

A Comparison of Combustion and Emissions Behaviour in Optical and Metal Single-Cylinder Diesel Engines

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ABSTRACT

Single cylinder optical engines are used for internal combustion (IC) engine research as they allow for the application of qualitative and quantitative non-intrusive, diagnostic techniques to study in-cylinder flow, mixing, combustion and emissions phenomena. Such experimental data is not only important for the validation of computational models but can also provide a detailed insight into the physical processes occurring in-cylinder which is useful for the further development of new combustion strategies such as gasoline homogeneous charge compression ignition (HCCI) and Diesel low temperature combustion (LTC). In this context, it is therefore important to ensure that the performance of optical engines is comparable to standard all-metal engines. A comparison of optical and all-metal engine combustion and emissions performance was performed within the present study. The objective was to investigate the principal differences between optical and all-metal engines and how these differences ultimately affect mixing, combustion and emissions formation processes. Experimental results reveal the significant impact of differences in heat transfer characteristics between optical and standard engine piston bowls on combustion phasing and engine-out emissions. Quantitative measurements of piston wall temperatures using a laser-induced phosphorescence technique were performed which allowed the subsequent definition of appropriate engine operating strategies so as to compensate for differences in heat transfer properties. Furthermore, differences in combustion chamber geometry were also studied. Geometrical differences can arise as a result of dynamic (compressive/tensile) and thermal loading of the extended piston-liner assembly on the optical engine, potentially leading to

changes in the effective compression ratio. In addition, intake charge dilution in optical engines is often achieved via the use of simulated exhaust gas recirculation (EGR). A comparison has been made between simulated EGR (using pure nitrogen) with real EGR under Diesel LTC conditions. Finally, 'pure', single component fuels are often employed in optical Diesel engines due to laser diagnostic constraints. However these fuels generally differ from standard Diesel fuel in terms of cetane number and fuel volatility which can significantly influence the combustion and emissions characteristics in optical engines. These aspects are discussed within the present study.

An improved understanding of the differences between optical and all-metal engines has allowed us to develop appropriate strategies to compensate for these differences on the optical engine. It is shown here that combustion phasing (and engine-out emissions) matching between optical and all-metal engines can be achieved even for advanced LTC Diesel combustion strategies. The ability to ensure fully representative combustion and emissions behaviour of optical engines ultimately increases the value of optical engine data, highlighting the importance of using such engines as research tools for the further development of innovative, low emission combustion concepts.

INTRODUCTION

Advances in internal combustion (IC) engine performance, notably in terms of improved fuel economy and reduced engine-out emissions have been largely a result of significant combined research and development efforts by automotive companies, suppliers, research institutes and universities. Over the last two decades in

particular, the development and application of both experimental and computational research and development tools has enabled for a more in-depth understanding of fundamental physical phenomena occurring in IC engines. With regards to experimental engine research, single-cylinder, optical-access engines have been widely used as they allow the application of both qualitative and quantitative, non-intrusive, optical diagnostic techniques to gain a detailed insight of the mixing, combustion and emissions formation processes occurring in-cylinder. Although earlier work performed on optical engines provided useful experimental data enabling an improved understanding of fundamental in-cylinder physical phenomena and for the validation of CFD models, the value of optical engine data was often deemed to be rather limited from the engine developer's point of view since optical engines were not considered to be fully representative of standard 'all-metal' engines. In particular, certain compromises are often made such as the use of simplified piston bowl geometries in order to maximise engine optical access. Furthermore, single-component fuels rather than standard commercial fuels are often employed due to laser diagnostic constraints. Non-standard piston rings manufactured from specialist materials are also used on optical engines due to the need to 'dry-run' these engines (*i.e.* the upper cylinder liner on the optical engine is not lubricated) and as a result, it is often claimed that engine blow-by is more significant in optical engines compared to standard engines.

More recently, studies of in-cylinder combustion processes are tending to rely upon a combined approach whereby experiments are performed on both an optical and an identical, standard, all-metal engine [8, 17, 18]. There are clearly several advantages to such an approach. Firstly, experimental data can be obtained on all-metal engines at a much higher rate in order to establish an expansive database in which a multitude of engine parameters can be studied. As shown in **Figure 1** for example, variations may include injection timing/strategies, coolant/intake temperature, level of charge dilution, equivalence ratio and intake pressure.

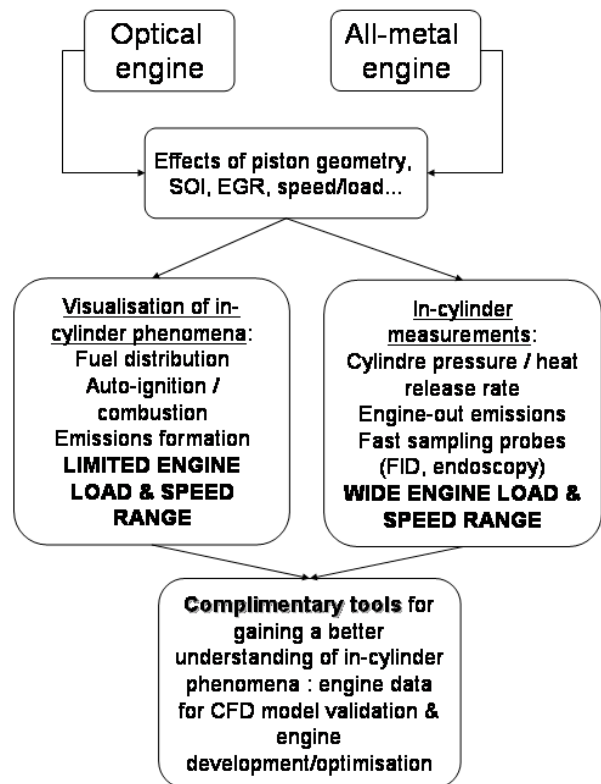


Figure 1 : Schematic flowchart illustrating a combined optical/all-metal engine experimental study and the complimentary data that can be acquired.

Experiments on all-metal engines therefore allow an exhaustive experimental database to be established relatively quickly. A subsequent analysis of these data may reveal interesting trends which can be investigated in more detail on the optical access engine. In particular, the application of appropriate laser-based diagnostic techniques on the optical access engine can provide results which can lead to an improved understanding of the physical phenomena occurring in-cylinder.

There have been surprisingly few studies dedicated to investigating the differences between optical and all-metal engines despite the widespread use of engine optical diagnostic techniques particularly in the last two decades. Work reported in Ref. [1] focused on characterising the piston surface temperatures on optical and all-metal engines via cycle-resolved thermocouple measurements in a direct-injection spark-ignition (DISI) engine. The experimental results revealed that surface temperatures on the optical piston significantly exceeded the so-called reference temperature of $\sim 150^{\circ}\text{C}$ corresponding to the all-metal engine. The data was then used to determine an optimum skip-firing routine (10 fired cycles followed by 100 motored cycles) so that optical measurements could then subsequently be performed at piston surface temperatures considered to be representative of the all-metal engine.

More recent studies [6, 7] have been performed on highlighting the need to characterise the differences between optical and all-metal engines. Colban et al [6] performed a detailed study into the effects of EGR composition and in particular the use of simulated EGR on optical engines and the importance of including the major species such as N_2 , CO_2 , H_2O , CO and UHC . In-cylinder pressure matching under motored conditions between the optical and all-metal engines was also discussed. The TDC thermodynamic conditions on the optical engine were matched to those of the all-metal engine by adjusting the intake mass flow and composition, intake temperature and fueling rate. Aronsson et al [7] studied several optical engine configurations and compared experimental data with results obtained on a standard all-metal engine. The authors reported the effects of the material properties of optical components (windows) on the combustion process. The use of low conductivity materials such as quartz was found to have a significant impact on the heat release rate characteristics.

Other aspects must also be considered. For example, the use of realistic optical engine combustion chamber geometries, identical to the geometries of their metal engine counterparts is also a major issue. Whenever possible, it is important to maintain a fully representative combustion chamber design since this plays a significant role on mixture preparation (in-cylinder airflow, fuel-air mixing, fuel-wall impingement), combustion and emissions. For optical-access Diesel engines, the application of diagnostic techniques is further complicated by the fact that the combustion process is confined within the piston bowl. The use of realistic chamber geometries therefore implies piston windows which incorporate piston crown shapes. Many optical engines used for in-cylinder visualisation studies have been based on simplified chamber geometries so as to facilitate optical access whilst minimising image distortion issues. A number of studies have however been performed with fully representative piston bowl geometries [2-5]. In Ref. [2], optical ray-tracing algorithms were employed so that the in-cylinder images could be post-processed in such a way as to 'correct' for image distortion due to curved window surfaces.

The objectives of the current study are not only to identify the principal differences between an optical engine and an equivalent all-metal engine but to understand the effects of these differences on optical engine performance (combustion and emissions characteristics). Furthermore, it is shown here that gaining a better insight into optical engine behaviour is useful in helping to identify a means by which experiments on optical engines can be performed under conditions which are fully representative of all-metal engines. Examples of such approaches are provided later in the paper. The need for a better understanding of optical engine characteristics and their comparison with standard all-metal engines is particularly important if optical engines are to be used in parallel with all-metal engines in order to gain a better understanding of engine combustion phenomena.

DIFFERENCES BETWEEN OPTICAL & METAL ENGINES

There are numerous fundamental differences between optical-access and all-metal engines which are discussed below. The 3D schematic shown in Figure 2 presents the main components of the IFP Diesel optical engine including the extended piston assembly, optical-access piston and grooves showing the piston ring and guide locations.

Materials & Heat Transfer Considerations

Optical-access engines, as their name implies rely on the replacement of a number of metal engine parts by 'transparent' windows, allowing visual access into the combustion chamber. The windows are typically made from quartz (fused silica) and/or sapphire. The single-cylinder, optical Diesel engine at IFP incorporates quartz piston windows in the base of the piston bowl and smaller windows housed within sections of the reentrant piston wall (Figure 3). A fully transparent sapphire ring is also used which is sandwiched between the cylinder liner and the cylinder head. The selection criteria for the choice of window materials is not only based on mechanical property considerations but also on their optical properties [6]. Furthermore, the optical-access piston head used in the current study which houses the windows is made from titanium due to its high strength-to-weight ratio. The extended piston used in this study was manufactured from steel which in this case offered the best strength-to-weight ratio.

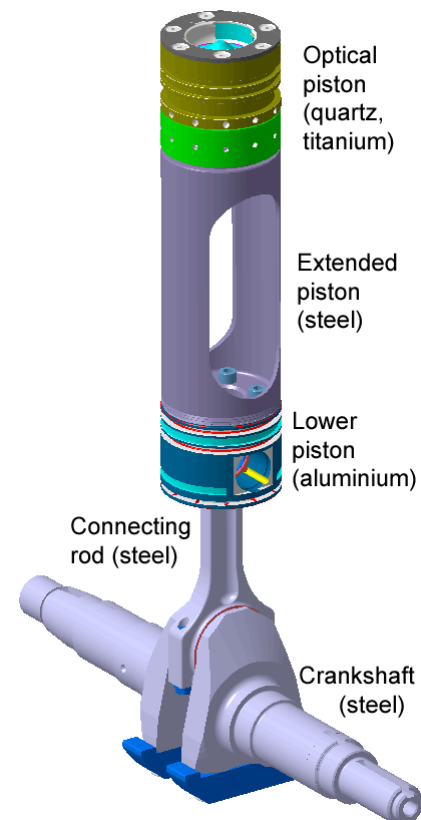


Figure 2 : 3D schematic showing main components of the optical engine including the extended piston assembly and optical piston.

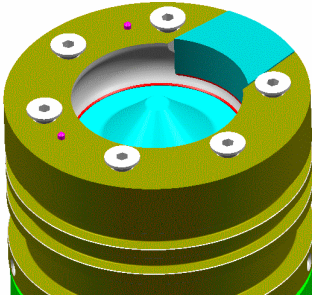


Figure 3 : Optical-access Diesel piston bowl showing location of quartz windows.

As will be discussed, the use of materials such as quartz, sapphire and titanium in optical engines has a significant impact on engine combustion characteristics thus bringing into question the fidelity of optical engine performance compared with an identical all-metal engine. The reason for this is that the thermal conductivity of the aforementioned materials is significantly lower than the thermal conductivity of aluminium (aluminium being the base material used for the manufacture of all-metal pistons). Table 1 compares values of thermal conductivity of typical materials used in combustion chambers of optical and all-metal engines. The three principal materials used in the IFP optical engine (titanium, quartz and sapphire) are all characterised by thermal conductivities which are significantly lower than that of aluminium. The differences in thermal conductivity between an optical-access piston and an all-metal piston will inevitably lead to considerable differences in engine heat transfer characteristics. Higher piston surface temperatures would subsequently be expected on optical engines which would then be expected to lead to notably higher bulk gas temperatures, thus having a major effect on the combustion characteristics. Furthermore, the high combustion chamber surface temperatures could potentially compromise the mechanical strength of the optical components. In particular, high temperature gradients across the windows might subsequently lead to excessive thermal-induced stresses and mechanical failure. Measurements have been performed within the current study in order to quantify the differences in piston wall surface temperature between optical and all-metal engines.

Table 1 : Comparison of values of thermal conductivity of common materials used in combustion chambers of optical and all-metal research engines.

Material	Thermal Conductivity ($\text{Wm}^{-1}\text{K}^{-1}$) at 20°C
Aluminium/Silicon (Al88/Si12)	121
Cast Iron	27-46
Titanium	22
Sapphire	35-40
Quartz	1.5

Geometry & Engine Architectural Considerations

As mentioned above, the use of optical engines often imposes simplifications to the combustion chamber geometry in order to facilitate the application of laser-diagnostic techniques. Differences in combustion chamber geometry between optical and all-metal engines can have a significant impact on the mixture preparation, combustion and emissions characteristics [6]. Furthermore, the location of the piston ring pack on optical engine combustion chambers might differ from that of the all-metal engine. On optical engines, the use of two-part optical-access cylinder liners (e.g. sapphire or quartz rings) requires that the upper piston rings are lowered (compared with a standard all-metal piston) so as to avoid overlap (and subsequent sealing problems) of the piston rings at the interface between the metal liner and the transparent ring. This difference inevitably leads to an increased piston top land crevice volume [8] which will reduce the engine compression ratio (CR). Other geometrical parameters such as the squish height and the injector nozzle tip protrusion should also be similar between both engines so as not to adversely affect the in-cylinder airflow/turbulence and jet-wall impingement location respectively.

Geometrical differences may also arise as a result of static and dynamic effects. Changes in the geometry of the extended piston assembly might occur due to excessive thermal loading. For example, the low conductivity of materials such as quartz, sapphire and titanium will give rise to higher temperatures which could lead to significant thermal expansion. Thermal expansion of the extended piston assembly will tend to reduce the squish height and thereby increase the compression ratio. Indeed, these effects were studied in Ref. [6] where it was reported that an expansion of 0.4 mm led to an increase of the CR of approximately 1.2. Dynamic effects due to compression of the extended piston assembly may also induce changes in the combustion chamber volume and therefore the effective compression ratio. Colban et al [6] attempted to characterise such behaviour using a hydraulic press to simulate such dynamic loading effects. Their measurements revealed that the overall length of the extended piston assembly reduced by approximately 0.23 mm when subjected to a static pressure of 85 bar corresponding to a decrease of the CR of 0.6. However, it should be noted that the experimental results reported in Ref. [6] did not account for inertial effects. Design calculations have been performed within the present study in order to estimate the compliance of the extended piston. The calculations performed here take into account the effects of the cylinder pressure which might result in compression of the extended piston. Furthermore, the inertial effects of the moving piston assembly are accounted for. The data was then exploited in order to evaluate whether differences of the measured in-cylinder pressures between the optical and all-metal engines (and therefore the effective compression ratio) were due mainly to the dynamic loading effects and/or the effects of engine blow-by.

Other considerations which might appear trivial but require particular attention when attempting to replicate a series of experiments on two separate engines concern the locations of instruments such as the pressure transducer, thermocouple and exhaust gas sampling line. The measurement location of parameters such as intake or exhaust gas temperature and pressure, CO₂ exhaust and intake gas sampling location for EGR measurements will have a significant influence on the measured values. It is therefore important that the measurements are performed at identical locations on both the all-metal and optical engines. These issues have been addressed for the experiments described in the current study on the all-metal and optical engines.

EGR Composition

The composition of recycled exhaust gases (EGR) is another potential source of differences between optical and all-metal engines since simulated EGR is often employed on optical engines. This is due to the fact that optical engines are often operated using skip-firing strategies which means that the engine-out exhaust gases from the previous motored cycle(s) will significantly dilute any EGR gases which might be recycled with the intake air. Optical engine experiments can of course be performed without skip-firing so as to operate using real EGR gases. However this approach will clearly exacerbate the issues related to the engine wall heat transfer characteristics. As explained above and as will be shown later in the paper, the combustion chamber surface temperatures are significantly higher in optical engines due to the low thermal conductivity of optical windows (quartz and sapphire). This leads to reduced heat flux resulting in higher combustion chamber surface and bulk gas temperatures. The higher combustion temperatures will have a significant effect on the fuel oxidation reactions and the subsequent formation of various pollutants such as NO_x, HC and CO. As a result, the EGR gas composition on the optical engine will be modified compared to a standard all-metal engine under similar engine operating conditions.

Blow-By

Differences in performance between optical and all-metal engines are often attributed to the effects of increased engine blow-by on optical engines. Although this parameter is measurable on standard, all-metal engines using flow meters, it is not straightforward to perform direct measurements of engine blow-by on standard optical engines.

Fuel considerations

As mentioned above, single component or 'pure' fuels are often used for experiments performed on optical engines. The use of such fuels is necessary due to laser diagnostic constraints and in particular to avoid the fluorescence of various molecular species (e.g. naphthenic and aromatic compounds) which are naturally present in standard or commercially available

Diesel and gasoline fuels. Single component fuels such as isooctane and n-heptane are widely used as surrogate fuels to represent standard gasoline since they have similar boiling points while lower volatility pure fuels such as decane and dodecane are often employed in Diesel engine studies. However in this latter case, the fuel cetane numbers of decane (CN ~76) and dodecane (CN ~71) are significantly higher compared with both standard Euro V (CN ~52) and US (CN ~42) Diesel fuels. Clearly, the use of higher cetane number pure fuels will have a major impact on the auto-ignition delay and under Diesel LTC operating conditions may also influence the low temperature (cool-flame) oxidation reactions. If non-fluorescing fuels must be used on optical engines, it is important to ensure that the fuel ignition characteristics are considered if the objective is to use the optical engine as a complimentary tool to study phenomena occurring on all-metal engines, the latter being operated using standard commercial fuels. These aspects have been investigated in the present study and are discussed later in the paper.

EXPERIMENTAL

The optical-access and all-metal engines used in this study were both single-cylinder and correspond to light duty direct-injection (DI) Diesel engines. The general engine characteristics are presented in Table 2. Both engines were equipped with common rail fuel injection systems (Bosch CP2) capable of supplying fuel at nominal rail pressures up to 1600 bar. A six-hole injector nozzle with a 60° included angle was used for the majority of the experiments described in this paper. In-cylinder pressure measurements were acquired using a water-cooled piezoelectric pressure transducer (Kistler 6043A60). Pressure data was obtained over 200 engine cycles while a 0-D combustion analysis was performed in order to obtain parameters such as heat release rate and burned mass fraction. An optical crank angle encoder providing 0.1 CAD resolution was used. Both engines were equipped with an intake heater allowing pre-heating of the fresh intake air (or in the case of the optical access engine, the air-nitrogen mixture for operation under simulated EGR conditions). Both engines were equipped with identical EGR circuits while the location of various measurement instrumentation such as pressure transducers, thermocouples and exhaust gas sampling lines were identical on both the optical and all-metal engines.

Table 2 : Engine specifications of the all-metal and optical-access engines used in this study.

	All-metal engine	Optical engine
Engine base type	2 litre, DI Diesel	2 litre, DI Diesel
Number of cylinders	1	1
Number of valves	2 int. + 2 ex.	2 int. + 2 ex.
Bore/stroke	85/88 mm	85/88 mm
Displacement	0.5 l	0.5 l
Squish height	0.80 mm	0.80 mm
Compression ratio	14	14
Swirl ratio	1.1	1.1