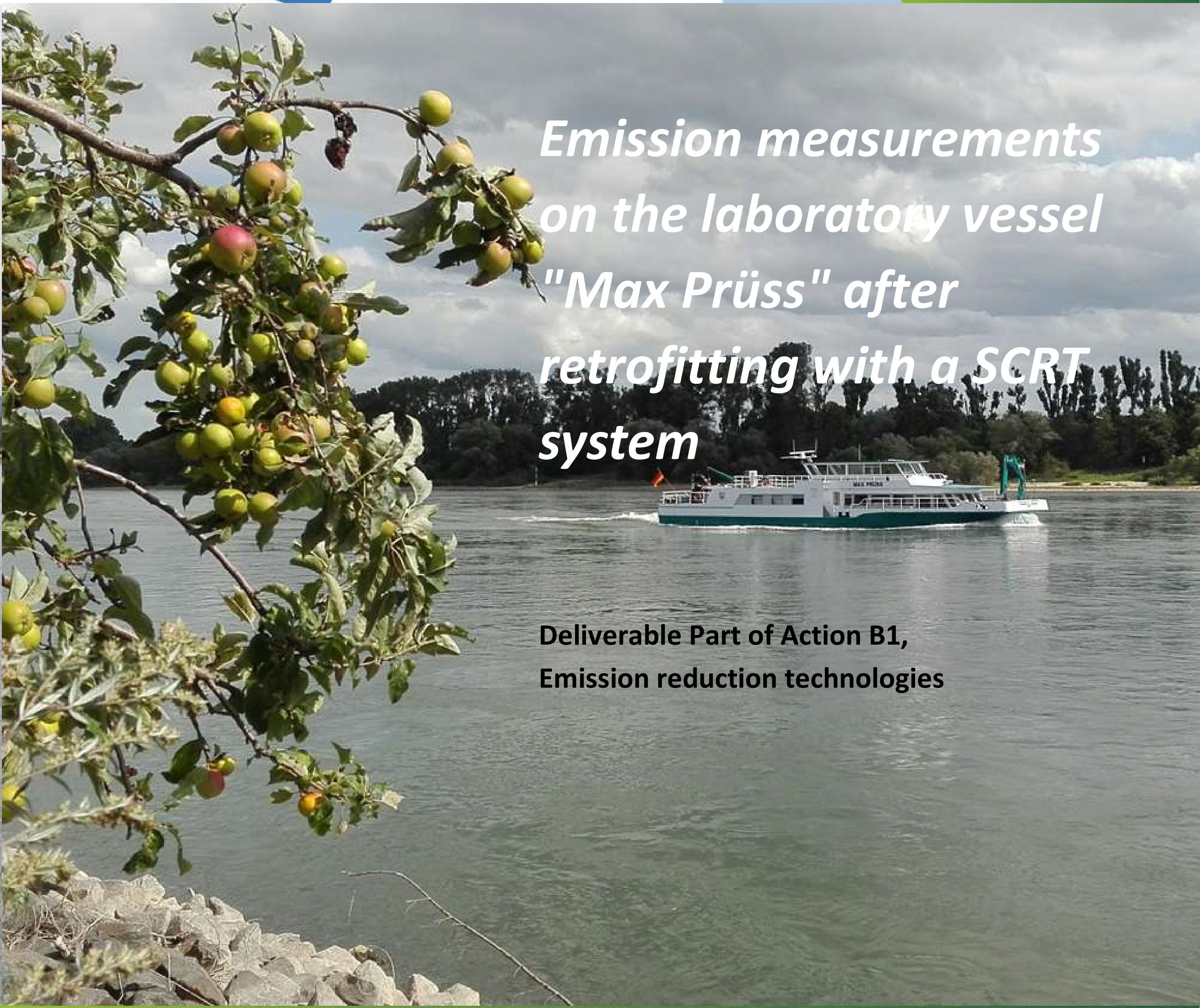
CLINSH

SUSTAINABLE WATERWAY TRANSPORT, CLEAN AIR



Emission measurements on the laboratory vessel "Max Prüss" after retrofitting with a SCRT system

Deliverable Part of Action B1,
Emission reduction technologies

CLEAN INLAND SHIPPING

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The objective of LIFE CLINSH is to improve air quality in urban areas, situated close to ports and inland waterways, by accelerating IWT emission reductions.

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1. INITIAL SITUATION

The Directive of the European Parliament and the Council of 21st August, 2008 on ambient air quality and clean air for Europe (2008/50/EC) as well as the Directives 2001/81/EC and 2004/107/EC set EU-wide binding air quality targets for the prevention or reduction of harmful effects on human health and the environment. These include binding targets for concentrations of air pollutants in residential areas (2008/50/EC), regulations on the maximum permitted emissions in the individual EU Member States (2001/81/EC) and mandatory emission limit values eg. for nitrogen oxides and particulates (PM_{10}) for plants and engines. Directive 2016/1628/EC (NRMM) on the revised *“Requirements relating to the emission limit values for gaseous and particulate pollutants and the type-approval of combustion engines for non-road mobile machinery and appliances”* includes, for example, mandatory maximum emission limits for the main engines (IWP) and auxiliary engines (IWA) of inland waterway vessels. These apply at the latest as of 01st January, 2020, but are valid only for new build ships or when replacing machines in older ships.

The particle emissions and nitrogen oxide emissions of currently used marine propulsion systems contribute to background concentrations near the shipping lanes and at the urban hotspot areas near waterways. In particular, for towns near waterways with large inland shipping activities, it is important to continue researching the emissions of marine propulsion systems and to identify ways to reduce the emissions of the main pollutants PM and NO_x/NO_2 by improvements to existing ships. Especially on the river Rhine with its intensive shipping traffic, these emissions play an important role in the clean air policy. In addition to the Netherlands and other Rhine-states, this topic is particularly relevant for NRW because the limit values of the EU Air Quality Directive for NO_2 (40 µg/m³, yearly average) are exceeded at many monitoring stations in the cities of NRW.

For the State Agency for Nature, Environment and Consumer Protection of the State of North Rhine-Westphalia (LANUV NRW) emissions from inland navigation vessels and their effects on air quality have been an issue for many years. The LANUV has dealt intensively with exhaust gas aftertreatment of diesel engines on cargo and passenger ships. In a pilot-project an installation of a SCRT catalytic converter and particle filter on the passenger ship “Jan von Werth” has been supported by the LANUV. In a second project an oil-water emulsion injection was installed on a cargo-ship. Measurement campaigns and technical support were carried out with the support of the “TÜV-Nord Mobilität GmbH & Co KG”. Some of the results have already been published in technical reports from the LANUV. *(LANUV-Fachbericht 49 (2013), „Minderung der Feinstaub-, Ruß- und Stickstoffoxidemissionen auf dem Fahrgastschiff "Jan von Werth" durch Nachrüstung eines SCRT-Systems“ and LANUV-Fachbericht 77 (2017) „Emissionen des Containerschiffs „MS Aarburg“, Auswirkungen der Nachrüstung mit einer Diesel-Wasser-Emulsionsanlage“).*

Due to the increasing discussion about the share of the various emission sources of the environmental pollution, the topic “inland vessels” has become more and more relevant. The EU Life-project "Clean Inland Shipping" (CLINSH) deals with the air pollution caused by inland waterway vessels and technical solutions for emission reduction.

With the “CLINSH” project the opportunity to investigate the emissions of inland navigation vessels arose more intensively with focus to search for the best technical solutions to reduce ship-related air pollution. In the first application phase of CLINSH and as part of the first application for the project in 2015, it was planned to equip the laboratory vessel "Max Prüss", which belongs to the LANUV, with an exhaust gas aftertreatment (SCRT catalyst and particle filter) and to take part in the subsequent measurement program.

Unfortunately, the start of the project was delayed, so the LANUV decided to retrofit “Max Prüss” with a SCRT system (combination of a particle filter and a downstream SCR catalytic converter for nitrogen oxide reduction, built by TEHAG Deutschland GmbH). This happened before the EU-project started and was financed from LANUV resources. With the retrofitting of its laboratory ship NRW plays a pioneering role for the German Rhine fleet.

The LANUV participates in the project in work package B.3 "Emission inventory and demo results" with the retrofitted "Max Prüss". The main topic of the project is the data acquisition by means of the long-term monitoring of the ship´s emission data and the effect of technical emission reduction measured under real life shipping conditions.

The emissions of 41 inland vessels equipped with different emission reduction technologies are examined under real operating conditions. The thus created database should be the basis for the determination of real life emission factors and so enable the EU Member States to see the effects of different measures on the real drive (navigation) emission (RDE) of the European fleet. For the continuous measurements and the detection of NO_X concentrations in the exhaust gas sensors on all vessels, participating in the CLINSH project, were installed by the “Multronic” company.

The exhaust emission measurements of the TÜV-Nord, planned after the retrofit of the "Max Prüss", will be included in the CLINSH project in order to validate the monitoring technology installed. Based on the discontinuous measurements the TÜV-Nord performed by using the E3 cycle (normally used for type approval of vessel engines), it is possible to determine emission factors for “Max Prüss” with and without exhaust retrofitting.

At the end of the yearlong continuous monitoring period, it should be possible to verify whether the "Real Drive (Navigation) Emissions" allow a better assessment of the actual ship emissions. This is already possible with the discontinuous measurement of the E3 cycles based on the results of the TÜV-Nord measurements.

2. INTRODUCTION

In October, 2015 the "Max Prüss" was retrofitted with a SCRT exhaust retrofitting system from “TEHAG Deutschland GmbH” on both main engines. The SCRT systems consist of a continuously regenerating wall flow particulate filter (2 filter cartridges) and a SCR catalyst with a controllable metering device for the aqueous urea solution AdBlue® for the reduction of NO_X emissions (description in chap. 3.2).

“Max Prüss” participation provided the following options for the CLINSH project: On the commercial cargo and tanker ships, participating in the CLINSH Project, it is generally very difficult to make suitable appointments for the installation of the right exhaust gas treatments, measuring equipment and any technical modifications that may be necessary. As the LANUV is the ship owner, it is able to quickly and easily access the “Max Prüss” as part of the CLINSH project. Scheduling and carrying out installations and measurement campaigns is also easy. The LANUV therefore offered the CLINSH project the opportunity to install and test the intended measuring technology in advance, before this technology should have been installed on all other participating ships.

The main task of the technical service of the “TÜV-Nord Mobilität GmbH & Co KG” in the project is to check and evaluate the effectiveness of the exhaust retrofitting system in untreated exhaust gas and tailpipe through

- Measurement of gaseous pollutant emissions and
- Measurements of soot and particulate emissions.

3. PROJECT SHIP

The laboratory vessel "Max Prüss" (Fig. 1) of the LANUV is used to monitor the condition of the watercourses in North Rhine-Westphalia and spends about 220 days a year on the Rhine, the main tributaries and the West German shipping channels. The Max Prüss travels more than 16.000 kilometers per year. Table 1 shows the most important technical data of the ship.

Figure 1: **Laboratory ship “Max Prüss“ [Source: TÜV-Nord]**

Table 1: Technical Data “Max Prüss“ [Source: LANUV]

Owner:	*State Environment Agency for Nature, Environment and Consumer Protection NRW (LANUV)*
Port of registry:	*Essen*
Dockyardt:	*Deutsche Binnenwerften GmbH, Werft Genthin;* *Production NO. 152*
Laying down:	*September 1998*
Launching:	*07.04.1999*
Delivery:	*07.05.1999*
Main dimensions:	
Lenght over all:	*33,00 Meters*
Width over all:	*7,57 Meters*
Side Hight:	*2,10 Meters*
Draught:	*1,10 Meters*
Propulsion System:	
Power output:	*2 x 250 kW (340 PS)*
Way of propulsion:	*conventional*
2 Marine-Diesel-Engines; MAN Type D 2866 LXE 43	
Number of cylinders:	*6*
Rated speed:	*1.800 rpm*
Cooling:	*Liquid coolant*
Starter:	*electrical; 24 V, couble-pole*
2 Ship reverse reduction gear boxes	
Type:	*WAF 143L*
Gear reduction:	*3,522*
2 Propellers	
Diameter	*1.000 mm*
Max. speed	*20 km/h*

3.1 Engine and Drive

The laboratory vessel "Max Prüss" has two 6-cylinder MAN D2866 LXE43 engines built in 1998. The power is specified at 250 kW/1.800 min-1 per engine on the identification plate. The total displacement of the engines is 11.967 cm^3. The engines have a mechanical governor and an exhaust turbocharging with charge air cooling. Figure 2 shows the starboard engine. Figure 3 shows the main performance charts. The transmission type WAF 143L comes from the company “Reintjes” and reduces the output speed in the ratio 3.522 : 1.

Figure 2: **Starboard propulsion engine MAN D2866 LXE43**

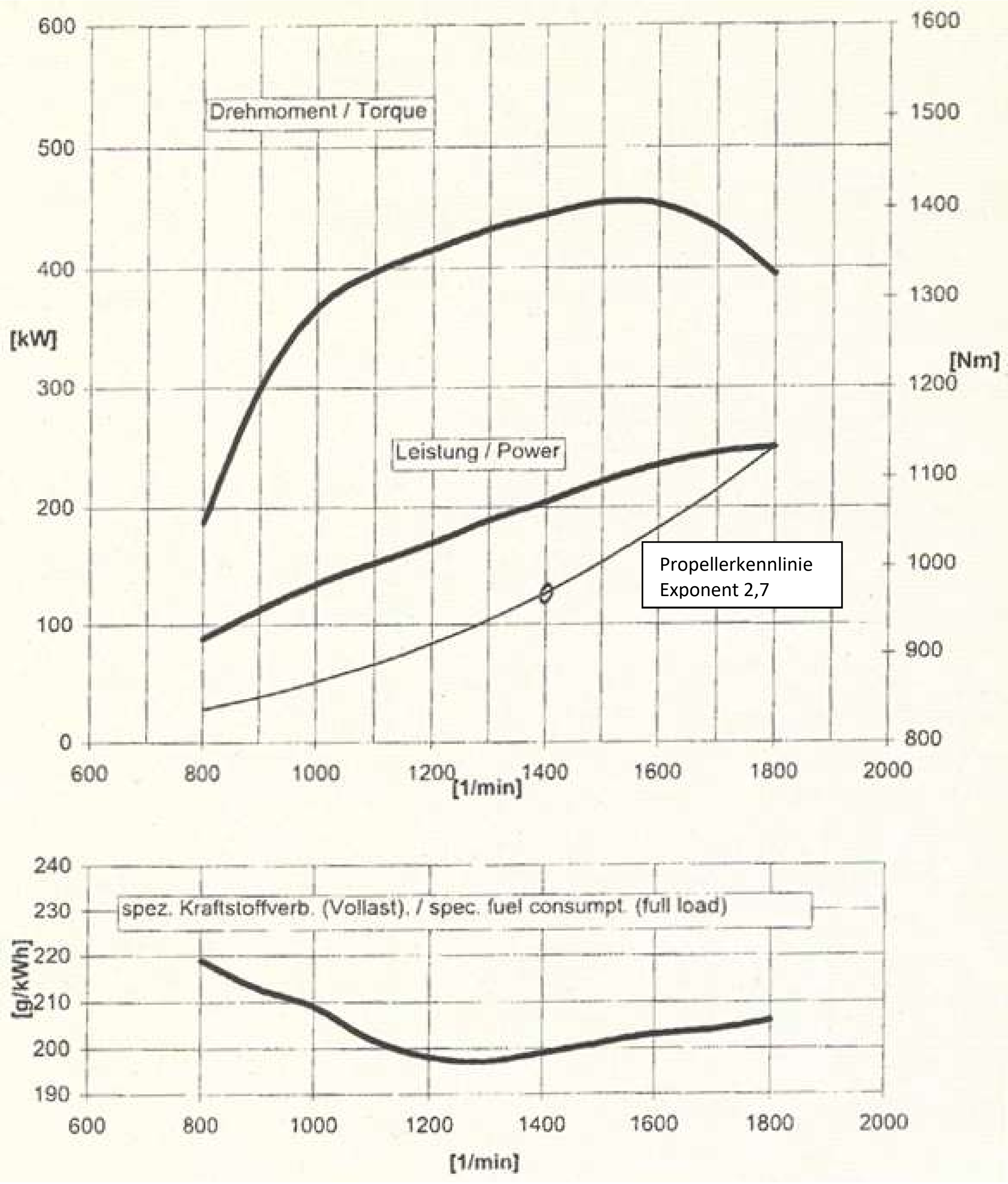


Figure 3: Power charts of engine MAN D2866 LXE43

3.2 Exhaust gas purification systems of “Max Prüss”

The “Max Prüss” engines are retrofitted with a wall-flow filter for particle matter and a SCRT catalyst system, created by the “TEHAG” company. Both propulsion engines of the “Max Prüss” are equipped with a combined exhaust gas purification system consisting of CWF soot particle filters and a t-blue NO_X reduction system (SCR) each. For the modification the existing exhaust systems (silencers, spark arrestors and piping) were completely dismantled. The new exhaust gas cleaning components were installed in the space created in this way (Fig. 2).

The conversion began on the existing compensator, which was mounted directly behind the turbo. From there on, the piping was laid on the outer wall of the port- and starboard sides of the engine room. The pipes lead into the exhaust gas inlet collectors of the soot particle filter systems, each consisting of 2 filter modules, size CWF 1700. All filter modules are combined with a collector construction and thus integrated as one component into the respective exhaust tract. The filter elements are coated with a catalytic coating for automatic regeneration of the filtered particles. From an exhaust gas temperature of approx. 230°C the soot particles are regenerated by an oxidation process.

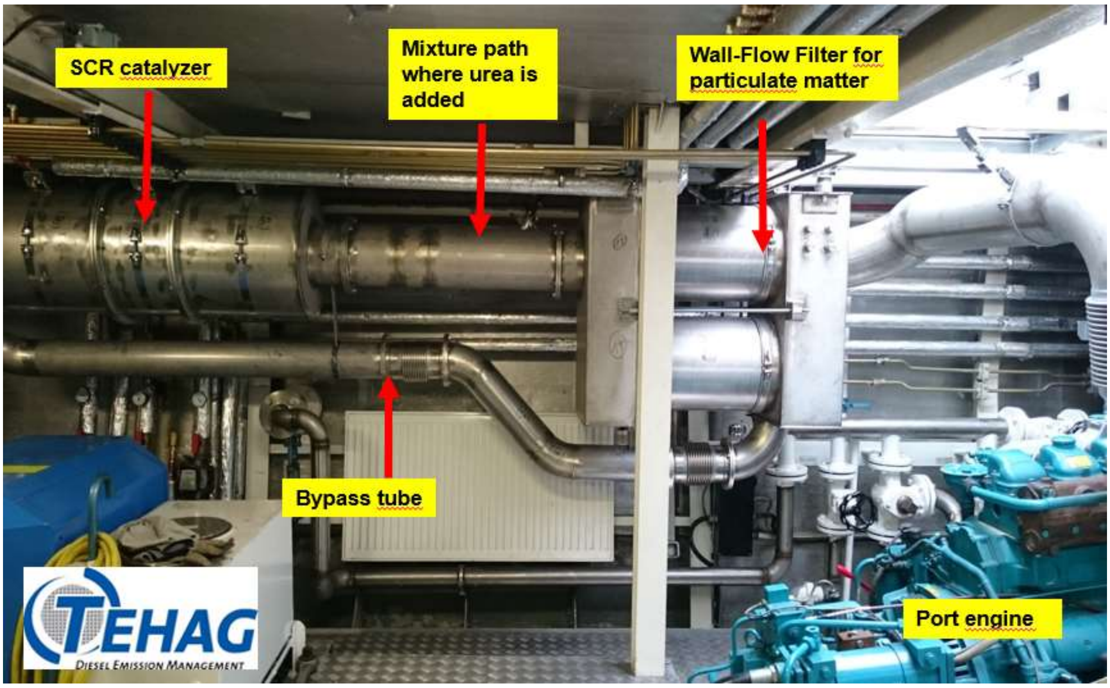


Figure 4: General view of the new exhaust system (port engine)

New brackets were created on the ceiling of the engine room for fastening the soot particle filter unit. Following the outlet collector of the soot filters a mixing section was positioned in which the injector for urea and a static mixer are integrated. The catalyst itself consists of three metallic carriers, which are coated with a reduction coating. The positions of the original silencers were used for the attachment of the SCR catalytic systems. Behind the SCR catalytic systems the exhaust lines were routed to the stern of the ship. Due to the enlargement of the pipe diameter (219 mm) the exhaust outlets at the stern were also enlarged.

As an additional safety measure, bypasses were installed underneath the main exhaust line in both systems. These were connected to the underside of the inlet manifold and reintegrated into the exhaust system with a Y-pipe behind the SCR catalysts. The bypass is opened via an electrically or manually operated flap. On the control side it is integrated in such a way that the bypass automatically opens when the return backpressure is higher. In the event of a power failure, the flaps can also be opened manually.

The control cabinets of both systems are mounted at the end of the engine room above the rudder system. The urea pumps and other controllers are positioned between the control cabinets. In the rear a 450 liter urea tank was installed in an existing free space between the frames. Additionally a 1000 liter IBC tank is positioned on deck. This tank can be exchanged as a delivery container. The crew regularly refills the 450 liter tank in the engine room from this source. A compressor for the additional air supply is installed in front of the tank unit in the engine room. All lines for electricity, air and urea supply were laid as far as possible on the ceiling, along existing cable ducts. Both exhaust gas purification systems, including bypasses, were finally packaged with highly efficient thermal insulation, so that the temperatures in the system are maintained and thus an optimum regeneration capability of all components is guaranteed. At the same time the isolation reduces the radiant heat in the engine room.

All disassembly and assembly work was carried out at the “Max Prüss” berth by “TEHAG” fitters.

4. PROCEDURE

4.1 General

In the period leading up to the retrofitting of the "Max Prüss", measuring technology for capturing exhaust gas temperature and exhaust back pressure as well as GPS measuring technology were installed on an engine on board and equipped with a data logger. Figure 4 shows the data logger system. Based on the results of these measurements the exhaust retrofitting technology was designed, built and installed aboard the "Max Prüss" by “TEHAG Deutschland GmbH”.

The sampling sockets and measuring flanges, required for an exhaust gas measurement, were tuned with the system builder “TEHAG”, when installing the SCRT-system and integrated into the exhaust retrofitting system for the measurement campaigns. The system installation on the "Max Prüss" took place in October, 2015.

As a result of substantial delays in the CLINSH project the monitoring technology for the exhaust data collection on the "Max Prüss" could only be installed by the company “Multronic Emission Systems” in 2018. The exhaust gas measurements for the validation of monitoring results should be carried out by the “TÜV-Nord” a reasonable time after installment of the continuous monitoring and could therefore only be executed in November, 2018.

4.2 Exhaust Emission Program

Inland vessel propulsion engines are subject to a type approval test procedure, which determines the engine emission behavior in different stationary test procedures. For motors with fixed propellers, the test cycle E3 according to ISO / FDIS 8178-4 is used. This test cycle defines the test stages to be used by power, load and speed. Since in real driving operation no direct influence on the power or the torque can be taken, as it results from the propeller characteristic, only the test speeds serve as a reproducible setting variable. These are at 100%, 91%, 80% and 63% of the rated speed. Then the weighted (0.2, 0.5, 0.15, 0.15) average over the 4-step test is stated as test result.

First evaluations of the RDE data showed that a maximum engine speed of 1.620 rpm was not exceeded in operation. Based on this and the above ISO 8178, the following measurement program was performed.

Simultaneous measurements of the gaseous emissions have been executed up - as well as downstream from the exhaust retrofitting on four different points:

(1.008 min^{-1}, 1.280 min^{-1}, 1.456 min^{-1} and 1.620 min^{-1})

on the resulting load curve. Parallel serial measurements with the *PAAS system* (micro soot sensor AVL 483) used for the detection of the elementary carbonaceous particle concentration as well as gravimetric particle measurements in quasi stationary driving conditions with the *Particulate Sampling System Micro-PSS* upstream and downstream the exhaust retrofitting were executed.

Figure 5: Data Logger for Measurement Data Recording

4.3 Measuring Procedure

In order to determine the reduction rates of the exhaust retrofitting (AGN), the untreated emissions of the engine must be related to the emissions in the tailpipe of the exhaust system. For gaseous emissions this was done by simultaneous measurement of the exhaust gas concentrations upstream AGN (untreated emissions) and downstream AGN (tail-pipe emissions) with two exhaust gas measuring systems. Only one instrument was available for the measurement of particulate and soot emissions. Therefore, the soot emissions and the tailpipe emissions could not be measured at the same time but one after the other. It was important to recreate the same measuring point setting for the result measurements to be valid.

In order to determine absolute emission masses, the exhaust gas mass flow in the respective measuring points has to be known. Three methods are possible. 1. A direct measurement of the exhaust gas mass flow. 2. A calculation with data of the exact fuel consumption. 3. A calculation with data of the exact intake air mass flow. In this project the exhaust gas mass flow was determined directly by means of a mass flow measuring tube (EFM).

To be able to determine performance related emission results knowledge of the engine power at the respective measuring points is necessary. Again, a variety of methods is available to determine engine power. One method of measuring engine performance would be e.g. the determination of the torque on the output shaft by means of strain gauges. Disadvantages of this method are the great cost of measuring strip application on the propeller shaft, the difficulty of calibration and an unknown influence factor due to the transmission efficiency. For modern, electronically controlled engines, there is still the possibility of determining the current engine output from ECU data. This would require access to the controller via a known interface. Moreover, it has to be ensured that the data from the ECU is validated.

The engines of the "Max Prüss" are pure mechanically governed, so that the method via ECU data is not applicable. For this reason a third method was used to determine the performance data. As already mentioned, the load condition of the engine is influenced by the type of propeller used. The power requirement at a specific speed can be determined from the power curve of the propeller (see fig. 3).

Under Real Drive Conditions this power requirement is still influenced by factors such as water level, flow, rudder position, etc. These inaccuracies in the performance determination are irrelevant for determining the conversion rates of the SCR catalyst, since the gaseous emissions are determined simultaneously for untreated- and tailgas. Only in the determination of the particulate emissions, the reproduction accuracy of the load adjustment has an influence on the result. The details of performance related exhaust emissions are also subject to the uncertainty described. Since the engine of “Max Prüss” cannot reach its rated speed of 1.800 rpm by means of governor settings on the injection pump, only a maximum speed of 1.620 rpm can be achieved. Therefore the exhaust gas test is defined for the four speeds above. The propeller power curve uses an exponent of 2.7, as documented at the engine power map, to determine the power requirement for the respective speed to calculate the performance related results.

5. Used Measurement Technology

To register the gaseous emissions, measurements were simultaneously conducted upstream of the exhaust retrofitting system and in the tailpipe of the exhaust system. Simultaneously the exhaust gas mass flow was determined by means of a measuring system. In addition to the determination of the absolute emission masses upstream and downstream of the exhaust retrofitting, the conversion rate of the SCR catalytic converter can be determined directly by the simultaneous measurement of the gaseous emissions. The determination of particulate and soot emissions did not occur simultaneously, because the corresponding measurement technology is not available in duplicate. Here a two-fold measurement of the corresponding load points was carried out with a measuring system upstream and downstream of the exhaust retrofitting.

The following chapters provide a detailed description of the measurement technologies used for the individual parameters. A schematic representation of the measurement setup is shown in fig. 6.

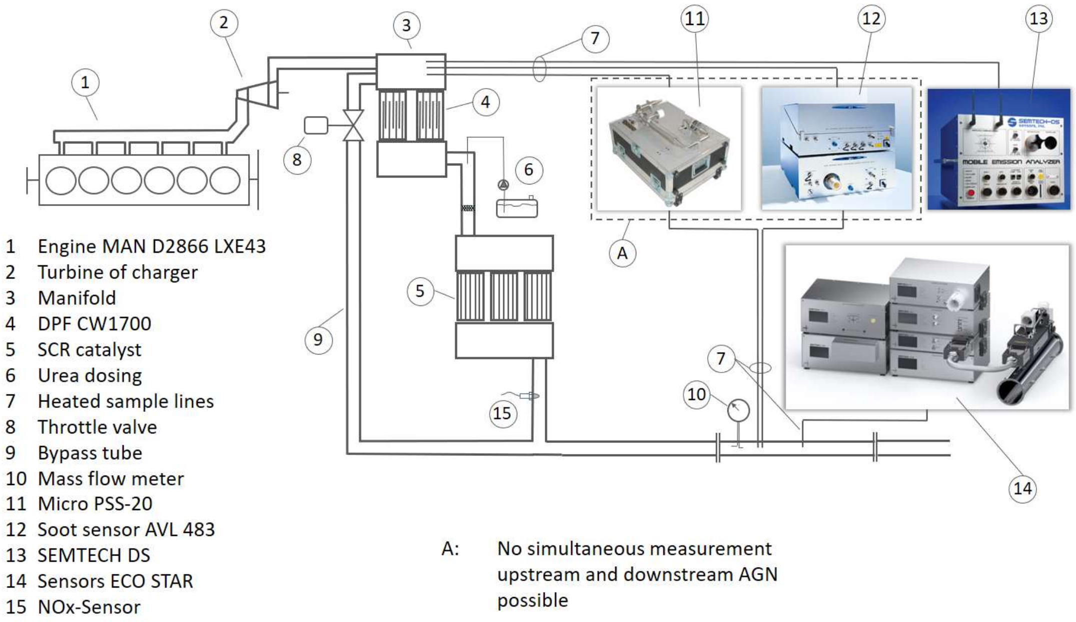


Figure 6: Schematic representation of the measurement setup

5.1 Measurement Technology for Gaseous Emissions

For the measurement of gaseous components the *SEMTECH-DS* from “Sensors*”* was used. With the exception of the NO_X analyzer the basic design of the system is similar to the measurement technique described in EC regulatory frameworks for measuring diesel engines in undiluted exhaust gas. There is a heated section that includes the gas sampling line and a heated filter and the FID (Flame Ionization Detector) to determine the total hydrocarbons. The heating to at least 180°C is necessary to prevent the condensation of hydrocarbons. A partial flow of the sample gas is transferred through a condenser for drying and then to the NDIR analyzer (non-dispersive infrared analyzer) for determining the CO and CO_2 concentration, the electrochemical O_2 analyzer and the NDUV measuring bench (non-dispersive ultraviolet measuring bench) for the determination of NO and NO_2.

Drying is necessary because these parameters cannot be operated with wet exhaust gas. A computer (PC 104), arranged in the measuring system, manages the entire system and combines the data from the different sources. Figure 9 shows the SEMTECH-DS measuring system from “Sensors” and at the same time illustrates the basic system structure. Tables 2 to 5 give an overview of the specification data of the analyzers used. In addition to the actual analysis system, data from a GPS system, an exhaust gas mass sensor and various analog and digital inputs can be collected as well. Also connected are sensors that acquire atmospheric data. To operate the system an external computer with the appropriate software is connected via LAN.

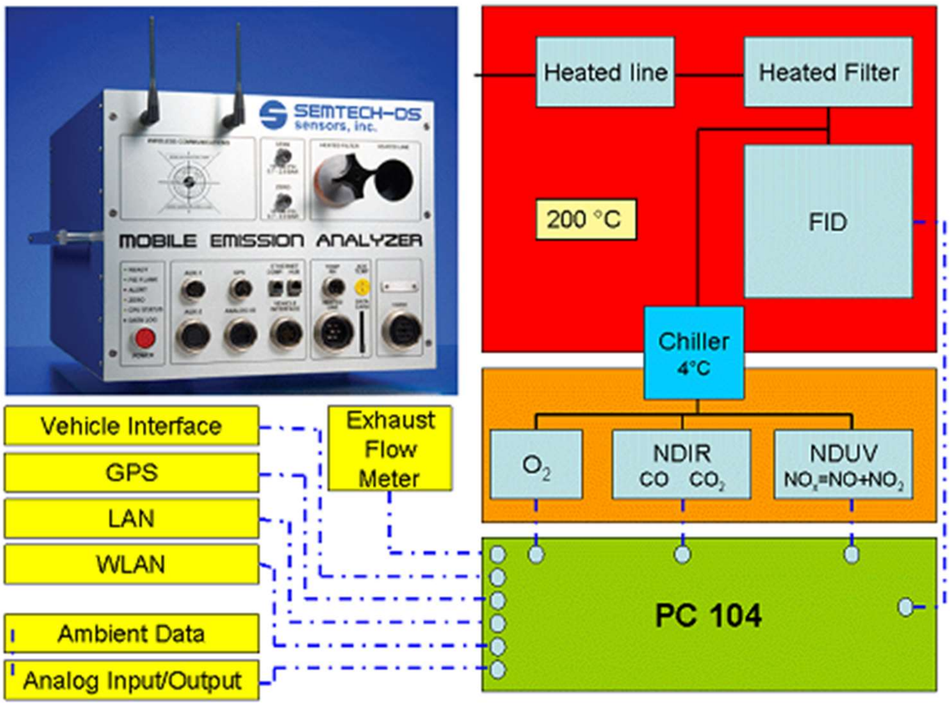


Figure 7: SEMTECH-DS-Equipment and System Configuration [Source: Sensors]

The gases required to operate the measuring system were carried aboard the project vessel. Since the gas consumption is very low, generally smaller compressed gas cylinders can be used, which in partial can also be accommodated in the SEMTECH-DS housing. For more extensive measurements it is necessary to use larger bottles. Since the entire gas sampling path and part of the measuring system is heated to 190°C, at least two hours of warm-up and preparation time is to be expected from the time the appliances are switched on to the operating state. At the end of this preparation the system is calibrated. This has to be done before and after each measurement.

Table 2: Specifications of the Flame Ionization Detector (THC-FID)

Range of Measurement	0 – 100, 0 – 1.000 and 0 – 10.000 ppmC User selectable	
	0 – 100 ppm Range	0 – 10.000 ppm Range
Accuracy	± 1,0 % of reading or ± 5 ppm whichever is greater	± 1,0 % of reading or ± 25 ppm whichever is greater
Resolution	0,1 ppm	1,0 ppm
Linearity	± 0,5 % of reading or ± 3 ppm whichever is greater	± 0,5 % of reading or ± 10 ppm whichever is greater
Repeatability	± 0,5 % of reading or ± 2 ppm whichever is greater	± 0,5 % of reading or ± 10 ppm whichever is greater
Noise	± 2 ppm	± 10 ppm
Span drift	± 0,5 % of reading or 3 ppm whichever is greater over 8 hrs	± 0,5 % of reading or 15 ppm whichever is greater over 8 hrs
Warm up time	60 minutes	60 minutes
Response time	T90 ≤ 2 seconds	T90 ≤ 2 seconds
Flow rate	2 LPM	2 LPM
Data rate	Up to 4 Hz, configurable	Up to 4 Hz, configurable
Operating temperature	191 °C	191 °C

Table 3: Specifications of the Non-Dispersive Infrared Measuring Bench

Gas	CO Low Range	CO High Range	CO_2
Range of Measurement	0 – 5.000 ppm	0 – 8 %	0 – 20 %
Accuracy	± 3 % of reading or 50 ppm whichever is greater	± 3 % of reading or ± 0,02 % whichever is greater	± 3 % of reading or ± 0,1 % whichever is greater
Resolution	1 ppm	0,001%	0,01%
Linearity	± 1,0 % of reading or 20 ppm whichever is greater	± 1,0 % of reading or ± 0,01 % whichever is greater	± 1,0 % of reading or ± 0,05 % whichever is greater
Repeatability	± 1,0 % of reading or 20 ppm whichever is greater	± 1,0 % of reading or ± 0,01 % whichever is greater	± 1,0 % of reading or ± 0,05 % whichever is greater
Noise	± 20 ppm	± 20 ppm	± 0,02 %
Span drift	± 0,5 % of reading or 20 ppm whichever is greater over 8 hrs	± 0,5 % of reading or ± 0,01 % whichever is greater over 8 hrs	± 2 % of reading over 8 hrs
Warm up time	45 minutes	45 minutes	45 minutes
Response time	T90 ≤ 3 seconds	T90 ≤ 3 seconds	T90 ≤ 3 seconds
Flow rate	2 LPM	2 LPM	2 LPM
Data rate	0,83 Hz	0,83 Hz	0,83 Hz
Operating temperature	5 to 50 °C	5 to 50 °C	5 to 50 °C

Table 4: Specification of the Non-Dispersive Ultraviolet Measuring Bench (NDUV)

	NO	NO_2
Range of Measurement	0 to 5.000 ppm	0 to 500 ppm
Accuracy	± 3 % of reading or 15 ppm whichever is greater	± 3 % of reading or 10 ppm whichever is greater
Resolution	1 ppm	1 ppm
Linearity	± 1 % of reading or 5 ppm whichever is greater	± 1 % of reading or 5 ppm whichever is greater
Repeatability	± 1 % of reading or 5 ppm whichever is greater	± 1 % of reading or 5 ppm whichever is greater
Noise	± 2 ppm	± 2 ppm
Span drift	± 1 % of reading or 20 ppm whichever is greater over 8 hrs	± 10 ppm over 8 hrs
Warm up time	45 minutes	45 minutes
Response time	T90 ≤ 2 seconds	T90 ≤ 2 seconds
Flow rate	3 LPM	3 LPM
Data rate	Up to 2 Hz, configurable	Up to 2 Hz, configurable
Operating temperature	5 to 50 °C	5 to 50 °C

Table 5: **Specification of the Electrochemical O2 Analyzer**

	O_2
Range of Measurement	0 to 25 %
Accuracy	± 2 % of reading or ± % oxygen whichever is greater
Resolution	0,1 %
Linearity	± 0,5 % of reading or ± 0,5 % whichever is greater
Repeatability	± 0,25 % of reading or ± 0,3 % Oxygen whichever is greater
Noise	± 0,1 % Oxygen
Span drift	± 1 % of reading or ± 0,5 % Oxygen whichever is greater
Warm up time	5 minutes
Response time	T90 ≤ 6 seconds
Flow rate	0,5 to 3 LPM
Data rate	Up to 2 Hz, configurable
Operating temperature	5 to 50 °C

5.2 Particulate and Soot Measurement Technology

5.2.1 Measurement Technique for Determining the Soot Concentration

To measure the particle emissions (elemental carbon) upstream and downstream of the AGN a micro soot sensor from AVL 483 was used. Figure 6 shows the PAAS system. The measuring principle is based on photoacoustic spectroscopy. The sample gas is irradiated with a modulated laser light. As a result the black, strongly absorbing particles are periodically heated and cooled again. The resulting expansions and contractions of the carrier gas cause cyclic gas vibrations detected with a sensitive microphone. Particle free air does not produce a signal. With soot loaded air the signal is proportional to the concentration of soot in the sample gas. Because the sensor is carbon sensitive, only the elemental carbon is detected, but not the entirety of the particulate emissions. The measurement results are not directly comparable with the values from the gravimetric measurements. Figure 7 shows the functional principle of photoacoustic spectroscopy (a) and the construction of a photoacoustic cell (b). Table 6 shows the specifications of the measuring instrument.

Figure 8: Micro Soot Sensor Type 483 [Source: AVL]

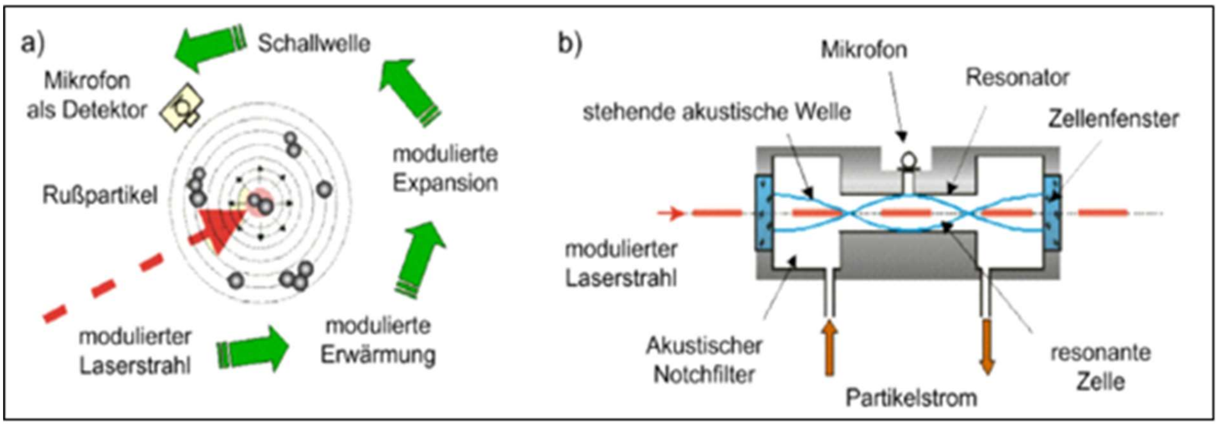


Figure 9: Function and Structure of a Photoacoustic Measuring Cell [Source: AVL]

Table 6: Specifications of the Micro Soot Sensor AVL 483, Part 1

Measuring Device	
Measuring unit:	Soot concentration (mg/m^3, µg/m^3) in diluted exhaust
Measuring range:	0 – 50 mg/m^3
Display resolution:	0,001 mg/m^3
Limit of detection:	~5 mg/m^3
Adjustment ratio:	1 : 5.000
Data transfer frequency:	Digital: 10 Hz
	Analog: 100 Hz
Rise time:	≤ 1 second
Operating temperature:	5°C up to 43°C
Flow rate probe/bypass:	~ 2 +2 l/min
Communication port:	RS232, Digital I/O, Analog I/O, Ethernet
Class of laser:	Laser class 1

Table 6: Specifications of the Micro Soot Sensor AVL 483, Part 2

Conditioning device	
Dilution rate (DR):	Adjustable 2 -10 and 10 - 20
	The real dilution ratio will be delivered with the below mentioned accuracy
Data transfer frequency:	Digital: max. 5 Hz
	Analog: 50 Hz
Accuracy (DR display):	Max. ± 3% in the range of DR [2…10]
	Max. ± 10% in the range of DR [10…20]
Power supply:	90 to 240V, 50/60 Hz, 500 VA
Pressure air:	Pressure of inlet 1 ± 0,2 bar relative
Flow rate:	> 4 l/min
Exhaust temperature:	Up to 1.000 °C
Exhaust back pressure:	Up to 2.000 mbar
Pulsation of pressure:	± 1000 mbar, but max. 50% of exhaust back pressure
Blow by volume flow:	Dependent on pressure, ~ 20 l/min at 1.000 mbar
Dimension:	Measuring device: W x H x D: ~ 19”x 5 Rack units x 530 mm
	Conditioning device: W x H x D: ~ 19”x 5 Rack units x 530 mm
Weight of device:	Measuring device: ~ 20 kg
	Conditioning device: ~ 12 kg

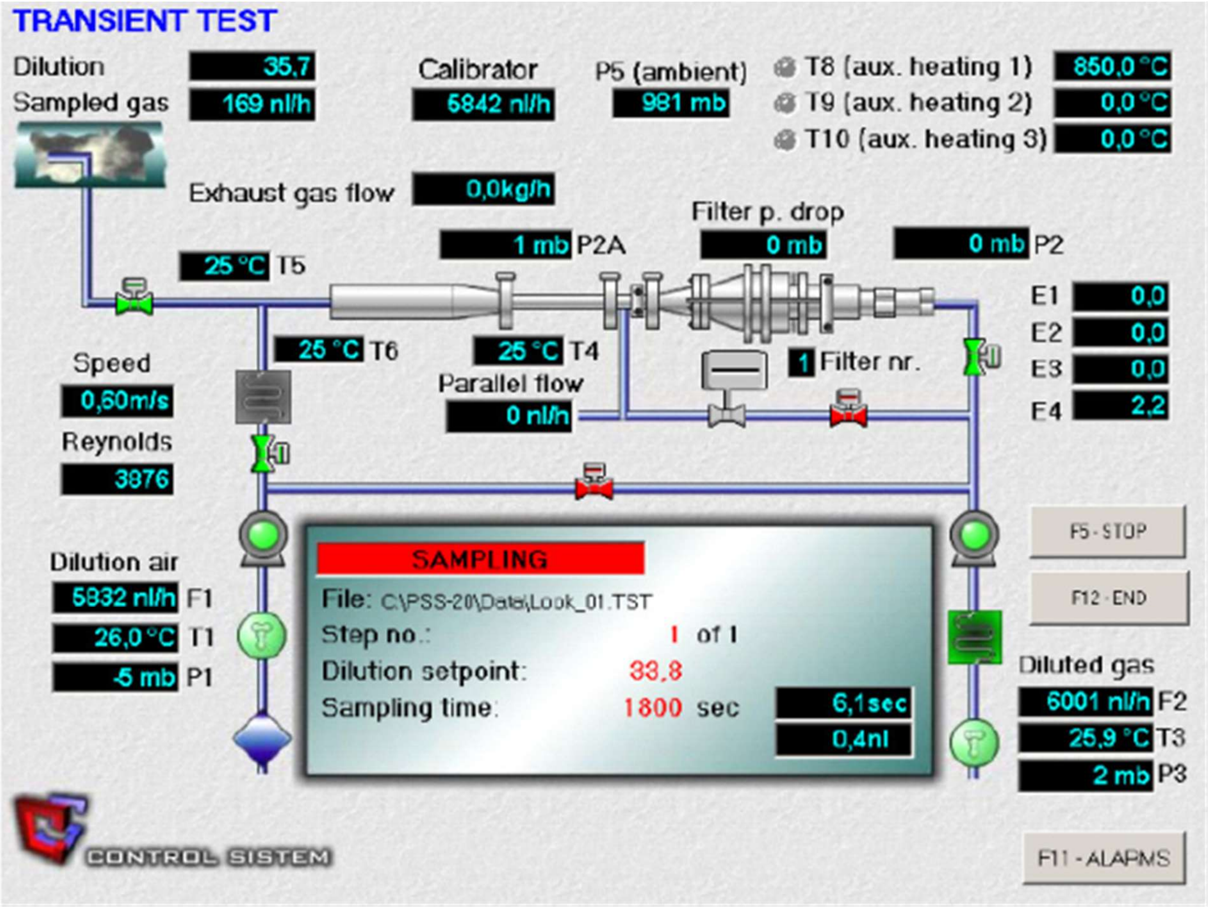
5.2.2 Measurement Technique for Gravimetric Particulate Measurement

Gravimetry is the regulatory standard prescribed by the legislation for the determination of particulate emissions from diesel engines. The emitted particle mass is deposited on a filter paper during a defined test cycle or test stage and is determined. This measurement method was used in up- and downstream of the AGN.

The Particulate Sampling System Micro PSS (Figure 8) extracts a partial flow from the exhaust gas mass flow of the engine and dilutes it with filtered ambient air. The diluted exhaust gas flows through the collection filter (Pallflex Enfag 47mm) where the particles to be determined by gravimetry are retained. Then the mass determination takes place via differential determination between the previously conditioned and empty weighed, and after the charge again conditioned and balanced filter paper.

The Micro PSS-20 is a partial flow dilution system with total sampling. This means, the system dilutes only part of the exhaust gas and then passes all of the diluted gas through the collection filter. The aim of the dilution is a reduction of the exhaust gas temperature, so that the exhaust gas can be channeled through the filter without condensation effects. Figure 9 shows an image of the user interface (software).

Figure 10: Particulate Measuring System for Gravimetric Determination Micro PSS [Source: Control Sistem]



TRANSIENT TEST

Dilution 35,7

Sampled gas 169 nl/h

Calibrator 6842 nl/h

P5 (ambient) 981 mb

T8 (aux. heating 1) 850,0 °C

T9 (aux. heating 2) 0,0 °C

T10 (aux. heating 3) 0,0 °C

Exhaust gas flow 0,0kg/h

Filter p. drop 0 mb

1 mb P2A

0 mb P2

25 °C T5

25 °C T6

25 °C T4

E1 0,0

E2 0,0

E3 0,0

E4 2,2

1 Filter nr.

Speed 0,60m/s

Reynolds 3876

Parallel flow 0 nl/h

Dilution air

5832 nl/h F1

26,0 °C T1

-5 mb P1

SAMPLING

File: C:\PSS-20\Data\Look_01.TST

Step no.: 1 of 1

Dilution setpoint: 33,8

Sampling time: 1800 sec

6,1sec

0,4nl

Diluted gas

6001 nl/h F2

25,9 °C T3

2 mb P3

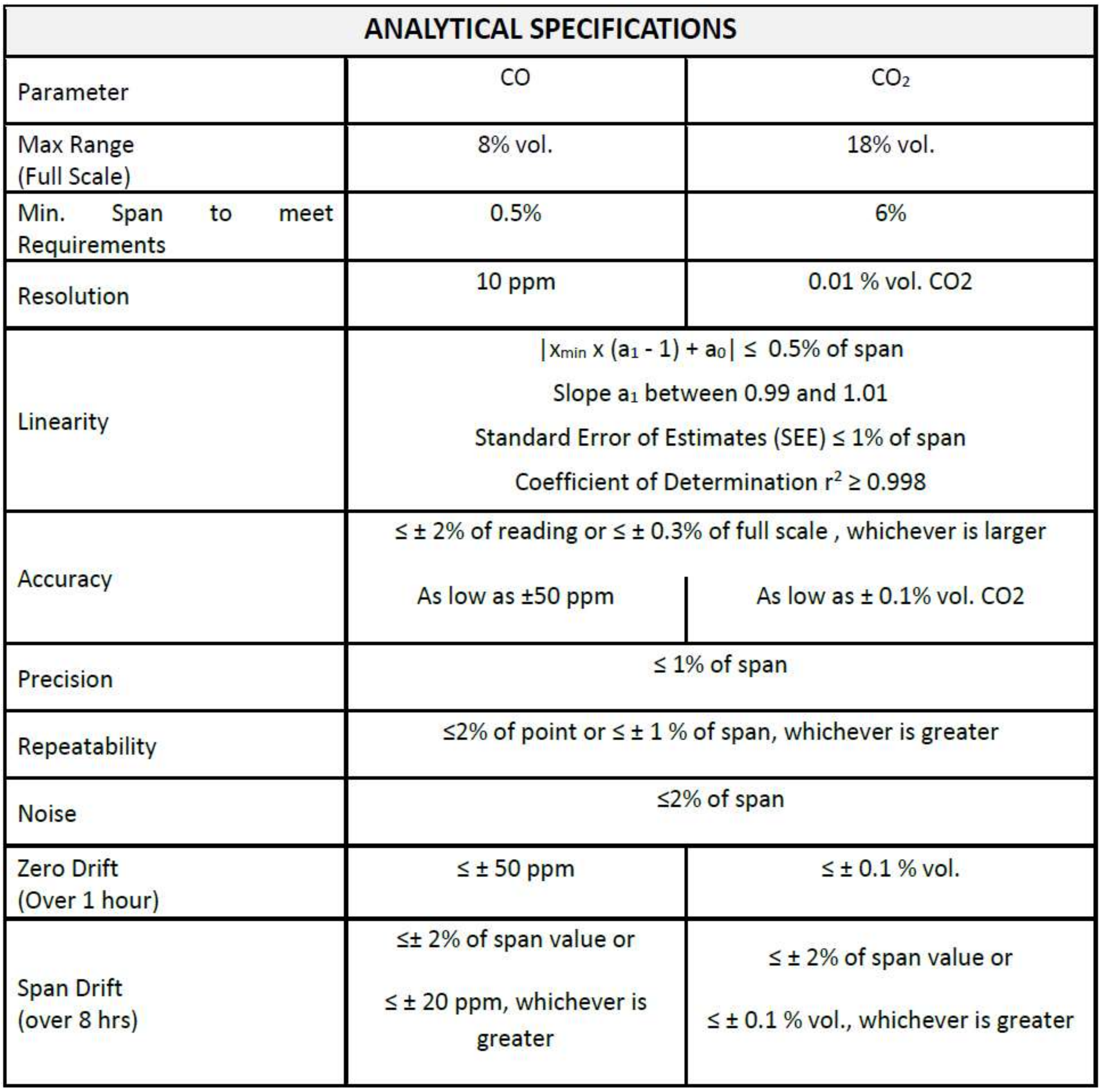
Figure 11: Illustration of the Gas Flow in the Micro PSS [Source: Control Sistem]

5.3 Measurement Technology for Gaseous Emissions downstream AGN

To measure the gaseous emissions downstream AGN the system EcoStar, which also comes from the company “Sensors”, was used. It uses the same analytic principles as the “SEMTECH-DS”. Figure 10 shows the measuring system and Table 7 gives information on the technical specifications. Table 8 shows the technical specifications of the different flowmeter sizes. The yellow deposited 5"-tube was used.

Figure 12: Measuring System Sensors EcoStar with Flowmeter [Source: Sensors)

Table 7: Specifications: Sensors EcoStar, Part 1

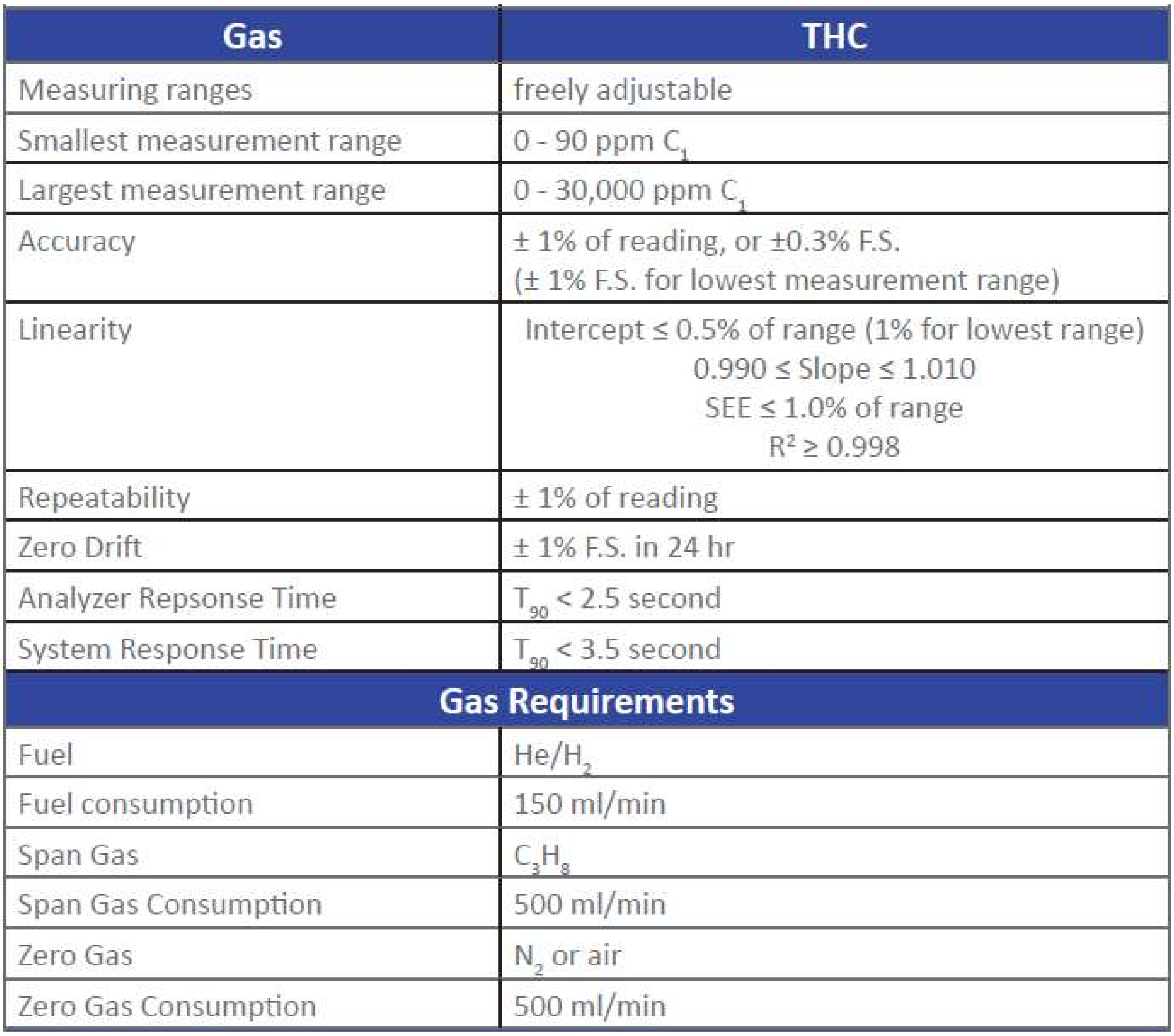


ANALYTICAL SPECIFICATIONS		
Parameter	CO	CO_2
Max Range (Full Scale)	8% vol.	18% vol.
Min. Span to meet Requirements	0.5%	6%
Resolution	10 ppm	0.01 % vol. CO2
Linearity	$\lvert x_{min}$ x $(a_1 - 1) + a_0 \rvert \le$ 0.5% of span Slope a_1 between 0.99 and 1.01 Standard Error of Estimates (SEE) ≤ 1% of span Coefficient of Determination $r^2 \ge 0.998$	
Accuracy	≤ ± 2% of reading or ≤ ± 0.3% of full scale , whichever is larger	
	As low as ±50 ppm	As low as ± 0.1% vol. CO2
Precision	≤ 1% of span	
Repeatability	≤2% of point or ≤ ± 1 % of span, whichever is greater	
Noise	≤2% of span	
Zero Drift (Over 1 hour)	≤ ± 50 ppm	≤ ± 0.1 % vol.
Span Drift (over 8 hrs)	≤± 2% of span value or ≤ ± 20 ppm, whichever is greater	≤ ± 2% of span value or ≤ ± 0.1 % vol., whichever is greater

Table 7: Specifications: Sensors EcoStar, Part 2

NOx ANALYTICAL SPECIFICATIONS		
Parameter	NO	NO_2
Max Range (Full Scale)	0 to 3000 ppm	0 to 1000 ppm
Min. span to meet requirements	300 ppm	300 ppm
Resolution	0.1 ppm	0.1 ppm
Linearity	$\|x_{min} \times (a_1 - 1) + a_0\| \leq 0.5\%$ of span Slope a_1 between 0.99 and 1.01 Standard Error of Estimates (SEE) ≤ 1% of span Coefficient of Determination $r^2 \geq 0.998$	
Accuracy	≤ ± 2% of reading or ≤ ± 0.3% of full scale, whichever is larger	
Repeatability	≤2% of point or ≤ ± 1 % of span, whichever is greater	
Precision	≤ 1% span	
Noise	≤ 2% of span	
Zero Drift	≤ 4 ppm / hour with $\Delta t \leq 10°C$ and using purified N_2 as zero gas	
Span Drift	≤ ± 2% of span value with $\Delta t \leq 10°C$	
Rise Time (T_{10-90})	≤ 2.5 seconds	
System Response Time (T_{0-90})	≤ 10 sec with rise time ≤ 2.5 seconds	
Data Rate	5 Hz	
Sample Flow rate	1.5 l/min	

Table 7: Specifications Sensors EcoStar, Part 3



Gas	THC
Measuring ranges	freely adjustable
Smallest measurement range	0 - 90 ppm C_1
Largest measurement range	0 - 30,000 ppm C_1
Accuracy	± 1% of reading, or ±0.3% F.S. (± 1% F.S. for lowest measurement range)
Linearity	Intercept ≤ 0.5% of range (1% for lowest range) 0.990 ≤ Slope ≤ 1.010 SEE ≤ 1.0% of range $R^2 \geq 0.998$
Repeatability	± 1% of reading
Zero Drift	± 1% F.S. in 24 hr
Analyzer Repsonse Time	$T_{90} < 2.5$ second
System Response Time	$T_{90} < 3.5$ second
Gas Requirements	
Fuel	He/H_2
Fuel consumption	150 ml/min
Span Gas	C_3H_8
Span Gas Consumption	500 ml/min
Zero Gas	N_2 or air
Zero Gas Consumption	500 ml/min

Table 8: Specifications of the Flowmeter

<table>
<tr><th colspan="10">HTF MODULE SPECIFICATIONS</th></tr>
<tr><td colspan="2">Exhaust temperature range</td><td colspan="8">-5 to 700°C</td></tr>
<tr><td colspan="2">Exhaust temperature accuracy</td><td colspan="8">± 1% of reading or ± 2°C, whichever is greater</td></tr>
<tr><td colspan="2">Flow measurement linearity</td><td colspan="8">$|x_{min} \times (a_1 - 1) + a_0| \le 1\%$ of max
Slope a_1 between 0.99 and 1.01
Standard Error of Estimates (SEE) ≤ 1% of max.
Coefficient of Determination $r^2 \ge 0.990$</td></tr>
<tr><td colspan="2">Flow measurement accuracy</td><td colspan="8">± 2% of reading or ± 0.5% of full scale, whichever is greater</td></tr>
<tr><td colspan="2">Warm up time</td><td colspan="8">≤ 5 minutes at 20°C ambient</td></tr>
<tr><td colspan="2">System response time $_{(T0 – T90)}$</td><td colspan="8">≤ 2.5 seconds; synchronized to match rise time of gaseous analyzers</td></tr>
<tr><td colspan="2">Data acquisition rate</td><td colspan="8">5 Hz</td></tr>
<tr><td colspan="2">Resolution</td><td colspan="8">0.1 kg/hr</td></tr>
<tr><td colspan="2">Power requirements</td><td colspan="8">12 VDC</td></tr>
<tr><td colspan="2">Communications</td><td colspan="8">RS 232</td></tr>
<tr><td colspan="2">Control module dimensions
W x D x H</td><td colspan="8">36 x 18 x 10 cm
14.2 x 7.0 x 4.0 in</td></tr>
<tr><td colspan="2">Control module weight</td><td colspan="8">4kg (9 lbs)</td></tr>
<tr><td colspan="2">Box dimensions
W x D x H</td><td colspan="8">38.4 x 14.5 x 8.4 1 cm
15.1 x 5.3 x 3.3 Inches</td></tr>
<tr><td rowspan="2">Flow tube dimensions</td><td>OD X L (mm)</td><td>25 x 521</td><td>38 x 521</td><td>51 x 521</td><td>64 x 648</td><td>76 x 648</td><td>102 x 648</td><td>127 x 762</td><td>152 x 914</td></tr>
<tr><td>OD X L (in)</td><td>1.0 x 20.5</td><td>1.5 x 20.5</td><td>2.0 x 20.5</td><td>2.5 x 25.5</td><td>3.0 x 25.5</td><td>4.0 x 25.5</td><td>5.0 x 30</td><td>6.0 x 36</td></tr>
<tr><td>Flow tube weight</td><td>Kg
(lbs)</td><td>4.4
(9.6)</td><td>5.7
(12.6)</td><td>8.0
(17.6)</td><td>8.4
(18.6)</td><td>8.9
(19.6)</td><td>10.3
(22.6)</td><td>11.6
(25.6)</td><td>13.0 (28.6)</td></tr>
</table>

<table>
<tr><th colspan="5">FLOW RATES</th></tr>
<tr><td>Temp</td><td colspan="2">100°C</td><td colspan="2">400°C</td></tr>
<tr><td>Nominal Tube Diameter (in.)</td><td>Min Flow (kg/hr)</td><td>Max Flow (kg/hr)</td><td>Min Flow (kg/hr)</td><td>Max Flow (kg/hr)</td></tr>
<tr><td>1</td><td>6.9</td><td>85.0</td><td>10.4</td><td>64.0</td></tr>
<tr><td>1.5</td><td>10.9</td><td>276.0</td><td>16.4</td><td>208.0</td></tr>
<tr><td>2</td><td>15.8</td><td>535.0</td><td>23.9</td><td>402.0</td></tr>
<tr><td>2.5</td><td>18.9</td><td>890.0</td><td>28.4</td><td>670.0</td></tr>
<tr><td>3</td><td>22.5</td><td>1250.0</td><td>34.0</td><td>930.0</td></tr>
<tr><td>4</td><td>30.7</td><td>2080.0</td><td>46.3</td><td>1550.0</td></tr>
<tr><td>5</td><td>38.6</td><td>3115.0</td><td>58.2</td><td>2345.0</td></tr>
<tr><td>6</td><td>46.2</td><td>4005.0</td><td>69.6</td><td>3015.0</td></tr>
</table>

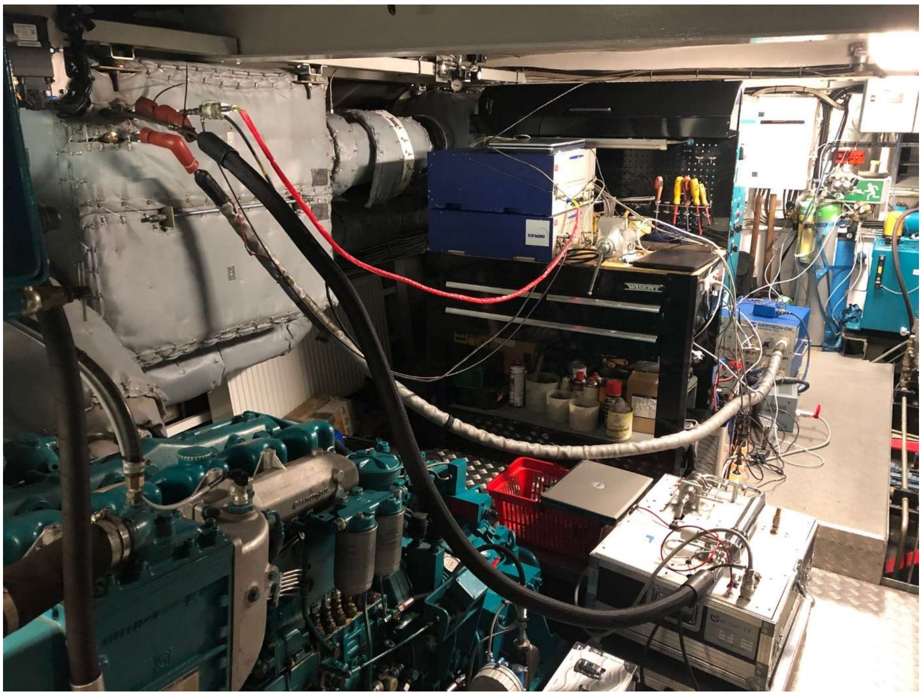


Figure 13: **Setup for Measurement upstream AGN (Gaseous and Particulate / Soot)**

Figure 14: **System Arrangement for Measurement downstream AGN (“End of Pipe” (Gaseous, Particle / Soot and Exhaust Gas Mass Flow))**

5.4 Further Measuring Technology

5.4.1 Temperature Measurement

For temperature measurement only 3 mm screw-in thermocouples NiCr-Ni of type K were used. The measuring range is specified by the thermocouple manufacturer from -90°C to + 1.370°C. Different sensor lengths can be used to realize the necessary positioning in the exhaust gas flow.

5.4.2 Measurement of Environmental Data

To determine the correction factors, necessary for the exhaust gas calculation, the atmospheric environmental data must be determined. Temperature and barometric pressure as well as the relative humidity are detected by suitable sensors. The arrangement of the measuring point is as close as possible to the intake of the engine combustion air. A commercial combined sensor is used to measure the air temperature and relative humidity and the signals are read into the SEMTECH-DS via the analogue inputs.

6. Results

6.1 General

The measurements of the emission data for the starboard engine of the "Max Prüss" were executed on the 22nd and 23rd November, 2018. Due to the low water situation on the Rhine the test drive started on the Meidericher lock of the Duisburg harbor. The first measurements in the E3 cycle with particle and soot determination were carried out on November 22nd. The sensors were located upstream of the exhaust aftertreatment. On November 23rd, a second measuring campaign followed in which the particle and soot determination were placed in the tailpipe. For parts of the measurements an upstream ride on the Rhine is absolutely necessary, since the highest speed points would lead to excessive speeds on a descent downstream. A survey in the inland canal network is not allowed for similar reasons. The highest measuring speeds would exceed the permitted speed limits.

For the gaseous emissions the measured data upstream and downstream from the AGN was recorded simultaneously over a longer time period. For evaluation the average values of the last minute of measurements were used. For particulate measurement two samples per measurement point were drawn for each measurement situation (upstream or downstream AGN).

6.2 Power Determination

For performance related evaluation of the measurement results the power output of the engine must be determined. The determination of the power takes place, as described in chapter 4.3, on the known data of the ship propeller. Figure 13 shows the different performance curves. The upper blue curve represents the full load curve of the motor. From its performance data a set point curve results for an E3 test according to ISO 8178, as represented by the square marking symbols. The governor settings of the starboard engine allow only a maximum speed of 1.620 min^{-1}, so this point is to be regarded as the maximum speed and load point in a real measurement.

If you determine the power for this point with the known propeller data and then determine the measuring points for an E3 test in accordance with ISO 8178, it results in the gray curve, marked with the triangles. The curve, represented by the circular marker symbols, shows the real sailing speeds with the powers determined from the real propeller curve. The power levels, determined up to this point, represent the power requirement at the propeller. Since the gearbox is installed between the propeller shaft and the engine, the efficiency of the transmission must be estimated for an approximate determination of the effective engine power. This is assumed to be 97% and is then used for the calculations of the engine power.

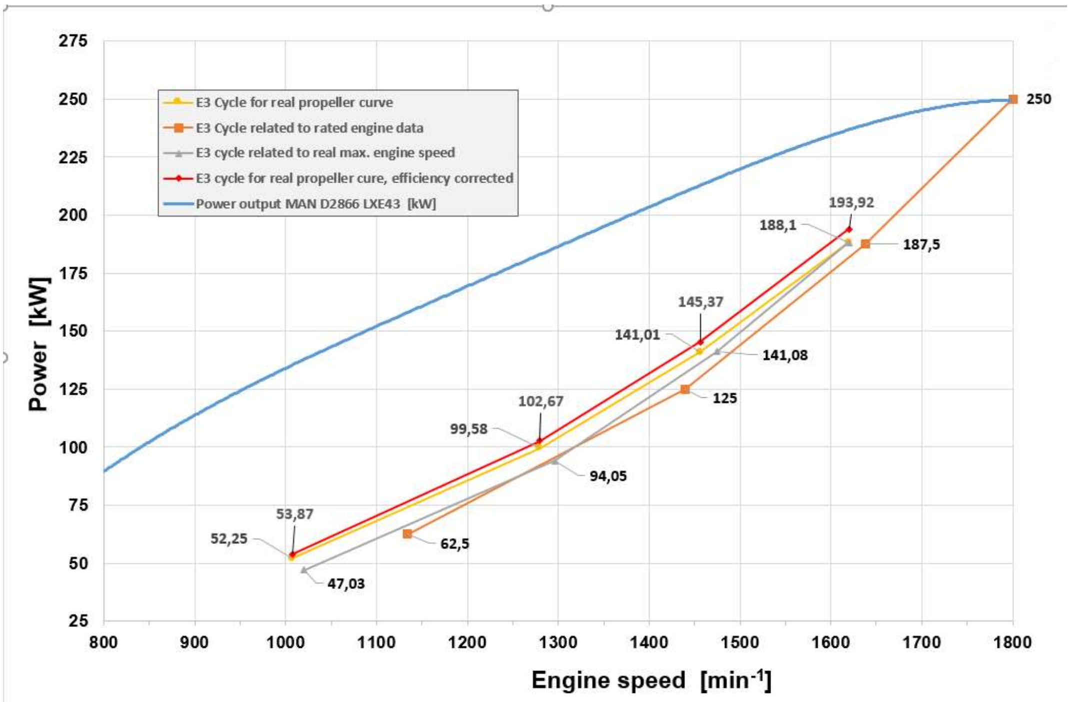


Figure 15: **Performance Curves, Engine speed**

6.3 Consideration of the Individual Measuring

The evaluation of the results takes place in several steps. First, the individual stage results are evaluated. For this purpose at the end of each speed step the quasi-stationary part is filtered out, averaged and displayed. These values are used to calculate the weighted overall result according to the evaluation criteria of the ISO. For the particle measurements the average values from the repeated measurements per measuring point and measuring situation (upstream or downstream AGN) are used to determine the overall result.

6.3.1 Concentration Traces of the Gaseous Emissions of the Individual Measuring Points

6.3.1.1 Measuring Point 1.620 min^{-1}

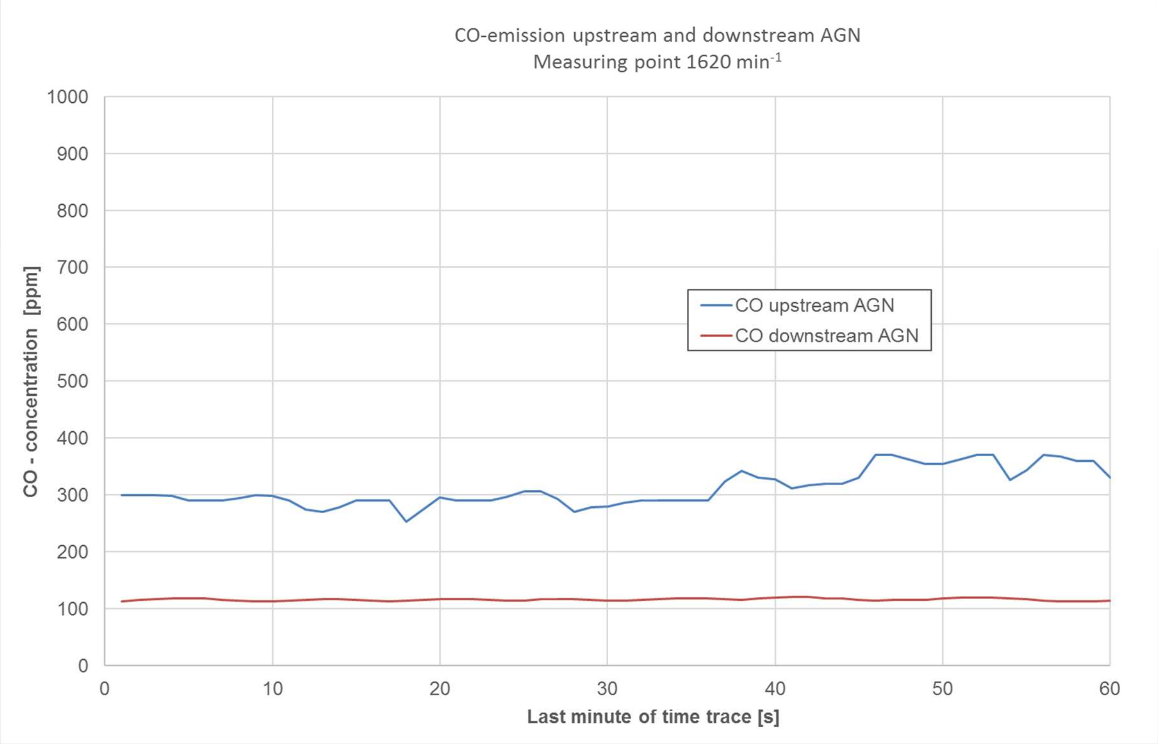


Figure 16: CO Concentration Trace upstream and downstream AGN

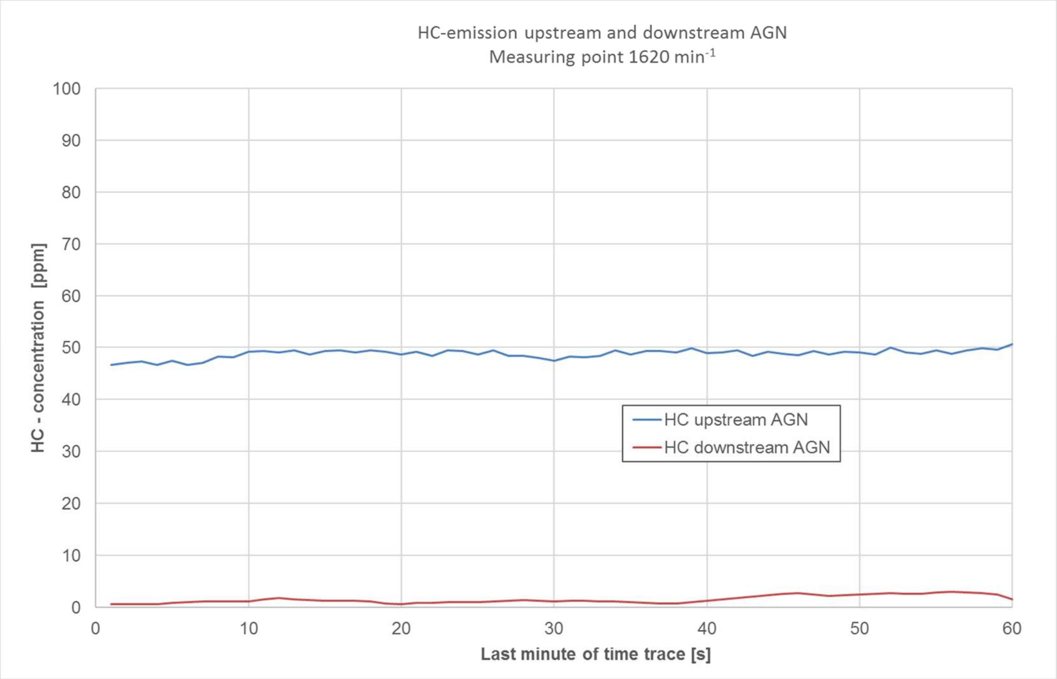


Figure 17: **HC Concentration Trace upstream and downstream AGN**

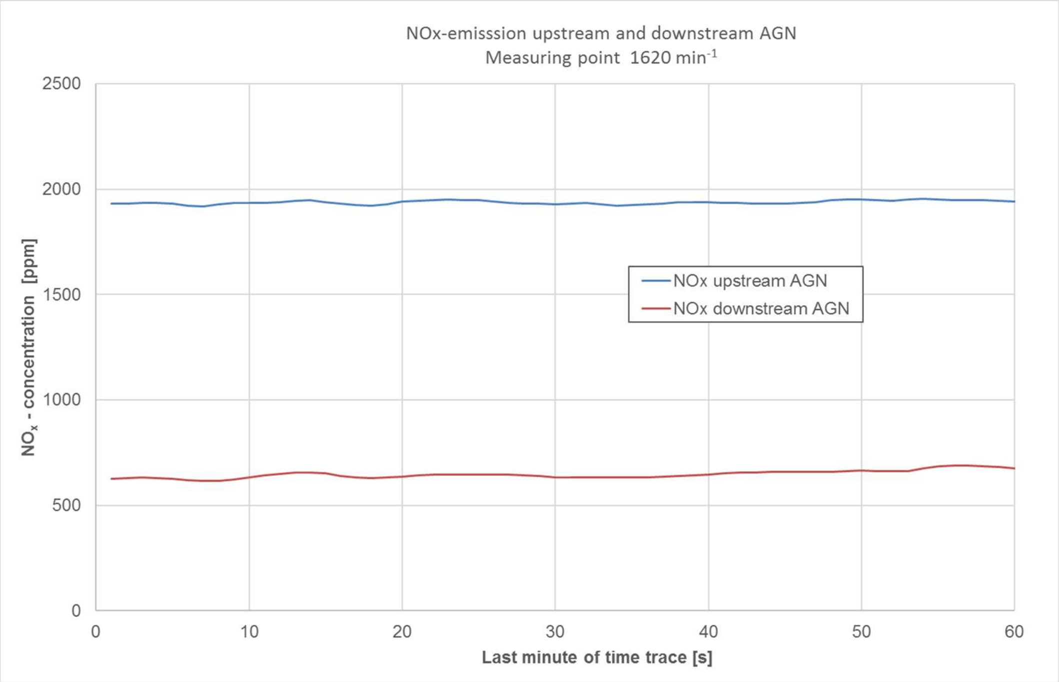


Figure 18: **NO_X Concentration Trace upstream and downstream AGN**

6.2.1.2 Measuring Point 1.456 min^{-1}

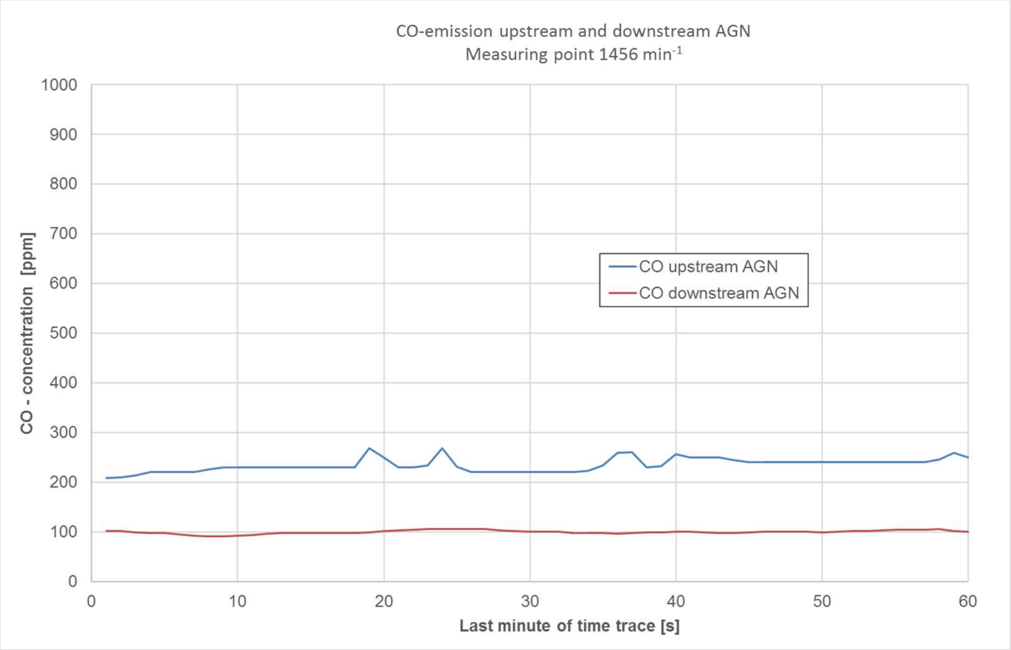


Figure 19: **CO Concentration Trace upstream and downstream AGN**

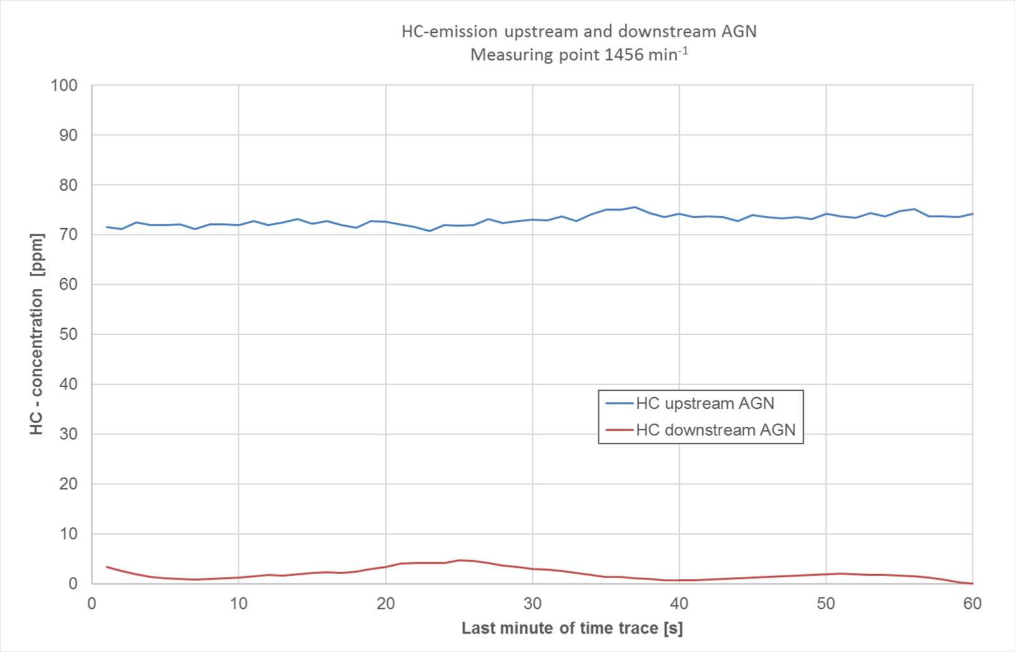


Figure 20: **HC Concentration Trace upstream and downstream AGN**

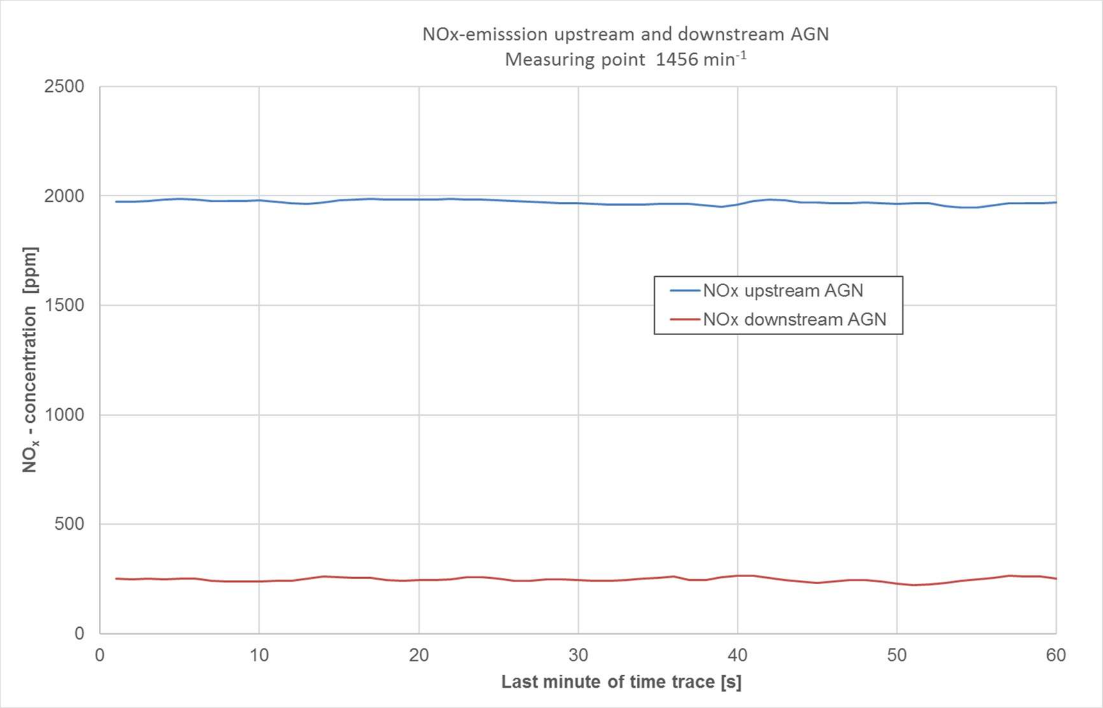


Figure 21: NO$_X$ concentration Trace upstream and downstream AGN

6.3.1.2 Measuring Point 1.280 min^{-1}

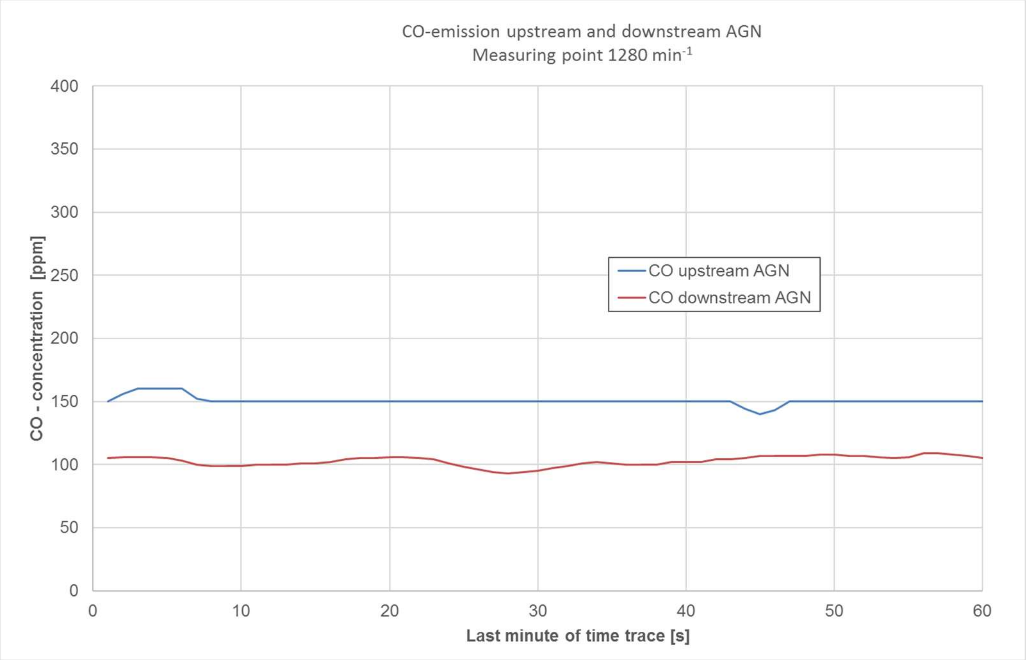


Figure 22: CO Concentration Trace upstream and downstream AGN

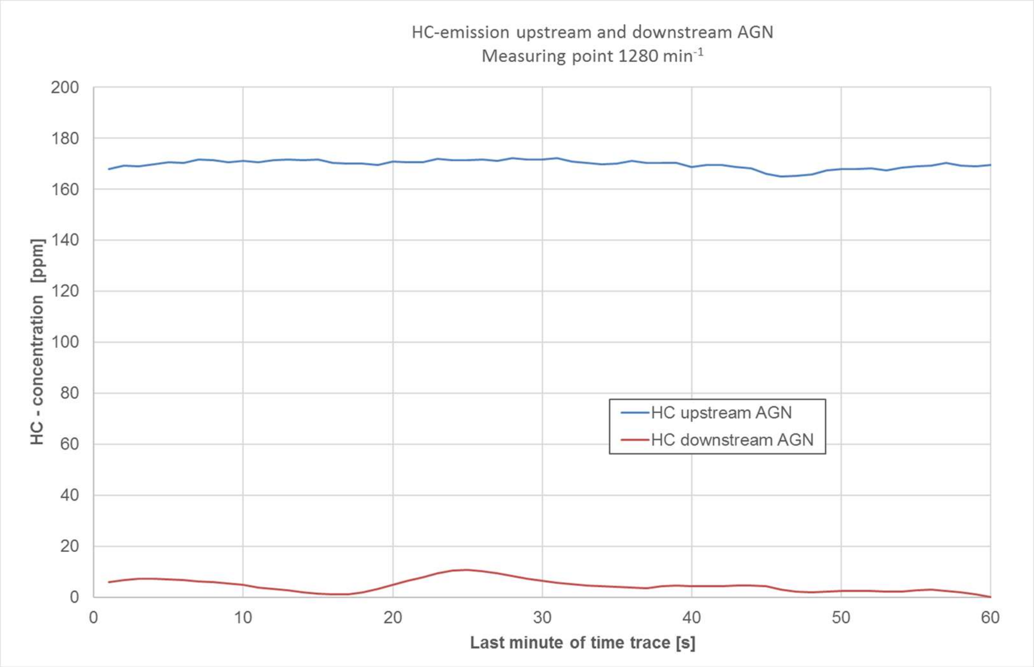


Figure 23: **HC Concentration Trace upstream and downstream AGN**

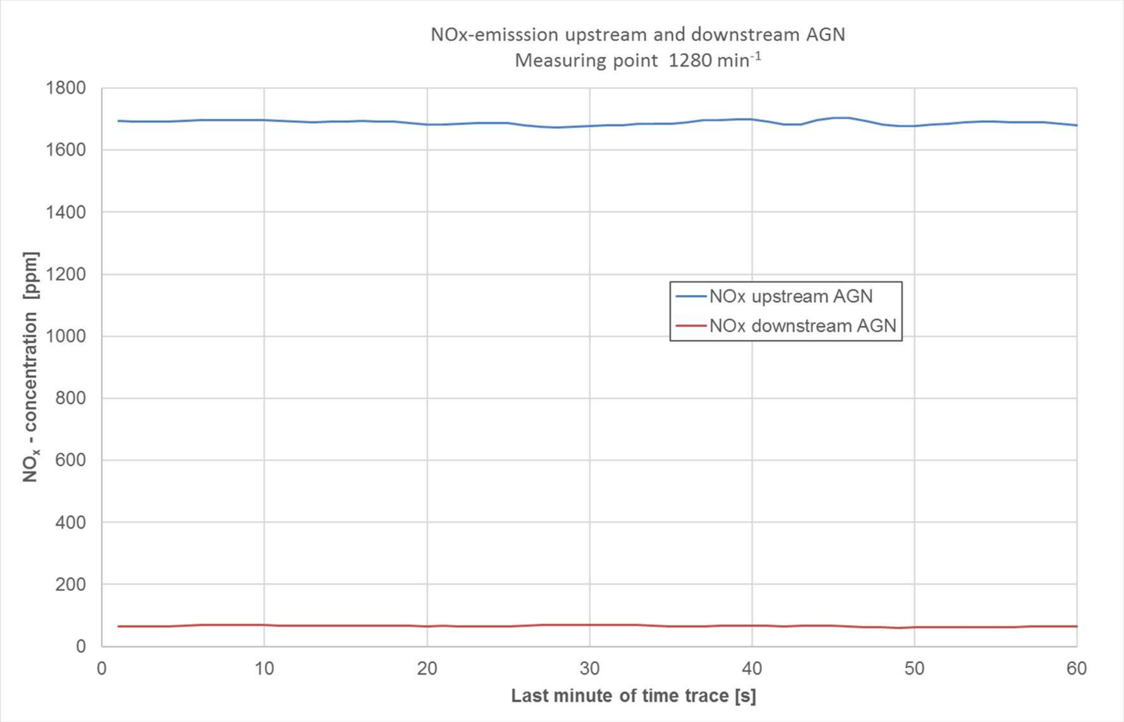


Figure 24: **NO_X Concentration Trace upstream and downstream AGN**

6.3.1.3 Measuring Point 1.008 min^{-1}

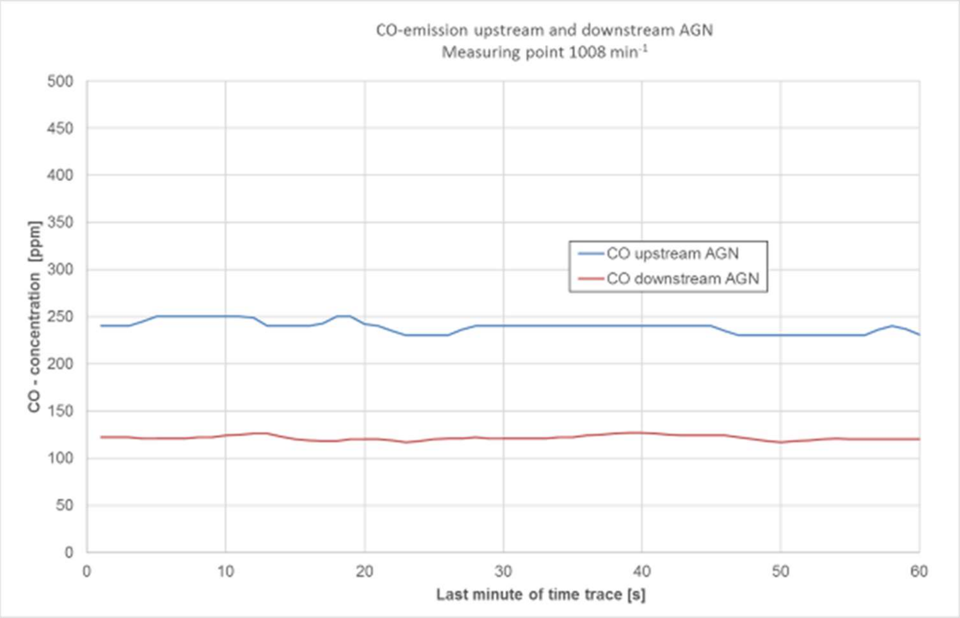


Figure 25: **CO Concentration Trace upstream and downstream AGN**

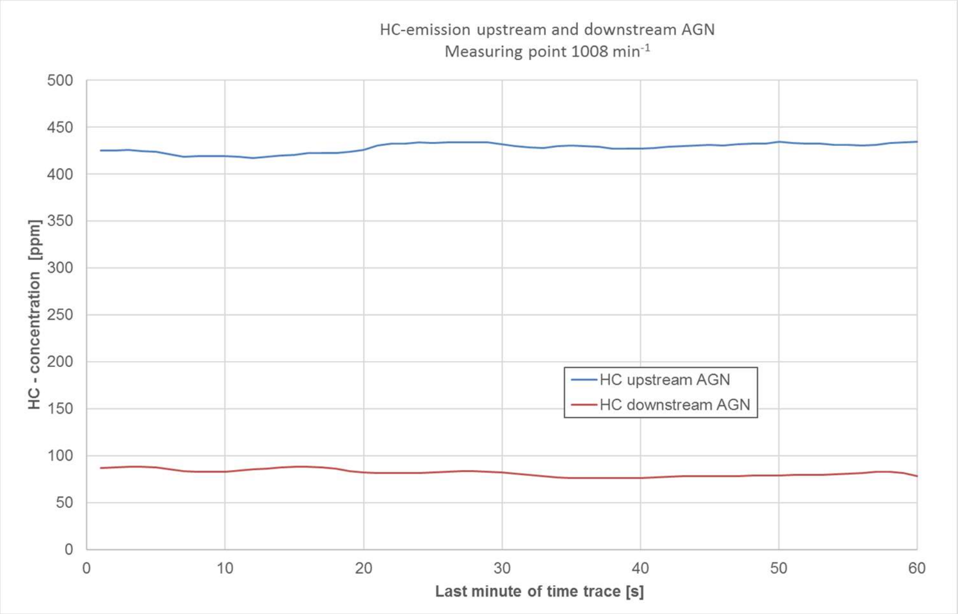


Figure 26: **HC Concentration Trace upstream and downstream AGN**

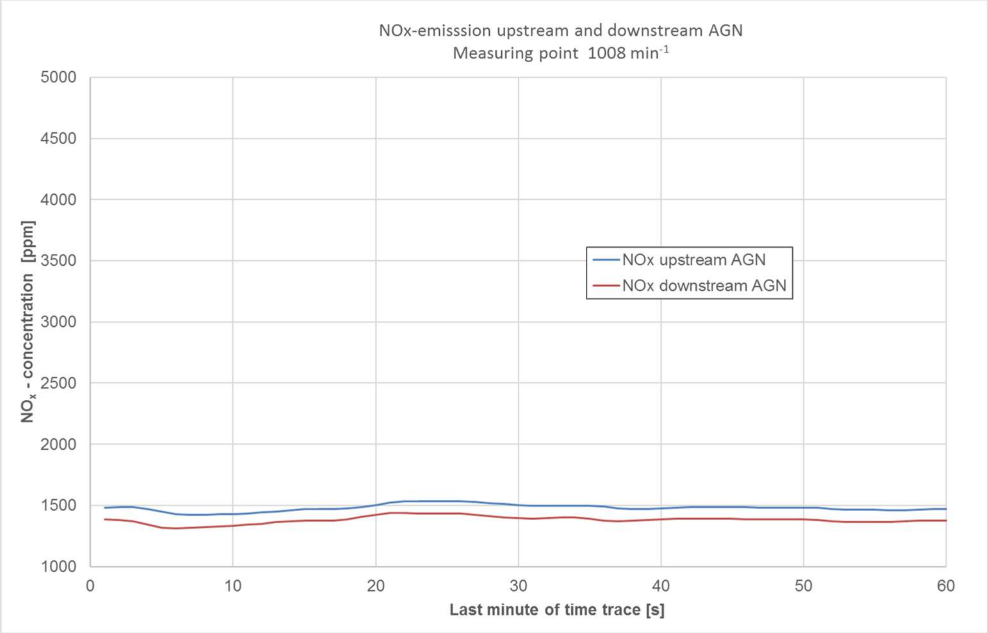


Figure 27: NO_X Concentration Trace upstream and downstream AGN

6.3.2 Particulate Emissions

For the gravimetric determination of the particulate emission two samples were drawn at each measuring point upstream and downstream from the exhaust retrofitting, using the measuring technique described in 5.2.2. Figure 26 shows exemplary in the test loaded filter plates.

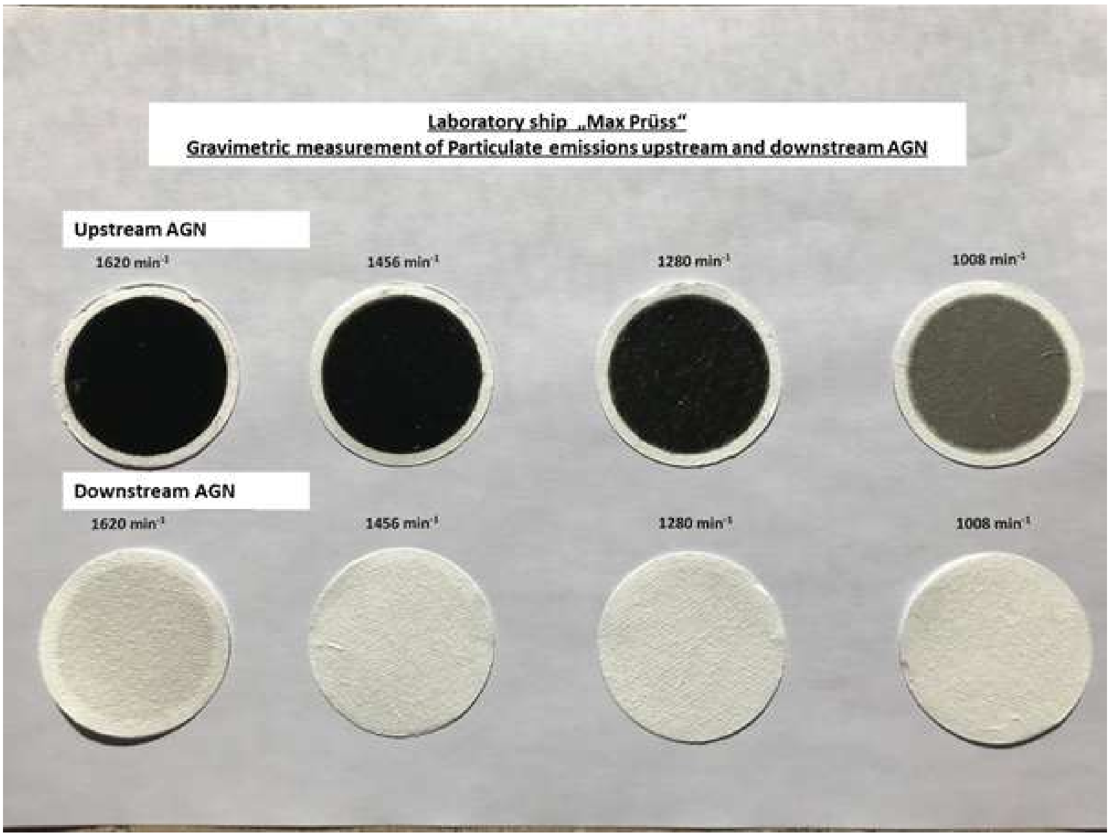


Figure 28: Particle Sample Filter upstream and downstream AGN

Table 9 and Table 10 show the averages of the two measurements per measurement point upstream and downstream AGN.

Table 9: Particulate Measurement Results upstream AGN

Setpoint	Engine speed	Power output	Filter loading	G_{edf} *)	Particulate mass flow	spec. Particulate emission
	min^{-1}	kW	mg	kg/h	g/h	g/kWh
1	1.620	193,9	1,0342	3.807,15	33,86	0,1746
2	1.456	145,4	0,6760	2.863,64	14,98	0,1030
3	1.280	102,7	0,6628	2.232,54	9,16	0,0892
4	1.008	53,9	0,7648	1.646,75	6,49	0,1206

*) equivalent diluted exhaust mass flow

Table 10: Particulate Measurement Results downstream AGN

Setpoint	Engine speed	Power output	Filter loading	G_{edf}*)	Particulate mass flow	spec. Particulate emission
	min^{-1}	kW	mg	kg/h	g/h	g/kWh
1	1.620	193,9	0,3825	3.807,15	7,51	0,0387
2	1.456	145,4	0,0692	2.863,64	0,82	0,0056
3	1.280	102,7	0,0515	2.232,54	0,39	0,0038
4	1.008	53,9	0,0449	1.646,75	0,22	0,0040

*) equivalent diluted exhaust mass flow

6.3.3 Soot Emissions

For the determination of the soot emission the measuring method, described in 5.2.1, was used. Table 11 and Table 12 show the results before and after the exhaust retrofitting.

Table 11: **Results of Soot Measurement upstream AGN**

Setpoint	Engine speed	Power output	Soot concentration	G_{exh} *)	Soot mass flow	spec. Soot emission
	min^{-1}	kW	mg/kg	kg/h	g/h	g/kWh
1	1.620	193,9	24,3033	951,79	23,1317	0,1193
2	1.456	145,4	14,6337	715,91	10,4764	0,0721
3	1.280	102,7	10,3337	558,14	5,7676	0,0562
4	1.008	53,9	1,9366	411,69	0,7973	0,0148

*) Exhaust mass flow

Table 12: **Results of Soot Measurement downstream AGN**

Setpoint	Engine speed	Power output	Soot concentration	G_{exh}*)	Soot mass flow	spec. Soot emission
	min^{-1}	kW	mg/kg	kg/h	g/h	g/kWh
1	1.620	193,9	0,0581	951,79	0,0553	0,0002853
2	1.456	145,4	0,0268	715,91	0,0192	0,0001320
3	1.280	102,7	0,0309	558,14	0,0172	0,0001679
4	1.008	53,9	0,0445	411,69	0,0183	0,0003403

*) Exhaust mass flow

6.3.4 Reduction Rates in the Individual Measuring Points

For the data presented in 6.3.1 to 6.3.3 the reduction rates shown in table 13 are obtained for the individual components. Figure 27 shows the reduction rates in a graph.

Table 13: Reduction Rates in the Individual Measuring Points

CO	Engine speed	Power output	upstream AGN	downstream AGN	Reduction rate
	min^{-1}	kW	g/h	g/h	%
1	1.620	193,9	260,00	97,57	62,5
2	1.456	145,4	148,60	63,28	57,4
3	1.280	102,7	75,79	51,86	31,6
4	1.008	53,9	90,33	45,97	49,1

HC	Engine speed	Power output	upstream AGN	downstream AGN	Reduction rate
	min^{-1}	kW	g/h	g/h	%
1	1.620	193,9	66,70	2,15	96,8
2	1.456	145,4	75,11	2,01	97,3
3	1.280	102,7	136,22	3,64	97,3
4	1.008	53,9	253,19	48,29	80,9

NO_X	Engine speed	Power output	upstream AGN	downstream AGN	Reduction rate
	min^{-1}	kW	g/h	g/h	%
1	1.620	193,9	2.385,96	800,74	66,4
2	1.456	145,4	1.846,63	231,84	87,5
3	1.280	102,7	1.258,97	48,88	96,1
4	1.008	53,9	824,22	770,07	6,6

Table 13: **Reduction Rates in the Individual Measuring Points, part 2**

PM	Engine speed	Power output	upstream AGN	downstream AGN	Reduction rate
	min^{-1}	kW	g/h	g/h	%
1	1.620	193,9	33,86	7,51	77,8
2	1.456	145,4	14,98	0,82	94,6
3	1.280	102,7	9,16	0,39	95,7
4	1.008	53,9	6,49	0,22	96,7
Soot	Engine speed	Power output	upstream AGN	downstream AGN	Reduction rate
	min^{-1}	kW	g/h	g/h	%
1	1.620	193,9	23,13	0,055	99,8
2	1.456	145,4	10,48	0,019	99,8
3	1.280	102,7	5,77	0,017	99,7
4	1.008	53,9	0,79	0,018	97,7

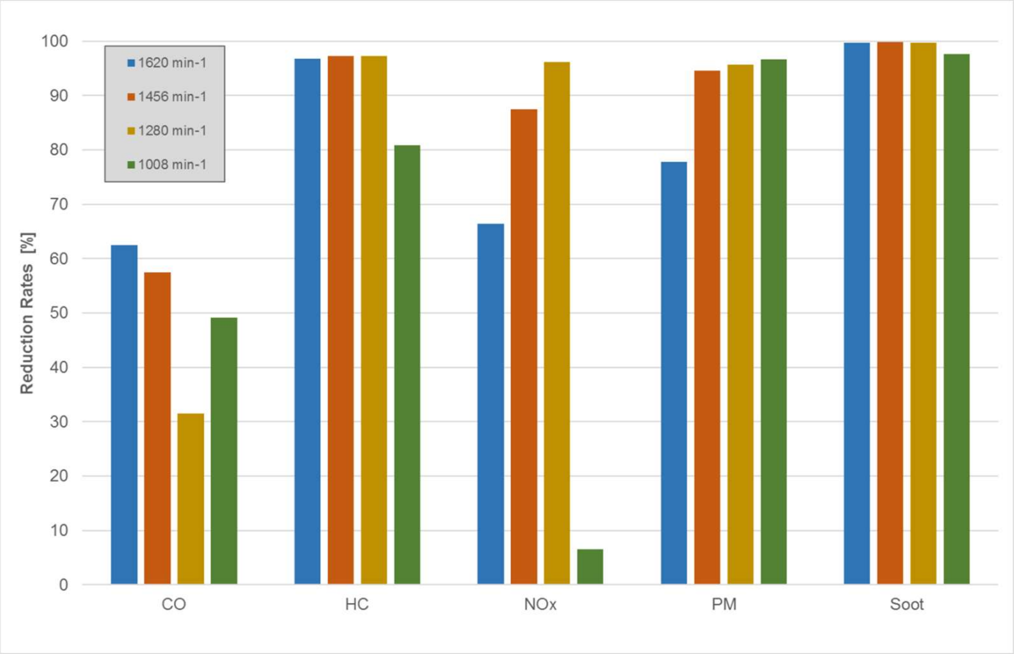


Figure 29: **Reduction Rates in the Individual Measuring Points**

6.4 Evaluation in Accordance with ISO 8178 E3 Cycle

If one uses the measurement data of the individual operating points for an evaluation based on ISO 8178 in the E3 cycle, the following results can be found. The results for carbon black are not used in this analysis because the measurement method used is not part of ISO 8178.

6.4.1 Evaluation upstream AGN

For an E3 evaluation with the exhaust gas values measured upstream exhaust retrofitting the results are shown in Table 14.

Table 14: E3 Results upstream AGN

E3 weighted results according ISO 8178		
CO	g/kWh	1,121
HC	g/kWh	0,810
NO_X	g/kWh	12,694
PM	g/kWh	0,134

6.4.2 Evaluation downstream AGN

For the measuring data, measured in the tailpipe, the result shown in table 15 is obtained using the E3 weighting (see chapter 4.2). These results yield the following E3 weighted reduction rates.

Table 15: Reduction Rates with E3 Weighting

E3 weighted results according to ISO 8178			E3 weighted Reduction rates	
CO	g/kWh	0,488	%	56,5
HC	g/kWh	0,068	%	91,6
NO_X	g/kWh	2,956	%	76,7
PM	g/kWh	0,016	%	87,9

6.5 Results for NO_2 Emissions

The NO_2 emission results are as shown in table 16.

Table 16: **NO2-Emissions**

NO_2	Engine speed	Power output	upstream AGN	downstream AGN	Reduction rate
	min^{-1}	kW	g/h	g/h	%
1	1.620	193,9	42,65	23,84	44,1
2	1.456	145,4	49,13	44,42	9,6
3	1.280	102,7	62,12	31,48	49,3
4	1.008	53,9	69,07	244,32	-253,7*)

*) for a precise explanation of the negative rates see +in the following chapter 7.1

7. Discussion of Results

7.1 Assessment of the Emission Results Presented

In 2002, the Central Commission for Navigation on the Rhine (ZKR) introduced limit values for the emission of gaseous pollutants and air polluting particles from diesel engines. The engines of the "Max Prüss", constructed in 1998, are still from the time before the introduction of these limits. The engines are still in their original condition and have not yet had a major overhaul. For an engine as installed in the "Max Prüss" the limit values of table 17, line 3, applied in 2002 are mandatory:

Table 17: ZKR Level I limits from 2002, valid for the "Max Prüss"

P_N [kW]	CO [g/kWh]	HC [g/kWh]	NO_X [g/kWh]	PM [g/kWh]
$37 \leq P_N < 75$	6,5	1,3	9,2	0,85
$75 \leq P_N < 130$	5,0	1,3	9,2	0,70
$P_N \geq 130$	5,0	1,3	$n \geq 2800\ min^{-1} = 9,2$ $500 \leq n < 2800\ min^{-1} = 45 \cdot n^{(-0,2)}$	0,54

With a rated speed of 1.800 min^{-1} and a power of 250 kW, this would result in a NO_x limit of 10.05 g / kWh.

As table 14 shows, the engine of the "Max Prüss" (without retrofitting) is below the limit values of the ZKR Level I for all components except NO_X. It must be pointed out however, that the engine tested cannot achieve its nominal speed of 1.800 min^{-1} in real operation and the required E3 test could only be run at a speed of 1.620 min^{-1}. The NO_X emissions of the "Max Prüss" engine (12,7 g/kWh without aftertreatment) are at a level that corresponds with rules of the year of construction. But these values also represent the primary challenge for exhaust retrofitting, in addition to particulate emissions.

The exhaust retrofitting system, chosen for the "Max Prüss", the combination of a closed (wall flow) particulate filter with a downstream SCR catalyst (Selective Catalytic Reduction), which uses an urea solution (AdBlue©) as reagent, is basically capable of decreasing all limited exhaust gas components. Here the upstream of the particulate filter oxidation catalyst is used for the oxidation of hydrocarbon compounds and carbon monoxide. At the same time this oxidation catalytic converter also has the task of increasing the proportion of NO_2 in the raw exhaust gas, which usually is between 3 and 10 % in diesel raw (untreated) exhaust gas.

This is necessary because the particle filter downstream of the oxidation catalytic converter is a continuously regenerating trap. NO_2 favors the oxidation of the collected soot and thus allows the successful regeneration of the particulate filter even at lower exhaust gas temperatures. Another reason for increasing the NO_2 content in the exhaust gas flow is the functionality of the SCR catalytic converter. Here a NO_2 / NO_X ratio of about 50% is desired. The measurement setup used in this project does not provide any measurement of the emission data between the particulate filter and the SCR catalytic converter, so that no statement can be made about the real NO_2 / NO_X ratio at the inlet of the SCR catalytic converter.

The results presented in chapter 6.3 are used for the determination of the reduction rates for the different exhaust gas components, as shown graphically in figure 27. Looking firstly at the soot emission, it can be seen that the elemental carbon is almost completely filtered out. This is an expected behavior for a high quality closed particulate filter. The fact that these filtration values, as observed for the soot, are not fully reflected in the gravimetric particulate measurement is due to the measurement method. By definition, particles are all substances that precipitate on the sample filter at temperatures below 52°C. Besides carbon, these may e.g. be also condensates of various compounds. The results are in line with expectations.

Nitrogen oxide emission reduction rates vary widely across load points, but are within the expected range for SCR systems (60% to > 90%) for the first three load points. Noticeable is the result for the last measuring point (lowest speed), which is documented with reduction rates well below 10%. The chemical conversion of the Adblue© to ammonia requires minimum temperatures of 220°C in the plant. On the system side the Adblue© injection is switched off when the temperatures measured on the SC catalytic converter are lower than 220°C.

Figure 30 shows a section of the fourth measuring point of the E3 cycle (1.008 min^{-1}). Shown is the NO_X concentration downstream of the exhaust retrofitting, the exhaust gas temperature in the tailpipe and the exhaust gas mass flow over a temporal excerpt of the measuring point. The steadily falling exhaust gas temperature at this measuring point can be clearly recognized. With the falling exhaust gas temperature it is observed that the NO_X concentration increases. The concentration increases drastically when a temperature lower than 220°C is reached. At this is point the urea supply (AdBlue©) is stopped.

If the measuring points are driven until stationary conditions are reached and the last minute of the measuring point is used for the evaluation, this measuring point (without urea supply) shows lower reduction rates than the others.

This reaction shows that the reduction rates in real operation are always dependent on the load history. For example if a maneuver has been driven after an upstream trip with a high load, requiring only a short time load point of e.g. 1008 min^{-1}, as presented here, high reduction rates are achieved during this time due to the still high temperatures in the system. But if one assumes a longer operation in such a low load point, the reduction rates would eventually fall to the documented value and remain there. It should be noted that an E3 test for this engine with 250 kW at 1800 min^{-1} would have a lowest load point of 1134 min^{-1} with 62.5 kW power, in contrast to 1008 min^{-1} and 53.9 kW in the driven test.

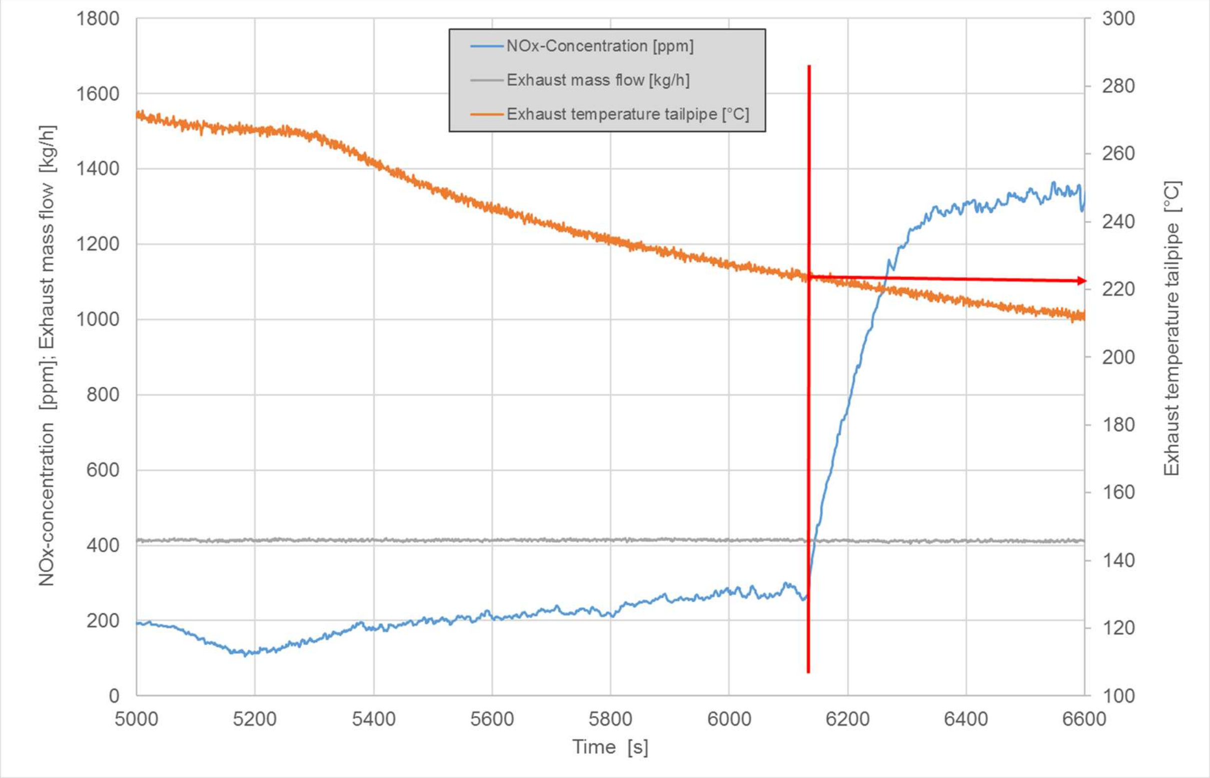


Figure 30: **Detail Measuring Point 1.008 min-1**

The described effects influence the NO_2 emissions, as shown in chapter 6.5 as well. The specified reduction rates are significantly lower than those reported for NO_X. This is due to the three different reaction paths, taking place in an SCR catalyst and directly being influenced by the NO_2/NO_X ratio in the catalyst inlet. The conspicuously high negative value in the last measuring point is explained by the system behaviour, as described above, with decreasing exhaust gas temperature lower than 220°C. After switching off the urea injection, there is no further conversion of nitrogen oxides, so the NO_2 concentration in the catalyst inlet is approximately the same as in the catalyst outlet. Since the NO_2 content in relation to the engine raw exhaust gas is significantly increased by the oxidation catalytic converter upstream of the particulate filter (see above), a significant increase in the NO_2 content of the total NO_X emission takes place in the lowest load point, which leads to the negative reduction rates above.

An important parameter for the functioning of an SCR catalytic converter is the correct reagent dose rate dependent on the load point. The reagent needed in the SCR catalyst is ammonia (NH_3). There are different techniques available to supply the catalyst with the correct amount of ammonia. For reasons of transport and storage safety the injection of an aqueous urea solution has been implemented. Here a 32% solution is injected into the exhaust gas stream and processed there by thermolysis or hydrolysis to ammonia. Too high a dosage of the reagent leads to a NH_3 slip through the catalyst and thus to NH_3 emissions. This needs to be avoided at all costs. A too low dosage leads to losses in the possible reduction rates. To avoid a possible NH_3 slip, SCR systems can be equipped with an ammonia slip catalyst. The system installed on the "Max Prüss" has no ammonia slip catalyst. For this reason, a certain safety distance to the maximum possible AdBlue© injection quantity must be maintained in this system in order to prevent NH_3 emissions.

The maintenance performed prior to the measurement campaign on the "Max Prüss" optimized AdBlue© injection into the system for optimum NO_X reduction resulting in overdose of AdBlue© with NH_3 slip.

At the beginning of the measuring campaign a distinct NH_3 odor was detected at the exhaust gas outlet. Since no suitable measurement technology was available for the determination of NH_3 emissions, it was not possible to quantify these emissions. An olfactometric determination suggests that the existing emissions are well above tolerable levels. Therefore, action is most certainly required. On the Max Prüss the AdBlue© injection during the measurement campaign was reduced so much that the comparison of the TÜV-Nord measurements with the measured values of the "Multronic" sensor (cross sensitivity to NH_3) no longer indicated any NH_3 slip.

This readjustment also ensured that the NO_X readings of the cross sensitive "Multronic" sensor were not corrupted by NH_3 slip. On all vessels, participating in the CLINSH with AdBlue© injection, it should be ensured that the continuous NO_X measuring signals were not falsified by NH_3 slip. The hydrocarbon emissions are, as expected, implemented with very high reduction rates. Only the last operating point also falls in its reduction rates. Again the explanation is the cooling down of the exhaust retrofitting system and the following switch off of the AdBlue© injection.

In a previous project (see LANUV Technical Report 49 (2013), Reduction of Particulate Matter, soot and nitrogen oxide emissions on the passenger vessel "Jan van Werth" by retrofitting a SCRT system, German language), a passenger ship had been equipped with an exhaust retrofitting (in an older technical standard) from the same manufacturer. In this project, increases in CO emissions had been detected downstream of the AGN. In case of the "Max Prüss" reduction rates are also observed for carbon monoxide. They vary greatly between the individual load points, but the technical devolpement to a better performance at that point could be shown.

7.2 Result relevance for the CLINSH project

In the CLINSH project NO_X emissions are continuously monitored on 41 vessels equipped with a wide range of emission reduction technologies. Using the continuous monitoring results, real time emissions data ("Real Shipping Emissions", RSE) is to be collected during real time operation and the effect of technical measures to reduce emissions can be assessed.

The emission measurement, described in this report, should on the one hand demonstrate the reduction rates of the installed exhaust retrofitting, but at the same time be used as a tool to validate the onboard technology for emission monitoring. The main focus is on the nitrogen oxide emission.

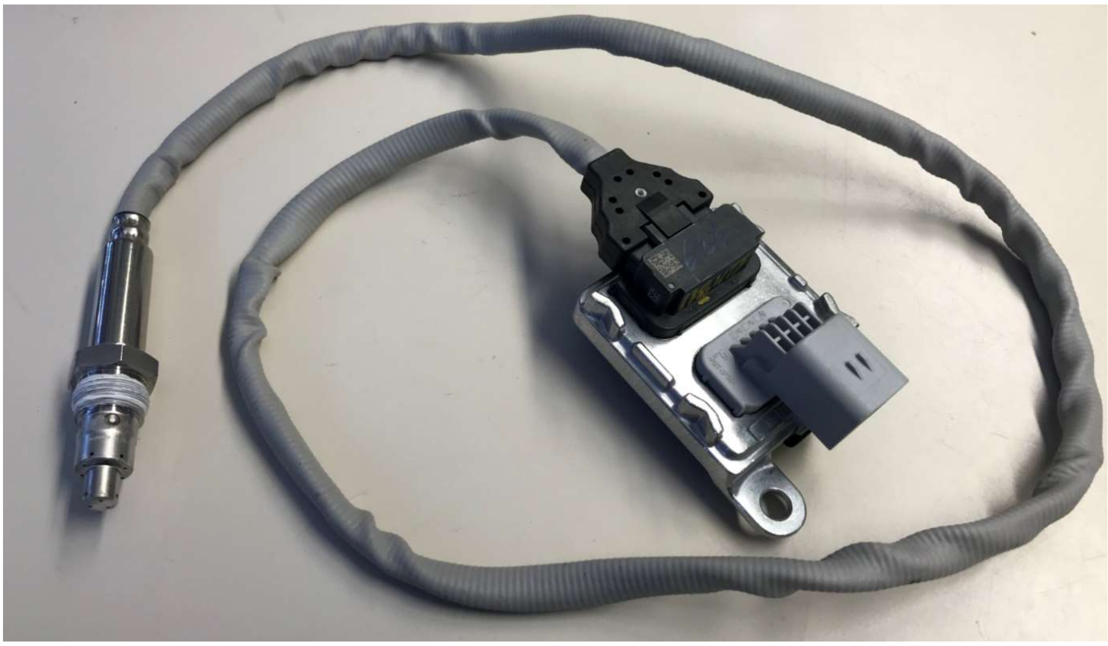


Figure 31: **NO_X-Sensor [Source: TÜV-Nord]**

The continuous (permanent) emission monitoring cannot be carried out with measuring techniques as used in the monitoring campaign by the TÜV-Nord, described in this report, since this is an expensive laboratory measuring technique.

Therefore, for permanent monitoring sensors are used, as installed for example in commercial vehicle technology, as mass serial product. Figure 31 shows an example of such a NO_X-sensor.

This sensor is screwed into the exhaust pipe after the exhaust retrofitting system. The suitability of such sensors for long-term stable detection of nitrogen oxide concentrations in the exhaust gas is undisputed. However, in this application there are risk factors for safe operation, wherefrom two should be named here. The quality of the recorded data and thus also the quality of the emission factors determined later are directly dependent on the operation of the monitoring sensor. For this reason, it is highly recommended to validate the sensor data in systems with reagent assisted SCR catalysis.

A direct comparison of the measurement results of the TÜV-Nord during the test drive with the results of the continuous measurement (“Multronic” sensor) yielded the following information:

The sensor principle used for continuous monitoring has a clear cross sensitivity to NH_3. If NH_3 slip occurs in the reagent based SCRT systems, this leads to higher measurement signals and thus gives the impression of higher NO_X concentrations in the exhaust gas. The effect of exhaust retrofitting will be underestimated. In addition, NH_3 emissions also cause environmental damage that should be avoided at all costs. A readjustment of the urea injection during the test drive subsequently provided comparable measurement results for both systems.

It must therefore be ensured that such sensors, when installed on the raw gas side, are arranged upstream of the supply of the reagent or, if they are installed downstream the exhaust gas retrofitting, there should be a warning system that detects NH_3-slip. As already mentioned, NH_3 slip can be avoided in different ways, depending on the system architecture. If a system without ammonia slip catalyst is installed, the application must ensure that no overdose of the reagent occurs at any operating point.

With a built-in ammonia slip catalyst, the reagent dosage can be applied closer to the NH_3 slip threshold, since low NH_3 slip is eliminated by the slip catalyst. One of these two measures requires the system manufacturer to realize a safety against NH_3 slip. As described in chapter 7.1, a non-tolerable NH_3 slip seems to be existent in the first phase of the monitoring period, so that measurement signal distortions due to the described cross-sensitivity are to be expected.

The second risk factor, to be mentioned here, is not due to the sensor principle, but consists in fluidic problems that can lead to inhomogeneities in the exhaust gas pipe at the point of sensor mounting. A homogeneous exhaust gas mixture behind the SCR catalytic converter can only be expected if a uniform admission of catalyst inlet with exhaust gas and reagent is achieved at all operating points. If this is not the case, "exhaust plumes" arise in the catalyst outlet, which will lead to an inhomogeneous concentration distribution over the pipe cross-section.

A sufficiently long pipe route with turbulent flow conditions can be the only solution. Used mixing bodies can be helpful here, but can cause an increase in the exhaust back pressure, which can lead to problems in borderline interpretations. In order to avoid incorrect measurements due to this second risk factor, appropriate measures must be agreed upon between the system manufacturer and the person responsible for the monitoring.

Finally it should be noted that successful monitoring of the exhaust gas situation under real driving conditions can only be guaranteed by the continuous measurements if, after the system installation (AGN and monitoring system), a validation of the measured data takes place in the usual operating range of the engine. It must be ensured that NH_3 slip can be avoided under all operating conditions. Only in this case risk factors for incorrect measurements can be identified and eliminated.

8. Summary

The LANUV (State Agency for the Environment, Nature and Consumer Protection of the State of North Rhine-Westphalia), owner of the "Max Prüss" laboratory ship, equipped the ship with an exhaust gas retrofitting system, which significantly reduces the nitrogen oxide emissions of the "Max Prüss" propulsion engines. Among the different systems, a combination of a continuously regenerating particulate filter and a downstream SCR catalyst were selected and realized by “TEHAG”. The retrofitted "Max Prüss" is also one of the project ships of the European Life project CLINSH (Clean Inland Shipping) and has been equipped with techniques in this project to enable continuous long term monitoring of exhaust emissions.

The project should demonstrate the effectiveness of the exhaust retrofitting system and at the same time offer the possibility to validate the installed monitoring system. The research concept provides measurements of emissions in real operation of the ship. In this project, the result of the measurement in four load points is to achieve a result comparable to an E3 test of ISO 8178, as prescribed for inland waterway engines. The examined starboard engine achieved a maximum speed of 1.620 min^{-1} in real operation due to the governor setting. Based on this speed, the other measuring points on the propeller curve of the used propeller are determined.

The measuring program provides for simultaneous measurement of gaseous emissions upstream and downstream of the exhaust retrofitting. In addition, gravimetric particulate measurements are performed as well as soot measurements with a photoacoustic aerosol sensor. These measurements are carried out in separate measuring campaigns upstream and downstream of the exhaust gas retrofitting, since the measuring technology is only available in a simple manner.

The results show positive reduction rates for all limited pollutants at all measuring points. For the nitrogen oxides, these are between 66% and 96%, except for the lowest measuring point. Here, due to low exhaust gas temperatures, the injection of the reagent is stopped. The reduction rate then drops to 6.6% during the measurement time. For soot reduction rates of 97.7% to 99.8%, the particulate emissions are reduced by 77.8% to 96.7%. For total hydrocarbons, reduction rates were between 81% and 97.3%. For carbon monoxide, the reduction rates vary between 31.6% and 62.5%. When looking at NO_2 direct emissions, reduction rates of 9.6% to 49.3% can be observed in the first three load points. For the last measuring point (lowest speed), the low exhaust gas temperature and the thus stopped reagent supply resulted in a very significant increase of the NO_2 content in the exhaust gas.

Considering the results weighted according to ISO 8178 for an E3 cycle, the following reduction rates result for the individual components: carbon monoxide 56.5%, hydrocarbons 91.6%, nitrogen oxide 78.7% and particles 87.9%. For the determined soot values no E3 weighting is provided. For nitrogen oxide (NO_X) emissions, the work specific emissions in the E3 cycle are reduced from 12.69 g/kWh to 2.96 g/kWh. When validating the monitoring data, two measurement risks could be identified. On the one hand side a clear NH_3 slip of the exhaust system could be detected during the measurement, which can lead to erroneous measuring signals due to cross sensitivities of the monitoring sensor, the “Multronic” company used for the continuous monitoring. The NH_3 slip could be minimized during the test drive by a readjustment of the system. On the other hand, there is a measurement uncertainty due to inhomogeneities in the exhaust gas flow downstream exhaust retrofitting.

The results show that measures must be taken to eliminate these two measurement risks. Here, the elimination of NH_3 slip is clearly the responsibility of the system manufacturer of the exhaust retrofitting system. For an improvement of homogeneity in the exhaust gas and determination of the optimal installation position of the nitrogen oxide sensor, a close cooperation between the system suppliers of the exhaust retrofitting and the suppliers of the continuous monitoring system is necessary. To achieve high quality continuous monitoring data, a validation after installing the system is absolutely necessary in order to minimize the risk of incorrect measurements.

Acknowledgments:

We would like to thank the crew of “Max Prüss” and the staff of the “TEHAG company” for the helpful support of the project work.

9. Literature

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10. List of Figures

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12. Partners in CLINSH

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