

A Comparison of Spray-Guided Stratified-Charge Combustion Performance with Outwardly-Opening Piezo and Multi-Hole Solenoid Injectors

2011-01-1217

Published
04/12/2011

James Smith

US Environmental Protection Agency

Gerald Szekely Jr, Arun Solomon and Scott Parrish
General Motors Company

Copyright © 2011 SAE International

doi:[10.4271/2011-01-1217](https://doi.org/10.4271/2011-01-1217)

ABSTRACT

This investigation was aimed at measuring the relative performance of two spray-guided, single-cylinder, spark-ignited direct-injected (SIDI) engine combustion system designs. The first utilizes an outwardly-opening poppet, piezo-actuated injector, and the second a conventional, solenoid operated, inwardly-opening multi-hole injector. The single-cylinder engine tests were limited to steady state, warmed-up conditions. The comparison showed that these two spray-guided combustion systems with two very different sprays had surprisingly close results and only differed in some details. Combustion stability and smoke emissions of the systems are comparable to each other over most of the load range. Over a simulated Federal Test Procedure (FTP) cycle, the multi-hole system had 15% lower hydrocarbon and 18% lower carbon monoxide emissions. Most significantly, the spray guided system with the multi-hole spray ended up having 3.0% lower fuel consumption than the piezo system over the simulated FTP cycle.

INTRODUCTION

The primary goal of this paper is to compare the steady-state, warmed-up, single-cylinder engine performance and emissions of a multi-hole spray-guided combustion system to a piezo spray-guided combustion system. The first is a spray produced by a conventional solenoid-operated inwardly-opening multi-hole injector. The second is a piezo-actuated outwardly-opening fuel injector. The sprays produced by each of these injectors are markedly different, and therefore it

is of interest to evaluate and compare the performance of the two combustion systems.

Based on the design of the piezo injector and early spray bench comparisons, the piezo injector seems to offer performance advantages relative to a solenoid injector when injector and spray characteristics are compared. Briefly, the piezo injector has a larger linear working flow range, higher static flow rate, has the capability of rapid multiple-pulsing producing closely spaced multiple injection events, can inject very small quantities precisely, has the potential of variable needle-lift, and because of its outwardly-opening poppet design is deemed more resistant to fouling. Further, the spray produced by a piezo injector is typically better atomized, less penetrating, and produces a more compact mixture cloud. It is expected at the outset that each of the above superior characteristics of a piezo injector should lead to superior engine combustion robustness, fuel economy, emissions, and control benefits relative to a solenoid-operated multi-hole injector. It is also widely assumed that the stratified charge operating region with a piezo injector will be larger. The question then is whether or not a spray-guided engine with a piezo injector actually delivers these expected benefits relative to a solenoid operated multi-hole injector.

This paper seeks to partially answer the above question. Engine performance and emissions with the two fuel injection approaches are compared directly. The spray-guided combustion system designs for each approach have been developed at the General Motors Research and Development center over the past few years and have reached a level of

maturity sufficient enough to be compared against each other. Very early results of the piezo combustion system have been previously published [1]¹, while various aspects of the multi-hole development work have been presented in references [2,3,4, and 5].

Spray-guided engines using the piezo fuel injector have been introduced for sale in Europe. For MY 2007, both 6-cylinder and 4-cylinder engines were introduced [6,7]. These engines employ a spray-guided direct-injection stratified charge combustion process using piezo injectors and a direct-injection gasoline fuel system [8,9]. It is implied in these studies that a piezo fuel spray is essential for the successful design of a spray-guided stratified charge engine. However, no comparative data is presented using alternative injectors producing swirl or multi-hole sprays with different characteristics. In fact, it is suggested that first generation stratified-charge combustion systems were limited to wall or air-guided stratified charge approaches because only solenoid-operated swirl or multi-hole injectors and injection systems were available at that time. It was only with the advent and availability of the piezo injector and its spray characteristics that the design of second generation, central-injection, closely-spaced (spark plug and injector), spray-guided, stratified charge combustion system was possible. This present investigation will either validate or refute the above statement with preliminary results. It is possible that benefits of spray-guided stratified charge relative to wall and air-guided stratified charge are erroneously attributed to the piezo fuel spray and injector. For these engines, fuel consumption improvements on the European drive cycle (NEDC) test cycle on the order of 20% relative to a baseline throttled homogeneous-charge engine, and 14% relative to an advanced variable-valve actuation engine are reported. These fuel consumption improvements are at a EURO 4 emissions level.

Another spray-guided combustion engine was introduced in Europe in June 2006 [10, 11]. The piezo fuel injection system for that engine has also been described in an earlier study [12]. In these studies, some attempts have been made to investigate and compare swirl, multi-hole and piezo sprays for their suitability for spray-guided stratified-charge application. However, these investigations largely involved the application of Computational Fluid Dynamics (CFD) and optical diagnostics at one or two operating conditions, which revealed that the piezo spray evaporated faster, penetrated less and benefited from multiple injections. Their conclusion was that a piezo spray is better suited for spray-guided stratified charge application. However, in contrast with the study presented here, no detailed data from metal engines at various speeds and loads were compared to gain a more comprehensive evaluation of the merits of each type of fuel

spray. For this engine, Reference [13] reports a fuel consumption improvement of 10% on the European combined driving cycle relative to its counterpart port-fuel-injection (PFI) gasoline baseline engine.

The present study also has to be considered preliminary in nature, since it is limited to steady-state, warmed-up test conditions with a single-cylinder engine. A more complete investigation would include cold operation over a transient test cycle with a multi cylinder engine. However, this paper is a first step towards the goal of making an informed technical choice between a piezo and a multi-hole injector for spray-guided stratified-charge combustion applications.

EXPERIMENTAL SETUP

ENGINE HARDWARE

For an accurate means of comparison, two single-cylinder research engines were constructed. The bore (86.0 mm) and stroke (94.6 mm) were identical between the two engines as was the compression ratio (12.0:1). The main features of both combustion chambers were similar; both having four valves and a centrally located fuel injector and spark plug. Both engines used the same cam profiles and similar hydraulic cam phasers, having 60° of phasing authority. Both also featured charge motion devices in the form of an intake port throttle, which could be modulated to block one of the two intake ports, resulting in various levels of swirl and tumble.

Except for the similarities noted above, the multi-hole and the piezo spray guided combustion systems were independently developed over the period of several years. Geometric variables for these combustion systems include spray angle, spray pattern (and number of holes in the case of the multi-hole injector), spark plug gap location, spark plug electrode design, and piston bowl shape. Operating variables investigated and optimized include swirl ratio, cam phasing, EGR level, and multiple injection strategies. Each design was allowed to evolve independently to obtain optimum performance. While an absolute optimum cannot be claimed for either design, the current status of both designs was deemed to be sufficient to be compared fairly against each other. The details of the development process for both sprays is beyond the scope of this paper, although a brief description of the major differences between the piezo and multi-hole spray is provided next. To maintain a fair comparison, both fuel systems were operated at a rail pressure of 20 MPa for all the test conditions reported here.

The outwardly opening piezo injector produces a significantly different spray compared to the multi-hole injector. Therefore, consideration was made in the design of both engines to optimize the relationship between the spark

¹Numbers in parenthesis refer to references at the end of the paper.

plug and injector, as well as the shape of the piston to best suit the injector/spray being used. Both systems utilized a piston with a bowl-type feature, although the exact geometry of the bowl was catered to the injector being used. The piston in the piezo system featured a wider, shallower bowl, reflecting the less-penetrating nature of the spray. In contrast, the piston in the multi-hole system had a deeper bowl. The Mie scattering images of the spray can be seen in [Figure 1](#).

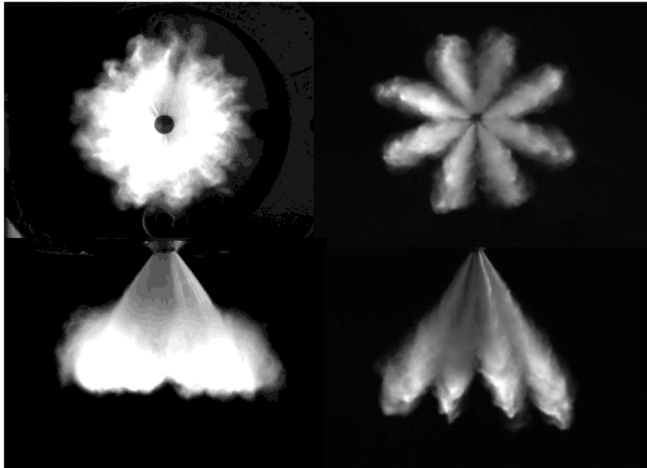


Figure 1. Mie scattering images of the Piezo spray (Left) and the multi-hole spray (Right).

The spatial relationship between the spark plug and fuel injector plays a key role in the spray-guided stratified-charge combustion chamber. Injector spray characteristics determine the optimum location of the spark gap. The piezo spray is conical in nature, forming a thin sheet of fuel of nominally equal thickness, independent of injector rotation. Conversely, the multi-hole spray, offers eight individual spray jets spaced at 45° intervals around the injector tip. For these reasons, the piezo system is insensitive to injector rotation, but the multi-hole system has the potential to be sensitive to injector rotation. In extreme cases, one of the eight fuel jets could be directed toward the spark plug or two jets could be passing on both sides of the spark plug in a straddling geometry. Directing a jet toward the spark plug raises concerns over spark plug durability due to relatively cold fuel hitting the hot spark plug causing thermal fatigue. There are also concerns regarding spark plug fouling during cold-start and warm-up conditions. For these reasons, all multi-hole experiments were conducted with the plumes arranged to straddle the spark plug.

For both systems, spark plug geometry and orientation could have a significant impact on mixture preparation and combustion. Changes made to the ground strap shape and rotational position impact mixture preparation by changing the aerodynamic environment near the spark gap. This can act to slow the passing fuel cloud, which may help ignitability. In addition, velocity near the gap will be affected. This may help

combustion by moving the flame kernel away from the electrodes, a source of significant heat loss, and also by moving the kernel to a region of more favorable mixture fraction. With a near-infinite combination of spark plug geometry and rotational position available, the scope of this study was limited to one case, generally regarded as the optimum condition. In this condition, a standard J-Gap spark plug geometry is used (albeit with an extended protrusion over more conventional spark plugs) and the ground strap is oriented at the position farthest from the fuel injector.

It must be noted that once a common cylinder head was chosen, the subsequent experimental studies to determine optimum injector location, spark plug location relative to the injector, swirl level, piston-bowl geometry, and other combustion system parameters were all developed independently of each other. Through developing both combustion systems around their respective fuel injectors, reasonable confidence is gained that any performance differences are due to physical differences in mixture preparation and combustion inherent to the injector type being used. In contrast, using one combustion chamber for both injectors would place one injector at an inherent disadvantage and false conclusions would likely be drawn.

CONTROLS

Both engines were controlled using engine controllers developed by GM. In addition to common operating parameters, such as spark advance, injection duration and injection timing, other engine operating parameters were also controlled with the set point controller. These included independent phasing of the exhaust and intake camshafts, fuel pressure, and multiple fuel injection events (when used). While automatic control functionality was available, exhaust gas recirculation (EGR) rates and air-fuel ratios were controlled manually for each test.

INSTRUMENTATION

Each engine was fully instrumented to record the ambient and boundary conditions for each experiment. This included barometric pressure, ambient temperature, intake/exhaust pressures and temperatures, oil/coolant temperatures, fuel temperature and pressure, and exhaust gas temperature and pressure. A critical orifice system was used to accurately measure intake air flow rate. In addition, fuel flow was measured using a high-pressure, low-volume, positive-displacement flow meter.

The fuel used for all the tests was Indolene, with an octane number of 92. Exhaust gas analysis was completed using a multi-function exhaust gas analyzer. This unit was capable of providing hydrocarbon emissions (on both wet & dry basis), nitric oxides (NO_x), carbon monoxide (CO), and carbon dioxide (CO₂) emissions. For validation purposes, the carbon

and oxygen balance air-fuel ratios, calculated from measurements by the exhaust gas sampling unit, were compared with the air-fuel ratio given by the measured fueling rate and measured air flow rate. All three air-fuel ratios were required to be within 0.2 for each test. In addition to the emissions bench, a filter smoke meter was also used as a means of identifying soot/particulate matter concentration.

Cylinder pressure was measured using a fast-response pressure transducer. The transducer was outfitted with a flame arrestor to minimize thermal shock. The signal was pegged to the intake manifold pressure late in the intake stroke and further processed by a real-time combustion analysis system. To ensure repeatable and reliable data, motoring data was taken at the beginning and end of each testing day. In addition, an early-injected, homogeneous, stoichiometric firing control point was also tested at the beginning of each day. The peak cylinder pressure, indicated mean effective pressure (IMEP), and exhaust emissions were monitored and if any discrepancies were found, corrective actions were taken before test results were adversely affected.

DATA PROCESSING

Slowly varying parameters, such as fluid temperatures, manifold pressures, EGR rate, and emissions data, were recorded at an approximate rate of 2 samples per second when taking data. During a normal experimental run, 200 samples would be recorded then averaged and stored. Simultaneously, a higher-speed data acquisition system would be recording cylinder pressure at one sample per crank-angle-degree for 1000 consecutive cycles. This system would not only supply real-time pressure traces, but perform a pressure analysis which provided real-time mean effective pressure (MEP) data with statistical analysis such as coefficient of variances (CoV), as well as crank angle location of the 50% mass-burned-fraction point (CA50), knock parameters, and a variety of cylinder pressure-related parameters.

RESULTS

ENGINE PERFORMANCE

Fuel Consumption

As one of the primary motivations for pursuing direct fuel injection, fuel consumption is of utmost importance. A direct comparison of the piezo-electric and multi-hole combustion systems will determine if the two deliver similar fuel economy. This comparison was conducted using two methods: 1) speed and load hooks, and 2) drive cycles simulated with steady-state test points.

For the most basic comparison, testing was conducted under varying speed or load conditions while holding the other constant. Specifically, speed was varied while at a constant

fueling rate (speed hook), and load (fueling rate) was varied while speed was held constant (load hook). These two tests centered around an engine speed of 2000 revolutions per minute (RPM), and 2.0 bar brake mean effective pressure (BMEP) (roughly equivalent to 9.3 mg of injected fuel per cycle) test point, which has been found to strongly influence overall drive cycle performance.

For the load and speed hooks each injection system was independently optimized. All piezo tests were run with multi-pulsed fuel injection (two to three injections per cycle), primarily to maintain acceptable combustion stability. The multi-hole, on the other hand, was run with a number of injection strategies ranging from close-spaced and wide-spaced double-pulsing to a single injection event. The reasons behind this were stability at light loads and fuel consumption and smoke reduction at higher loads.

Figure 2 shows a comparison of the net-specific fuel consumption (NSFC) over a load range from approximately 50 kPa to 700 kPa net mean effective pressure (NMEP) at 2000 RPM. Both engines display comparable fuel consumption, with the multi-hole showing a slight benefit between 150 and 400 kPa NMEP. At very light loads (<100 kPa), the piezo was more efficient, which could be due to the finer atomization and lower penetration of the piezo spray which lead to more optimum combustion phasing. These load hook results indicate that both systems perform similarly in the high-load stratified charge region. Beyond 500 kPa, both systems transition to a more homogeneous type operating condition characterized by two injection events. The first is an early injection event around 300 degrees bTDC, where most of the fuel is injected. This is followed by a second, short injection event typically between 60 - 40 degrees bTDC. This second injection event is usually shortly before ignition timing. Without transitioning to this condition, both systems lose stability and fuel consumption benefits. In the homogeneous regime, both systems achieved approximately similar fuel consumption.

Figure 3 compares fuel consumption from 600 RPM to 3500 RPM at a fueling rate of 9.3 mg per cycle. While overall very similar, the multi-hole injection system tends to yield lower fuel consumption at lower engine speeds, while the piezo system excels at higher engine speeds. At no speed, however, was this difference greater than about 3%. These speed hook results for fuel consumption as well as those for combustion stability and hydrocarbon (HC) emissions to be seen later, indicate that the piezo system generally performed better at the high-speed stratified charge region.

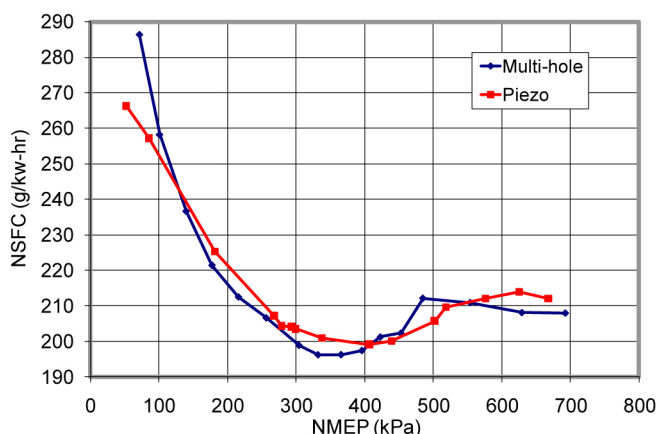


Figure 2. Fuel consumption as a function of load at 2000 RPM.

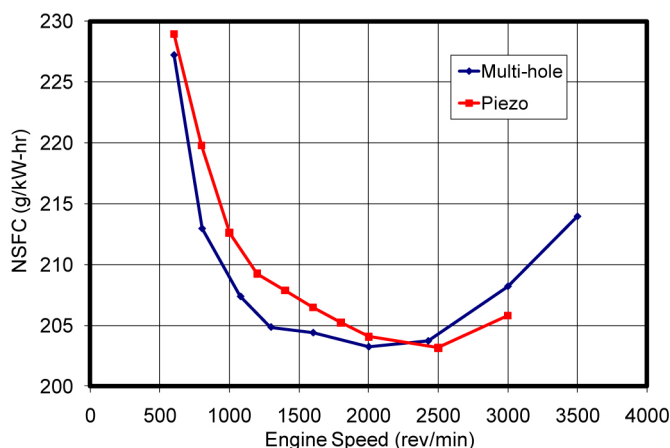


Figure 3. Fuel consumption as a function of speed at 9.3mg of fuel per cycle.

Figure 4 shows the NEDC 5-point data. The center point, 2000 RPM / 2.0 bar, is generally considered to be the most important in regards to road load on the NEDC drive cycle. As is shown, both systems achieve the same fuel consumption here, in addition to also being the same at the low-speed, high-load acceleration point (1000 RPM, 3.0 bar). The piezo system again tended to do better at very light loads, while the multi-hole achieved better fuel economy at the highest speed-load point.

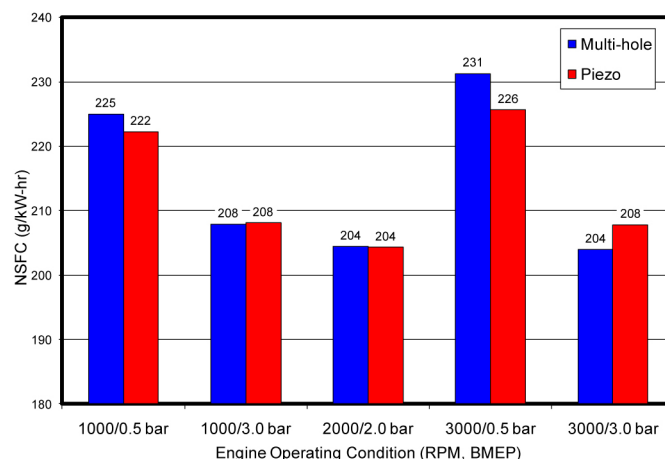


Figure 4. Fuel consumption over the NEDC 5-Point test.

Figure 5 shows the FTP 10-point comparison. As in the load hook, certain points in the multi-hole dataset were run with multiple fuel injection events, while the piezo system was run almost exclusively double-pulsed. The exception for both cases is point 7 which has a load high enough to warrant a more traditional, intake-stroke injection, homogenous-charge operation. Across all points, the multi-hole system achieved better fuel consumption. This is particularly true at the light load points (points 1, 3, and 8). At the higher speed, higher load points, the multi-hole system maintained an approximate 2% benefit over the piezo system.

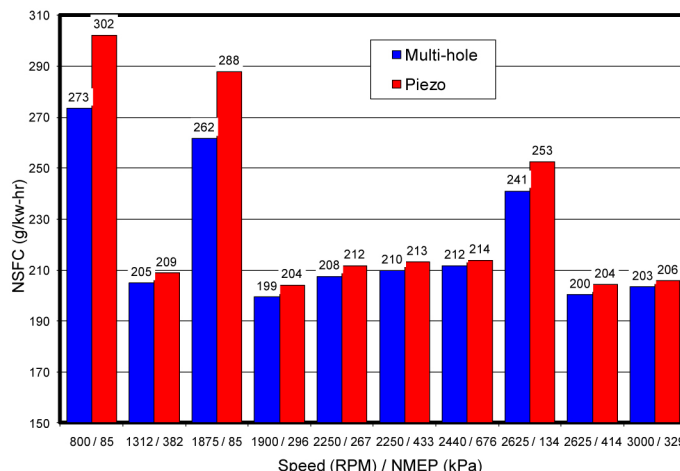


Figure 5. Fuel consumption over the FTP 10-Point test.

Peak Load

In addition to the fuel economy benefit, direct fuel injection has the potential to increase wide-open-throttle (WOT) performance. This is mainly achieved through cooling of the intake air due to the evaporation of the liquid fuel. When timed correctly, this can allow a higher mass of air to enter the cylinder, and thus allow more fuel to be injected. The cooling of the charge by the spray is also expected to alter knock characteristics. Since the piezo and multi-hole sprays are significantly different, it is of interest to compare the two under WOT conditions to see which yields higher load. For this test, both engines were run at 2000 RPM, 14.7:1 air-fuel ratio and knock-limited spark timing. The end-of-injection (EOI) timing was varied throughout the intake and early compression stroke. Since the intake system was essentially the same for both spray-guided systems in this test, differences in performance can be attributed to the spray and combustion characteristics alone.

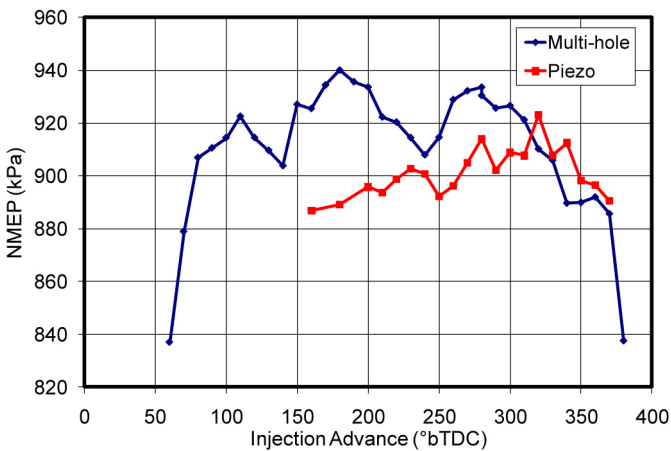


Figure 6. Peak Load performance at 2000 RPM, WOT.

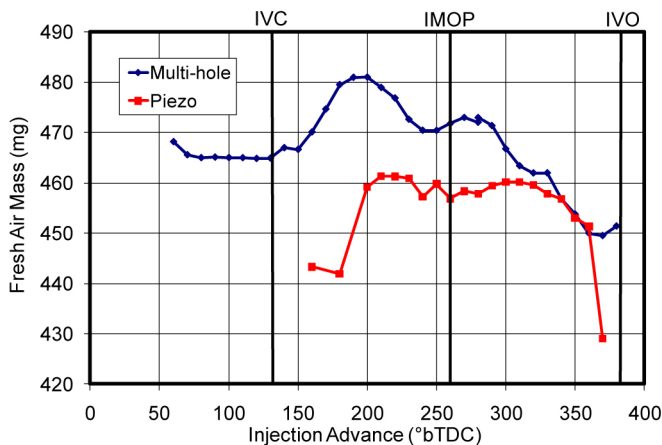


Figure 7. Fresh Air Induction at 2000 RPM, WOT.

Figure 6 shows the load as a function of end-of-injection for both combustion systems. Compared to a typical production engine, these peak NMEP levels are low. This is because for the single-cylinder engines tested here, no enhanced charging effects due to tuned intake manifolds and runners exist. The object of this particular test was simply to discern relative differences between the two fuel injectors and not the attaining of maximum absolute NMEP. The piezo system would not operate well at injection timings less than 160 °bTDC. The multi-hole system, at an injection timing of 180 °bTDC, is capable of producing a 2% higher peak load than the piezo system at an injection timing of 320 °bTDC. This extra output is a direct result of the multi-hole system being able to induct more air as shown in Figure 7. The multi-hole spray is directed more downward into the combustion chamber and penetrates faster. Therefore, the faster air engagement and air entrainment by the multi-hole spray helps to cool the charge earlier, thus inducing more air than the piezo spray.

While the two systems produce similar loads at early injection timings, the piezo system decreases in performance as injection is retarded and the intake valve opens, while the multi-hole system gains as EOI timings are retarded toward top-dead-center-firing. While there is surely a combination of second order effects that can produce this result, the first order effect is the airflow behavior, since as seen from figures 6 and 7 the load and the airflow for each system correlate well.

It is noted that while the multi-hole system inducted 5% more fresh charge, it resulted in only a 2% increase in load. This result is due to knock. Figure 8 shows spark timing for both systems to be equally knock-limited at earlier injection timings. However, at later injection timings the multi-hole system is more knock-limited, which is probably because there is more charge. It could also be because it is less mixed at these later injection timings and therefore the correspondence with airflow is not one-to-one. Thus, the peak in engine load for the multi-hole system as injection timing is retarded is largely a tradeoff between an increase in airflow due to spray cooling and a decrease in knock tolerance due to insufficient mixing.

Based on the comparison of data over the range of operating conditions just discussed, the fuel consumption benefits appear to be similar between the piezo and multi-hole combustion systems. If anything, the multi-hole system shows a small (1-2%), but consistent advantage over the piezo system over many of the operating conditions studied. In addition to showing similar if not better fuel economy, the multi-hole combustion system also produced a higher peak load at 2000 RPM, which was attributed to more efficient spray-cooling of the charge which increased volumetric efficiency.