

Numerical Simulation Study of Carbon Build-up and Oil Consumption in a Heavy Duty Diesel Engine

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ABSTRACT

Nowadays, the use of numerical simulations is an important tool in order to optimize the engine and components behaviors, directly contributing to the emissions and lead-time development project reduction.

With the increase of engine thermal specific loading, excessive piston carbon build-up may be an issue, eventually causing liner polishing and excessive Lube Oil Consumption (OC). During the development of a Cummins heavy duty 8.9L engine, preliminary engine test results indicated excessive OC levels, above the engine specification limits. Also, a considerable carbon build-up, mainly in the second ring groove, was observed.

This paper presents the application of piston rings numerical simulation to predict the piston ring pack behavior and evaluate potential sources of OC which may explain the excessive values obtained in engine tests. After that, the effect of relevant geometric parameters in the ring dynamics stability was analyzed and a proposed Power Cylinder Unit (PCU) was recommended as a potential solution for the excessive OC.

Endurance engine test was performed using the proposed PCU from the numerical simulation and the results showed a significant OC reduction. Then, a complementary study was done in order to understand the effect of the carbon build-up in the ring dynamics behavior and OC. Some possible mechanisms leading to the observed blow-by and OC spikes observed during the engine tests are discussed.

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INTRODUCTION

Since the beginning of XX century, Internal Combustion (IC) engines have been performing an important role to the evolution of the industry and modern society generally. Invented by Rudolph Diesel in 1892 (patent date) when studying a way to improve efficiency of steam engines, the Diesel engine has the best thermal efficiency of any regular IC engine, resulting in better fuel consumption and work output when compared to other IC architectures like spark ignition. Some marine low-speed Diesel engines can reach almost fifty percent of thermal efficiency [1]. With a better thermal efficiency, small weight and bulk of the engine and fuel, the Diesel concept became essential to the transportation [2] and so on being widely applied in several applications such as submarines, locomotives, large trucks, electric generating, ships and most recently, passenger cars.

Due to its considerable importance to industries and transportation, Diesel engines has passed through several

technology improvements with the intention to have more work output with less size, this increased the population of Diesel engines over the years. However, due the dramatically increase on vehicles (and engines) population around the world, mainly in the 60's and 70's, the governments have started to work on emissions standard and the engine manufacturers started to looking not only to efficiency, work and durability but also to the environment.

With this mindset, nowadays the new engines being developed to attend emission standards pass through extensive numerical simulations and experimental tests for assessment of its durability, reliability and emissions consistency, before launch in production.

Over the past years, Cummins Brazil has been working on platforms to attend the new emission standard in Brazil from 2012, the Proconve P-7 from CONAMA, equivalent to Euro 5 standard [3]. During the validation phase of one of the platforms, it was detected an issue with engine OC. It is well

known into the automotive industry that all 4-stroke IC engines consume a small portion of the lubricant oil. This is necessary to aid lubrication to the PCU components and it must be controlled, otherwise engine can have problems with reliability when low (e.g. cylinder scuffing) or emissions when excessive (e.g. oil slobber through exhaust, PM, HC, C, CO and CO₂). The operating condition that demonstrated unacceptable OC was at rated speed and power (maximum advertised).

In order to address this issue, Cummins and MAHLE have revised the project with the relief of a simulation tool. It is world-widely known that piston rings numerical simulation tools are important instruments to support new product developments, contributing to improve product performance, reduce costs and testing lead-time. With its help, rigorous studies of the PCU can be done to better understand the piston/rings movement and predict the engine behavior in terms of blowby and OC tendencies [4]. The numerical simulation software used to perform the study presented in this paper was the MIT Piston.

RING SIMULATION

SIMULATION METHODOLOGY

The MIT Piston software is a development of the Consortium on Lubrication in IC Engines - Sloan Automotive Laboratory of the Massachusetts Institute of Technology - and uses an axisymmetric (2D) approach to simulate the ring dynamics behavior, considering mixed-lubrication in a steady-state engine running condition [5]. The mainly inputs are listed below:

- Basic engine parameters (i.e. displacement, speed, etc);
- Engine running conditions (i.e. speed, cylinder pressure versus crankshaft angle graph, etc);
- Piston Finite Element Analysis (FEA) results (temperatures and deformations);
- Hot bore distortion;
- Piston geometry;
- Rings geometry and running faces profiles;
- Lubricating oil properties.

The software has two basic modules called “ringpack” and “friction”. The “ringpack” module calculates the inter-lands pressures, gas flow and ring pack motion behavior, the “friction” module calculates the friction forces and oil transportation between rings. In addition to the two basic packages mentioned, an optional package for the Oil Control Ring (OCR) can be used. This module gives more detailed results for the OCR and generates inputs for the two basic modules. In this work only the basic modules were used. The modules are executed iteratively and the mainly outputs are listed below:

- Ring motion (lift + twist);
- Inter-lands gas flow;
- Ring gaps dynamic opening;
- Oil film thickness between ring and cylinder;
- Friction forces.

The Figure 1 shows schematically the MIT Piston inputs and outputs.

Analyzing the results of the simulation it is possible to predict the ring pack behavior regarding gas flow and ring motion and qualitative OC tendencies [6].

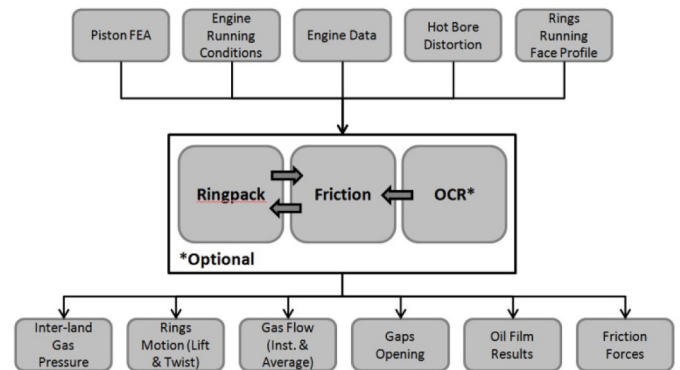


Figure 1. Diagram of some MIT Piston Inputs and Outputs

RING DYNAMICS MODELING AND FIRST IMPROVEMENT PROPOSAL

As mentioned in the introduction session, when running an endurance test with over-fuel during the “product validation” phase, it was verified an improper OC condition. The Figure 2 shows the OC results over the test:

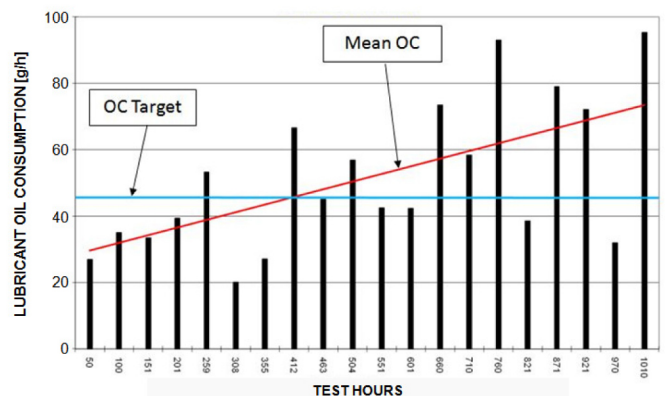


Figure 2. First endurance test OC results (Baseline PCU)

Two main characteristics can be highlighted from the data in Figure 2:

- Inter-lands gas pressure;

1. Overall OC Level - compared with the target defined for this engine (blue line), the linear mean OC (red line) was out of specification. This is the first requirement to match and indicates that, if no external leakages are verified, a potential source of OC through PCU and combustion exists, affecting negatively emissions. Once the scope of the project was to attend emissions standard, this can be considered critical.

2. OC stabilization - it is expected that the OC, throughout the test, to be stable (low standard deviation) and does not increase over a certain level defined by engine manufacturer and product expertise, preferably lowering. If the OC increases more than the specification, the engine can show emission issues at a certain mileage.

BASELINE MODELING AND RESULTS

As a first step of the simulation work, a baseline model was developed in order to better understand the ring-pack behavior during the test condition, trying to detect the possible sources of the high OC. Based on this analysis, potential solutions could be proposed. It is very important to emphasize that the MIT Piston software is only able to perform simulations at steady-state conditions.

Basic engine configuration and running conditions information were provided by Cummins, other inputs were assumed according to MAHLE expertise. [Table 1](#) shows basics engine parameters. [Table 2](#) shows basic piston parameters. [Figure 3](#) shows the liner Finite Element Analysis temperature results and [Figure 4](#) shows the 2D bore deformation used in the ring dynamics simulation.

Table 1. Basic engine parameters

Engine Manufacturer	Cummins
Engine Type	Heavy Duty Diesel
Displaced volume	8.9 L
Stroke	144.50 mm
Bore	114.02 mm
Connecting Rod	216.00 mm
Compression ratio	16.6:1

Table 2. Basic piston parameters

Material	Aluminium-Silicon Alloy
Total Height	109.245 mm
Ring Zone Height	36.40 mm
Combustion Bowl Type	Re-entrant

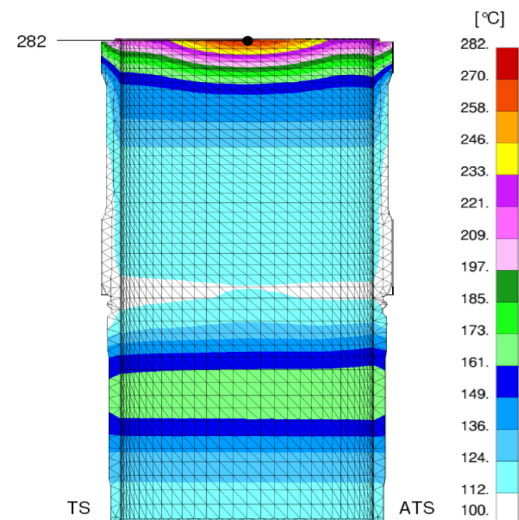


Figure 3. Liner temperature (FEA)

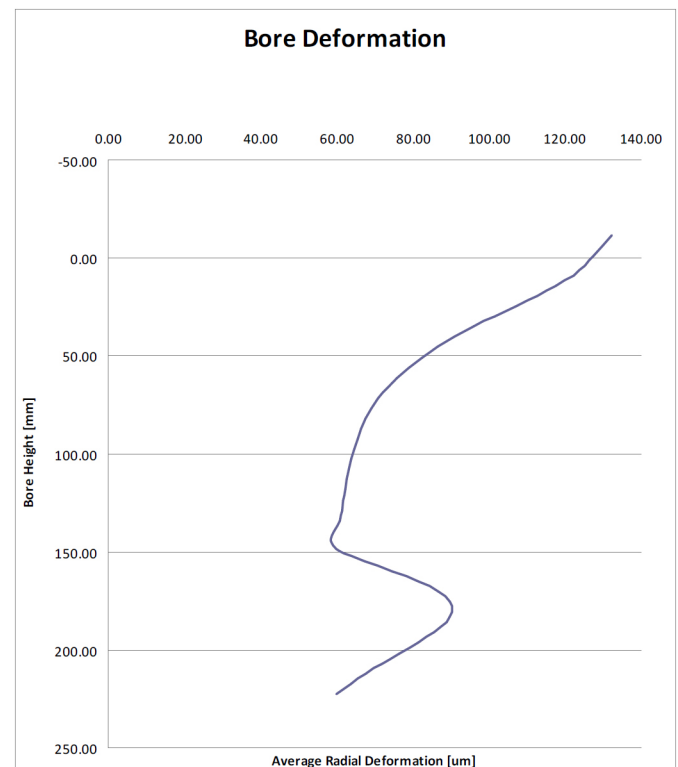


Figure 4. 2D Bore deformation (Radial)

The simulation results of the Baseline model for Rated Power condition showed an undesirable pressure overlap between the cylinder pressure and second land pressure ([Figure 5](#)). This overlap influenced the top ring axial lift inside the groove, generating ring instability at the end of the expansion and beginning of the exhaust strokes ([Figure 6](#)).