

Analysis of Oil Emission Mechanisms by Simulation and Mass Spectrometry

2010-01-1562

Published
05/05/2010

Marcus Gohl
APL Automobil-Prueftechnik Landau GmbH

David Adams
Ford Motor Company Ltd.

Copyright © 2010 SAE International

ABSTRACT

The improvement of engine efficiency, without adversely affecting oil consumption, blowby-gas, wear, or costs are desirable objectives for today's engine manufacturers as they strive to improve engine performance while trying to meet increasingly stringent emissions regulations.

In this context the development of piston ring designs as well as optimized surface texturing and lubricating oil formulation is of main interest.

The combination of simulation programs and the application of dynamic online oil emission measurement techniques lead to a target oriented development and a deeper understanding of the mechanisms causing oil consumption. The paper presents the results of the experimental and theoretical investigations of oil consumption mechanisms. A mass spectrometric method developed by the author et al., was used to measure the online oil emission in the exhaust gas by means of direct analysis of the lubricating oil molecules.

Running-in tests were conducted with a four-cylinder gasoline engine to observe the changing tribological performance due to variations in cylinder surface topography and piston ring geometry. In this context the results of the oil emission of a conventional honed surface in comparison with an optimised structure is discussed. Dynamic engine operation, as well as complete engine oil emission maps over different steady state conditions were evaluated.

INTRODUCTION

The exhaust gas legislations as well as a desired high customer satisfaction lead to a necessary minimisation of the oil consumption during the engine development. The shortened development cycles demand in this respect efficient and quick methods of the purposeful optimisation of the lubricating oils and the tribological system of the piston group (piston, piston rings and cylinder liner wall).

Using latest online measurement technologies in mass spectrometry it is possible to analyze cylinder specific, steady state as well as dynamic engine operating conditions. Oil emission maps may be generated from these measurement results within a short period of time of a few hours. This permits an early layout of pistons, piston rings and cylinder liner surface, as well as early determination of critical component tolerances.

Although the fast oil emission measuring technique has become the standard during the last years [1, 2, 3], the combination of online measurements and simulation techniques lead to further methodical advantages. It allows for significant reduction of time and cost intense engine tests to evaluate specific engine configurations.

Moreover the parameterisation of the simulation model can be improved by the use of the online oil emission measurement results [4]. It is an additional advantage of the simulation, that not only the total oil consumption, friction loss and blowby is part of the results, but also crank angle resolved data is available separable by effective mechanisms. This information provide a further insight to specify the source of the emission and deliver important details for the oil consumption and friction reduction.

OIL CONSUMPTION MECHANISMS

If one presupposes for a balance of the lubricant in the oil sump that the portions from oil deposits and leakage are negligible, proportionate oil losses remain caused by the piston-ring-liner system, unprecipitated oil aerosols in the crank case ventilation system, the valve stem lubrication, and with charged engines oil spill of the turbocharger. When using gravimetric or volumetric balance methods for measurements of the lubricant in the oilsump the fuel entrainment is to be considered ([figure 1](#)).

See [Figure 1](#) after last section of paper

As far as the piston-ring-liner system is concerned, different mechanisms have been identified: evaporation, scraping or throw-off, blowby and reverse blowby. Moreover the influence of the mixture formation on the oil emission has been observed, especially due to the change from port fuel injection to direct injection with SI engines. The mechanisms are schematically illustrated in [figure 2](#).

Especially during severe operating conditions when the thermal loading of engine components is high, oil evaporation is found to contribute significantly to the oil emission from the piston group. Furthermore the oil can be transported into the crankcase with the gas flow passing the piston rings (blowby). During some periods of the cycle when the second land pressure becomes higher than the combustion chamber pressure, reverse gases (reverse blowby) flow into the combustion chamber through the top ring gap and around the top ring groove. This mechanism can cause a direct oil transport with the reverse blowby into the combustion chamber.

See [Figure 2](#) after last section of paper

A hypothesis is the mechanical transport of liquid oil into the combustion chamber due to inertia forces caused by acceleration and deceleration of the piston assembly (throw-off) or by scraping. Recent results in the industrial research community of the “Forschungsvereinigung Verbrennungskraftmotoren” (FVV) prove the influence on the oil consumption caused by fuel mixture formation. Fundamental experiments indicated that the interaction of fuel and lubricating oil can lead to a significant increase in the oil emission by factor 7 [[5](#)]. Further experiments at a direct-injecting single-cylinder SI-engine demonstrated that the fuel entrainment into the oil film decreases by leaning the mixture from $\lambda = 0.8$ to $\lambda = 1.1$ by approx. 30%, while at the same time the oil emission decreases about 11%. With an additional tumble charge motion the fuel entrainment decreases once more about approximately 35% and at the same time the oil emission decreases another 27%.

Whether one or the other mechanism dominates mostly depends on the engine design specific oil transport rates, engine operating parameters, and lubricant properties. Evaporation of oil from the cylinder surface is highly affected by the surface texture of the cylinder. A smooth surface yields reduced friction, good sealing and good wear characteristics because of the increased bearing area. Oil consumption is also lower compared to a rough surface, because of reduced oil retention. On the other hand, scuff resistance is decreased with reduced oil retention. Therefore cylinder roughness turns out to become one of the key parameters to be optimized.

The present paper describes the combination of simulation programs and the application of dynamic online oil emission measurement techniques. The methodology is demonstrated using the example of the influence by changed cylinder roughness.

ANALYTICAL TOOLS

OIL EMISSION MEASUREMENT SYSTEM

The concentration of the exhaust gas components from the lubricating oil of modern combustion engines is in the range of a few parts per million (ppm). For this reason a measurement system with high selectivity and a low detection limit is essential for the dynamic oil emission measurement. Mass spectrometers meet these requirements and have been optimised during the last years especially for this application [[6](#)].

A quick transportation of the exhaust gas from the test bench to the detector is necessary for rapid online measurements of oil components. Using a heated transferline the exhaust gas is conducted under avoidance of condensation effects into the prevacuum chamber ([figure 3](#)).

See [Figure 3](#) after last section of paper

A small amount of sampling gas is extracted continuously from the exhaust gas and transported into the ion source. This technique permits for an extremely high time resolution with a sampling rate from up to 250 hertz, so that even crank angle resolved measurements within the cylinder become possible [[7](#)]. The hexapole transports the ions into the high vacuum area of the mass spectrometer. Three quadrupol mass filters permit the selection of certain components from the exhaust gas which then reach the detector.

See [Figure 4](#) after last section of paper

The large number of single compounds cause a complex mixture of hydrocarbons in the exhaust gas. In order to isolate the ions of single hydrocarbon groups a special high



pass filter method is applied, thus allowing a differentiation between fuel and lubricating oil portions in the spectrum. Whereas gasoline consists of hydrocarbon groups with up to 11 carbon atoms (mass range < 170 atomic mass units), analysis of lubricating oil shows higher molecular hydrocarbons with a range between 20 and 36 carbon atoms. This characteristic is used in the online analysis and allows for a direct measurement of the oil portion in the exhaust gas (range > 170 amu). Thus the use of tracer substances is not needed.

SIMULATION PROGRAMS: KORI3D, PRO

The KORI3D piston ring dynamics simulation used in the course of this study was developed within the scope of different FVV projects [8,9]. The prime development objective was the piston ring design in respect to friction losses and seal effects. It calculates the oil amounts in the system (thickness of lubricating film on the cylinder liner wall) as well as the gas flows (blowby and reverse blowby).

KORI3D describes the movement behaviour of the rings as a function of internal and external forces relative to the ring groove and the cylinder wall. Basis for this is the description of the dynamics for the multi systemic movement behaviour of the rings. In this context the interactions determined by gas dynamics, inertia effects as well as the influence of the surface micro structure of the piston ring and cylinder with respect to the hydrodynamic lubricating film is considered.

See [Figure 5](#) after last section of paper

PRO is yet another programme developed in the scope of several FVV projects [11]. It provides thermal information of the cylinder oil emission on the basis of residual lubricating films, minimum gap width and blowby or reverse blowby mass flow from the KORI3D simulation.

In PRO implemented models calculate the oil consumption caused by the evaporation from the cylinder wall, as well as the mechanisms linked to the gas flows, blowby and reverse blowby.

ENGINE DESIGN

A four-cylinder production spark ignition engine (PFI) was selected for the experiments. Details are listed in [table 1](#).

See [Table 1](#) after last section of paper

To perform oil emission measurements the mass spectrometer can be attached to the exhaust port of cylinder 2&3 or of cylinder 1&4. The engine test configuration is shown in [figure 6](#).

See [Figure 6](#) after last section of paper

The method of honing is suggested and widely used by engine manufacturers in order to establish the trade-off between reliability, life and oil consumption. The method involves creating deep scratches and then removing the peaks by additional abrasive machining. Deep scratches retain oil, provide cooling to the contact area and absorb debris. Two different cylinder blocks were manufactured for the experiments in order to investigate the difference between a rough and a smooth liner surface. The texture parameters of the test engines are given in [table 2](#).

See [Table 2](#) after last section of paper

The measurements were conducted with a piston ring pack design consisting of a barrel-faced compression ring, a taper faced Napier ring (hook) in the second gap and a three-piece oil control ring. [Figure 7](#) shows the details of the piston ring pack design.

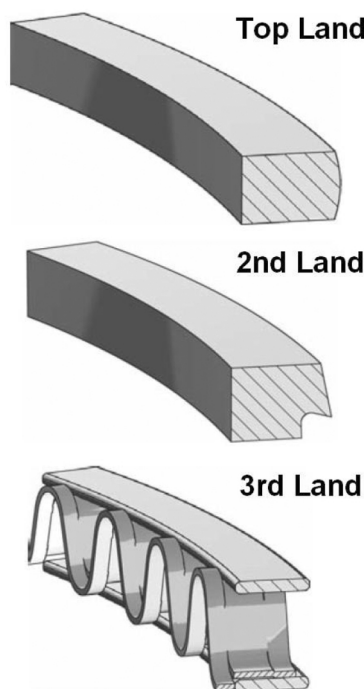


Figure 7. Ring Geometry

EXPERIMENTAL RESULTS

Two identically constructed engines were equipped with differently honed cylinder blocks. Particular care was taken to ensure that piston clearances, ring gaps and ring loads were within the same range for both engines to minimise variability from these sources. In this way the effect of bore surface finish would be the dominant factor in the test work. Both engines went through the same break-in programme of 100 hours and the oil emission was measured in multiple

operating points after different run times using the mass spectrometer.

With the applied Mapping Cycle, revolutions per minute were increased by 1000 rpm each. Within every step a variation of the torque was performed from high to low load. From the oil emissions in the 42 different stationary phases oil emission maps throughout the overall operating range of the engine can be created. [Figures 8](#) and [9](#) show the measured oil emissions at the beginning in the middle and at the end of the experiment.

See [Figures 8 - 9](#) after last section of paper

All following results are normalized to the stationary oil emission of 5000 rpm and full load (wide-open throttle, WOT) of surface A. The value in gram per hour was set to 100%.

Due to higher oil retention the rough surface shows higher emissions, as expected. The usual increase of the oil emission with an increase of the load can be observed with both variants. A significant decrease of the oil emission over the run time can be observed particularly under full load (100%) and with 75% of load. It must be noted that Surface B shows a larger influence.

[Figure 10](#) shows the change of the oil emission of both engines over the time of 100 hours at 5000 rpm and full load. It becomes clear that surface A shows no significant break-in behaviour whereas the oil emission of surface B decreases about approx. 40%.

See [Figure 10](#) after last section of paper

Different theoretical and experimental investigations already have demonstrated the impact of initially abrasive wear on the surface topography and the oil consumption [[12](#)]. The highest surface peaks decrease as the wear effects continue to remove the surface material during the running-in process. Hence the surface becomes smoothened and the modified microstructure has an optimised sealing characteristic and less remainder quantity of oil on the cylinder wall. The reduced amount of oil transported into the combustion chamber leads to a decreased oil emission.

Oil emission maps were created from the measured data of the Mapping Cycle considering the steady state results of the 42 different points of operation (cf. [figure 8.9](#)). [Figure 11](#) shows the oil emission maps of the two different honings after the run-in period. The improvement of the revised surface B becomes particularly apparent under full load conditions. Compared to the overall full load operation the measurements at 2000 and 3000 rpm and WOT show unusual high oil emission rates.

Apart from lower oil emission rates in steady state conditions a further benefit of surface B can be observed in certain dynamic phases of the Mapping Cycle. [Figure 12](#) shows the oil emission measurements from 2000 rpm low load (20%) to full load (100%) at 5000 rpm.

See [Figure 11](#) after last section of paper

During these transients, the oil emission of configuration A reaches a peak that is significantly higher than the steady state values, whereas configuration B reaches the steady state level of the final operating condition almost immediately. A similar behaviour can be monitored when the engine is forced into motored conditions.

See [Figure 12](#) after last section of paper

The increase of oil emission can possibly be caused by top ring instability during late expansion and early exhaust strokes. During this period of the cycle, when the inertia force is downward, higher second land pressures cause the top ring to reduce its sealing ability and to flutter during the transient at full load. During top ring flutter, reverse gas flows not only locally through the gap, but also through the groove. This causes entrainment of the oil accumulated in the groove during low load conditions and driving it into the combustion chamber. The improved sealing ability of surface B obviously reduces this effect.

See [Figure 13](#) after last section of paper

In order to consider customer relevant operation the oil emissions were analysed in a dynamic City Cycle programme ([figure 13](#)) with moderate speed and load conditions. Particularly the dynamic phases of the cycle show lower emission for the revised surface B, resulting in an overall lower average by approximately 50% throughout the whole cycle.

See [Figure 14](#) after last section of paper

[Figure 14](#) shows that the dynamic oil emissions can range significantly above the steady state value. The result of the comparable area of the steady state oil emission map (see frame in [Fig 11](#)) demonstrates that the influence of the dynamic operation is less for surface B.

SIMULATION AND THEORETICAL RESULTS

To create the simulation model the parameters of the crank shaft, the piston ring pack, the cylinder distortion, the formulation of the lubricating oil and the surface structures have to be considered. These values originate either from the construction data or from results of further component measurements and laboratory as well as test stand analysis.

In the following the simulation results are demonstrated in the quasi-stationary operation in 4 different points: at 2000 rpm, 25% load and WOT as well as at 5000 rpm, 25% load and WOT. The measured oil emissions in these operating conditions (see [figure 11](#)) are shown for reference in [figure 15](#). All simulation results are normalised to the steady state values at 5000 rpm, WOT of surface A. The values of oil film thickness [μm], oil emission [g/h], blowby [l/min] and friction [W] were set to 100%

See [Figure 15](#) after last section of paper

A significant contribution to the oil emission can be caused by the mechanism of evaporation. A direct connection between the evaporation and oil film thickness is derived from the temperature profile, coming from the combustion chamber, passing the oil film and the cylinder wall, reaching the cooling water. From a tribological view the basis of an estimation of oil evaporation is first of all a consideration of the oil film between the piston rings and the cylinder wall. [Figure 16](#) shows the computed average oil film thickness.

See [Figure 16](#) after last section of paper

Higher revolutions per minute cause better hydrodynamics and with it improved pressure buildup. Thereby average film thicknesses rise at 5000rpm. In the area dominated by the gas pressure increased cylinder pressures push the 1st and 2nd ring radically stronger against the cylinder wall, therefore under full load the film thickness decreases. Due to increased pressure buildup of the solid state contact pressure the rougher cylinder wall causes thicker oil films.

See [Figure 17](#) after last section of paper

During the combustion, the expansion and the exhaust stroke high combustion chamber temperatures lead to a rapid heating of the oil film. During the combustion process as well as in the exhaust stroke partial evaporation of the oil film can be observed. The evaporated oil is released to the exhaust gas system. The different evaporation rates in the operating points ([figure 17](#)) are a function of the different energy entry and subsequent oil film surface temperature. The reduced oil emissions of the smooth cylinder B are a result of the computed lower oil film thicknesses in [figure 16](#).

See [Figure 18](#) after last section of paper

Other portions of the oil emission are oil enriched blowby and reverse blowby quantities in the area of the top land and top ring. Due to the pressure gradient between combustion chamber and crank case a portion of the combustion gas escapes past the ring package because of incomplete sealing. The computed blowby quantities are shown in [figure 18](#). As expected the maximum emission values arise under full-load. The more efficient sealing of the smooth cylinder surface

reduces the amount of gas that reaches the crank case. With oil-loaded blowby a consumption mechanism is not automatically implied. Parts of these oil quantities condense on cooler components and surfaces within the crank case or are resupplied by separators into the oil cycle. For this reason such mechanisms will not be considered in detail.

Depending on the pressure gradient one can observe a gas flow towards the combustion chamber (reverse blowby) in parts of the cycle. This can cause lubricant to be transported along from the 2nd land clearance or the ring groove. It may occur as evaporated oil within the hot combustion gas or by entrainment of liquid oil aerosol. This mechanism must be considered concerning the oil emission and is displayed in [figure 19](#).

See [Figure 19](#) after last section of paper

Optimised surface texture parameters and its consequential reduction of oil film thickness is directly linked to a reduction of losses by hydrodynamic and solid state friction. [Figure 20](#) shows the overall friction of all 4 operating points. The results clearly demonstrate the strong correlation of speed and friction. The highest influence of the changed surface roughness can be observed at 5000 rpm WOT.

See [Figure 20](#) after last section of paper

SUMMARY AND CONCLUSION

Experimental and theoretical investigations demonstrated that the lube oil emission, blowby and friction is directly related to the sealing efficiency of the tribological system of piston, piston ring and cylinder liner wall. The optimised texture parameters of surface B lead to a reduction of the oil emission in the steady state operation - approx. 35% reduction throughout the overall oil emission map. Another benefit is a significant reduction of the emissions in dynamic driving cycles, being the most representative for customers (approx. 50%). The blowby amounts decrease about 2% and are not substantially influenced by this measure. Also the friction values are comparable and decrease slightly about 5% at 5000rpm, WOT.

The computed results show an oil emission improvement for the mechanisms evaporation and reverse blowby in steady state operation. The simulation does not allow the direct explanation of the observed increase in oil consumption at 2000rpm and 3000rpm WOT. The difficulty in modelling oil consumption lies in predicting the oil transport, and the amount of oil present in the clearances of the partially flooded piston-ring-liner system. Current and future research activities investigate new oil emission mechanisms as well as transient operation.

This example demonstrates that for the operational optimisation concerning reduction of oil consumption, blowby and friction losses, a combination of simulation programs and the application of dynamic online oil emission measurement techniques is very efficient and leads to a deeper understanding of the complex mechanisms for further improvement.

REFERENCES

1. Rehr, A., "Innovative Ölverbrauchsmesstechnik - Chancen und Erkenntnisse aus der Anwendung der Massenspektroskopie an Otto-Hochleistungsotomotoren," presented at Tagung Haus der Technik: Ölkreislauf von Verbrennungsmotoren I; Chemnitz, April 12-13, ISBN 3-8169-2492-1, 2005.
2. Knirsch, S., Kerkau, M., Neußer, H.J., "Die neuen 6-Zylinder-Boxermotoren für den PORSCHE 911 Carrera / The New Flat-Six Engines for the PORSCHE 911 Carrera," presented at 26. Internationales Wiener Motorensymposium, Wien, April 28-29, 2005.
3. Gohl, M., Appel, N., Robota, A., "Comparative Investigations of Oil Consumption and Oil Emissions on Spark Ignition Engine," *MTZ Motorentechnische Zeitschrift* 67(5):360-367, 2006.
4. Gohl, M., Kehrwald, B., "Optimierung von Ölverbrauch, Reibleistung und Verschleiß durch Simulation und dynamische Messverfahren / Optimisation of Oil Consumption, Friction and Wear by Simulation and Dynamic Measurement," presented at VDI-Tagung Zylinderlaufbahn, Kolben, Pleuel - Innovative Systeme im Vergleich, Baden-Baden, June 11-12, ISBN 978-3-18-091994-2, 2008.
5. Gohl, M., Pischinger, S., Matz, G., Knoll, G., "Influence of the Mixture Formation on the Lubrication Oil Emission of Combustion Engines," *SAE Int. J. Fuels Lubr.* 3(2):733-744, 2010, doi:10.4271/2010-01-1275.
6. Gohl, M., Matz, G., Püffel, P., "Development and Application of a new Mass Spectrometer Based Measurement System for Fast Online Monitoring of Oil Emission in the Raw Exhaust Gas of Combustion Engines," SAE Technical Paper 2002-01-2713, 2002.
7. Krause, S., "Massenspektrometrisches Verfahren zur Charakterisierung der Ölverdampfung im Brennraum von Ottomotoren / Mass Spectrometry for the Characterisation of Oil Emission in the Combustion Chamber of SI Engines," Ph.D. thesis, Department of Measurement Technology, Technical University Hamburg-Harburg, Hamburg, ISBN 978-3-86931-127-2, 2009.
8. Peeken, H., Knoll, G., Lechtape-Grüter, R., "Kolbenringreibung I," Forschungsvereinigung Verbrennungskraftmotoren Final Report, FVV Heft 502, 1992 and 513, 1993.
9. Knoll, G., Lechtape-Grüter, R., "Kolbenringreibung II," Forschungsvereinigung Verbrennungskraftmotoren Final Report, FVV Heft 570-1, 1994 and 570-2, 1995.

10. Knoll, G., Schlerege, F., "Berechnungsverfahren zur Ölemission eines Ottomotors / Calculation Method for Oil Emission of a Gasoline Engine," presented at Tagung Haus der Technik: Ölkreislauf von Verbrennungsmotoren III; Chemnitz, Mai 12-13, ISBN 978-3-8169-2907-9, 2009.

11. Knoll, G., Lechtape-Grüter, R., "Ölverbrauchssimulation," Forschungsvereinigung Verbrennungskraftmotoren Final Report; FVV Heft 707, 2001.

12. Jeng et al, "Changes of Surface Topography during Running-In Process," *ASME Journal of Tribology* 126, 620-625, 2004.

CONTACT INFORMATION

Dr. Marcus Gohl is Principal Engineer in the Research and Engineering Department at APL in Landau, where he specialises in online measurement techniques and simulation tools for engine development.

Dr. Marcus Gohl
Research and Engineering Department
APL Automobil-Prüftechnik Landau GmbH
Am Hölzel 11, 76829 Landau, Germany
Tel. +49 (0)6341/991-380
Fax +49 (0)6341/991-199
marcus.gohl@apl-landau.de

Dr. David Adams of Ford is Europe's Technical Specialist for Piston & Rod assemblies, where he supports ongoing diesel and gasoline engine development programmes.

Dr. David Adams
Dagenham Diesel Center
Ford Motor Company Limited
Dagenham, Essex, UK
Tel. +44 208 526 6445
Fax. +44 208 526 3344
dadams69@ford.com

DEFINITIONS/ABBREVIATIONS

amu	atomic mass units
FVV	Forschungsvereinigung Verbrennungskraftmotoren
Mr1	Peak material component
Mr2	Valley material component