reduce the dwell time enough to achieve proper multi-striking operation, which is to maximize the duration of relatively high-current spark in the gap during the spark event.

The multi-strike system offers several advantages over a traditional, single discharge coil. First, when a low-impedance / short dwell time coil is used or the system is operated at high primary voltages, the “duty-cycle” of the spark, defined as the percentage of time that there is current flow in the gap, can approach nearly 75% and achieve a quasi-continuous discharge. Second, the duration of the spark can be extended without resorting to excessively large coils or, due to the nature of the typical coil discharge, excessively high secondary currents. Third, the current in the gap during the discharge remains high for most of the period, which is good for flame kernel growth and stability. Finally, the duration of the event can be tailored to the operating conditions to maximize energy efficiency. As the results will show, the multi-strike system improved EGR tolerance in the engine significantly.

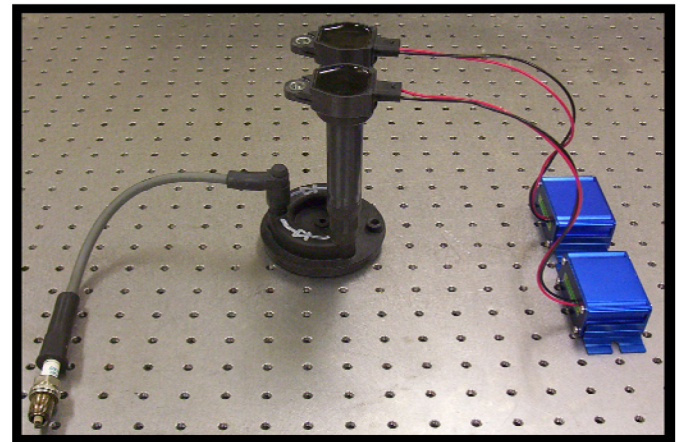
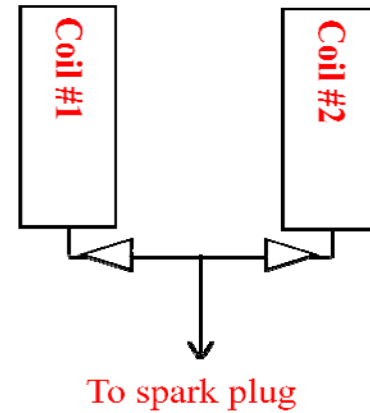


**Figure 4. Schematic and picture of SwRI's DCO ignition system with pencil coils**

Despite the EGR tolerance improvements from the M/S system, it was believed that a continuous discharge system would further improve the functionality of the system. Primarily, a continuous system, if designed properly, would have a fairly constant current level in the spark gap that could be a parameter of the engine operating conditions, allowing fully variable spark duration. In addition, the multiple breakdown events of the M/S system have the potential to cause spark noise interference with the vehicle electronics and a continuous system would not have this problem. However, previous attempts to design a continuous discharge system have resulted in systems that are either not practical for production due to cost, packaging or energy consumption reasons. In an attempt to overcome these deficiencies, a system was developed that uses production-style hardware to accomplish the goal of continuous discharge. SwRI's DCO™ system consists of two standard inductive coils connected to a common spark plug through a diode block (see Figure 4). The diode block used in the laboratory application is one typically used on racing applications for redundant ignition systems, but it is envisioned that, for production purposes, the diode system could be integrated into a standard coil pack. With two coils now discharging through a common sparkplug, the coils in the system can now be fired simultaneously or in an