LUBE OIL CONSUMPTION MEASUREMENT ON INTERNAL COMBUSTION ENGINES

TRACK OR CATEGORY
Engine and Drivetrain

AUTHORS AND INSTITUTIONS
Bernhard Rossegger
Claudia Schubert-Zallinger
Andreas Wimmer
Institute of Internal Combustion Engines and Thermodynamics, Graz University of Technology, Austria

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INTRODUCTION
Lube oil consumption (LOC) exerts a major influence on life cycle cost and emissions of internal combustion engines. As the LOC of combustion engines must be reduced to meet future emission standards and advance economical operation, accurate LOC measurement is necessary. Since state-of-the-art methods for measuring LOC are not fully satisfactory for different reasons, the motivation to develop new measurement systems is high. The deficiencies of currently available measurement techniques are illustrated by comprehensive literature research and tests on large engines using the SO_2 method. Because tracer methods are considered to be the most promising due to their ability to detect minimal levels of oil consumption, research is focused on developing new tracer substances and/or detection methods. The main challenges in developing marker compounds are exemplified by test bench experiments that use barium as tracer.

STATE-OF-THE-ART IN LOC MEASUREMENT
There are two general types of LOC measurement methods: direct measurement of lube oil in the oil reservoir and indirect measurement of oil-borne substances in the exhaust gas and mathematical conversion to oil consumption as shown in Figure 1.
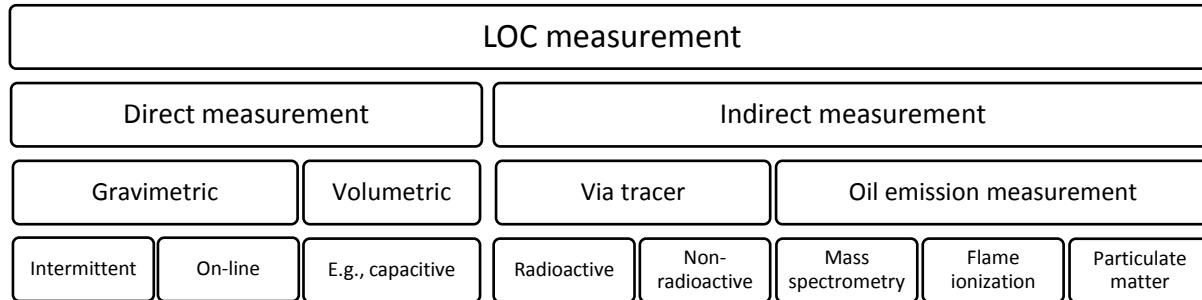

Figure 1: State-of-the-art lube oil consumption measurement – overview, cf. [1]

The former is conducted via gravimetric or volumetric and intermittent or continuous (on-line) measurement. The latter is mainly based on detecting hydrocarbons or tracer substances that originated in the oil. As state-of-the-art combustion engines consume quite low amounts of lubrication oil compared to their oil reservoir and the tendency is for this consumption to decrease, gravimetric and volumetric methods are – for different reasons – not satisfactory in terms of time and accuracy. Two main challenges arise when methods of hydrocarbon detection are used, e.g., mass spectrometry as described in [2], flame ionization or particulate measurement. First, lube oil components that take part at the combustion process and thus are oxidized to H_2O, CO, CO_2 etc. are ignored. Second, separation of fuel and oil-borne hydrocarbons is highly questionable especially when it comes to measurement on diesel engines. In the face of these challenges, the hydrocarbon method should be most strictly separated from LOC measurement and thus called oil emission measurement. At present, tracer methods describe the most sensitive and accurate

technique in LOC measurement. So as not to change the physical and chemical properties of the oil, the marker should ideally be found naturally in the base stock or additives. However, this does not apply to radioactive tracers, which also demand extra effort regarding safety standards for humans, nature and infrastructure. As a result, research at the LEC generally focuses on non-radioactive tracers. Furthermore, tracer substances should be stable throughout the entire duration of the experiments – especially during the combustion process. They should also be assignable to the lube oil and detectable in the exhaust gas. As all these requirements apply to sulfur and its combustion product SO_2, the SO_2 method as described for instance in [3] is considered to be the most efficient and universally applicable in terms of engine category, size and fuel; however, trends to low SAPS oils (ACEA C1-12: total sulfur ≤ 0.2 wt%) might negatively affect its accuracy or sensitivity.

LOC MEASUREMENT ON LARGE ENGINES VIA THE SO_2 METHOD

In the SO_2 method, oil consumption is measured by determining sulfur balance at the inlet and at the exhaust (after the combustion chamber). As shown in Figure 2 with a homogeneous natural gas operated engine, sulfur is introduced into the system via the operating fluids (sulfur concentration in the air $\mu_{S_{air}}$ is negligible), thus the sulfur mass concentrations in the oil $\mu_{S_{oil}}$ and the natural gas $\mu_{S_{NG}}$ respectively have to be determined with high accuracy. Provided that the engine is operated homogeneously, a partial flow of the air/fuel mixture can be separated and directed through the sulfur detector as well; the benefits of this action will be explained later. As the air/fuel mixture may contain manifold sulfur compounds, these are only partially oxidized to SO_2 during combustion. Therefore, the sample is directed through an oxidizer in order to make sure all sulfur components are converted to SO_2 by the high temperature and ozone injection. To detect SO_2, manifold methods have been developed, for example TOF-MS as described in [3] and IMR-MS [4].
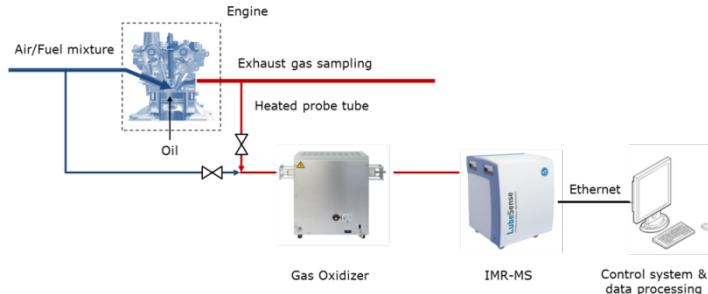

Figure 2: Schematic depiction of SO_2 measurement setup, cf. [5]

The volumetric concentration of SO_2 in the exhaust gas v_{SO_2} is determined via IMR-MS and converted to a mass concentration via molar masses of sulfur M_S and the exhaust gas $M_{ex.gas}$. Finally, oil consumption $\dot{m}_{oil}$ can be calculated with equation [1] – cf. [4].

$$\dot{m}_{oil} = \frac{v_{SO_2} \cdot \frac{M_S}{M_{ex.gas}} - \overbrace{\mu_{S_{air}}}^{\approx 0}}{\mu_{S_{oil}} - v_{SO_2} \cdot \frac{M_S}{M_{ex.gas}}} \cdot \dot{m}_{air} + \frac{v_{SO_2} \cdot \frac{M_S}{M_{ex.gas}} - \mu_{S_{NG}}}{\mu_{S_{oil}} - v_{SO_2} \cdot \frac{M_S}{M_{ex.gas}}} \cdot \dot{m}_{NG} \qquad \textbf{Equation [1]}$$

When propagation of uncertainty is calculated, it becomes apparent that the sulfur concentration in fuel exerts a major influence on the accuracy of oil consumption measurement as the mass flow of natural gas is about three orders of magnitude higher than the "mass flow" of engine oil. The gas supplier's odorization processes should be taken into account with natural gas operation in particular. To provide an idea of the influence of the sulfur concentration in the fuel on oil consumption, Table 1 shows the measurement uncertainties with a large natural gas engine assuming oil consumptions of $\dot{m}_{oil_{exp.1}} = 0.5 \; g/kWh$ and $\dot{m}_{oil_{exp.2}} = 0.10 \; g/kWh$ for high uncertainty (±1 ppmw) and for low uncertainty (±0.1 ppmw) in measurement of sulfur concentration in the fuel (natural gas).

Table 1: Influence of the uncertainty of sulfur measurement in natural gas on LOC measurement uncertainty

Name	Variable	Units	Total sulfur in natural gas 12±1 ppmw		Total sulfur in natural gas 12±0.1 ppmw	
Assumed specific LOC	$\dot{m}_{oil_{exp.spec}}$	g/kWh	0.50	0.10	0.50	0.10
Specific uncertainty	u_{spec}	g/kWh	0.05	0.05	0.03	0.02
Relative uncertainty	u_{rel}	%	10.8	48.6	6.0	18.2

If the sulfur in the natural gas is determined more accurately, LOC measurement accuracy with high oil consumption (0.5 g/kWh) can be improved by 40 % and with low oil consumption (0.1 g/kWh) by even 60 %. Figure 3 shows endurance run LOC measurements on a large single cylinder gas engine where the sulfur concentration in the natural gas is measured regularly.
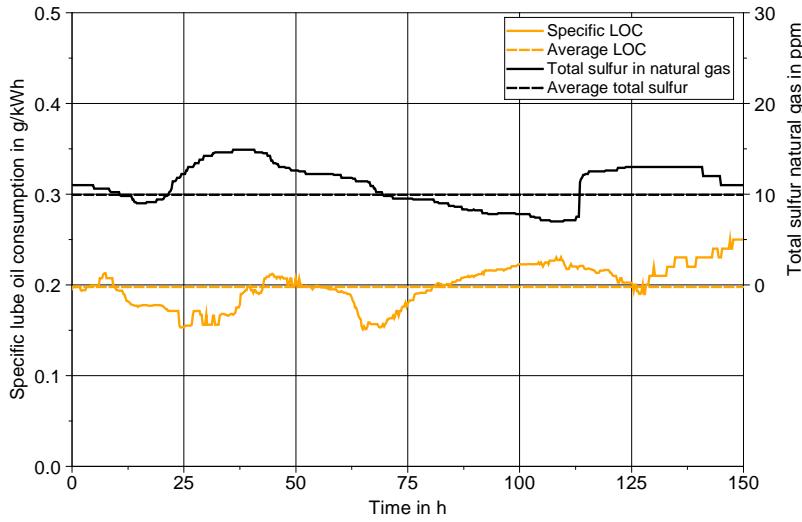

Figure 3: LOC measurement on a single cylinder engine

With diesel engines, however, which cannot be operated homogeneously, online measurement of the fuel or fuel air mixture prior to combustion is not a viable option. Moreover, sulfur concentration measurement of diesel fuel must be performed using UV fluorescence or a similar technology (RSD <± 1 %) because the standard specification sets a minimum reproducibility limit of ±3.1 ppm at 10 ppm (as per EN ISO 20884), which would result in inacceptable measurement uncertainty with the SO_2 method. Nevertheless, the measurement uncertainty of the more or less fluctuating tracer amount in the fuel results in uncertainty in LOC measurement (the lower the LOC, the higher the influence of fuel, the higher the measurement uncertainty). Thus research into alternative tracer substances is being conducted at the LEC.

DEVELOPMENT OF NEW TRACER SUBSTANCES: BARIUM

The deficiencies of the SO_2 method and the challenges it will face in terms of detection limits, accuracy and selectivity justify the exploration of new tracer substances. As mentioned above, the ideal tracer should already be present naturally in the base oil or additives so it does not have an impact on the lube oil's physical and chemical properties. Consequently, barium compounds such as the detergent additive barium sulfonate are being investigated. Barium sulfonate is a mixture of non-polar compounds such as mineral oil and barium salts such as barium sulphate and barium carbonate (strongly polar). Artificial oil aging experiments have shown that barium sulfonate can be blended into engine oil in a rather high concentration (up to 5 %) without significantly changing the oil properties that affect oil consumption.

Because of the composition of the additive, it seemed likely that the barium salts would neither vaporize nor participate in combustion and thus would remain and accumulate in the oil sump. In this case, the increasing concentration might indicate a way to measure oil consumption. However, long run experiments on a large gen-set gas engine showed that the concentration of barium remained level, thereby indicating that barium must be consumed at the same rate as the engine oil. During further preliminary experiments, oil consumption was calculated by analyzing the dilution of barium in the oil when barium-free oil was periodically added. The result was oil consumption between 0.15 and 0.18 g/kWh with a small standard deviation. However, the barium concentrations in the exhaust gas as well as deposits in the engine or infrastructure have not been measured yet for verification. To measure barium via the exhaust gas, calculations similar to those in the SO_2 method can be applied with the exception that the engine oil is considered to be the only barium source within the system boundaries of the engine. Since it is uncertain whether the barium compound would transfer into a gaseous phase and reach the minimum detection limit of the IMR-MS when blended into the engine oil, barium sulfonate was added to the diesel fuel at different concentrations (100, 500, 1000 and 2400 ppm) instead of directly to the oil during feasibility testing. Because the lightest barium isotope has a molecular weight of 130 amu and barium has seven stable isotopes, a significant peak pattern at a mass-to-charge ratio higher than 130 Da was expected (with ion molecule ionization, multiple ionization and fragmentation can be excluded). However, for the sake of completeness mass-to-charge ratios between 17 Da and 299 Da have been observed. Mass spectrum comparisons between the reference measurements (0 ppm of barium in diesel fuel) and measurements at 2400 ppmw in diesel fuel are shown in Figure 4, Figure 5, Figure 6 and Figure 7.
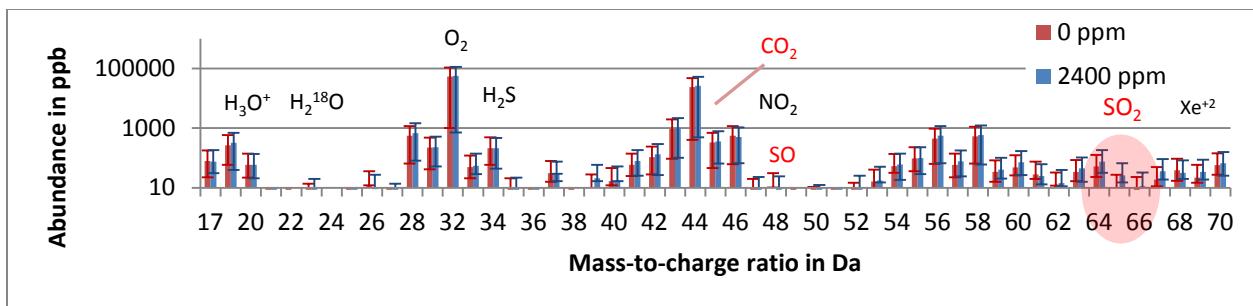
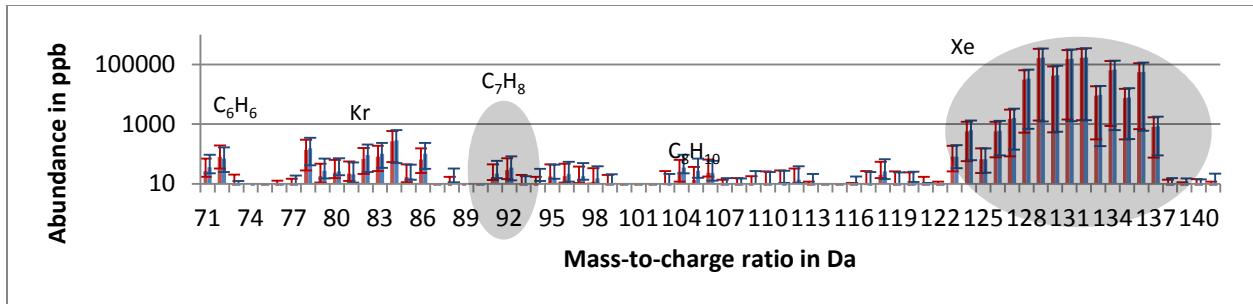Figure 4: Mass spectrum between 17 and 70 Dalton

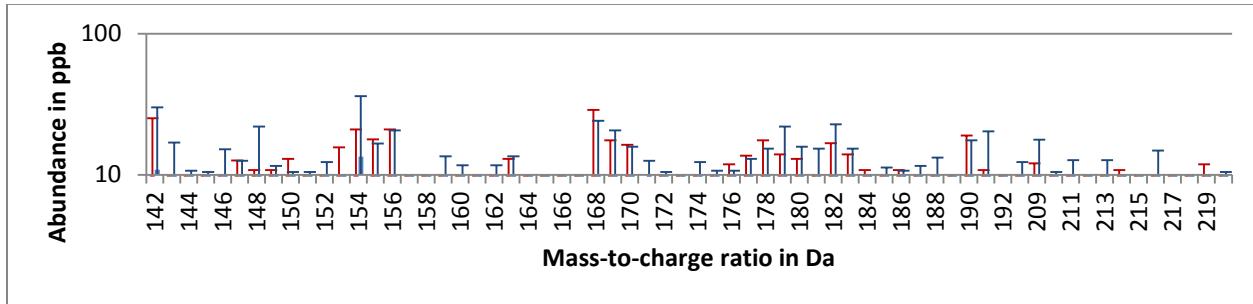Figure 5: Mass spectrum between 71 and 141 Dalton

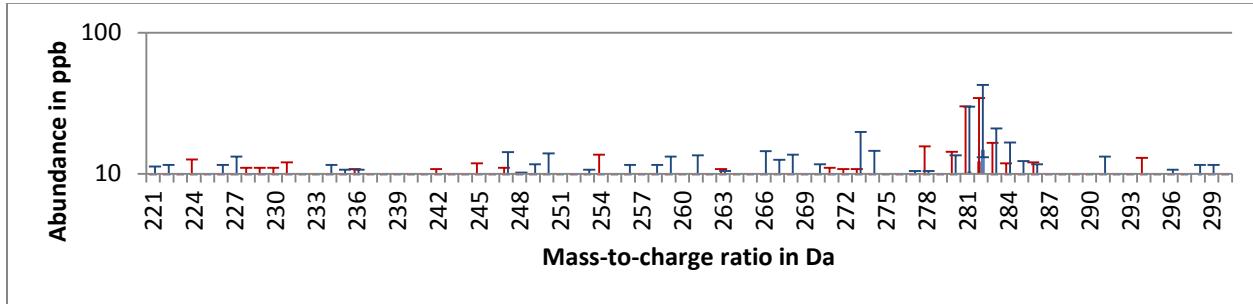Figure 6: Mass spectrum between 142 and 220 Dalton

Figure 7: Mass spectrum between 221 and 300 Dalton

Since masses from 130 Da to 299 Da are observed, it is clear that neither barium itself nor barium compounds can be detected by the mass spectrometer. Signals occurring between 122 Da and 137 Da represent the ionization gas xenon.

However, a look at Figure 8 reveals that the results of the mass spectrometry are justified. On the left, significant changes in particle filter samples are visible due to emission of barium containing particles. In addition to engine tests, thermogravimetric experiments are conducted that include analyses of vaporization residues and comparison with particle filter samples via x-ray diffraction. The right side of Figure 8 shows the existence of a significant similarity between the composition of the vaporization residues and the

particle matter emitted by the engine, thereby leading to the conclusion that barium sulfonate is not oxidized during the combustion process but releases its organic moiety by vaporization and is emitted in its original form as barium salts.
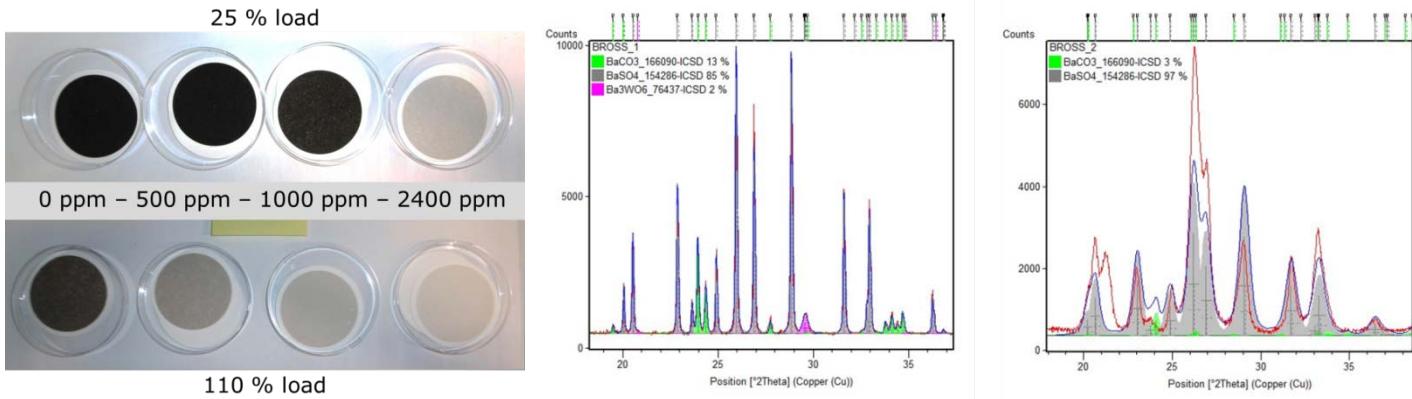
Figure 8: Particle filter samples containing barium (left); X-ray diffraction of vaporization residues and engine particle matter, respectively (right)

Unfortunately, the amount of barium particle matter emitted is not high enough to enable accurate quantitative oil consumption (or in this case diesel consumption) measurement via measurement of particle mass.

CONCLUSION

Conventional lube oil consumption measurement methods (gravimetric, volumetric) are no longer feasible especially with large engines as the oil consumption compared to the oil reservoir is currently too low and the amount of time required for measurement is too high and thus cost intensive. For today's lower detection limit and accuracy requirements, tracer methods have to be the tool of choice for measuring LOC. Even though the SO_2 method has certain deficiencies, it has been found to be the most satisfactory procedure in terms of accuracy, detection limit, cost and handling. However, future trends such as low sulfur fuels and LOW-SAPS (**S**ulphated **A**sh, **P**hosphorus, **S**ulfur) oil or sulfur adsorption systems in the field of biofuels are leading to low trace amounts of sulfur in the exhaust gas. This will be a challenge for the IMR-MS detection limit or selectivity between oil and fuel consumption.

Experiments using barium as a tracer reveal the manifold challenges and interferences in the development of new tracer substances. Barium as a tracer fulfills many of the requirements such as high oil solubility without significantly changing oil properties, proportionality between tracer consumption and oil consumption, high selectivity (the oil is the only source of barium in the system), low cost and no safety restrictions when operating with the tracer. Unfortunately, online detection is possible with neither IMR-MS nor comparable systems because high-boiling particles must be able to be detected. If proper detectors for measuring barium salts at low concentrations in gas mixtures won't be developed in the near future, different tracers will have to be found. Another potential new tracer method is currently under investigation at the LEC and is hoped to be ready for presentation by 2018.

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