

## On line engine oil consumption monitoring via the gaseous total sulfur signal SO<sub>2</sub> in the raw exhaust of the engine utilizing the sensitive ion molecule reaction mass spectrometry

*The dynamic monitoring of oil consumption in IC engines is approached with various techniques ranging from radioactive counting to detection of halogenated tracer compounds or polyaromatic hydrocarbon tracers, to monitoring unburned hydrocarbons as residues from engine oil.*

*This article discusses the method of gaseous SO<sub>2</sub> measurement in raw exhaust it's benefits and limitations of today's status. Modern engines consume about 2 to 5 g/h of engine oil under low and medium load but consumption may go up to 130 g/h in negative load conditions. Particulate filters must be desulfated every 5000 km even when sulfur free fuel is in use. For the oil measurement in the raw exhaust all possible Sulfur compounds are converted to SO<sub>2</sub> in a hot oxidizing atmosphere. Additional pure oxygen in the form of ozone is added to the oxidizer for very low lambda engine conditions and the conversion of sulfur on particulates into SO<sub>2</sub>. A sensitive mass spectrometer operating in an ion molecule ionization mode measures gaseous SO<sub>2</sub> from concentrations of 0.02 ppm to 50 ppm in measurement cycles from 2 Hz to 0.2 Hz depending on if long term measurement or dynamic operation is chosen. Technical description of pressure reduction, gas transfer, oxidation efficiencies and lower detection levels of the instrumentation are given as well as data on a complete engine map and data on reproducibility of the SO<sub>2</sub> method are presented.*

*Key words: engine oil consumption, oil consumption monitoring, spectrometry*

### 1. Introduction

Downsizing of engines in cylinders and capacity, increasing compression ratios and MEPs, turbocharging, reduction of piston friction, use of CNG as modern fuel: all these strategies result in elevated temperatures of engine parts and engine oil, reduced oil viscosity, elevated blow by rates, and hence increasing oil loss of modern IC engines. Nitrogen traps as well as particulate filters reduce their operation efficiencies by the adsorption of sulfur compounds along their active sites of the catalyst and so complex desulfation strategies must be applied in today's after gas treatment technologies. Even when sulfur free fuel is used the amount of sulfur given by engine oil loss makes desulfation steps necessary every 5000 km of driving. Desulfation is typically achieved by injection of fuel or as post injection, however the amount of hydrocarbons must be chosen in a way that only SO<sub>2</sub> desorption takes place and not reduction of sulfur into H<sub>2</sub>S. This would cause a severe odor problem and hence extensive testing is necessary. The reduction of any sort of sulfur in the raw exhaust is of high priority in engine development.

Monitoring engine oil consumption in dynamic measurements was performed since the 1970s with radioactive tracers added to the engine oil (J. Meyer – General Motors [1]). As radioactive materials were banned in many research facilities over the years many researchers in the past 20 years tested various non-radioactive oil tracer methods like pyrene added to engine oil and being detected by a laser ionisation mass spectrometer (Püffel Thiel BMW [2–4]), addition of dibromnaphthalene (V&F) [5]. Matz and Gohl (TU Hamburg Harburg) [6] developed aE oil consumption monitoring

method based on measurements of high molecular weight hydrocarbons in the raw exhaust. The SO<sub>2</sub> method as described in detail below was developed by Rabl and Artmann (University Regensburg) [7] but also developed by other researchers like Moteur Moderne, Ford, Turkey, Da Vinci [8] Emission Services, or Horiba, Japan [9]. Still today there are no clear preferences of one or the other method of monitoring and depending on engine types and fuel used one or all methods may work for oil consumption monitoring. To us the SO<sub>2</sub> method seems to be the most reliable and easiest to use technique as should be shown below.

Tracers in engine oil bear two intrinsic problems. First, they must withstand the high combustion temperatures in the cylinder in order not to oxidize and so to change their chemical structure and the second restriction is their single boiling point temperature, compared to a boiling point curve from 200 to 400°C of the engine oil. Low boiling point tracers will be distilled out of the oil over operating time and thereby reduce the concentration in the oil and high boiling point compounds like pyrene cannot be detected well at low oil temperatures and more at low exhaust gas temperatures.

The survival of tracers at high combustion temperatures may be tackled with inorganic halogenated compounds but halogenated compounds may form aggressive acids that are not welcome by engine operators.

Another approach is the addition of aromatic compound like pyrene that have very high flame resistance but also have high boiling points and will condensate at low oil temperatures and low engine load applications.

There are specific compounds in the engine oil that are not present in fuels and hence could be detected in the raw

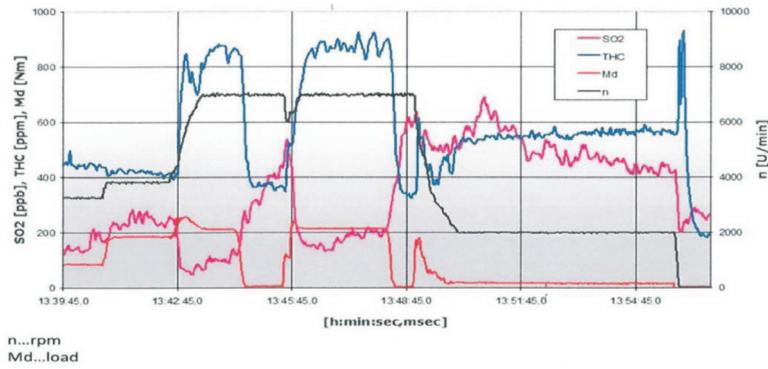


Fig. 1. Measurement of oil throw limit at high rpm and transition from high load to no load

exhaust gas as information of engine oil loss. Zinc and phosphorus additives in engine oil would represent specific markers of engine oil if they came in a gas phase but they are not; they leave the combustion zone in oxidized states with no gaseous vapor pressure and condense along surfaces.

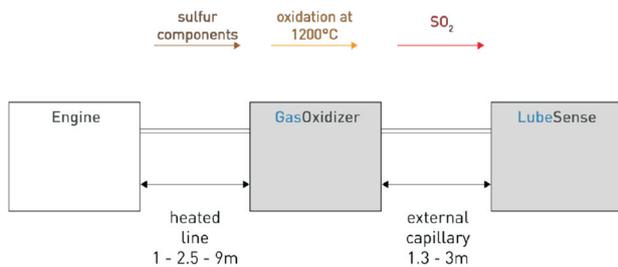


Fig. 2. Schematic setup for oil consumption measurement

Organic sulfur additives to engine oil leave the combustion chamber as gaseous sulfur compounds, mainly as  $SO_2$ . Under some combustion conditions like in very low lambda burning as in negative load operation of the engine  $H_2S$ ,  $CH_3SH$  is formed, in soot formation conditions sulfur attaches to particulates and in very high temperature flames carbon monoxi sulfide COS may be formed. All these gaseous sulfur compound may add up to 3% next to  $SO_2$  as main Sulfur emission. Since oil transport into the combustion

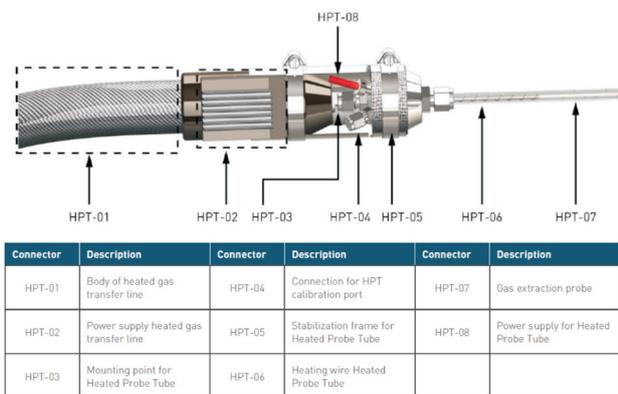


Fig. 3. Connector layout for V&F heated prove tube in oil consumption measurement

chamber is in both liquid and vapor form, a consistent sulfur concentration in the oil is required in order to assume that consumed oil in the exhaust that has the same concentration of sulfur as in the original oil.

## 2. Exhaust gas extraction from engine and pressure regulation

Sample gas should be taken in front or after turbo charger and long stretches of cast iron manifold should be avoided. Cast iron has a strong tendency to store  $SO_2$  by adsorption and so memory effects can be seen at changing temperatures of cast iron (stainless steel does not store  $SO_2$ ). The gas extraction has a heated tip reaching into the manifold and a heated ceramic filter. This assures high enough temperatures of the gas to avoid condensation at low exhaust gas temperatures.

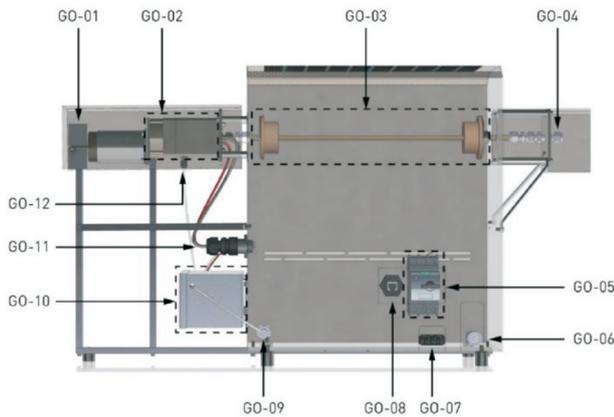
Right after the gas extraction a fast pressure regulator keeps a constant gas flow rate of 1 liter per minute in the pressure range from 0.3 to 8 bar of manifold pressure.

## 3. Back-flash and calibration gas inlet

Behind the front tip of the gas probe gas can be added to the gas transfer line. This done out of 2 reasons. First a back flash gas can keep the gas line clean from soot and condensation water during engine stop or cold start and secondly  $SO_2$  calibration gas may be flushed through the gas line. By activating the calgas two features of the transfer line may be verified. First the degree of contamination. The analyzing system has a  $t_{90}$  gas response time of 50 msec oxidizer has a response time of 300 msec. In case the response time on  $SO_2$  becomes more than 2 seconds a contamination of the gas line mostly by soot particles is indicated. Another important check with  $SO_2$  calgas added at the tip of the transfer line is the measurement of the overall gas travel time from manifold to analyzer. This time becomes important when dynamic and instationary time resolved oil consumption is measured. As the electric signals of mass fuel flow and engine air flow are ahead of the  $SO_2$  gas signal a correction of this travel time must be done in the calculation of mass output of oil.

## 4. Oxidizing oven

$H_2S$ , COS,  $CS_2$  and sulfur bound on particulates can be oxidized to pure  $SO_2$  gas phase in a high temperature  $O_2$  containing environment. Temperatures generated by a heated filament along a ceramic tube must be in the range of 1200 deg and residence time of the exhaust gas at these temperatures should be no less than 20 msec. A constant flow of exhaust gas between 1 to 2 liters per minute allows the necessary residence time in the hot oxidizing zone. For engine operating conditions below lambda 1 where the residual oxygen concentration in the raw exhaust goes to zero, additional oxygen must be added to the oxidizing chamber. An additional gas flow of pure  $O_2$  controlled by a mass flow controller at 60 ml per minute is added to the sample gas and is sufficient to guarantee enough oxygen even under Lambda 4 operating conditions.



Connector	Description	Connector	Description	Connector	Description
GO-01	Mounting point for heated gas transfer line	GO-05	Automatic circuit breaker	GO-09	Ozone Generator inlet connector
GO-02	Pressure reducer and mixing chamber	GO-06	100% Oxygen inlet	GO-10	Ozone Generator
GO-03	High temperature zone with alumina rod	GO-07	Power cable port	GO-11	Mixing chamber heating connector
GO-04	Mounting point for AirSense external capillary	GO-08	Optional: RJ45 communication port	GO-12	Ozone Generator outlet connector

Fig. 4. Connector layout for V&F heated probe tube in oil consumption measurement



Fig. 5. Mass spectrometer

### 5. The monitor

The instrument in use is based on an ion molecule reaction mass spectrometer described in [10, 11].

A high vacuum chamber houses electromagnetic devices that separate ions of different molecular weight and count these ions in short (msec) time intervals. The formation of ions from the sample gas molecules is achieved by charge exchange from an ion beam to the neutral molecules in two body collisions. This technique suppresses background matrix interferences to a minimum and realizes a high linearity over 4 orders of magnitude. The ion counting system enables either very low detection levels 10 ppb at 3 sec or a high time resolution of 100 ppb at 300 msec.

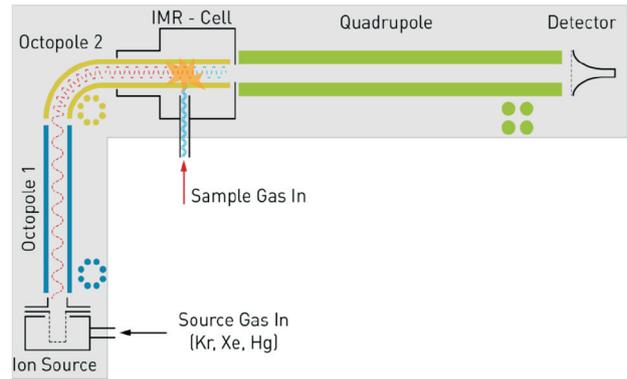


Fig. 6. Principle of mass spectrometer measurement

### 6. Measurement boundary requirements

To properly measure the amount of oil consumed the other sources of sulfur should be minimized, or better still, eliminated. There are two other sources that can alter the amount of sulfur present in the exhaust gases: air and fuel. Air contributes very little sulfur to the combustion products. However the common gasoline that is purchased at the pump may have a relatively higher amount of sulfur. So for this method low sulfur research gasoline which has a sulfur percentage of less than 2 ppm has to be used. The oil consumption rate is calculated from mass flow rate of fuel and air, and total sulfur concentration in oil, fuel, air and exhaust gas. At higher sulfur levels there will be a higher offset in the  $SO_2$  signal and the resolution of  $SO_2$  measurement related to engine oil is diminished.

Sulfur content in CNG gas may be determined easily by running CNG fuel air mixture through the oxidizer and measuring the  $SO_2$  level.

For long term experiments a supply of fuel should be stored as there are variations of sulfur content in online fuel supply lines.

#### 6.1. Sulfur defined engine oil

Standard engine oil has a sulfur content from 3000 to 5000 ppm. For very sensitive oil consumption measurements

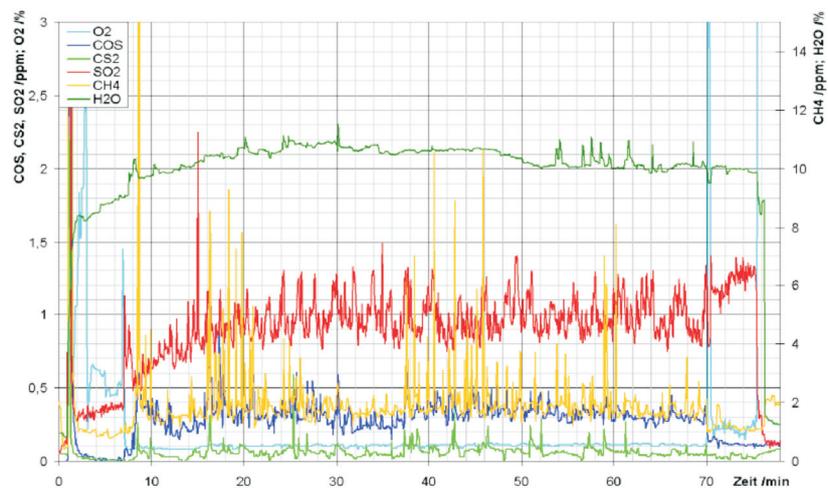


Fig. 7. Distribution of sulfur compounds in the raw exhaust of a normal aspirated engine (Rabl, Artmann FH Regensburg)

a content of 10000 ppm is desirable and may be purchased from companies like Lubrizol. In any case a proper sulfur analysis of the engine oil is desirable. After changing to a fresh oil the engine should run for 3 hours to standardize the sulfur components in the oil. From experience it is known that engine oil slowly diminishes the sulfur content after 30 to 50 hours of operation. In cases where heavy fuel contamination of the engine oil is an issue the sulfur content should be analyzed in 10 hour operating periods.

Fixed values of mass flow or online data are given to the monitoring instrument in order to convert the ppm signal of  $SO_2$  into g/h or g/kWh signals.

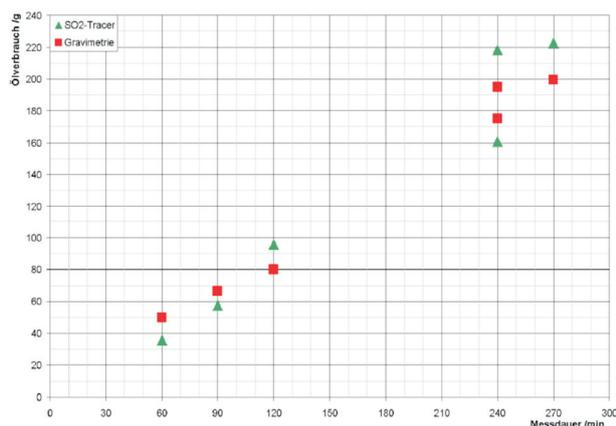


Fig. 8. Comparison of gravimetric and  $SO_2$  measurements (Artmann, Rabl, FH Regensburg)

### 6.2. Measurement examples

The picture below shows a time resolved measurement of various molecular gaseous compounds from the raw gas of a normal aspirated engine running in unstable combustion caused by a high throughput of oil. The graph shows that within several sulfur compounds  $SO_2$  is by far the highest signal in the raw exhaust. The oxidizing oven does convert all of  $CS_2$ ,  $H_2S$  and  $COS$  into  $SO_2$ .

### 7. Comparison and difference of the $SO_2$ method against gravimetric measurements

The classic way to obtain oil consumption of an engine is running the engine for a length of time, typically 10 hours and then draining the engine oil pan. Determining the difference in weight before and after should describe the engine's oil consumption. For some measurements like the one shown below (Rabl, Artmann) the two methods show good agreement. For other operating conditions this cannot be the case. The basic difference of the gravimetric method compared to all tracer methods where the oil loss is measured by a signal in the raw exhaust is:

Tracer methods show the amount of oil passing the combustion region as a positive signal, whereas the weight loss of engine oil is a negative

signal. Not only are oil leaks on engine seals included in the gravimetric signal, but also aldehydes that can be formed in the oil and result in sludge sticking to the oil pan and it also includes oil dilution by fuel input to the oil that may even result in a weight gain of the engine oil.

Gravimetric determination of oil consumption gives an integral signal of oil loss over the period of time. This is a disadvantage in developing engine components to minimize oil loss. Tracer methods, especially the  $SO_2$ -method allows a dynamic study of oil loss under transient engine conditions.

Oil loss of engines are measured with different test procedures. In engine development a comparison between a standard piston, piston rings and liner is made against modified parts in another cylinder of the same engine. Large engines like ships and power generator engines are operated in stationary modes in various load conditions and so the values are given in g/kWh. The oil consumption may reach up to 100 kg of oil in 24 hours. For small engines there are test cycles in use like the "Tokyo test" where the engine is operated between idle and low load, low rpm sequences for 20 min time intervals. Other tests use the standard FTP test as is seen below. The figure below expresses the characteristic reproducibility of test runs.

### 8. Conclusion

The  $SO_2$ -monitoring technique in the raw exhaust with an oxidation chamber between gas extraction and analyzer for a complete conversion of sulfur-containing molecules and particulates into  $SO_2$  is more and more accepted by engine developers as the most universal technique. The disadvantage of need of sulfur free or very low and constant sulfur levels in the fuel is compensated by a simple calibration procedure. Other tracer methods suffer in complex calibration procedures or nonlinear loss of tracer during operation. Over the past years sensitivity and selectivity of the  $SO_2$ -detection method was improved. Matrix effects of fuels like

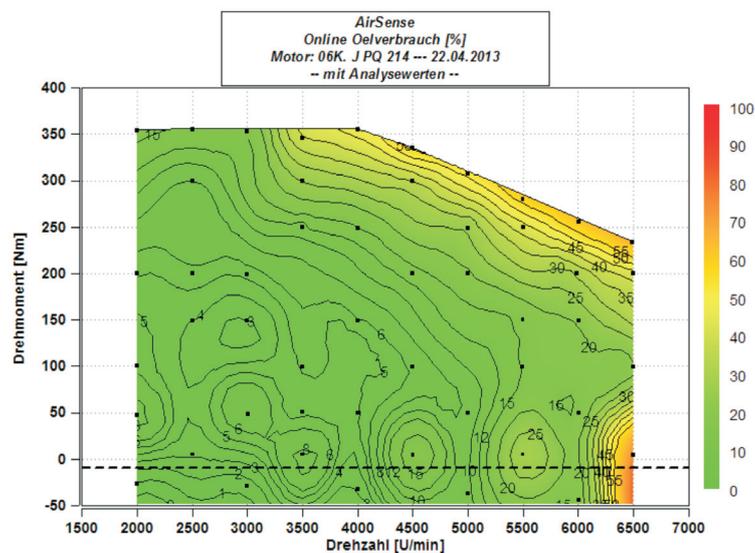


Fig. 9. A map of stationary operating points of rpm against torque of an engine (courtesy of Audi)

O<sub>2</sub> and water content were eliminated, as especially was the particulate load under rich operating conditions by the high temperature oxidizer concept with the addition of ozone. A special high temperature pressure reduction system allows to extract low flow volumes of 1 to 3 l/min gas from high pressure regions before turbocharger. Zero and calibration gas is directly fed into the onset of the probe line, hence gas travel times can be measured accurately and contamination of gas lines is detectable without decoupling the system from the engine. The highly sensitive ion molecule mass spectrometer setup is built with sulfur free components for low background signals and the additional control of H<sub>2</sub>O signal and O<sub>2</sub> signal (50 sec measure time) assures that no water condensation along the gas lines and connectors (H<sub>2</sub>O signal spikes when

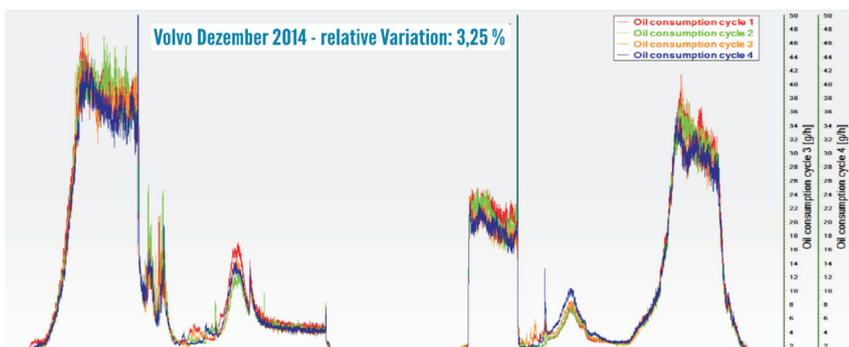


Fig. 10. Repeatability oil consumption in test cycles

droplets are formed) occurs and that there is always enough oxygen present even under very rich engine operating conditions. A further development within engine oil analysis bears the measurements of water and aldehyde content in engine oil for a on line determination of oil degradation over operating time of the engine.

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