

# Analysis of Errors in Heat Release Calculations Due to Distortion of the In-Cylinder Volume Trace from Mechanical Deformation in Optical Diesel Engines

Ulf Aronsson

Volvo Group Trucks Technology

Hadeel Solaka, Guillaume Lequien, Oivind Andersson and Bengt Johansson  
Lund University

## ABSTRACT

Optical engines of Bowditch design may suffer from distortion of the in-cylinder volume trace due to mechanical deformation from inertial, pressure and thermal forces. Errors in heat release calculation associated with such deformation were investigated in detail. The deformations were quantified by measuring the squish height during operation using high speed video. Deformations of all-metal engines were also estimated for comparison. The volume change caused by deformations did not change the calculated load significantly but caused errors in the heat release calculations both for optical and all metal engines. The errors at a given operating condition are smaller for all-metal engines but the importance is not necessarily smaller, since these engines normally are operated at higher loads. The errors can be eliminated by a corrected in-cylinder volume equation and a subtraction of heat release from a motored case.

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## INTRODUCTION

Optical engines are useful tools to analyze the combustion process in diesel engines. Without optical investigations the present understanding of diesel combustion would not be as detailed as it is. To achieve optical access, however, it is necessary to modify the engine's design, which might have an impact on its behavior. Visual access to the combustion chamber is gained by fitting parts of a transparent material to the engine. Different materials are used but sapphire and quartz are most common. Glass is used here as a generic term to simplify the terminology. Normally, multi cylinder engines converted to obtain optical access are only operated on one cylinder. The degree of optical access varies. Some optical engines have access only through an endoscope and others have most of the combustion chamber manufactured in glass. A common optical engine configuration is the Bowditch design [1]. It features optical access to the combustion chamber from the side through the cylinder liner and from below through the piston crown. To make this possible the cylinder head is elevated, the piston extended, and an angled mirror placed in the bottom of the hollow piston extension as indicated in [Figure 1](#).

Since the combustion can be studied both from the side and from below this design is suited for laser diagnostics where the imaging normally takes place perpendicular to the laser beam [2]. The beam is sent in through the liner and radiation is imaged through the piston crown via the mirror, or through the liner perpendicular to the beam.

The purpose of diagnostics in optical engines is to understand the combustion process in all-metal engines and it is desirable to make as small changes to the engine as possible. The combustion process might be affected by changes in heat transfer, flow pattern and compression ratio. The optical access impairs the heat transfer from the engine for two reasons: glass is a much poorer heat conductor than steel or aluminum [3] and water cooling of the glass parts is impracticable. It is also common to move the piston rings in order to avoid them passing the joint between glass and steel in the liner. This affects the in-cylinder flow pattern and the compression ratio.

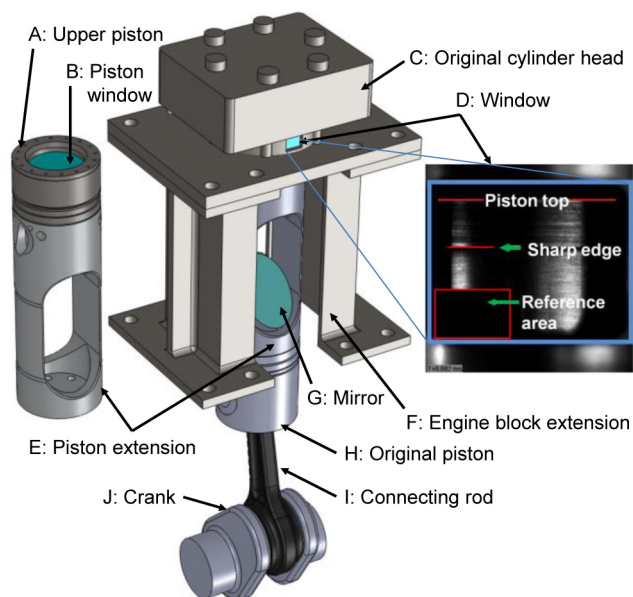


**Figure 1. An optical engine of Bowditch design (E1 in Table 1). The piston extension is shown both inside the engine and enlarged to the left in the image. The window ring in the cylinder liner is equipped with four windows perpendicular to each other. The inset to the right shows the field of view of the camera with some important objects marked for clarity.**

The impact of the optical access on the combustion process in diesel engines has been addressed previously. In [4], the differences in combustion characteristics between different engine configurations with various degrees of optical access are analyzed. The comparison shows that the low heat conductivity of the optical parts advances combustion if the engines are operated with the same inlet conditions. This is also observed in [5]. A solution to the problem is presented in [4], where the optical and an all-metal engines are made to produce similar combustion phasing and engine out emissions by operating the optical engine with a lower inlet temperature. In [6] the thermodynamic state at Top Dead Center (TDC) and the trends in engine-out emissions were matched between an optical and an all-metal diesel engine by carefully selected Exhaust Gas Recirculation (EGR) level and intake flow rate. Also other combustion concepts have been investigated briefly [7, 8]. With homogeneous combustion additional problems occur since the larger top-land volume becomes a significant source of Unburned Hydrocarbons (UHC) [7].

Combustion engines are exposed to forces from high pressures, thermal expansion, and acceleration due to the piston movement. These forces have an impact on the engine structure, causing stresses and vibrations. When designing engines, these have to be considered to obtain a durable and usable engine. However, the forces also affect the in-cylinder volume since different engine parts expand or become compressed due to the forces. The effects are present in all

engines but are more severe in optical engines since both the piston and engine block are extended, items E and F in Figure 1.

The deformations are expected to have a rather small impact on the combustion process but since the in-cylinder volume and its derivative are essential for pressure analysis it is useful to quantify them. In this investigation the impact of inertial, gas, and thermal forces on the in-cylinder volume are analyzed using high speed video. Finite element method (FEM) analysis and compression tests are used to support the observations.

## Experimental Setup

Two optical diesel engines of Bowditch design were studied, one heavy duty and one light duty engine, see Table 1. The deformation from inertial, thermal, and pressure forces were investigated in detail on the heavy duty engine (E1 in Table 1) while only the deformation from pressure forces was measured on the light duty engine (E2). The measured deformations on E2 were then used to study the impact on pressure analysis on E3, which is an all-metal engine. Before E2 was converted to get optical access it was similar to E3. All three engines were equipped with external boost systems and electric heaters. This allowed independent control of inlet pressure and temperature. Figure 1 shows a computer aided design model of E1. E2 has a similar design for the piston extension but the engine block extension is much more rigid with four supports instead of two since all cylinders have a common cylinder head. To minimize errors due to false phasing of the pressure trace the TDC position for E3 was determined in using a Kistler 2629A capacitive sensor. For E1 and E2 the TDC position of the piston was determined from the image series.

The piston position in relation to the cylinder head surface was imaged using a Phantom v 7.1 high speed video camera from Vision Research, equipped with a 140 mm  $f\# = 2.8$  lens. The repetition rate of the camera was between 600 and 7200 Hz depending on engine speed. The exposure time of each image was 20  $\mu$ s. The imaged area was illuminated with a powerful halogen lamp to increase the signal strength.

**Table1. Engine properties.**

|                                        | E1   | E2             | E3             |
|----------------------------------------|------|----------------|----------------|
| Geometric compression ratio, $R_c$ [-] | 16.8 | $\approx 16.5$ | $\approx 16.5$ |
| Displacement volume [l/cylinder]       | 1.95 | 0.48           | 0.48           |
| Bore [mm]                              | 127  | 81             | 81             |
| Stroke [mm]                            | 154  | 93.2           | 93.2           |
| IVC [CAD BTDC]                         | 151  | 174            | 174            |
| EVO [CAD ATDC]                         | 146  | 164            | 164            |
| Piston pin offset [mm]                 | 0    | 0.25           | 0.25           |
| Optical [Y/N]                          | Y    | Y              | N              |

## Theory

Thermal forces expand the engine parts linearly with temperature but, since the engine is built from different materials, a uniform temperature increase for all parts may lead to a change in squish height (i.e. the clearance between the piston top and the cylinder head surface at TDC). The engine does not have a uniform temperature since heat flux from the combustion chamber causes a temperature gradient in the surrounding parts during operation. Most of E1 is built in cast iron or steel but the piston extension and original piston are made from aluminum. The upper piston crown (item A in [Figure 1](#)) is made from titanium and the windows in the piston and the cylinder liner are made from fused silica.

The acceleration,  $a$ , of engine parts is described in the literature [9,10,11]. The first and second order terms of the acceleration of the oscillating parts as function of the crank angle,  $\theta$ , is described by

$$a_{osc} = r_{crank} \omega^2 \left( \cos \theta + \frac{r_{crank}}{L_c} \cos 2\theta \right) \quad (1)$$

where  $\omega$  is the angular velocity,  $r_{crank}$  is the crank radius, and  $L_c$  is the connecting-rod length. The acceleration force is equal to the oscillating mass times the acceleration.

The centripetal acceleration,

$$a_{cp} = r \omega^2 \quad (2)$$

where  $r$  is the radius, leads to a centripetal force on the rotating engine parts. Note that the force from a given mass element will increase linearly with the radius from the crank center.

The acceleration force that acts on a given cross section of the oscillating parts is equal to the acceleration multiplied by the total mass above this cross section. The acceleration force from the oscillating mass will therefore be largest at the crank axis and zero at the piston top. The force from the centripetal acceleration at a given cross section is obtained by integrating [Eq. 2](#) from the most distant rotating mass element to the cross section in question. The oscillating acceleration force will act to elongate the oscillating parts close to TDC and to compress them near BDC. The centripetal acceleration force will always act to increase the crank radius independently of crank position.

At TDC the centripetal and oscillating accelerating force both act in the same direction, straight away from the crank axis, and the impact on the deformation will be proportional to  $\omega^2$  in any given cross section. The gas force presses the piston downwards and the cylinder head surface upwards. The magnitude of the force is equal to the pressure times the cylinder cross sectional area.

## Structural Analysis

To better understand the experimental results the strain resistance of different engine parts from the heavy duty

engine, E1, was analyzed. A hydraulic press designed for tensile and compression tests was used to compress the piston extension equipped with the titanium piston and quartz window, as well as an original piston assembled with a connecting rod. Locking the joint with socket screws prevents angular movement between the connecting rod and the original piston. The lower end of the connecting rod was cut parallel to the piston top to obtain a stable support. The cut was close to the bearing surface against the crank radius to use the whole free length of the connecting rod. Both assemblies deformed linearly with the force between 20 and 100 kN. Below 20 kN the deformation of the original piston assembly was not linear, plausibly due to deformation of the brass bearing. The spring constants,  $k$ , in the linear region were 0.0016 mm/kN for the original piston assembly and 0.0028 mm/kN for the piston extension assembly. A Finite Element Analysis, FEM, of the piston extension and the upper piston gave the same  $k$ -value as the compression test,  $0.00268+0.00015=0.0028$  mm/kN. FEM was also used to analyze the radial deformation in E1 and E2. Radial deformation of the cylinder liner will have an impact on the in-cylinder volume but FEM analysis indicated that the impact is insignificant in relation to

## Dead Volume

The dead volume was measured for the heavy duty engine, E1, since the in-cylinder volume as function of crank angle is essential in this investigation. To determine the dead volume, the cylinder head was dismounted from the engine and placed upside down in level. The window ring was mounted and the sealing gasket was compressed with screw clamps to its proper thickness. The cavity was filled with ethanol using a precisely graded pipette, providing an accurate measure of the volume. Ethanol is suitable since it has low surface tension, substantially lower than water for example. The dead volume was then obtained by adding the piston bowl, clearance, and ring-land volumes to the volume of the filled cavity minus the core cylinder volume. The result was compared with computer aided design models and the models were improved to capture all features. It is difficult to precisely model small volumes in pockets around valves, windows, the pressure transducer in the glow plug hole, the injector, and the gasket between the head and the window ring.

## Evaluation

The objective of the measurements is to determine the influence of mechanical deformation on the in-cylinder volume. The volume change can be due to compression or expansion of the moving parts (piston, piston extension, connecting rod, and crank axis) and it can be due to expansion of the fixed engine parts (engine block and cylinder liner). The expansion of the cylinder liner may be both axial and radial. The radial expansion was analyzed with FEM. The axial deformation was determined from the squish height. A change in squish height can thus be due to axial