Analysis of Mixture Conditions close to Spark Plug Location using a Time Resolved Gas Sampling Valve

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ABSTRACT

The quality of air-/fuel-mixture is of prime importance for cycle fluctuations of combustion. Investigations of mixture formation and conditions in SI engines have been subject of intensive research since many years.

The scope of this work was to investigate crank angle resolved determination of qualitative and quantitative mixture conditions inside the combustion chamber in dependence on various engine operating conditions. For this experimental investigation a time resolved Gas Sampling Valve (GSV) was combined with a flame ionisation detector (FID), a CO_2-analyzer and a mass spectrometer. The GSV also enables the determination of residual gas concentration. Measurements on a DI gasoline engine show influences of air-/fuel-mixture in dependence on various engine operating conditions when the engine runs in charge stratification mode. Moreover, experimental results of local mixture composition are compared with fuel distribution, calculated from CFD-codes.

INTRODUCTION

Future engine concepts like the direct injection SI-engine require a profound understanding of the different states of the cylinder charge. High resolution measurement techniques are required for the analysis of these transient processes. Gas analysis devices can provide an important contribution to the determination of mixture formation and combustion processes.

Most of today's gas analysis devices require a very long response time (> 100 ms) due to their measuring technique which makes it impossible to measure with a resolution of few crank angles. Furthermore it is not possible to extract large quantities out of the combustion chamber. A solution to this problem is the combination of a fast, synchronized gas sampling valve with a standard gas analysis device. The gas sampling valve is capable of extracting smallest amounts of gas from the combustion chamber or from the exhaust system. The sampling can be assigned both to a specified crank angle and to a certain measurement location. This measurement device has already been used, particularly in combination with a FID to analyze the charge inhomogenity in SI-engines [1,2,3,4].

MAIN SECTION

THE GAS SAMPLING VALVE (GSV) - The gas sampling device used for the described investigations is a fast, synchronized valve made by SMETec GmbH for the extraction of gaseous samples from the combustion chamber of fired engines. Figure 1 shows the systematically arrangement of the GSV.
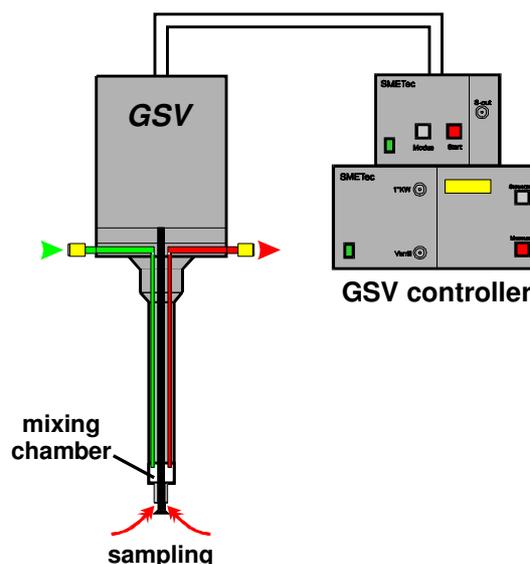

Figure 1: Gas Sampling Valve (GSV)

The devices, electromagnetic principle in particular, facilitates the adaptation and the handling in contrast to hydraulic systems [1,2,3,4,5,6]. The valve head is distinguished by a very small diameter of 6 mm and a length of 14 mm. At the mixing chamber the shaft of the GSV expands to a diameter of 13 mm. The valve lift can be adjusted between 0,4 and 3 mm. The opening time from 0,6 to 3 ms depends on the valve lift. The GSV contains two tubes. One of them can be flushed with inert gas to transport the sample in the other tube to the analyzer. The tubes can be heated up to 200°C to prevent the gases from condensing. Furthermore, the GSV contains a sensor to indicate the movement of the valve. The mass of the sampled gas depends on the opening time and the combustion pressure at the time of sampling. Table 1 shows sampled masses recorded at a speed of 2000 rpm and an indicated mean effective pressure of 2 bar for two different pressures in the combustion chamber.

Combustion chamber pressure at the time of sampling [bar]	mass of the sampled gas [mg]	percentage share of combustion chamber charge [%]
4.9	0.53	0.31
8.4	0.74	0.43

Table1: mass of the sampled gas

The sampling procedure is controlled by an electronic device with an integrated microprocessor. This controller synchronizes the valve with a resolution of +/- 1°CA. Depending on the speed of the engine, it is possible to take a sample each fifth cycle [7]. The gas sampling valve can be inserted into the engine for example instead of a pressure transducer (figure 2).
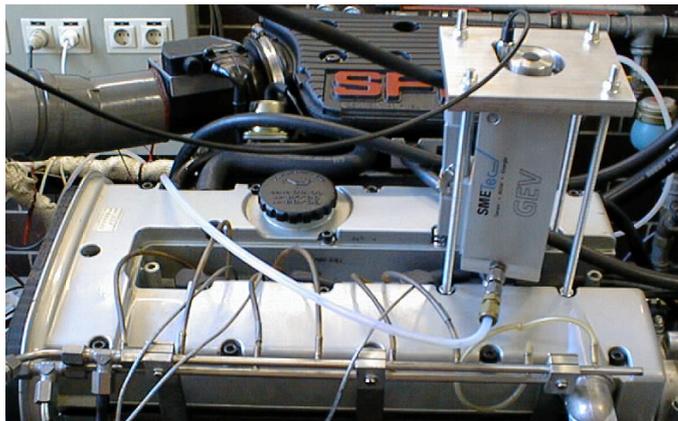

Figure 2: Adaption of the GSV

The valve allows sampling even during combustion. Problems with the valve's tightness occur after approximately 400 to 600 samples depending on the power level and on location of installation. The valve body itself can easily be exchanged so that the interruption of the investigation process is very short. More than 1000 samples are possible when the GSV operates in areas

with fresh mixture before combustion occurs or in the exhaust manifold.

HYDROCARBON ANALYSIS TO DETERMINE THE AIR-FUEL MIXTURE RATIO

Setup and function of the measurement technique - Figure 3 shows the investigation setup of the GSV in combination with a flame ionization detector (Testa: FID 123) to analyze the hydrocarbons and to calculate the ratio of air-fuel mixture. The sampled gas mixture is transported from the mixture chamber inside the valve to the FID with the help of the carrier gas (Nitrogen) which is heated up to 200°C. The gas mixture is constantly heated on its way to the analyzer to prevent the hydrocarbons from condensing on the tube walls. To determine the sample volume, the mass flow of the transportation gas and the sampled gas mixture are measured with two mass flow meters.

To determine the mixture quantity, 10 samples from successive cycles are necessary for each measuring point. The accuracy of this procedure is about 4% of the maximum level of indication.

Since the FID is calibrated with propane (C_3H_8), it is necessary to convert the indicated value to that of a real fuel (in this case: $C_{7,1}H_{12,8}$ - established from a fuel analysis) with the help of the carbon ratio. Taking into account the required air (14,5 $^{kg\ air}/_{kg\ fuel}$) for this special fuel, an equivalent indication value of approx. 46.400 ppm can be established for a stoichiometric mixture.
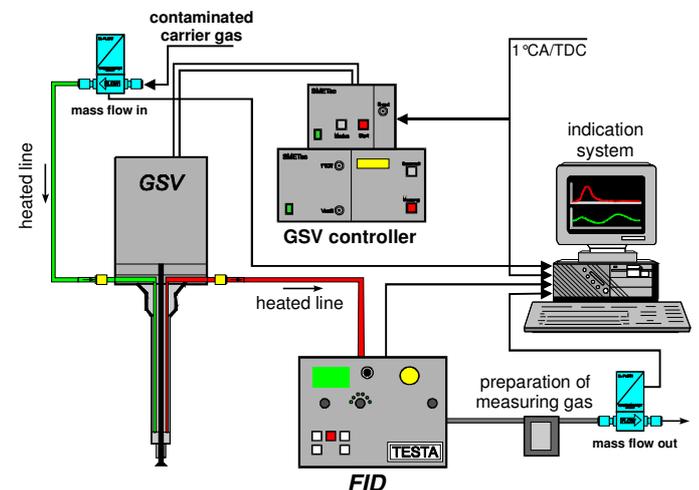

Figure 3: Test configuration for HC-analysis

Investigation procedure and results - During the investigation, the signals of the measurement devices were recorded with an engine indication system and averaged over 300 cycles with a resolution of 1°CA. During this time interval, the GSV takes 60 samples (every 5th cycle) out of the combustion chamber. The following measurement results are mean values of 3 to 4 measurements per measuring procedure at constant engine parameters and test setups. During the cycles in

which samples were taken, the ignition was switched off to prevent the combustion. The engine used for the investigation was an one-cylinder four-stroke SI-engine with a displacement of 500 ccm converted into a direct injection engine.

Engine conditions:

T_{water}	=	85 °C
T_{oil}	=	85 °C
T_{fuel}	=	18 °C
T_{air}	=	23 °C

GSV:

valve lift	=	0.4 mm
opening duration	=	0.6 ms

Figures 4a - 4c show in principle the adaption of the GSV, the data acquisition and the results at homogenous operating conditions. The GSV was installed in the same radial position as the spark plug relative to the injection valve (figure 4a). Figure 4b shows the signal of the GSV's movement sensor, the input and output of mass flow and the signal of the FID in dependence of time. The engine speed in this particular investigation was 2000 rpm by an indicated mean effective pressure of 3 bar. The GSV sampled at 45 °CA before TDC. The cycle by cycle fluctuations of the hydrocarbons, caused by variations in the fuel dosage, are conspicuous. Tendencies toward cyclic fluctuations of the combustion are visible for this sampling point. The acquired air-fuel ratios in figure 4c are compared with the air-fuel ratios calculated by Brettschneider-equation [8]. From the comparison it can be seen that the air-fuel ratio in the spark plug area (GSV-samples) is slightly leaner than the air-fuel ratios calculated from concentration of exhaust emission.
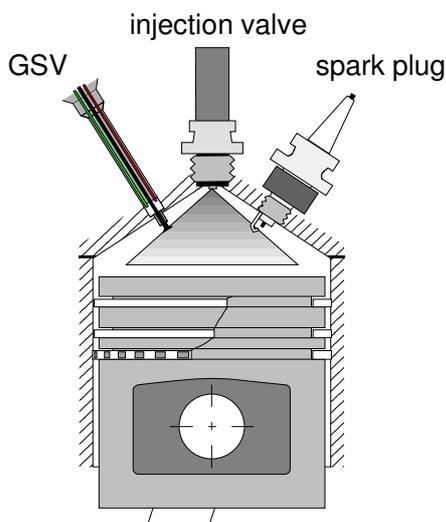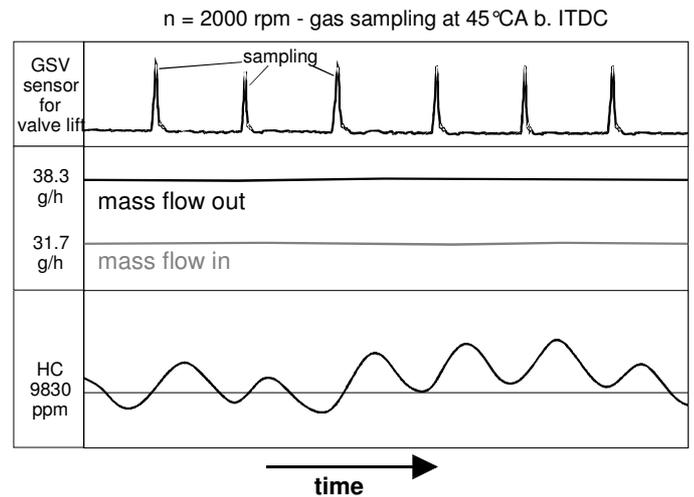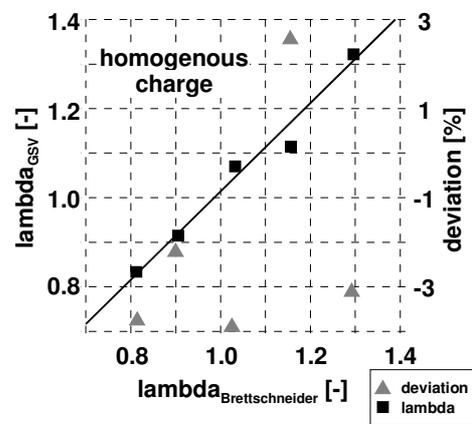

Figure 4b: Data logging

Figure 4c: Result

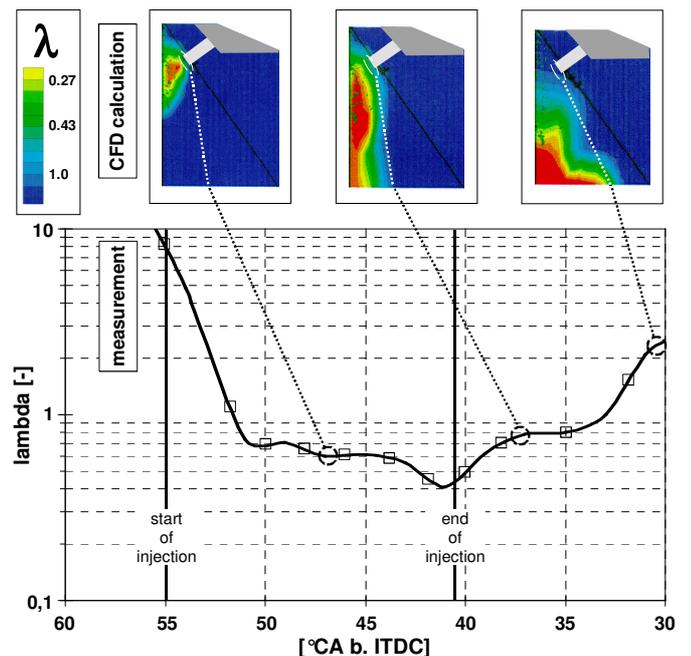Figure 5 shows the course of the air-fuel ratio in dependence on the crank angle at charge stratification.

Figure 5: Lambda determination and CFD calculation

Figure 4a: Adaption

The operating condition was 2000 rpm and an indicated mean effective pressure of 2 bar. The gas samplings were taken every 2 to 3 °CA, so that a series of the air-fuel ratios could be acquired with overlap of the measurement intervals. This course shows significant rich mixtures in the range of 50 to 38 °CA before TDC which can not be ignited. Furthermore, CFD calculations of fuel spray expansion carried out by Kech [9] are compared to single moments of the measurement. There is a good agreement between the calculation and the measurement.
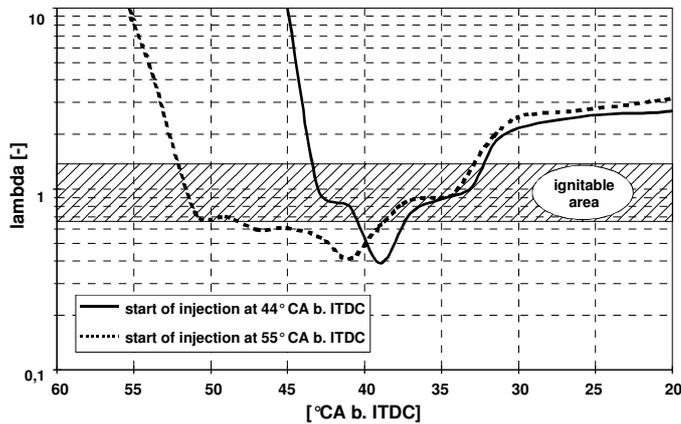
Figure 6: Lambda determination in dependence on start of injection

Figure 6 shows the course of the air-fuel ratios in respect to the crank-angle for two different starts of injection at 55 / 44 °CA before TDC at the same duration of injection and the same injection pressure. The smaller time interval in the rise from rich to lean mixture is remarkable for late injection. These results give information to the crank-angle in which a safe start of ignition is possible.

CARBON DIOXIDE ANALYSIS TO DETERMINE RESIDUAL GAS

Setup and function of the measurement technique - The investigation setup of the GSV in combination with an infrared absorption analyzer (carbon dioxide analysis - Hartmann & Braun: URAS) instead of the FID to determine the local residual gas is the same as in figure 3. The measurement analysis corresponds to the HC analysis. With a second CO_2-analyzer, the CO_2 concentration near the exhaust valve is measured conventionally. A comparison between the CO_2 concentration of the fresh charge in the combustion chamber and the CO_2 concentration in the exhaust gas makes it possible to estimate the local residual gas fractions (CO_2-concentration in combustion chamber / CO_2-concentration in exhaust gas • 100%). Ten gas samples are necessary for this quantitative analysis. The accuracy in this method is lower than ± 4% of the maximum indicated level.

Investigation procedure and results - The signals of the measurement devices were recorded and analyzed similar to the HC analysis. The GSV was installed instead of the pressure transducer. For these investigations a production 4 cylinder SI engine with a displacement of 2000 ccm was used.

Engine conditions:

T_{water}	=	90 °C
T_{oil}	=	90 °C
T_{fuel}	=	18 °C
T_{air}	=	23 °C

GSV:

valve lift	=	0.9 mm
opening duration	=	1.0 ms

Figure 7 shows the local CO_2-concentration as well as the burning rate calculated from the mean pressure trace of 100 cycles with a thermodynamic two-zone model dependent on °CA. The engine operation conditions were 2000 rpm by an indicated mean effective pressure of 2 bar. The upper left in the figure 8 shows the location of the adapted GSV in the cylinder head. The simultaneous rise of the CO_2 and the burned mass fraction are significant. That means that the samples collect a mixture of fresh charge and burned mixture across the flame. From approximately 5 °CA after the top dead center the CO_2 course shows greater gradients in relation to the burned mass fraction because of the local gas sampling.
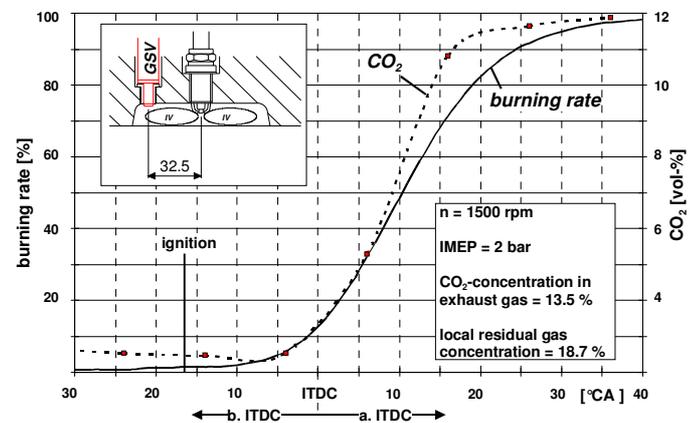
Figure 7: Residual gas analysis in comp. with the burning rate

Figure 8 shows the exhaust residual fraction in relation to speed, load and exhaust back pressure. The sampling for the operating points happened at 5 °CA before the start of ignition. As expected, the exhaust residual fraction decreases with increasing speed or increasing load and with decreasing exhaust back pressure. It is remarkable, that the exhaust residual fraction decreases linearly with increasing speed and constant load.
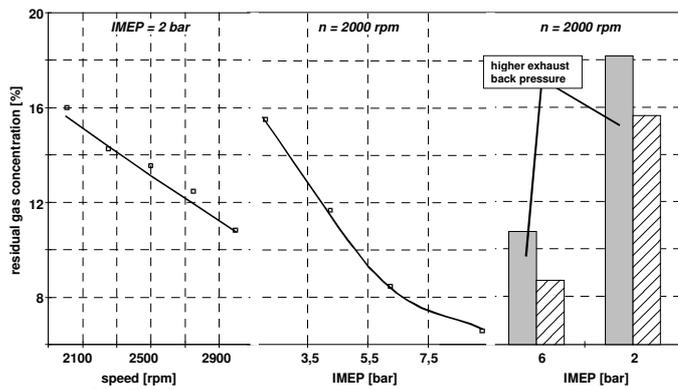
Figure 8: Residual gas analysis in dependence on speed, IMEP and exhaust back pressure

MULTICOMPONENT GAS ANALYSIS WITH A MASS SPECTROMETER

Setup and function of the measurement technique - Figure 9 represents the investigation setup of the GSV in combination with a Mass Spectrometer. The gas used for this investigation contains a component of known concentration which is not present either in the fresh mixture nor in the exhaust gas, but can be detected by the Mass Spectrometer. Therefore it is possible to calculate the rate of dilution which makes mass flow meters unnecessary for this investigation.
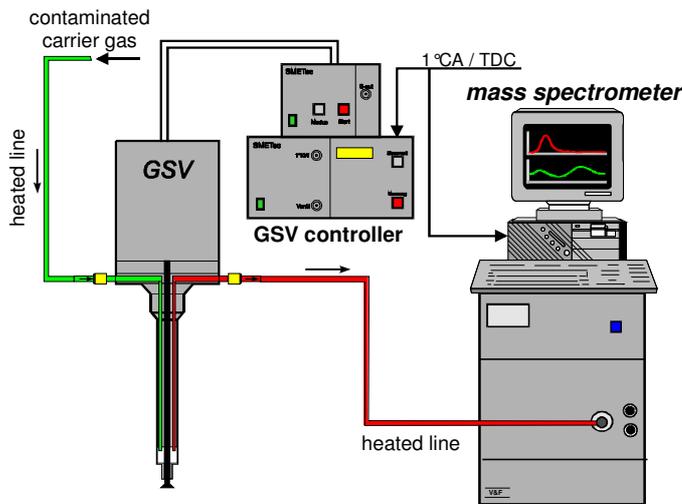

Figure 9: Test configuration for multi component gas analysis

The test engine, the operating conditions and the adaptation of the GSV were set as for the CO_2 analysis. The signals of the measurement devices were recorded and analyzed similar to the HC and the CO_2 analysis.

Investigation procedure and results - Figure 10 shows the concentration of benzene and toluene as well as carbon monoxide and nitrogen oxide in relation to the crank-angle at a speed of 2000 rpm by an indicated mean effective pressure of 2 bar. This results are represented qualitative. Additionally the figure shows an averaged combustion chamber temperature calculated with a thermodynamical one zone model. At 30 °CA after TDC concentrations of CO, benzene and toluene reach a minimum because the flame is passing. The concentration profiles of the nitrogen oxides as well as the combustion temperature however reach a maximum at this crank angle which has been described in other investigations, too [10,11]. Equally significant is the invers behavior of the NO and the CO concentrations. This anti-correlation indicates that different gas pockets are passing by the sampling valve. The CO oxidation of the expanding exhaust gases depends mainly on the imbalance of the C-O-H reaction. The NO concentration decreases because of the chemical balance of the reaction. However, during the combustion process, these NO back formations come to a steady level due to the low temperature. Characteristically, the NO formation, depending on temperature, is delayed in relation to the formation of carbon monoxide [10,11]. The concentration of the hydrocarbons increases when the gas expands, probably caused by unburned fuel in gaps or by combustion chamber deposits.
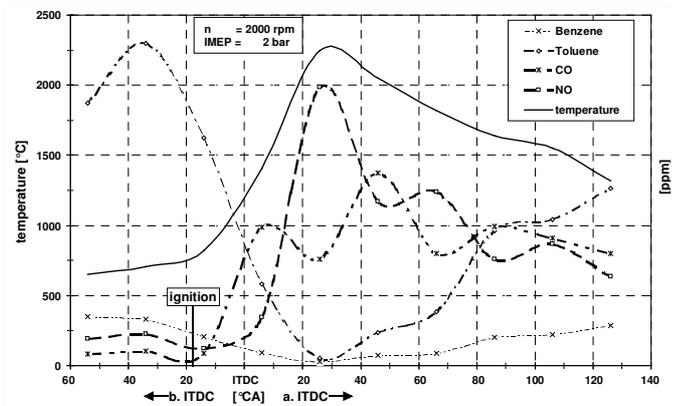

Figure 10: result for multi component gas analysis

CONCLUSION

The Gas Sampling-System including gas analysis procedure is suitable as a measuring tool to obtain increased knowledge about the behavior of combustion chamber charge during transient operating conditions.

With this easy to use measuring method, which is of a high durability and insensitivity towards particle contamination, it is possible to achieve a short sampling time. The electromagnetic principle of the GSV allows a good correlation to the crank angle. Because of the low mass of the sample there is very small influence on the combustion cycle. To analyse a particular sampling, the GSV and the Mass Spectrometer represents an ideal combination.

The disadvantages of this system are, that several cycles are needed to take reliable quantitative measurements. Depending on the speed of the engine, it is possible to take a sample only each fifth cycle. Additionally there is sometimes an expensive adaptation, depending on the location of the probe.

This method provides an opportunity to validate e.g. CFD calculations of fuel spray expansion or calculation models such as the determination of residual gas

distribution [12,13]. Further application possibilities are the combination of the GSV and a NO_x-Analyzer or a Soot Detector. The NO_x-Analyzer in particular could be used for the validation of optical NO-Measurements [14]. Other applications of this Measuring System, e.g. the measurement of the intake and exhaust port gas composition are also possible, if an additional sampling gas pump is installed.

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