

A Detailed Comparison of Emissions and Combustion Performance Between Optical and Metal Single-Cylinder Diesel Engines at Low Temperature Combustion Conditions

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ABSTRACT

A detailed comparison of cylinder pressure derived combustion performance and engine-out emissions is made between an all-metal single-cylinder light-duty diesel engine and a geometrically equivalent engine designed for optical accessibility. The metal and optically accessible single-cylinder engines have the same nominal geometry, including cylinder head, piston bowl shape and valve cutouts, bore, stroke, valve lift profiles, and fuel injection system. The bulk gas thermodynamic state near TDC and load of the two engines are closely matched by adjusting the optical engine intake mass flow and composition, intake temperature, and fueling rate for a highly dilute, low temperature combustion (LTC) operating condition with an intake O_2 concentration of 9%. Subsequent start of injection (SOI) sweeps compare the emissions trends of UHC, CO, NO_x , and soot, as well as ignition delay and fuel consumption. The effect of EGR composition is also investigated to determine the level of chemical equivalency required for adequate EGR simulation in an optical engine. Five simulated EGR conditions are compared to evaluate the influence of water vapor, CO, and UHC.

Results show that the optical engine pressure and heat release characteristics are influenced by the larger crevice volumes and the compliance of the extended optical piston. Greater fueling rates are also needed in the optical engine to achieve an equivalent load. The same general trends in emissions behavior are found in

both engines, capturing the location of minimum UHC and CO emissions with changes in SOI. In addition, quantitative emissions levels agree well. Simulated EGR composition is found to have a minor influence on combustion behavior and emissions levels, but does not affect the general emissions trends.

INTRODUCTION

Internal combustion (IC) engines are the most prevalent powertrain in today's automotive-dominated global transportation infrastructure, and have been so for over 100 years. Despite the long history of IC engines, further improvements in efficiency and reductions in emissions are required due to increasing air pollution, evidence of CO_2 -induced climate change, and the depletion of petroleum-based fuel resources. Achieving the desired improvements in an already mature technology will require a greater understanding of in-cylinder combustion processes and the ability to accurately model their behavior with computer simulations.

Optically-accessible IC engines provide the opportunity to quantitatively explore flow and combustion processes using laser diagnostics and to gain greater physical insight into the sources of engine-out emissions, yielding significant advancements in our understanding of both spark ignition and compression ignition combustion. Both the insight obtained and the quantitative data gathered for model validation allow, in turn, the development of cleaner and more efficient IC engines.

However, in order to ensure that the information obtained from optical engines is truly useful and not misleading, it is necessary to verify that the performance and emissions behavior in the metal engine can be faithfully duplicated by the optical engine. Despite nearly 50 years of optical engine studies since Bowditch's seminal work [1], detailed comparisons of both combustion performance and emissions between metal and optical engines are few.

There are inherent and unavoidable differences between optical and metal engines. The primary areas in which optical and metal engines differ are materials, heat transfer, geometry, and exhaust gas recirculation (EGR) composition.

Materials:

To obtain optical access into the combustion chamber, transparent viewing windows are typically placed into the cylinder walls, head, and/or an extended Bowditch-type piston. Optical property considerations (minimal birefringence, no UV fluorescence, etc.) often dictate that the windows be made from fused silica (quartz), which is a brittle material. Significant design effort is invested to prevent failure of the windows at high loads and boosted conditions while minimizing piston mass.

Heat Transfer:

Moreover, the thermal conductivity of quartz is extremely low. Surface temperatures can thus reach levels uncharacteristic of metal engines, and generate additional thermal stresses that can lead to failure [2]. Exacerbating the influence of low window thermal conductivity is the reduction in combustion chamber cooling capacity, due to the surface area occupied by the windows and the necessity to restrict cooling passages to enable window installation. Maintaining moderate temperatures is one of the factors motivating skip-fired operation of optical engines.

Geometry:

Optical access requirements also lead to compromises in the combustion chamber geometry of optical engines. A side-view enabling observation of the flow structure and mixture distribution in a vertical plane within the bowl is required to clearly understand the mixing and combustion processes. Consequently, the upper compression rings must be located below the piston bowl floor. The resulting large top ring-land crevice yields a lower compression ratio (CR) for optical engines than for metal engines. Moreover, despite the critical importance of bowl geometry if the relevant flow phenomena and spray-wall interactions are to be preserved, small changes in the bowl geometry can often significantly enhance side-view imaging capabilities [3]. Additional geometric variations may also be caused by removal of valve cut-outs from the piston top [3], installation of a window in place of one of the exhaust valves [4], and compressive strain of the

extended piston assembly at high cylinder pressures [5]. Finally, large optical piston mass may cause dynamic variations in the combustion chamber geometry.

EGR Composition:

As noted above, skip-firing of optical engines is required to control combustion chamber temperatures. Additional factors motivating skip-firing include the need to limit pressure and heat loading on the (often unlubricated) ring pack, the desire to limit fouling of optical surfaces, and the inability of some commonly used laser and imaging diagnostics to operate faster than 10 Hz. When the engine is operated in a skip-fired mode, however, it is not possible to use the exhaust for EGR because it is diluted by motored cycles.

For complete, stoichiometric combustion, engine exhaust gases will be a mixture of N_2 , CO_2 , and H_2O . However, typical diesel combustion is neither stoichiometric nor complete, and the exhaust gases can contain significant levels of O_2 , NO/NO_2 , unburned hydrocarbons (UHC), CO , and H_2 —as well as numerous trace species. Furthermore, with EGR cooling, some of the H_2O vapor in the EGR stream may be condensed and removed, lowering the concentration of H_2O vapor in the EGR and further increasing the deviation from a stoichiometric composition. Ideally, simulated EGR should have the same chemical composition as real EGR. It is not feasible, though, to replicate the complex chemical composition of real EGR, and some level of approximation is required. How closely the simulated EGR must match real EGR before the difference significantly impacts the combustion process is an unresolved question.

Many variations of simulated EGR have been used for optical engine studies, including: simple N_2 dilution [4], N_2 and CO_2 [6, 7], and stoichiometric products of complete combustion (N_2 , CO_2 , and H_2O) [8]. Studies of the impact of EGR composition have shown the importance of maintaining the specific heat ratio of real EGR gases for matching ignition phasing and combustion temperature [9]. Additionally, chemical effects associated with the dissociation of CO_2 and H_2O have also been shown to influence combustion and emissions formation processes [10-12]. Finally, it is reasonable to assume that for conditions having significant CO and UHC emissions, inclusion of those species into the simulated EGR will be required to reproduce correct behavior, if only to account for their intrinsic heating value. However, to the authors' knowledge, no studies have systematically examined the influence of CO or UHC in simulated EGR.

The current study aims to match the geometry, near-TDC thermodynamic conditions, and load of an optical engine as faithfully as possible to that of a metal engine, and to closely compare the ensuing combustion performance and emissions behavior of the two engines. Intake charge composition matching was performed using simulated EGR composed of N_2 , CO_2 , H_2O , CO .

and UHC (represented as C_3H_8). Subsequently, injection timing sweeps were employed to examine the ability of the optical engine to reproduce metal engine emissions trends. Finally, the level of precision required for simulated EGR is systematically investigated through variations in EGR composition.

EXPERIMENTAL FACILITIES

The optical engine experiments for this study were performed in the Combustion Research Facility at Sandia National Laboratories, while the metal engine experiments were performed in the Engine Research Center at the University of Wisconsin-Madison.

RESEARCH ENGINES

Both single-cylinder research engines are derived from a 4-cylinder General Motors 1.9L light-duty diesel engine. Specific geometrical parameters for both engines, as well as valve timing events, are listed in Table 1. The bore, stroke, displacement volume, and bowl profile are identical for both the metal and optical engines. The bowl profile for the two engines has been modified from the production engine to reduce the effective compression ratio in the metal engine from 17.5 to roughly 16.6 in order to facilitate low temperature combustion.

In addition to preserving the metal engine bowl profile, the optical engine retains the piston top valve cut-outs as well as the details of the head crevices. The top ring-land volume and, to a lesser extent, the squish volume, are the only geometrical deviations. Figure 1 details the dimensions of these volumes. The ring pack on the optical engine is positioned lower on the piston, due to both structural and optical considerations. However, the ring land width has been maintained as small as is feasible, and equals the metal engine value. Although the squish height is slightly larger on the optical engine, its value is well within the production engine tolerances.

Prediction of the effective compression ratio from the measured engine geometry is not straight-forward. For example, in the optical engine the TDC clearance

	Optical	Metal
A: Squish Height	0.78 mm	0.72 mm
B: Ring Land Height	29.57 mm	8.0 mm
C: Ring Land Width	0.18 mm	0.18 mm

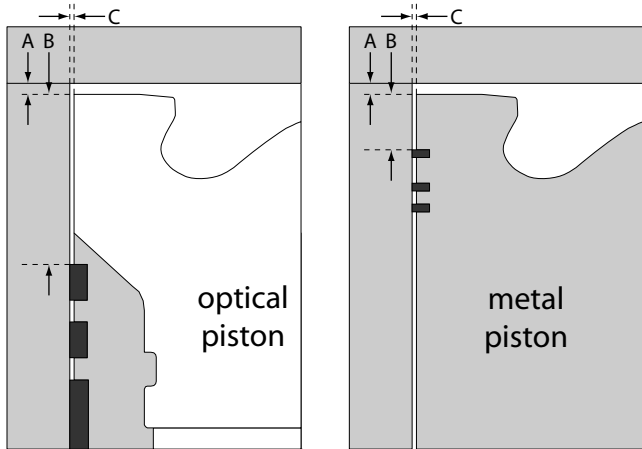


Figure 1. TDC clearance volume comparison schematic. Although not drawn precisely to scale, the bowl profile is accurately represented.

volume, estimated by “cc’ing”¹ the piston bowl, valve cut-outs, top-ring land, and head crevices (including the crevice around the injector and the glow plug hole which houses the in-cylinder pressure transducer) is $30.42 \pm 0.22 \text{ cm}^3$, a value that agrees with calculated volumes to within approximately 1/2 of the measurement uncertainty. The calculated geometric compression ratio based on the full stroke is 16.7 ± 0.1 . However, when modeling the optical engine operation in the 1-D combustion simulator WAVE 7.1, in order to match the computed motored peak pressure to the measured motored peak pressure, the effective compression ratio had to be reduced from the measured value of 16.7 down to 13.95. Using the value of effective compression ratio determined numerically by WAVE, there is a 20% difference in the effective TDC clearance volumes between the two engines.

To examine the possible reasons for this variation, the various factors that could influence the clearance volume are considered, including dynamic variations in the length of the extended piston assembly. This length can vary due to both thermal expansion as well as loading from the cylinder pressure. When assembling the engine, thermal expansion is accounted for by increasing the cold squish height by an amount equal to the anticipated thermal expansion at the engine speed and load being investigated. The hot squish height is verified after bringing the engine to a semi-steady temperature characteristic of the testing schedule. Because the optical engine is designed to allow rapid access to the combustion chamber for cleaning the optical surfaces, the hot squish height can be measured before significant cooling of the extended piston

Table 1. Engine Specification and Valve Timing Comparison (differences are highlighted)

	Metal	Optical
Bore	82.0 [mm]	
Stroke	90.4 [mm]	
Displacement Volume	0.4774 [L]	
Effective CR	16.6	13.95
Squish Height (cold)	0.72 [mm]	0.78 [mm]

	Metal	Optical
IVO	356°CA	358°CA
IVC	-146°CA	-144°CA
EVO	136°CA	
EVC	-350°CA	

¹ A process wherein a pipette is used to precisely fill the piston bowl and volumes with liquid, thereby accurately determining the volume in cubic centimeters (“cc”).

assembly occurs. The thermal expansion of the piston assembly was measured in this manner to be approximately 0.4 mm, which would result in an increase in compression ratio of roughly 1.2.

A second factor which can influence the length of the extended piston assembly is piston compression under load. To account for this factor, the deflection of the optical piston assembly was measured under load using a hydraulic press, and the squish height is reduced by an amount equal to the anticipated piston compression near TDC in a motored engine cycle. At 8500 kPa, this compression is approximately 0.23 mm resulting in a reduction in compression ratio of 0.6.

The intake valve closing (IVC) timing could also reduce the effective compression ratio obtained, particularly if there is some error in the modeling of the wave dynamics in the intake system. However, the compression ratio calculated based on the volume swept by the piston after the design IVC is reduced to only 16.0, and it is unlikely that this effect can account for the low effective compression ratio observed. The actual valve event timings for both engine builds were determined by close examination of the pressure and apparent heat release rate (AHRR) records. Although slight differences from design values and between engines were observed (Table 1), there is overall excellent agreement.

None of the aforementioned factors can account for the significant difference between the measured and simulated optical piston compression ratio. The difference is therefore assumed to be primarily due to a combination of blow-by—although very little blow-by is expected from the gap-less rings based on previous experience with the same ring-pack design—and heat transfer effects associated with the large crevice volume.

To obtain the same thermodynamic conditions near TDC in both the metal and optical engines, it is necessary to compensate for the lower effective CR in the optical engine. There are three available options: modification of the piston-bowl shape/volume, reduction of the squish height at TDC, or an increase in the intake pressure and temperature. Experience has shown that the flow-structure within the bowl is very sensitive to piston-bowl geometry. Hence, it is desirable to maintain the identical bowl geometry. Reduction of the squish height in the optical engine is also problematic, due to dynamic changes in the extended piston length. Because the squish height has already been adjusted for compression of the extended piston, its length at TDC overlap is greater, and the corresponding squish height smaller by about 0.22 mm. Further reductions in the squish height will increase the danger of piston contact with the head or valves near TDC overlap. Therefore, the method chosen in this study to counteract the CR reduction is to increase intake pressure and temperature.

A comparison of fuel injection system parameters between the optical and metal engines is shown in

Table 2. In both engines a centrally located and vertically oriented Bosch CRIP2-MI injector was used. Both injectors were supplied by a common rail. The injectors used in the optical and metal engines were essentially identical, the only disparity being a 1° difference in included angle. Differences in included angle primarily affect the spray targeting on the piston and could influence emissions and performance for the same SOI [13]. However, the 1° difference in this study is considered insignificant and is unlikely to impact the current comparison of optical and metal engine behavior.

Finally, there are differences in the head and cylinder cooling characteristics between the metal and optical engines. To outfit the optical engine with windows in the upper portion of the cylinder, cooling passages in the head that normally communicate with the cylinder liner were blocked. Moreover, cooling in the upper region of the optical cylinder is minimal (approximately 90% of the upper 35 mm of the optical cylinder assembly is uncooled). Although a detailed study of the head and liner temperatures has not been performed, we estimate that the skip-fired operation maintains these temperatures close to the range of normal metal engine temperatures (within 10–30°C of the coolant temperature). The quartz piston surface temperatures can be considerably hotter due to lower thermal conductivity. With skip-fired operation, the average temperature is anticipated to remain close to the surface temperature achieved under motored operation, which has been estimated in a similar engine to be approximately 250°C [5].

EGR SYSTEMS

The metal engine employed a conventional high-pressure, cooled EGR loop, described in [14]. The simulated EGR system in the optical engine is illustrated in Figure 2. In the optical engine, the intake flow is composed of fresh air mixed with additional gases to simulate EGR: N₂, CO₂, H₂O, CO and C₃H₈. The bulk of the intake charge (air, N₂, and CO₂) is mixed and heated well upstream of the intake plenum, which is held at the desired intake temperature. Water is delivered to a separate boiler by a precision metering pump, and a portion of the N₂ stream is diverted and employed as a carrier gas to transport the ensuing H₂O vapor to the intake plenum. The N₂ carrier stream was preheated before entering the boiler, and the lines from the boiler to the intake plenum were heated to avoid H₂O

Table 2. Fuel Injection System Comparison (differences are highlighted)

	Metal	Optical
Included Angle	148°	149°
Number of Holes	7	
Sac Volume	0.12 [mm ³]	
Nozzle Hole Diameter	0.14 [mm]	
Bosch Flow Number	440 [cc/30sec]	
Rail Pressure	200 Bar	
Fuel	#2 Diesel	

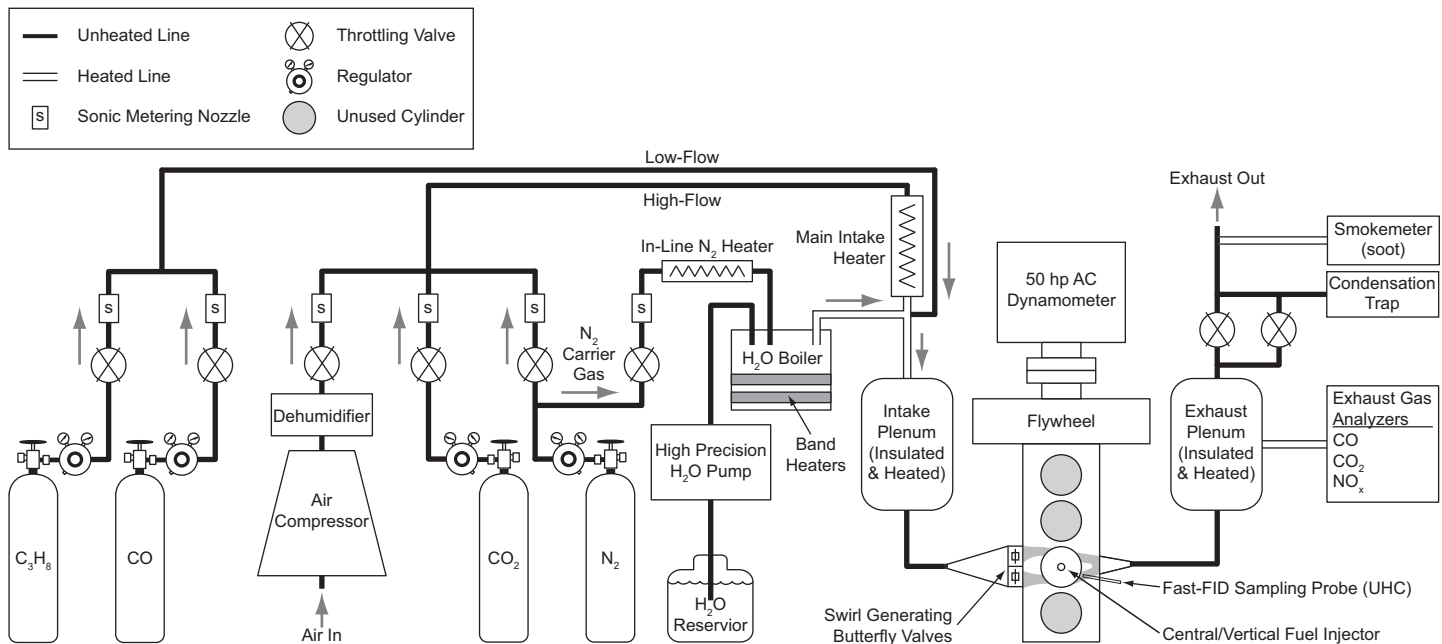


Figure 2. Schematic of the optical engine facility, illustrating the method used to simulate EGR.

condensation. Unheated CO and C₃H₈ were mixed in upstream of the intake plenum as well. The temperatures of each intake charge feed stream were set such that a mixture temperature equal to the desired intake temperature would be achieved in an adiabatic mixing process.

EMISSIONS MEASUREMENT EQUIPMENT

A full suite of emissions measurements, including NO_x, CO₂, CO, UHC, and soot, was performed for both engines.

For the metal engine, emissions measurements were made using a California Analytical Instruments (CAI) 400 HCLD Analyzer (NO_x), a CAI 300 NDIR Gas Analyzer (CO₂, CO, and O₂), a CAI 300S HFID (UHC), and an AVL 415S Smoke Meter (soot). Additionally, CO₂ and O₂ levels in the intake were measured using a HORIBA emissions bench (AIA-23 and MPA-21A) to determine the real-time EGR mass percentage. More detailed information on the emissions equipment and analysis for the metal engine can be found in [14].

Emissions from the optical engine were measured using a CAI 600 HCLD Analyzer (NO_x), a CAI 300 NDIR Gas Analyzer (CO₂ and CO), a Combustion HFR 400 fast-FID (UHC), and an AVL 415S Smoke Meter (soot). The measured gaseous emissions were corrected for skip-fired operation. Likewise, the calculation of filter smoke number incorporated a correction to the sample volume to reflect only the fired cycles. When the engine is fired on only one of every N cycles, the volume correction factor is 1/N. The adjusted sample volume, together with measured paper blackening numbers, was then used to calculate FSN. Because the fast-FID provides a temporally-resolved measure of UHC mole fraction, the measurements must be weighted by the instantaneous

exhaust flow rate and appropriately averaged to obtain the emissions index reported here. Additional details regarding this procedure and other details relevant to the emissions sampling and analysis can be found in [15].

OPERATING CONDITIONS

The experiments reported below involved two distinct phases. First, the speed, load, charge composition, and near-TDC thermodynamic conditions were matched as closely as possible for a baseline operating condition. From this baseline condition, the behavior of key combustion parameters and emissions were contrasted as SOI was varied. Second, the EGR composition was varied, while maintaining similar near-TDC density and temperature histories. At each EGR composition variant, a full SOI sweep was performed to examine the possible influence of EGR composition on trends in combustion performance and emissions.

GENERAL CONDITIONS

General operating conditions applicable to the baseline condition and to the SOI or EGR composition sweeps are shown in Table 3. All measurements reported here were done at an engine speed of 2000 RPM, a moderate (nominal) engine load of 6 bar IMEP_g, and a 9% intake oxygen mole fraction. The baseline condition employed an advanced ignition timing of -41.7°CA. This LTC operating regime is often referred to as "PPCI" (partially-premixed compression ignition) and is similar to Toyota's smokeless rich combustion [16], AVL's dilution controlled combustion system [17], and Mitsubishi's premixed compression ignited combustion (PCI) [18].

The shaded portions of Table 3 highlight differences in the operating conditions between the optical and metal