SMOKE VALUE MEASUREMENT WITH THE FILTER-PAPER-METHOD

Application Notes

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AT1007E, Rev. 02

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1 What You Should Know

1.1 Safety Instructions

This documentation contains important **warnings and safety instructions** to be observed by the user. Smooth operation only is ensured, if the necessary prerequisites and safety measures are kept.

1.2 Intended Application

The product is only intended for the area of application which is described in the documentation. No warranty and/or liability is granted, if the product is applied in areas other than those described, or if the necessary prerequisites and safety measures are not met.

1.3 Introduction

Because of simple operability, the fast data availability and the clear indication of the emitted soot concentration in the exhaust gas of internal combustion engines, but also due to the cost efficiency, the smoke measurement with the filter paper method has become the standard for engine test bed applications.

This application paper describes the suitability of smoke meters for the measurement of low particle emissions, as they are found in modern diesel engines in cars, trucks and in direct injection otto engines. Fundamental functional necessities for the smoke measurement at very low soot emission levels will be shown, research results of factors influencing the measurement data are going to be identified and measures to guarantee the measurement accuracy will be presented.

Low emission levels of modern and future diesel engines require a technological advancement of instruments for particle and smoke measurement. With the rising demands on the measurement accuracy of the smoke meter, the specifications of the sensor itself are no longer the only decisive factor but also the control over the whole measuring system is key to an increased reproducibility.

As a result of the advancement of the AVL Smoke Meter a heating system for the unit and the sampling line was implemented. Because of these measures to raise the accuracy, measuring differences between the old and the new (AVL 409, 415, 415S) Filter Smoke Meters were found. Also results differed between the heated and non-heated units, between AVL 415S G001 and G002 and also for different sample probe locations. In this application paper the results of a research upon the influential impact of different units and different probe locations upon the measuring results are shown. In addition, an example shall be given with a detailed description of the experimental setup, under which conditions the measurements of different equipment types can be compared to each other.

In addition this application paper shall give recommendations for the test setup and the application for special measurement tasks.

All represented numerical values the (deviations, differences between the instruments) are connected closely to test carrier that has been available for the examination.

Different combustion chamber geometries, burning methods etc. cause for example different particle size distributions for different engine load situations. An exact (quantitative) verification should therefore be carried out with the corresponding emission sources themselves. However the comparison of measurements between different test carriers has shown that the obtained numerical values describe different influences on the measurement results qualitatively well.

1.4 About this Documentation

Target group

This documentation refers to application engineers and technicians in measurement engineering.

Further information

For further information please refer to the following documentation:

- AVL 415S Smoke Meter, Operating Manual
  (material number AT1240E)
- AVL 415S Smoke Meter, Special Sampling Option 415S
  (material number AT1838E)
- AVL 415S Smoke Meter, Calibration and Adjustment Procedure
  (material number AT0755E)

1.4.1 Typographic Conventions

This documentation uses the following icons (symbols) and standard text styles:

ATTENTION!

Icon and text indicate a warning of situations or actions that could potentially lead to personal injury, hardware damages and/or significant data loss.

Important: Icon and text indicate very important information or instructions. If these instructions are ignored, you will not be able, or will have (significant) difficulties, to finish the actions described in this documentation.

Note: Icon and text indicate specific or further information (e.g. tip, other documentation).

1.4.2 We Want to Hear from You

Your comments and suggestions help us to improve our documentations.

Whether you want to suggest an improvement to a particular manual, complain that a concept is not explained well enough or point out an error, we want to know.

To this end, we have created the following e-mail address for all documentation-based correspondence:

docu@avl.com

We look forward to hearing from you!

2 Functional Principle

2.1 General

2.1.1 Measuring Principle

A subset of the exhaust gas is taken from the exhaust gas line with a probe and sucked through a filter paper. The blackening of the filter paper caused thereby is measured with a reflectometer and indicates the soot content in the exhaust gas.

The blackening of the filter paper primarily depends on the soot concentration in the exhaust gas and the "effective filter length" (exhaust gas volume related to the filter area.)

The value 0 is assigned to the unloaded, clean filter paper and the absolutely black paper filter that is loaded with soot is assigned to the value SZ_B 10 (blackening number according to Bosch), or 100 % blackening (primarily in Asia shown as a pollution level PL).

2.1.2 Effective Sampling Length

The decisive parameter for the smoke meter is the exhaust gas volume related to the loaded filter face, which is the "effective sampling length". In order to create comparable conditions, this has to be related to norm conditions.

ISO DP 10054 is defined:

$$\text{effective sampling length} = \frac{\text{sampled volume} - \text{dead volume} - \text{leakage volume}}{\text{filter area}}$$

whereas the volumes are to be related to 298 K and 1 bar (see Fig. 1 on page 12)

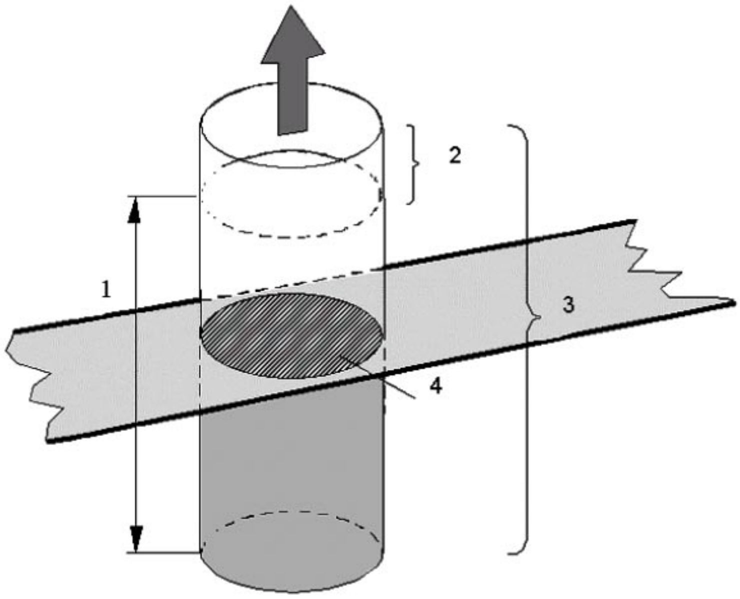
The effective length was standardized from ISO DP 10054 with 405 mm, because this value results of the nominal sizes of standard smoke meters (Bosch hand pump), a sampled volume of 330 cm³ and a loaded paper face of 8.15 cm² (Ø 32 mm).

That means, that the Filter Smoke Number (FSN) defined from ISO with the effective sampling length of 405 mm under consideration of pressure and temperature of the sampled volume (298 K, 1 bar) is nothing else than a more precise defined Bosch Number.

The *dead volume* is the volume of the gas way from the sampling point up to the filter paper (consists of the volume of the sampling probe, the sampling line and the gas way in the device between the line connection and the filter paper). By purging the system with clean air immediately before the sampling it can be guaranteed that no soot particles are present in the dead volume.

The leakage volume is caused mainly by transverse currents of the filter at the suction unit, but also by leakages in the sampling system (for example sampling reciprocating sealing).

Diagram showing the principal of exhaust gas sampling with FSN measuring instruments (AVL 415, AVL 415S), relationship between sampling volumes, effective length and filter area



1 Effective sampling length
2 Dead volume
3 Take out volume
4 Filter area

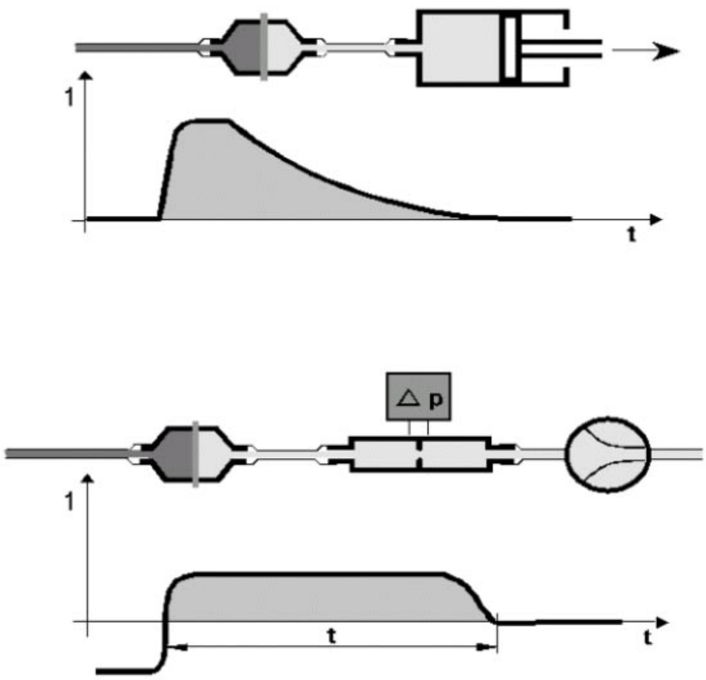
Fig. 1

2.1.3 Diaphragm Pump versus Reciprocating Pump

The AVL Smoke Meters 415 and 415S use, unlike the AVL 409, a new sampling technique: The traditional reciprocating pump is replaced by a continuously sampling diaphragm pump.

Through the use of the electronically operated diaphragm pump it is possible to make a sampled volume and/or sampling time preselection. Especially with smoke values in the low range (below 1 SZ_B, particularly below 0.5 SZ_B) it is not possible to reach dependable results with devices based on the reciprocating pump principle with a fixed sampled volume. The reason for this is the small filter blackening close to the white reference level that does not allow any precise optical evaluation. The problem can be solved with an increased sampled volume in a way that the filter loading is increased so far that the optical evaluation is performed at optimal blackening degree.

Reciprocating pump versus diaphragm pump



1 Exhaust gas stream

Fig. 2

With the electronically operated diaphragm pump the sampled volume can be varied. The speed of sample taking is constant.

2.1.4 "Auto Range" Measurement

The sampled volume preselection should be set in a way that the current paper blackening is at 2.5 ± 1.5. The standard sampled volume of 1 liter is to be increased for example to 3 liters at small engine load levels, with high load levels a reduction has to be made for example to $^{1}/_{3}$ liters.

The AVL Smoke Meters 415 and 415S are equipped with "Auto Range" functions, that suck up the ideal sampled volume for the evaluation of the result . This is performed either by consideration of the pressure drop ("Auto Range" Online), or based on the filter blackening of a first pre-measurement with a defined sampled volume of 200 cm³ ("Auto Range"). This is further described in section 5.7 of the Operating Manual.

The "Auto Range" measurement with a pre-measurement guarantees a paper blackening closer to the optimum value than the measurement "Auto Range" Online does. Due to this it should generally be preferred. The paper consumption in this case is higher than with the measurement "Auto Range" Online.

In case the exhaust gas pressure may change at the sample location during the measurement, the "Auto Range" Online measurement should generally not be used.

2.1.5 "Auto Range" Online Measurement

As already mentioned above, with this type of measurement an optimal filter loading is determined by the pressure difference over the filter. After a certain threshold value is reached (upper and lower limit can be set manually in order to protect the system) the measurement is stopped and the result will be shown.

Since the device does not have the ability to recognize whether the pressure drop is due to the filter loading or due to the the exhaust system, the measurement may only be made at fixed points, the exhaust gas temperature at the sampling point should be constant and the venting system should work continuously in order to guarantee a constant pressure at the sampling point.

2.1.6 Optical Evaluation

The filter blackening is measured with a reflectometer.

Filter paper loaded with soot reflects almost ideally diffuse and the absorption characteristics are independent of the light's wavelength to a large extent. The influence on the reflectometer's value through the geometrical setup of the light source and sensor, the kind of light and the spectral sensitiveness of the sensor can be neglected in general.

In contrast most gray value discs available on the market have opposite qualities during the optical calibration. Their reflection is partly directional and their absorption depends on the wavelength. These gray standard discs can therefore not be used for the calibration of different reflectometers.

Under the condition "Reflectometer value = 0" (this means a sample with absorption = 100 % and reflection = 0 %) there are two different definitions for the relative reflectometer value (radiance factor) and the actual measured value of the filter smoke meters:

- For Asia (JIS D 8004) the filter blackening is measured absolute, this means according to an independent white value standard and is shown as a pollution level (PL) in %.
- In Europe and America (ISO 10054) the filter blackening is relative, this means it is compared to the unblackened filter paper and shown as a Filter Smoke Number (FSN).

2.2 Explanation of Terms

2.2.1 Paper Blackening (PB), Blackening Number (SZ and/or SZ_B)

Under paper blackening PB, the blackening degree which is detected on the filter paper is ment. PB is also often described as a blackening number from 0 to 10. Since this value does not only depend on the soot concentration in the exhaust gas but also on the effective sampling length, such "raw blackening values" are related – for the better comparability – to a sampling length of 405 mm (Bosch hand pump) and shown as a blackening number according to Bosch (SZ_B).

The paper blackening is determined by diffuse reflection of the blackened filter paper. The measuring principle is shown in Fig. 3 on page 17.

Definition of the paper blackening value (PB):

$$PB = \frac{100 - R_R}{10} \quad (1)$$

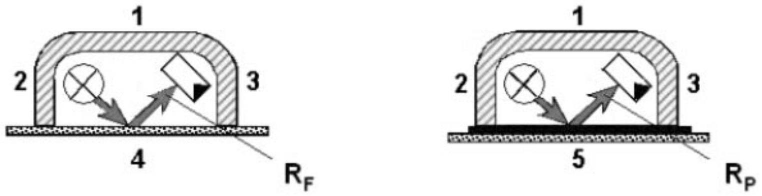
$$R_R = \frac{R_P}{R_F} \cdot 100\,\% \quad (2)$$

R_P … reflectometer value of sample

R_F … reflectometer value of the unblackened paper

R_R … relative brightness of the sample (relative radiance factor)

Components of the reflectometer head and measuring principal of the Smoke Meter.



1 Reflectometer
2 Light source
3 Detector
4 Clean filter
5 Blackened filter

Fig. 3

The following situation should be pointed out: The Bosch blackening scale reaches, as already mentioned, from 0 to 10. At the old AVL Smoke Meter 409 only values of SZ = 0 to SZ = 9 could be measured.

The basis for that can be found in the sampled volume being 1 liter for the AVL 409 (that is the triple sampled volume of the Bosch pump) and the absolute blackening of the filter paper already occurs at SZ = 9. The conversion of the 409 paper blackening with 1 liter sampled volume to the value of SZ_B (for 330 cm^3 sampled volume) was performed either by the Lineariser 4011-A01, at the non-linear analog scale or via compensation of the measurement data acquisition (PUMA) for the test bed version 409-S.

2.2.2 Filter Smoke Number (FSN) According to ISO 10054

Definition of the measured value "Filter Smoke Number "(FSN):

FSN = PB, if the corresponding effective sampling length is 405 mm.

The sampled volume is related to 298 K and 1 bar.

Note: The filter blackening is relative, that means it is determined in relation to the unblackened filter paper. Because of this the measured value becomes virtually independent of the brightness of the unblackened filter paper.

2.2.3 Pollution Level (PL) According to JIS D 8004

Definition:

$$PL = 100 - 1{,}15 \cdot R_A [\%] \tag{3}$$

The corresponding effective sampling length is ~380 mm.

$$R_A = \frac{R_P}{R_S} \cdot 100 \tag{4}$$

R_P … reflectometer value of the sample

R_S … reflectometer value of a standard white value (for example magnesium oxide)

R_A … absolute brightness of the sample (absolute radiance factor)

Only at R_A = 87 % for unblackened filter paper the measured value of a "clean" exhaust gas (no soot) is at PL = 0.

JIS D 8004 defines, however, R_A = 90 ± 1.5 % for the unblackened filter paper.

Usually the measuring instrument is calibrated with gray standard discs (R_A = 43.5 % and therefore PL = 50 %).

Due brightness variations of gray standard discs and unblackened filter paper, negative measured values (-2 % to … -10 %) may occur in practise for "clean" exhaust gas.

Remark:

The filter blackening is absolute; this means it is determined by an independent standard. Due to this fact the measured value of a hardly blackened sample becomes strongly dependent on the brightness of the unblackened filter paper.

For a rough comparison SZ_B and FSN can be multiplied (for 405 mm effective sampling length) with 10 in order to find a percentage value for the pollution level (PL). Since the measured value depends also on the brightness of the unblackened paper – with this absolute calibrated procedure – in the practice, however, the following factors have to be considered [CHR-94]:

If an AVL Smoke Meter is to be compared with a device that shows the results as pollution level, the measured value of the AVL Smoke Meter should be converted in following way:

1. Find the "offset" of the absolute optical evaluation of the comparative instrument.

   Offset = measurement value PL in % at unblackened filter paper

2. Calculate the equivalent pollution level (PL_{equi}) of the AVL Smoke Meter as follows:

$$PL_{equi}\,[\%] = FSN \times \frac{100 - Offset}{10} + Offset \tag{5}$$

Example:

From an offset = -6 % follows:

$$PL_{equi}\,[\%] = FSN \times \frac{100 + 6}{10} - 6 \tag{6}$$

Relationship between FSN and PL with an offset of -6 %

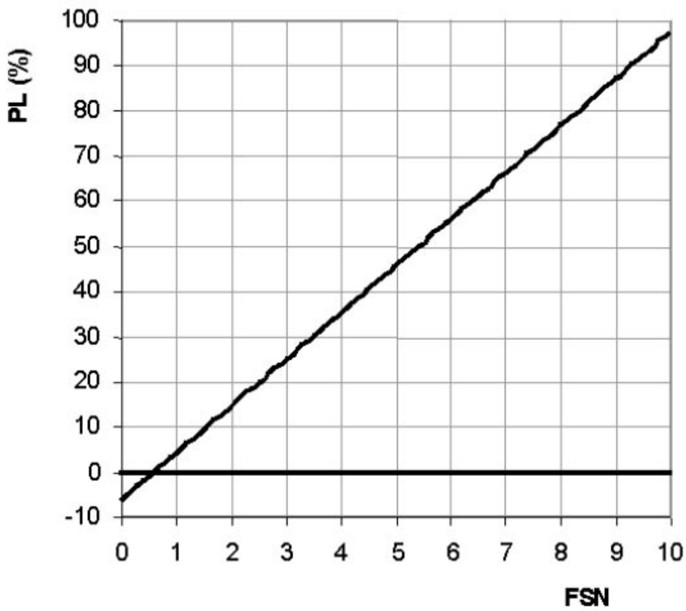


Fig. 4

2.3 AVL Smoke Meter 409

The AVL Smoke Meter 409 arose by improvement of the wide spread Bosch hand pump. Due to this the AVL 409 shows the "blackening number according to Bosch" as a non-linear measure of the soot content in the exhaust gas. Between the smoke value (SZ_B) and the soot content in gram/cubic meter an almost logarithmic connection exists.

The AVL 409 instrument consists of the sampling- and measuring instrument "409D2 Sampler", the electronic controlling and evaluating-device "4010-A01 Smoke Meter" and the exhaust gas sampling probe along with polyvinyl chloride sampling line. Sampling with the reciprocating pump, filter paper transport and the paper fastening device "sampler 409D2" the instrument acted pneumatically and was controlled by the evaluation device "4010-A01" and an engine driven cam controller mechanism with magnetic valves [AVL-87].

Mechanics on the inside of the AVL Smoke Meter 409

Fig. 5

The principle of sampling through a reciprocating pump is outlined.

2.4 AVL Smoke Meter 415

The AVL Smoke Meter 415 was developed as a succession device of the AVL 409 around the increasing demand for accuracy and repeatability of measurements with low smoke values and to minimize the maintenance efforts.

The essential constructive change formed a new sampling technique: The traditional reciprocating pump was replaced by a continuously sampling, electronically operated diaphragm pump. This allows free variation of the sample quantity (and sampling time) and therefore also the measurement of very small soot concentrations. Recording of the test gas pressure and temperature builds the basis for the comparison of results to standards. According to ISO 10054 [ISO-98] the measured value is defined in FSN (Filter Smoke Number) and no longer as SZ_B (Bosch blackening number). The FSN is, unlike the $SZ_{B,}$ defined, among other things, by the thermodynamic state of the test gas with 25 °C and 1 bar for the sampled volume [CHR-93]. The sampling speed is constant in this case and it is possible to determine correct, reproducible integral values for transient engine applications.

Further differences to AVL 409 are the operation without compressed air, the possibility of multiple measurements with automatic averaging and the "Auto Range" feature [AVL-98].

The option two channel measurement provides the connection of a second sampling line and increases the efficiency of the Smoke Meter.

AVL Smoke Meter 415 – sampling principle by using a diaphragm pump

Fig. 6

2.5 AVL Smoke Meter 415S

The AVL Smoke Meter 415S operates with the same principles as the already described AVL Smoke Meter 415. The improvements in comparison to the AVL 415 concern the optionally integrated heating of the device and sampling system as well as a raised filter paper capacity including the recoiling system for the filter paper, which essentially increases the number of tests that can be performed with one roll of filter paper.

A further difference to AVL 415 is based in the improved operability due to the modified device design (for example replacement of the filter paper role).

As a new sampling line material Viton replaces the silicone material used for the AVL 415.

The protection against intrusion of solid foreign bodies and water is guaranteed in the AVL Smoke Meter 415S according to class IP34.

The control of the instrument can be performed via the operating terminal interface of a test bed computer or via the Instrument Controller AVL 4210 [AVL-02].

AVL Smoke Meter 415S, mechanics – sampling via a diaphragm pump (principle)

Fig. 7

3 Factors Influencing the Measurement Value

3.1 General Guidelines for Smoke Value Measurements

3.1.1 Choice of Sampled Volume

Fundamentally the sampled volume is supposed to be chosen in a way, that the value of the resulting paper blackening is not below PB = 0.5 and not above PB = 8. A PB range of > 1 and < 5 is recommended. In the "Auto Range" mode the sampled volume is chosen for a paper blackening of PB ~2.5.

If the expected FSN level is near FSN > 1, the device should be operated with a sampled volume of 1 liter (corresponds to a sampling time preselection of 6 s).

To measure very high soot concentrations (FSN > 6) the sampled volume must be reduced down to $^{1}/_{3}$ liters.

With smaller load levels (FSN < 1) the sampled volume has to be increased in a way that the paper blackening is approximately 2.5.

Investigations on the device variance showed that a sampled volume and/or sampling time increase affects the variance positively. A comparison between heated and unheated smoke meters show increasing measurement value differences at increasing sampled volumes.

The reason therefore is the condensate loss inclination rising with advancing sampling time which can be compensated by heating of the sampling system and the device.

Details on this can be found in “Setting the Optimal Sampling Time” on page 44.

The connection between suction time and sampled volumes is in given by following relation:

6 sec of sampling time correspond to about 1 liter sampled volume

This connection partly depends on the measured value itself, the particle kind and the particle composition.

3.1.2 Exhaust Gas Sampling

The sampling probe is supposed to be mounted in a straight section of the exhaust pipe. Curves in the exhaust pipe should not occur in a minimum distance of 6 times the tube diameter and the triple diameter's to the sampling probe.

The sampling probes and sampling line should be applied ascending (condensate backflow is supposed to be possible).

The sampling line is supposed to be mounted with as few unnecessary bends as possible. An exhaust gas connection as straight as possible from the sampling point to the device prevents larger deposits.

The corresponding sampling line for the device types always has to be used.

The sampling lines are supposed to be as short as possible and when doing comparison measurements (also two channel measurements) of the same length. With a long sampling line (>2 m) heated lines are recommended.

In order to use the heating function of the sampling lines and the device in the most efficient way, it should be noted that also the exhaust gas and the components in front of the heated sampling system (sampling probe, standard sampling line connection) should have a temperature of at least 70 °C.

Even if the AVL 415S Smoke Meter is not in operation, by the time condensate forms inside and particles deposit in the sampling probe and lines. Therefore the probe should be dismantled from the exhaust pipe, when no tests are performed for a longer period of time.

The sampling lines should be purged with compressed air on a regular basis in order to remove condensate and particle deposits (use cleaned, oil and condensate-free compressed air). For this purpose see section 11.3 of the Operating Manual.

3.1.3 Filter Paper

In the AVL 415S Smoke Meter instrument AVL S&S type 597LA standard paper is used.

The filter paper used in smoke meters consists of cotton fibers whose state is influenced by hardly controllable factors such as climatic conditions during the growth of the cotton plant. Because of this AVL standard paper passes tight quality controls and only those paper charges that correspond to the narrow specifications are accepted.

The segregation-efficiency of the AVL standard paper for diesel particles at the flow rate applied in the smoke meter is considered in the correlation curve paper blackening versus filter loading for the determination of the Filter Smoke Number. If filter paper is used which does not correspond to the AVL standard deviations of the measured value have to be expected.

AVL paper type 597LA is specified with 50 % of segregation degrees for normparticle DOP (DOP = Dioctylphtalate) for 0.3 µm (DOP. artificial particles with a homogeneous size of 0.3 µm). The filter effect for soot particles is, however, practically 95 % (also for particle sizes of 100 nm and smaller). This means, that even particles that are smaller than the spaces between the fibers of the paper is filtered.

Important: The quality of the filter paper has a considerable influence on the measured FSN values. Only when using original filter paper the results of the device can be guaranteed to be right!

Further warehouse conditions can influence certain filter paper parameters during time.

Store the filter paper in a contamination-free environment, that is protected against chemical influences, light, radiation, heat, cold, moisture, dust etc.

Recommendations:

- Temperatures in the range of 15 to 28 °C.
- A relative air humidity in the range of 30 to 65 % and
- The avoidance of sudden temperature and moisture variations.

Under these conditions the filter paper is sufficiently protected in its original packing and will last for about 10 years.

According to differing environmental conditions the filter paper has to be stored in corresponding containers, as for example:

- Densely sealing metal, glass or plastic containers,
- Glued or welded plastic or metal foils or plastic-coated paper.

Make sure, when choosing plastics, that chemical influences can be avoided!

For the transportation and short storage (up to 14 days) the temperature and humidity conditions outside, when packed in its original packing, may be outside of the specifications. However, condensation moisture and wetness must be avoided. While handling with the filter paper, pollution of any kind should/must be avoided.

3.1.4 Maintenance

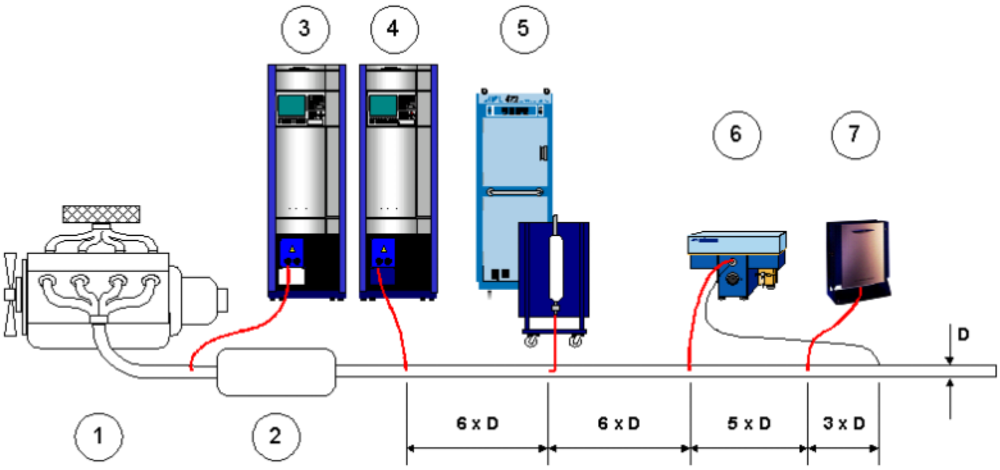
To guarantee a high accuracy and repeatability of the instrument, regular maintenance of the device is necessary. A more precise explanation can be found in chapter 11 of the Operating Manuals of the respective device [AVL-98], [AVL-02]. At this place only the most important measures are supposed to be called into memory:

- Regular calibration of the sampled volume
- Regular leak check by performing external and internal leakage tests
- Control and cleaning of the optical measurement head
- Regular check of the soot blackening at the filter paper (diameter, homogeneousness and edges of the blackened area)
- Regular cleaning or preferably replacement of sampling probe and sampling lines
- Regular exchange of the internal pre-filters of the instrument
- Regular lubrication of all moving parts of the filter paper transport and clamping device

3.2 Recommended Test Setup

Fig. 8 on page 27 shows a recommendation on how to locate the sample probes of different exhaust gas analyzers into the exhaust pipe of an engine. For certification, attention must be paid to laws and regulations. The requirements of the individual systems must be considered from the documentation.

Recommended order of sample probe locations of different exhaust gas analyzers in the exhaust pipe



1 Engine
2 Catalyst
3 Analysis of exhaust gases plant pre-cat.
4 Analysis of exhaust gases plant post-cat.
5 Partial flow dilution tunnel for the gravimetric particle measurement
6 Opacity measuring instrument
7 Smoke Meter

Fig. 8

The measurements of the different instruments are supposed to be coordinated in a way that no measurement is carried out while another device is being purged which is mounted upstreams in the exhaust gas line.

Devices that lead back the entire or even a part of their sample volume, should do so downstreams all other sampling points.

During analysis of influencing factors onto a considered parameter a reference must be available for comparison. Since combustion engines (in this case used for the exhaust gas generation) already show variations, it is reasonable to capture the basis through the use of a reference device with constant settings. The influence of a parameter variation can in this case be seen as the difference between to the test- and the reference device.

Important: From our experience in particle measurement we noticed that results measured on engines in different laboratories can show deviations up to 15 % [STE-89].

3.3 Influence of Exhaust Gas Humidity, Device- and Sampling Temperature

3.3.1 Moisture Influence

Definition and explanation of basic terms:

Relative Humidity [%]

The state of (unsaturated) moist air is defined by parameters such as temperature, pressure and a variable that describes the vapor content of the air (or of the sample gas).

A defined volume of moist air at a certain temperature can only absorb a certain amount of water vapor. If this amount is exceeded, water turns out as condensate (for example unheated sampling line, when its state is under the point of condensation of the exhaust gas → condensate falls out → the particles are held partly in the line and do not reach the filter paper → measured value is smaller).

- 0 % relative humidity means dry air.
- At 100 % of relative humidity the maximum vapor content is reached (more water can not be absorbed and water begins to fall out).

Definition [BAE-92]: Relative humidity is defined as the ratio of the absolute humidity to its maximum value at the prevalent temperature (T).

The relative humidity φ is also indicated as a ratio between the partial pressure of the water vapor p_W and the saturation pressure of the water vapor p_{Ws}.

$$\varphi = \frac{p_W(T)}{p_{W_s}(T)} \qquad (7)$$

If one cools off unsaturated moist air, p_W remains constant, until the point of condensation is reached. At the same time the saturation pressure of p_{Ws} is reduced, dependent on the air temperature.

Humidity Degree or Absolute Humidity g_{H_2O}/kg_{air} **or** g_{H_2O}/m^3_{air}

The relative humidity was defined as a partial pressure ratio according to equation (7). The humidity degree is indicated as a mass ratio in equation (8).

$$x_W = \frac{m_W}{m_L} \tag{8}$$

m_W indicates the – dependent on the respective state (p, T) – variable water vapor mass. It is by definition based on the normally constant mass of dry air (m_L).

The range of values reaches from $x_W = 0$ for dry air to $x_W \rightarrow \infty$ for pure water.

During the investigation the relative humidity and the relevant air temperatures were measured in the device interior in the exhaust gas line after the filter paper. From both values the humidity degree can be determined with the equation [PIS-89]:

$$x_W = 0.622 \frac{p_{W_s}(T)}{\frac{p}{\varphi} - p_{W_s}(T)} \text{ [kg H}_2\text{O/ kg dry air]} \tag{9}$$

The greatest water vapor loading x_{Ws} for satisfied moist air with j = 1 (is equivalent to 100 % relative humidity). From equation "(9)" on page 29 results:

$$x_{W_s}(T, p) = 0.622 \frac{p_{W_s}(T)}{p - p_{W_s}(T)} \text{ [kg H}_2\text{O/ kg dry air]} \tag{10}$$

This value depends on the temperature T and the total pressure p.

Because xW > x_{Ws} is usually not possible, there is a condensate stage, the water vapor content when in the exhaust gas [kg H_2O/ kg dry exhaust gas] is larger than this value x_{Ws}.

The connection between the relative humidity and the absolute FSN difference above the test device temperature is shown in Fig. 9 on page 32, Fig. 10 on page 33 and Fig. 11 on page 34.

3.3.2 Temperature Influence

The temperature influence was investigated on an arrangement of two devices in synchronous measurements:

- Reference device
  - AVL 415S
  - Sampling line and measuring instrument kept on 65 °C
  - Sampling line length = 1 m
- Test device
  - AVL 415S
  - Temperature of sampling line and measuring instrument variable
  - Sampling line length = 1 m

The following table shows a survey of the examined and FSN levels and sampling times (see Fig. 9 on page 32, Fig. 10 on page 33 and Fig. 11 on page 34).

Variation of sampling times at different FSN levels

FSN-level	Sampling Time [s]				
0.4 FSN	(6)	(12)	18	24	30
0.8 FSN	6	12	18	24	30
2 FSN	6	12	18		

Tab. 1

Fig. 9 on page 32, Fig. 11 on page 34 and Fig. 10 on page 33 show the absolute FSN-differences between the test device and the reference device that was kept on constant 65 °C.

FSN difference = measured value of test device – measured value of reference device (11)

If the FSN difference is negative, that means that the test device indicates less than the reference device.

The test device was thermally conditioned departing from 75 °C to 65 °C (same temperature as the reference device) in steps of 10 °C to 35 °C. Next to the variation of device and sampling temperature also the influence of the sampling time (the sampled volume) is shown in the diagrams.

The measured value differences are greatest when the test device is unheated. With the FSN levels 0.4 and 0.8 – the water content in the exhaust gas is very small at these FSN – significant differences do not occur before a device temperature below 45 °C. With a FSN level of 2 and high sampling time (30 s corresponds to 5 l of sampled volume) a noticeable measure value difference is shown already at temperatures under 55 °C.

The absolute humidity in the exhaust gas of the test volume has about doubled from FSN 0.4 on to FSN 0.8 and also from FSN 0.8 to FSN 2.

The graph of the relative humidity shows the states in the device depending on the temperature. With low device temperatures the relative humidity is higher in the device than at instruments conventionally heated (65 °C). The probability, that water trops out in parts of the gas path (in the line and/or in the device interior), is of course higher. The decreasing FSN level correlates to the raising humidity values. This relation is caused by the absorptive effect of the condensate – per test performed – less particles reach the measurement point.

Under standard conditions (exhaust gas back pressure <500 mbar) the point of condensation of water is below 55 °C for diesel exhaust gases. On one hand a heating of the sampling system and the device at 65 °C guarantees a positive temperature effect on the measuring accuracy and reduces on the other hand the thermal stress of the Smoke Meter components. Since the humidity was measured after the filter paper it must be reckoned, that with measured values above 50 % humidity, condensate already occurs at local cold spots in the sampling path.

Absolute FSN difference in dependence of the device and sampling temperature and the relative humidity with a FSN level of ~0.4

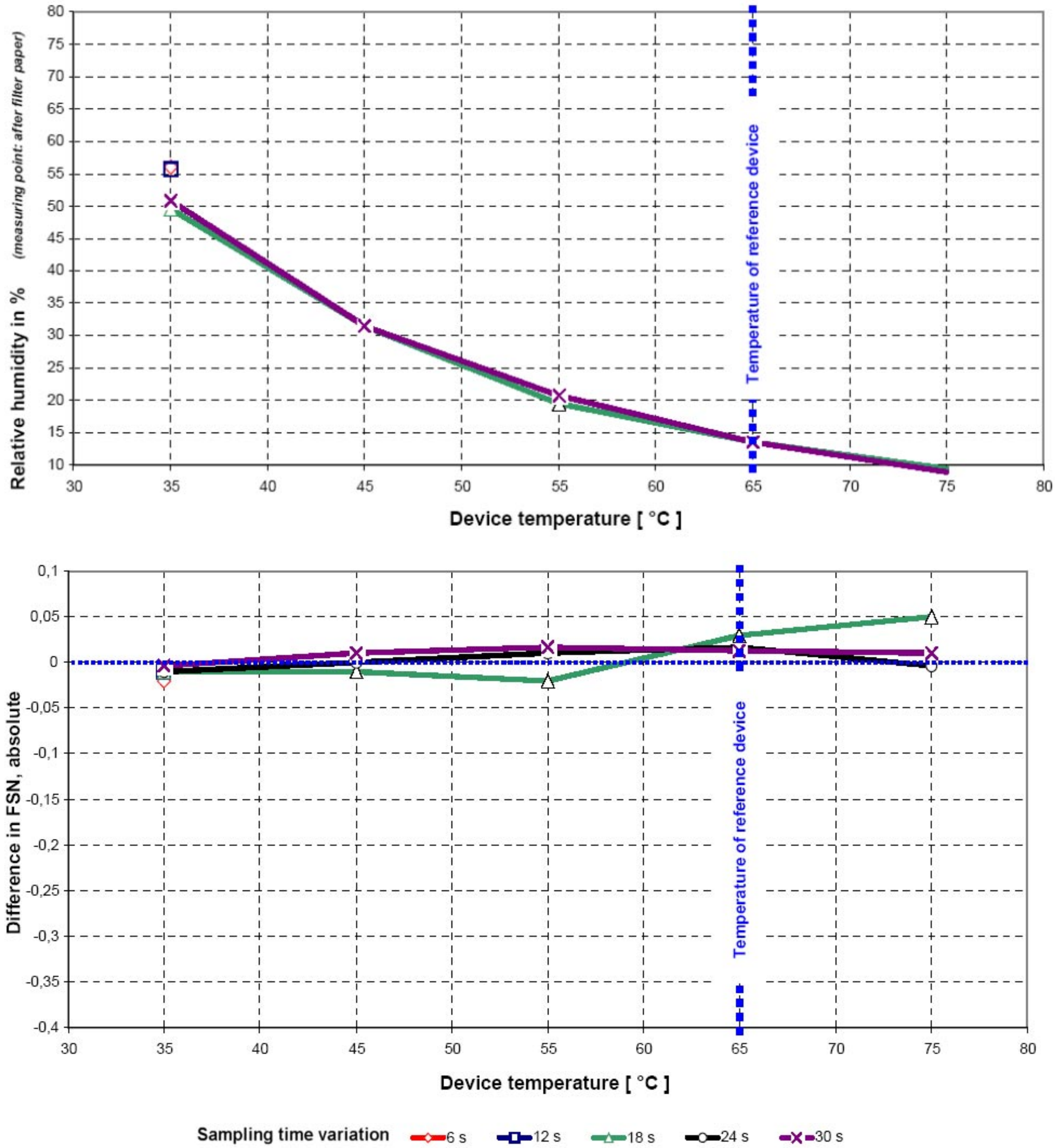


Fig. 9

A temperature varied test device was compared to a reference device with 65 °C. The abscissa is scaled with the test device temperature.

Absolute FSN difference in dependence of the device and sampling temperature and the relative humidity with a FSN level of ~0.8

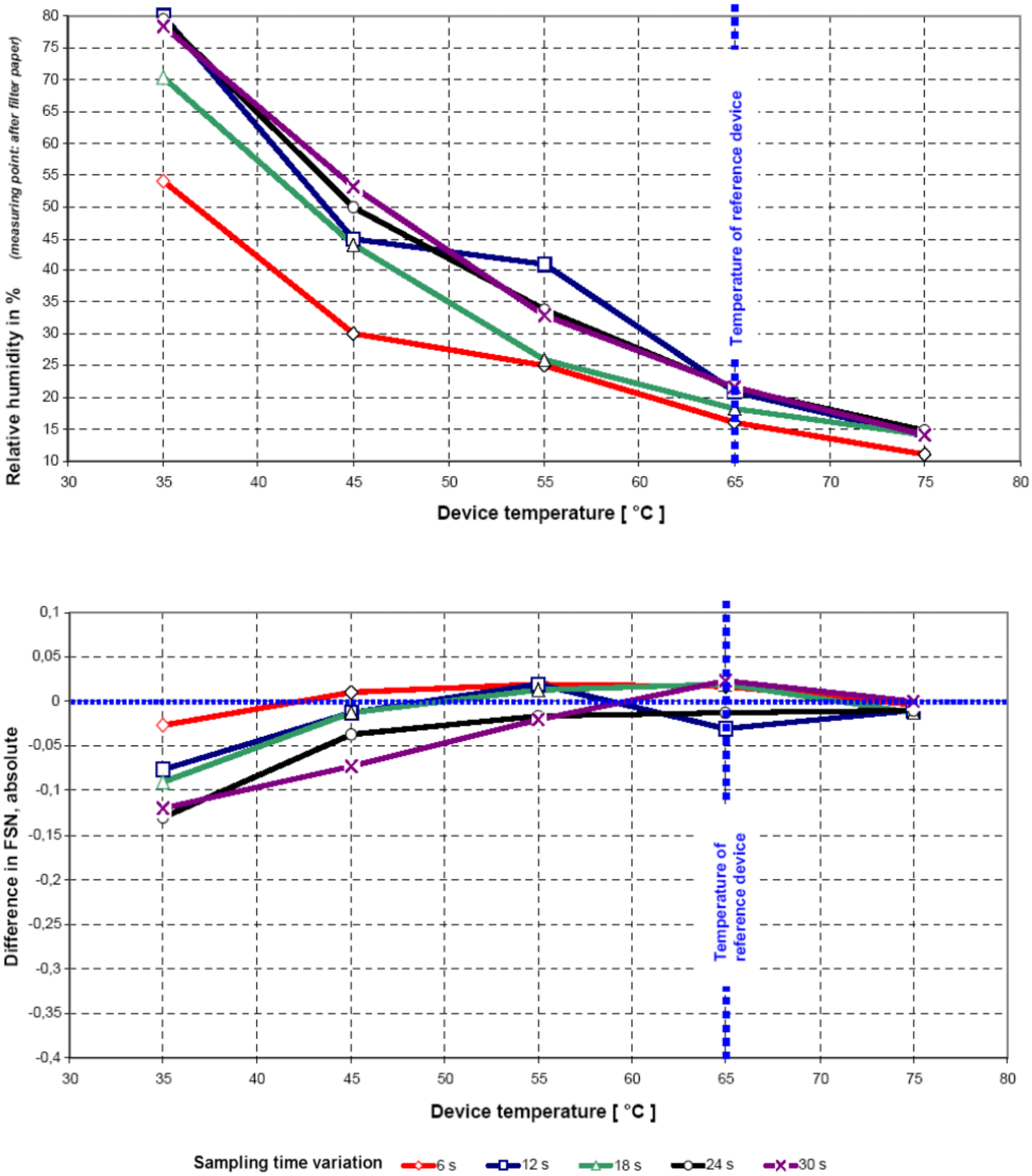


Fig. 10

A temperature varied test device was compared to a reference device with 65 °C. The abscissa is scaled with the test device temperature.

Absolute FSN difference in dependence of the device and sampling temperature and the relative humidity with a FSN level on ~2

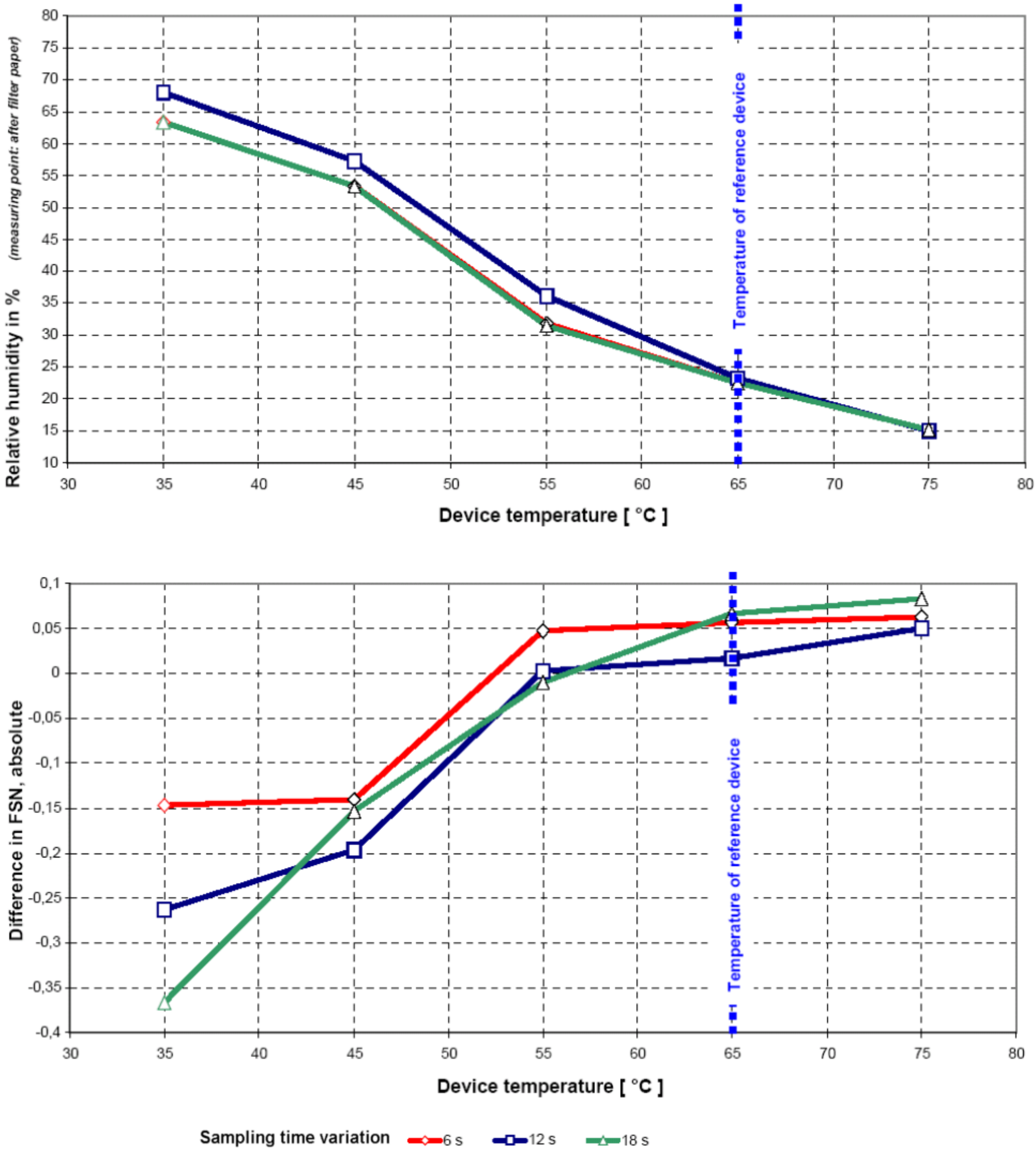


Fig. 11

A temperature varied test device was compared to a reference device with 65 °C. The abscissa is scaled with the test device temperature.

3.4 Influence of the Sampling Technique

The length of the sampling line, when unheated, showed the greatest influence on the result.

3.4.1 Length and Material of the Sampling Line

The results of the sampling line length influence with an unheated sampling system were found in a comparison measurement with an unheated AVL 415 and an unheated AVL 415S.

Different sampling situations (Fig. 12 on page 36)

	Test device AVL 415, unheated	**Reference device AVL 415S, unheated**
	Sampling line	
1) 2 m Silicone / 1 m Silicone	2 m Silicone	1 m Silicone
2) 2 m Viton / 1 m Silicone	2 m Viton	1 m Silicone
3) 1 m Silicone / 1 m Silicone	1 m Silicone	1 m Silicone
4) 1 m Viton / 1 m Silicone	1 m Viton	1 m Silicone

Tab. 2

Bars 1) and 2) show the influence of 1 m difference in length. The deviation when using different sampling line materials was below the repeatability limit of the instruments (this means no material influence has to be observed).

Variant 3) was measured, in order to determine the device deviation (for both devices with the same sampling line: 1 m of Silicone). Here also bars 3) and 4) show no noteworthy difference concerning the material choice.

From Fig. 12 on page 36 it becomes clear, that a length difference of the sampling line of 1 m already causes a significant reduction (4 % at 2 FSN) of soot particles that reach the measuring point. Due to this fact, it is recommended to use short sampling lines, to reduce the amount of soot deposits in the sampling lines.

Absolute FSN difference with a variable line length in an unheated state.

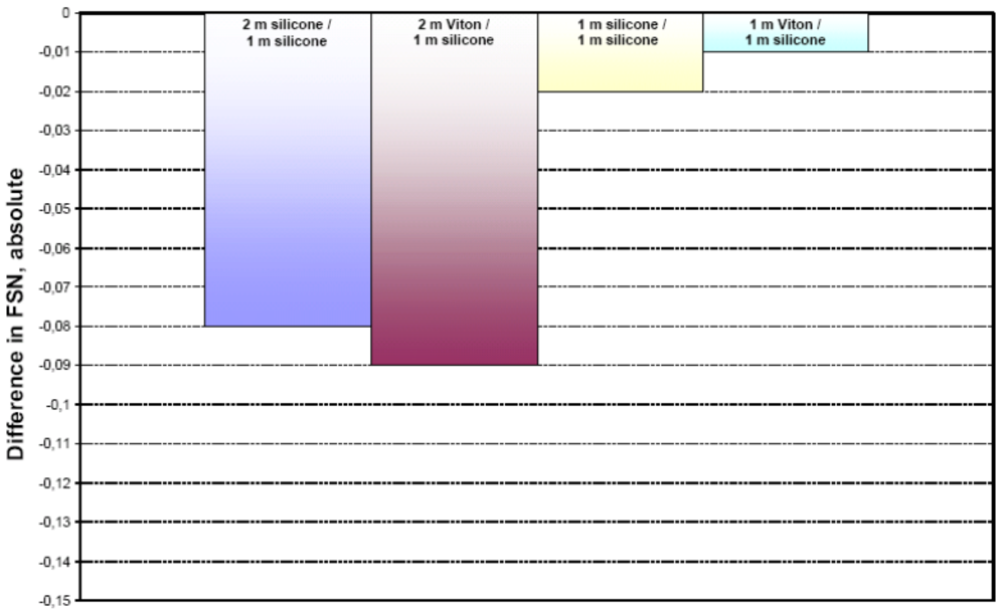


Fig. 12

From the picture no appreciable hose material influence can be seen (Viton vs. Silicone). An extension of the sampling lines from 1 m to 2 m can cause, when unheated, the deviation shown at FSN level by ~2. The two right bars (1 m vs. 1 m) correspond in the order of magnitude to the device deviation.

4 Precision Measurements with Smoke Values < 0.5 FSN

4.1 Necessary Test Conditions

4.1.1 Environment and Device Construction

- The ambient temperature is supposed to be as stable as possible.
- Probe, sampling line and measuring system are not supposed to be exposed to any vibrations.
- The ambient air may not be contaminated. The contamination should be smaller than 10 $^{\mu g}/_{m^3}$ (corresponds to approximately 0.001 FSN). This value corresponds to approximately $^{1}/_{5}$ of the currently permissible maximum immission limit (PM10 particulate material: 50 $^{\mu g}/_{m^3}$ day average).

4.1.2 Engine and Exhaust System

- Deposits of particles can occur in the whole exhaust system of an engine. These can cause, at low emissions, measurement artifacts.
- Magnitude of the effect: to approximately 1 % of the former measurement value in FSN for a duration of some minutes up to approximately 20 min. typically for the next 5 to 20 measurement values.
- The pressure pulsations of the exhaust gas are supposed to be as small as possible at the sampling point. Great pressure pulsations can increase the break away of particles which were deposited from former measurements on the tube walls (exhaust system, probe and sampling line) and cause a degradation of the repeatability.
- No exhaust gas is supposed to escape into the ambient air because it could contaminate it.

Important: Statistical or also systematical measurement value variabilities that come from the engine itself or from the exhaust tract can not be reduced through the measuring system or – with long sampling times – only rudimentarily changed.

If during a test run measurements are performed simultaneously before and after an exhaust gas after-treatment system such as a catalyst or particle filter, it is recommended to use two different instruments. This should prevent that remaining exhaust gases in the sampling system or in the measuring instrument with very different emission levels before and after the exhaust gas after-treatment system can influence measurement values behind the after-treatment system or falsify them.

4.1.3 Measuring System AVL 415S and Operation

Preparation:

- The measuring system must be serviced very well (see Operating Manual: maintenance chapter).
- The probe and the sampling line, possibly also the sampling head, the reflectometer head, the paper management of the AVL 415S is supposed to be cleaned if emissions with FSN >0.5 have been measured before. Cleaning of the hoses and probe should be done with pulsating compressed air, as described in the Operating Manual (chapter: maintenance / sampling probe and sampling lines).

Important: The compressed air used for purging must show "breathing air quality" and may not contain particles, water droplets or oil.

- The internal fine filters (see also Fig. 3 in the Operating Manual) are supposed to be in a "as good as new" state or are to be exchanged.
- If the device is off, but the engine is turned on, the probe of the instrument always has to be removed from the connection to the exhaust gas line. Otherwise the measuring system (probe, line, suction unit, reflectometer head, clamping lever …) must be cleaned before precision measurements. (see above).
- Standard configuration (device heated at standard temperature of 65 °C, sampling line with standard length and standard probe). Other line lengths and probes can be used, but influences on the repeatability and reproducibility of the measurement values are possible.
- The device must be a heated measuring system (heated sampling line and measuring device).
- Check internal protection filters (see Operating Manual, chapter maintenance / General and Fig. 3) and exchange them if they are colored gray or black. Exchange hoses if they are contaminated with particles.

Measurement:

- The instrument must be continuously heated.
- Only correctly stored filter paper type AVL SS 597LA may be used for the measurements.
- If a new filter paper roll is/was inserted, a thermal conditioning time of at least 30 min must be kept for paper and device to adapt.
- The automatic purging is supposed to be carried out.
- Approximately 5 to 10 pre measurements with sampling times of approximately 5 to 10 s are recommended in order to avoid the biggest offsets if detailed cleaning is not supposed to be/or can't be done.
- It should – if possible – be measured in ranges with a paper blackening of (PB) 2 to 5, in any case however PB >1 and PB < 6.
- The used sampling times are supposed to be longer than 10 s.
- The "Auto Range" functions can be used as long as the paper blackening does not become smaller than 1. For very small soot concentrations the parameterization of the maximum sampled volume of the "Auto Range" function is editable. The "Auto Range" default setting of 5 liters corresponds in about a maximum sampling time of 30 s.
- If automatic test cycles with very different soot concentrations are supposed to be run (partly high and partly very low concentrations): perform forced purging between the test modes.

4.2 Zero Point Accuracy

4.2.1 Dependency on the Sampling Length

With the following formalisms or graph it can be estimated, with which sampling length settings, which repeatability of the zero point signal can be achieved with very well cleaned systems. The values are valid for a cleaned, heated device when using the unit in clean air environment (ambient air contamination smaller than 3 $^{\mu g}/_{m^3}$ soot).

The zero point deviation (95 % confidence interval, 2 × standard deviation σ_N) is typically given by:

zero point deviation in FSN = $\pm$ 0.1 FSN/sampling time (12)

zero point deviation in $^{mg}/_{m^3}$ = ± 1.5 $^{mg}/_{m^3}$/sampling time (13)

(sampling time in s)

zero point repeatability (1σ value):
σ_N = zero point deviation/2 (14)

Zero point deviation (FSN) as a function of the sampling time

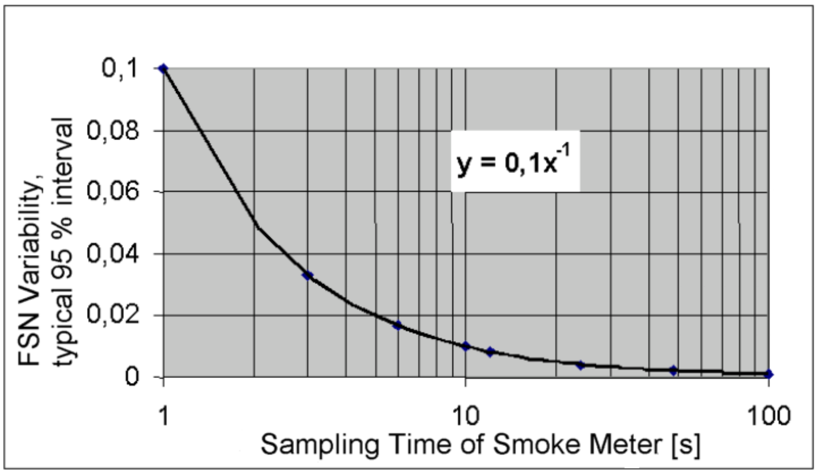


Fig. 13

Fig. 13 on page 40 shows 2 sigma, 95 % confidence interval of the typical, only in clean ambient air (contamination of the ambient air smaller 3 $^{\mu g}/_{m^3}$) measurable, zero point value deviation of the FSN value in dependence of the sampling times.

The graph or formulas “(12)” on page 40 to “(14)” on page 40 can be used to estimate the minimum sampling time for measurements where very small values are anticipated in order to achieve a required repeatability of the measurement values. The sampling time can be parameterized by 1 to 120 s in ranges from 1 s, the sampled volume from 50 ml to 20000 ml.

6 s of sampling time correspond to about a sampled volume of 1000 ml.

4.2.2 Checking of the Zero Point Accuracy

While working at engine test beds, or also during sampling, or due to environmental impurities, contaminations can occur in the sampling lines, ambient air etc. This chapter gives an overview on how the repeatability can be verified with the zero point, this means to see if the device is "clean" enough for measurements of very small values or if for the expected value the device needs to be cleaned respectively if the ambient air is contaminated with too many particles.

In “Setting the Optimal Sampling Time” on page 44 it will be shown (with an example) how the device parameters must be set for a "clean" system to keep the device deviation small.

Test Setup:

- Measuring system is at the correct temperature.
- Remove the probe from the probe connection and make sure that no impurities (Soot, dust, dirt …) from the floor or from other surfaces or from other gaseous origin may be sucked in.
- Measurements are carried out with ambient air. The ambient air should be "clean" <10 $^{\mu g}/_{m^3}$ particles.
- During this test the paper blackening is checked at different sampling times.
- Approximately 10 measurements with a sampling time of 1 to 3 s
- Approximately 10 measurements with a sampling time of approximately 50 to 100 s

Criteria/Analysis:

If the ambient air is not contaminated, and the measuring device (probe, line, sampling head) is clean enough and the device is working correctly, the deviation of the measured paper blackening is in general not dependent on the sampling time. It is symmetrical to the zero value PB = 0 and 95 % of all values can be found within an interval of PB = 0 ± 0.06 (see also example in Fig. 14 on page 42).

Typical zero point deviation with a clean, correctly operating system when no contamination of the ambient air is present

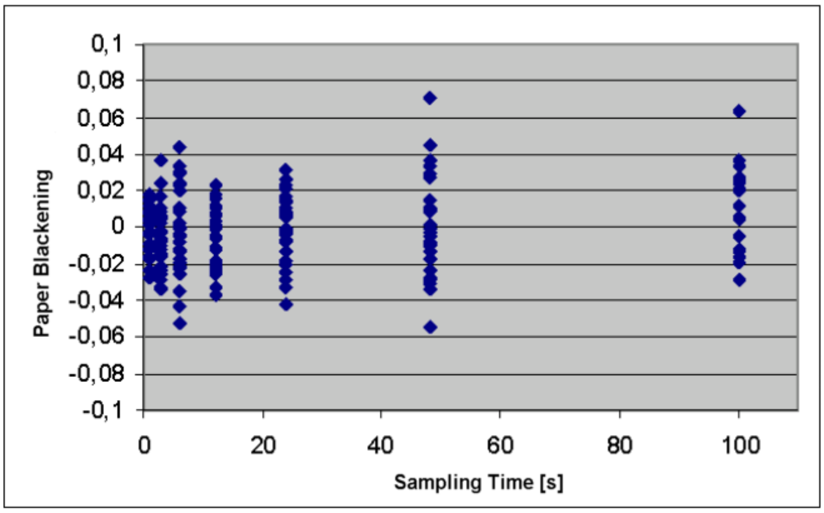


Fig. 14

- When the deviation of the paper blackening, in particular at the short sampling times (1 to <5 s) shows more positive than negative values, this indicates an impurity in probe, line or sampling head. Clean the system and carry out again approximately 10 to 30 measurements with short sampling times and observe the evaluation. The last 10 measurement values are supposed to be symmetrical around the zero point.
- When the deviation of the paper blackening is asymmetrically shifted for all sampling times to positive values and more than 10 % of these PB values are >0.06, then an adherent remaining contamination is present: Clean the probes and lines with clean compressed air.
- If the deviation of the paper blackening is statistical around the zero point, but more than 10 % of all values are outside of the range of ±0.06 or if systematic deviations to negative values show up, check the measuring system (clean, leakage test, paper, contaminations, change filter …).

- When the measurement value deviation at short and long sampling times is approximating in a range of ±0.06, or the measurement value deviation increases with longer sampling time and in addition an, with longer sampling times, increasing positive offset (average of all values) can be found, a contamination of the ambient air with particles is existing (see Fig. 15 on page 43).

Example of measurements with an ambient air contamination of 20 $^{\mu g}/_{m^3}$ due to a weather inversion. In addition small offsets due to particle deposits were seen in the first few measurement values.

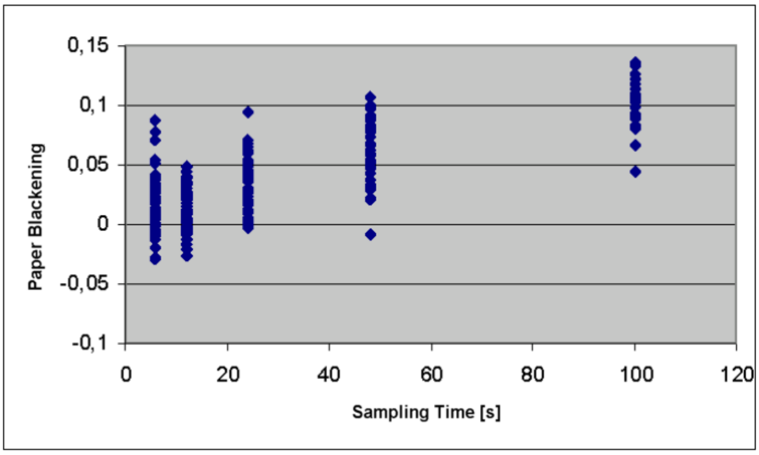


Fig. 15

In Fig. 15 on page 43 all paper blackenings are shifted asymmetrically to the zero line, and the middle paper blackening increases with increasing sampling time: The "clean" ambient air is contaminated. The contamination of the ambient air can show influences in this magnitude on the test results.

The first 5-10 measurement values at 3 s sampling time were clearly higher than the following measurement values: The cause was a small remaining contamination in the probe, line or reflectometer head since no cleaning with compressed air has been carried out.

4.3 Setting the Optimal Sampling Time

4.3.1 Paper Blackening with Soot Concentrations <10 $^{mg}/_{m^3}$ respectively FSN <=1 – Dependence on the Sampling Time

In order to measure low soot concentrations with high accuracy and repeatability, it is necessary, to examine the connection between sampling times, FSN (or concentrations in $^{mg}/_{m^3}$) and paper blackening. From these connections – see Fig. 16 on page 44 and Fig. 17 on page 45 – the suitable settings for optimal measurement results can be determined. This is also valid for those cases in which due to the test sequence attention must be paid to boundary conditions for example if the sampling time per sample is supposed to be restricted, or the measurement values can vary during the test over a large range.

Typical connection between sampling times, FSN and paper blackening.
Parameter: paper blackening (PB = 0.5 to 7)

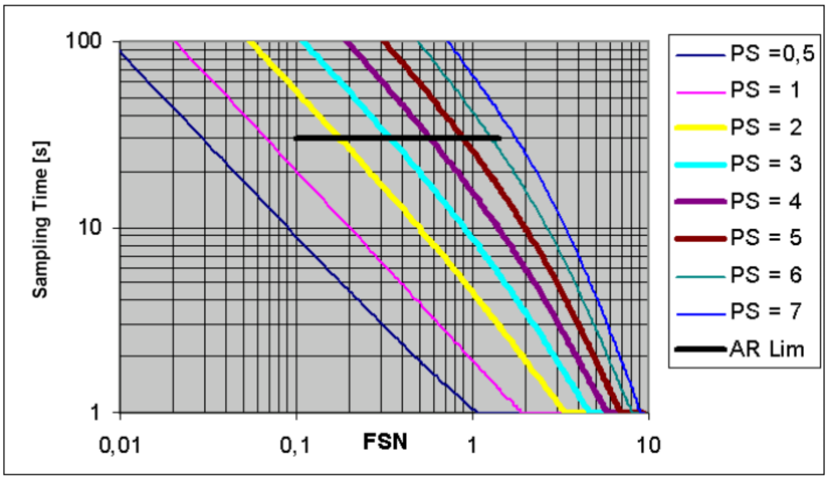


Fig. 16

Fig. 16 on page 44 shows – approximately – the connection between FSN and the sampling time at the Smoke Meter which is necessary in order to receive a certain paper blackening PB (represented as a parameter by 0.5 to 7). For example if a FSN = 0.1 should be obtained, a sampling time of 55 s is required to reach PB = 2. For such or smaller concentrations sampling times of >50 s are to be recommended.

The thick lines indicate the field for measurements in the "Auto Range", at which the black crossline represents the maximum sampling time set by default in the "Auto Range" mode. This maximum can be parameterized via the setting of the maximum sampled volume.

Fig. 17 on page 45 shows the equivalent dependence on the soot concentration in the exhaust gas.

Typical connection between sampling times, concentrations in $^{mg}/_{m^3}$ and paper blackening. Parameter: paper blackening (PB = 0.5 to 7)

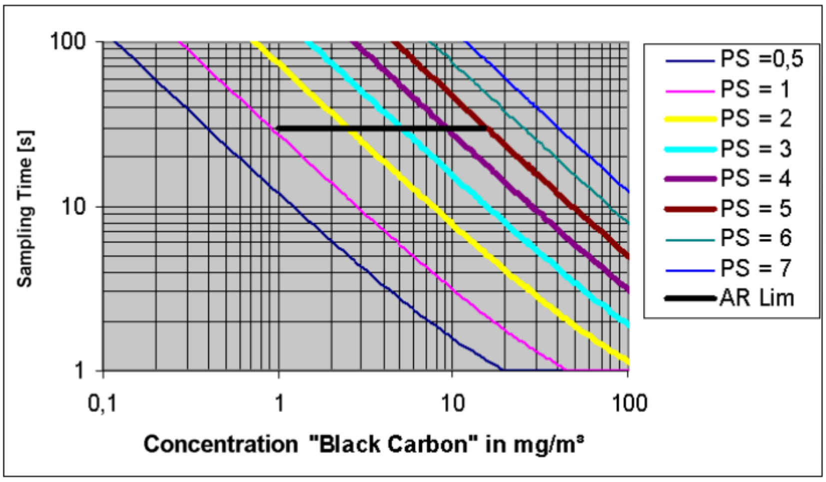


Fig. 17

4.3.2 Example for the Optimal Setting of the Sampling Time

Repeatability of the measurement value (as standard deviation)

The *device-conditional* repeatability of the measurement value ($1\sigma_{tot}$), the repeatability at absolute constant emission levels, is according to specification 3 % of the measurement value (MW), plus the (sampling length dependable) zero point repeatability σ_N. Since the repeatability of the zero point and the measurement value is statistically independent, this means:

$$\sigma_{\text{tot}} = \sqrt{(0.03 * MW)^2 + \sigma_N^2} \qquad (15)$$

Assumption:

At a test series mainly FSN 0.01 to 0.1 are expected, which are to be measured as precise as possible. But it is possible that for individual test points levels of FSN = 1 are reached. These can be significant for the total emissions.

Demand:

Necessary *device-conditional* repeatability of the measurement values:

±5 % of the measurement value or ±0.005 FSN (the higher value has to be used)

Notice that this demand can only be valid for completely stable emissions, which are not given in general. In order to eliminate the variability of the emissions, the experimental setup suggested in the chapter "comparison measurements" must be chosen.

Possibilities (from of Fig. 16 on page 44 and Fig. 13 on page 40):

- Measurement with "Auto Range", – pre-measurement – , at which the default boundary value for the maximum sampled volume must be changed to approximately 15 liters (corresponds to approximately 100 s of sampling time) in order to achieve good accuracy for all measurement values.

  According to Fig. 16 on page 44 and under the assumption that in "Auto Range" the system chooses its sampling time in a way that a PB ≈2.5 or smaller is reached, the duration per measurement value varies between approximately 6 s (at FSN = 1) and 100 s (at FSN <0.08).

  According to equation “(15)” on page 45 and Fig. 13 on page 40 respectively equation “(12)” on page 40 and “(14)” on page 40 the repeatability is then $\sigma_{tot:}$ always within the necessary boundaries (notice that Fig. 13 on page 40 shows the curve for $2\sigma_N$):

  For FSN = 1:

  $$\sigma_{tot} = \sqrt{(0.03)^2 + 0.009^2} = 0.032\text{, is smaller 5 \% of FSN = 1}$$

  For FSN = 0.1:

  $$\sigma_{tot} = \sqrt{(0.003)^2 + 0.0007^2} = 0.0031\text{, is smaller 5 \% of FSN = 0.1}$$

  For FSN = 0.01:

  $$\sigma_{tot} = \sqrt{(0.0003)^2 + 0.0005^2} < 0.001\text{, is smaller than FSN = 0.005}$$

  If for any reasons the sampling time is supposed to be as short as possible, it must be evaluated (see Figure 13), at which sampling time the required measurement value repeatability is still sufficient for all cases. The crucial range is located around FSN ≈0.1.

- The equation

  $$\sigma_{tot} = \sqrt{(0.003)^2 + \sigma_N^2} < 0.005\text{ (0.005 FSN = 5 \% of 0,1 FSN)}$$

  must be solved, from this a sampling time of >12.5 with σ_N <0.004 and with Fig. 13 on page 40 respectively from equation (12) – (half zero point deviation – only $1\sigma_N$!) results. Nicely the sampling time is to be set at a constant 15 s, respectively the sampled volume at 2.5 l. to guarantee a repeatability for small values (1 sigma, 63 % confidence interval) of FSN = 0.005.

- If a constant sampling time is supposed to be set and the measurement sequence allows to extend the time calculated in b) to improve the accuracy, it should be set to a maximum of 30 s (5 l of sampled volume), in order not to exceed a paper blackening of PB = 5 at FSN = 1 (see Fig. 16 on page 44).

It must be pointed out, not only for the given example, that after a sampling with FSN = 1 the following 5 to 15 measurement values can show a *hang-up* of approximately 1 % of the former measurement value, here at approximately FSN = 0.01, with an exponentially declining tendency.

5 Comparison Measurements

5.1 Methodics

5.1.1 General

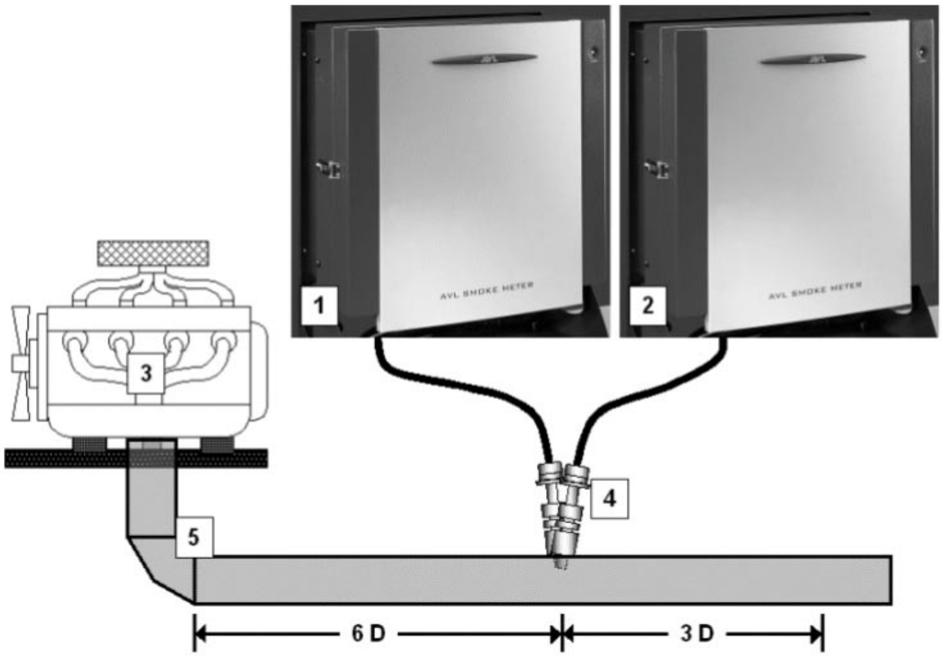
- If results of different devices are compared, same test conditions are fundamentally necessary.
- Devices perfectly maintained and calibrated (permanent controls)
- Comparing only heated or unheated devices to each other
- Using sampling lines of the same length
- Paying attention to recommended test setup (see Fig. 18 on page 50)
- Possible influence of the filter paper (Exchange the filter paper roles) has to be considered.
- Possible influence of the exhaust gas sampling connections (swap sampling probe and sampling lines)
- Using same respectively comparable operating modes (sampling times, sampled volumes, time of start and end of the measurement and of the purging cycle)
- Avoiding mutual influencing of the measurement (apply sampling probes in a plane of the cross section of the exhaust line)
- In the case of simultaneous metering synchronized measurements have to be carried out in order to avoid influences through the sample purging system. While one device is being purged the other device may not conduct any measurements because the measurement values may be influenced.
- Carry out comparison tests only with preset sampling times or sampled volumes, because otherwise the purging of a device – at the end of the test – can influence the measurement values of the second device.

Note: After closing the instrument's door a heating stage of about 15 min must be kept for the thermal stabilization of the heated smoke meter.

5.1.2 Testing Equipment Layout

In Fig. 18 on page 50 a suggestion for the layout of the testing equipment for comparison measurements is shown for investigations of the influencing parameters. The tests were performed at a stationary engine test bed. A modern 4-cylinder DI-diesel engine with an common rail injecting system was used for the test. The exhaust gas was led through a standard pre-catalytic converter and a muffler system. Several sampling probes were applied at the same place (without mutual influence) in increasing angles in the exhaust line. That way it was possible to compare two (in the examined case different parameterized) smoke meters synchronously to each other and to get cross comparisons.

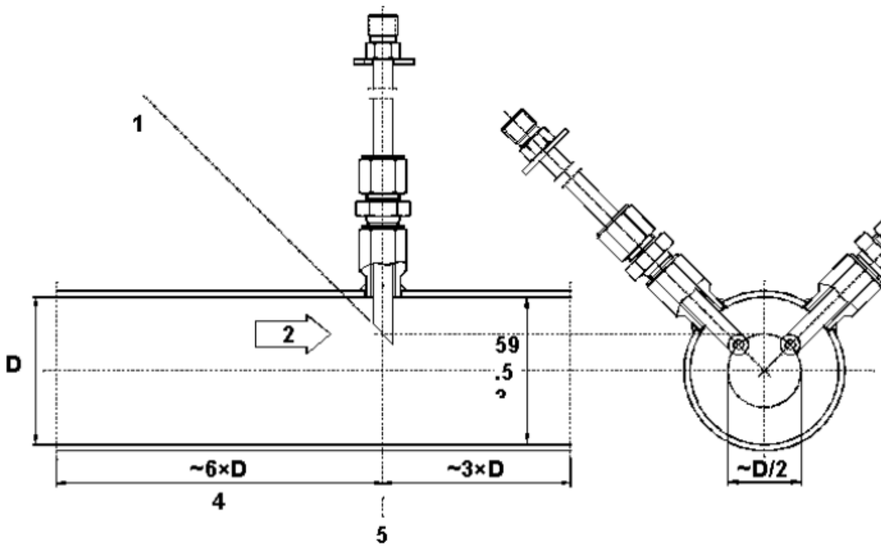
Suggestion of an experimental setup for a device comparison on influencing parameters, schematic view of the sampling point and alignment of the Smoke Meters



1 Reference device
2 Test device
3 Engine
4 Sampling probe
5 Exhaust line

Fig. 18

Detailed view of the application of the sampling probes in the exhaust line



1 45°-inclined against the flow direction
2 Flow direction
3 Sampling probe and sampling lines have to be mounted with upward incline (condensate backflow!)
4 Straight exhaust line section
5 Align sampling probes in one plane

Fig. 19

5.1.3 Recommendation for the Statistical Evaluation of Measured Data with Synchronous Arrangement Measurements of two Devices

The device deviation is an important measure for the judgement of the measurement accuracy. Within the framework of this investigation the deviation is indicated as standard deviation according to equation "(16)" on page 51.

$$s = \sqrt{\frac{n\sum x^2 - \left(\sum x\right)^2}{n(n-1)}} \tag{16}$$

s … Standard deviation taken from a spot sample (variation, uncertainty of measurement). The here calculated standard deviation is an accurate universal estimation of the standard deviation (for an infinite number of measurements).

n … Number of the measurements. The correct evaluation of standard deviations requires at least more than 10 sample results, recommended are >20 results. With too few measurement values the probable deviation of the obtained average value is to be corrected (with different deviation tables).

x … Value of the argument (measurement value difference between test and reference device)

In Fig. 20 on page 55 the measurement value differences of a heated AVL Smoke Meter 415S to a reference device are shown as deviation bands. This illustration shows a deviation of the measurement value differences. For the presented comparison the fraction of the device itself was determined according to the following considerations.

Assumption:

The measurement value M is a combination of the true physical value W and a random device influence G. Then the following can be defined for device 1 and 2:

$$M1 = W + G1 \tag{17}$$

$$M2 = W + G2 \tag{18}$$

The difference "D" of the two measurement values then is:

$$D = M1 - M2 = (W + G1) - (W + G2) = G1 - G2 \tag{19}$$

The standard uncertainty s is then:

$$s_D^2 = s_{G1}^2 + s_{G2}^2 \tag{20}$$

(The deviation of the two devices is uncorrelated)

After the introduction of the average device deviation

$$s_G^2 = \frac{s_{G1}^2 + s_{G2}^2}{2} \tag{21}$$

results:

$$s_D^2 = 2 \cdot s_G^2 \tag{22}$$

respectively

$$s_G = \frac{s_D}{\sqrt{2}} \tag{23}$$

In words:

"The device’s share on the entire deviation is $1/\sqrt{2}$ - times the deviation of the difference values" (shown as a transparent line in Fig. 20 on page 55, placed over the measurement points).

5.2 Definitions

The definitions and descriptions were taken from ISO 5725-1 [ISO5725].

5.2.1 Accuracy

The accuracy is a measure of the correlation of a measurement value with an "accepted reference value".

The trueness is a measure of the correlation of the average value from a great number of measurement values with an "accepted reference value".

An accepted reference value is a value accepted for a comparison, derived from:

- a scientifically well-founded theoretical or established value,
- a certified or approved value, of an international standard for example a calibration gas or a calibration standard (with certificate),
- a consensus or certifying-value, being based on experimental scientific research under surveillance of an expert group,
- the anticipated value of a measurable parameter, for example the average value of a specified number of measurements (if none of the above mentioned reference values are available).

5.2.2 Precision

Precision is a measure of the correlation of independent test results, which is obtained under agreed/defined conditions.

5.2.3 Repeatability

Repeatability is the accuracy, which is reached under the conditions for repeatability measurements.

Conditions for repeatability measurements are:

- an identical test method (points and general conditions)
- identical test objects (calibration gases, engine, …)
- the same laboratory
- the same operating personnel
- the use of the same test equipment (device)
- the execution of the tests within a short period of time

The standard deviation of these single measurements is the standard deviation under repeatability conditions.

Note: The correct evaluation of standard deviations requires at least more than 10 sample results, recommended are >20 sample results.

With only a few measurement values the probable deviation of the obtained average value is to be corrected with different deviation tables.

5.2.4 Reproducibility

Reproducibility is the accuracy, which is reached under the conditions for reproducibility measurements.

Conditions for the repeatability measurements are:

- an identical test method (points and general conditions)
- identical test objects (calibration gases, engine, …)
- different laboratories
- different operating personnel
- the use of different test equipment (devices, …)

The standard deviation of these measurements is the standard deviation under reproducibility conditions.

5.2.5 Comparison Measurements of Different Devices

These fall into the general term of reproducibility.

Important basic conditions for comparison measurements (for example probe, heating, sampling hose material and line length), that can influence the measurements and measurement values, must be defined in the protocol of the test method.

5.2.6 Reproducibility of the AVL 415S (Heated)

Fig. 20 on page 55 shows an example of a reproducibility measurement:

Test with:

- Two different AVL 415S devices
- Both devices heated, normally maintained (that means: devices were not cleaned especially before the test, were, however, in good maintained shape)
- Test on an engine, maintained in a normal way
- Sampling with 1 m of sampling line
- Sample probe and setup as in Fig. 18 on page 50 and Fig. 19 on page 51
- Synchronous measurements
- Sampled volume pre-selection: 1 liter sampled volume/sample
- Engine and measuring instruments fully heated up and stabilized.

Reproducibility test results of a synchronous comparison test at low measurement values around 0.2 FSN.

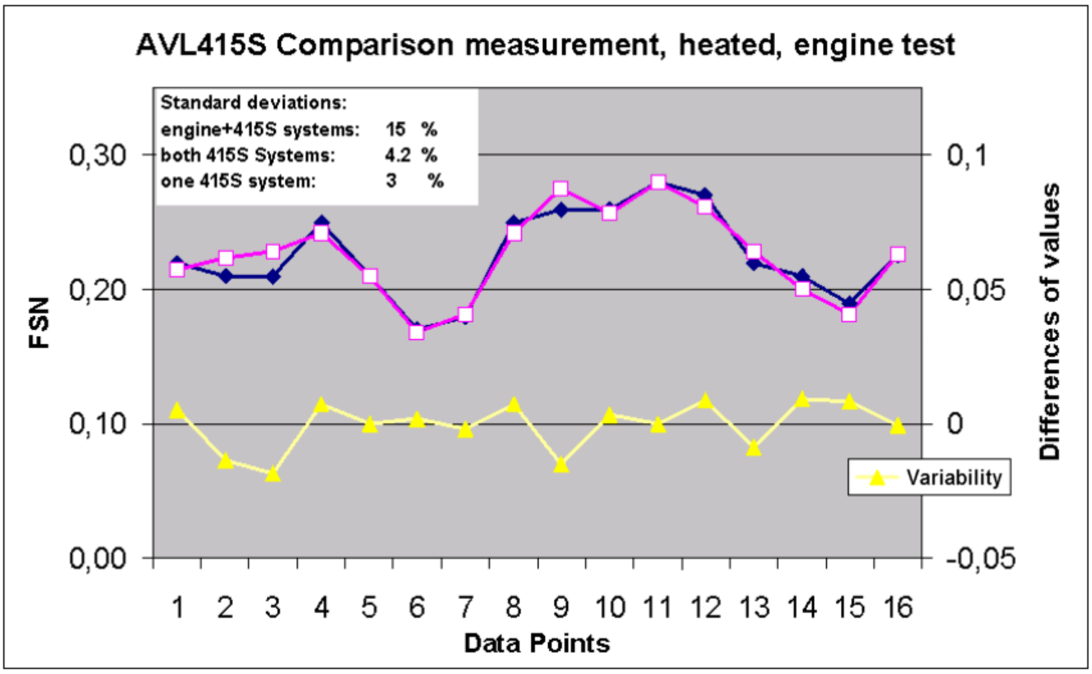


Fig. 20

The anticipated reproducibility depends on various factors such as the device settings, the test setup, the contamination of the measuring system and last but not least on the engine.

Results of these examples:

The average values were virtually identical for both devices:

0.23 FSN

Standard deviation of the measurement values of each device:

$\sigma_{Single\text{-}test}$: 0.034 FSN or approximately 15 % of the measurement value (same deviation for both devices within <0.001 FSN)

As can be seen in Fig. 20 on page 55, this variation was caused primarily only by the engine itself.

Standard deviation of the differences of the measurement values:

$\sigma_{(Differences)}$: 0.009 FSN or approximately 4 % of the measurement value

This is the combined standard deviation of both devices during this test.

Standard deviation which was caused by one device on the average:

$\sigma_{(1\ system)}$: 0.006 FSN (= 0.009/root (2)) or approximately 2.5 % of the measurement value

The anticipated value of the standard deviation of the reproducibility is (under the condition that the emission of the engine is better 1.5 % of the value and constant):

$\sigma = \pm$ (σ_N +6 % of the measurement value) = $\pm$ 0.023 FSN

σ_N from Fig. 13 on page 40 is 0.009 FSN for 1 liter sampled volume (corresponds to a sampling time approximately 6 s)

6 % of the measured average value = 0.014 FSN

The standard deviation of the individual tests lies indeed above these values, but the value is primarily dominated by the variability of the emission of the engine itself.

Since a parallel measurement with the two devices was carried out, the variability due to the engine can be calculated from the differences of the simultaneously measured FSN values:

The reproducibility of the devices themselves, with a $\sigma_{(Differences)}$ of 0.009 is smaller than the anticipated value, this means both devices measure completely equivalent and reproducible.

5.3 Comparison of Measurement Values AVL 409, AVL 415 and AVL 415S

5.3.1 Device Comparison AVL 409 / AVL 415

For comparison measurements with an AVL 409 attention must be paid, besides the above mentioned requirements, on the use of a 6 V lamp (changed in 1989 from 12 V to 6 V).

The deviations when comparing the AVL 409 to the unheated AVL 415 (in Fig. 21 on page 58) explain themselves to temperature and pressure influences, that are compensated at the AVL 415, mainly through the fact that the AVL 415 records the actual momentary sampled volume (throughput measuring pipe) along with the temperature and pressure and therefore they are included in the measurement, while the reciprocating pump with its suction effect (that also depends on the pressure situation at the sampling point) only fills the free sampled cylinder volume. The main influence derives from the fact that the aerodynamic resistance inclines at the filter paper with increasing particle loading and thereby worsens the volumetric efficiency in the sampling cylinder. Because of this at increased blackening (loading levels), less test gas can pass the filter paper and thus the indicated smoke value can turn out to be a lot smaller. [AVL-95].

Beside these different general conditions, other detectors, which also contribute to the deviations, are used for the reflectometer head of the AVL 409.

The relation between SZ (measured with AVL 409) and FSN (measured with AVL 415) shows the measurement value depending on the FSN level.

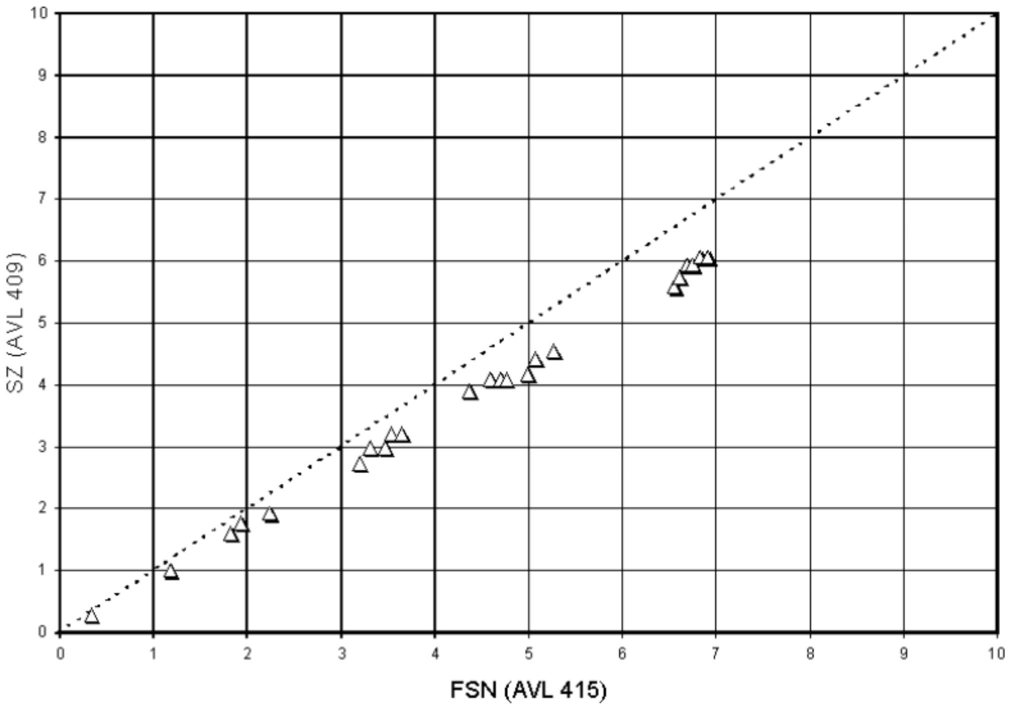


Fig. 21

5.3.2 Device Comparison AVL 415S (G001 Unheated)/ AVL 415S (G001 Heated)

With introduction of heated sampling systems and heated reflectometer head it was proved that substantial soot amounts deposit themselves in unheated systems. Up to a heating of all exhaust gas leading parts of 65 °C the amount of the soot deposited on the filter paper increases. The effect is in general >10 %.

This means, that in order to receive the same FSN value, it requires a a lot higher soot loading for unheated systems than for heated systems.

Comparison of soot loading heated/unheated for different FSN levels

FSN	$^{mg}/_{m^3}$ heated	$^{mg}/_{m^3}$ unheated	FSN	$^{mg}/_{m^3}$ heated	$^{mg}/_{m^3}$ unheated	FSN	$^{mg}/_{m^3}$ heated	$^{mg}/_{m^3}$ unheated
1	17.84	17.87	5.2	336	458	9.5	3908	6709
1.1	20.24	20.42	5.3	353	485	9.6	5261	9343
1.2	22.76	23.14	5.4	371	514	9.7	7655	14038
1.3	25.43	26.04	5.5	389	543	9.8	11840	22265
1.4	28.23	29.13	5.6	409	575	9.9	19027	36384
1.5	31.19	32.42	5.7	429	608	10	31127	60098

Tab. 3

Further details see also chapter "Measurement and calculation method of FSN" in the appendix of the Operating Manual.

In Fig. 22 on page 60 a-c a unheated AVL415 is compared, for different load levels (FSN levels), to an unheated and a heated AVL415S. From all smoke meters (AVL 415 and AVL 415S) the unheated AVL 415S shows the lowest measurement value level.

Measurement:

The devices to be compared (in each case 2 devices of the same type) were measured synchronously with a (third) reference device type (AVL 415S, heated). The dotted line in Fig. 22 on page 60 a-c indicates the FSN level of the reference device. Per series of measurements 15 single measurements were performed. Between the single measurements the pulsated purging was awaited until the next measurement was triggered.

The heated AVL 415S is a G001-device and uses the conversion formula of the AVL 415 ("unheated function").

Generally the following can be stated about comparison measurements:

Values obtained with an unheated Smoke Meter cannot be converted into values of a heated Smoke Meter (and vice versa) because the water vapor content of the exhaust gas and the ambient temperature of the unheated sampling line during the unheated measurement are usually not known due to condensed exhaust gases and their influence on the particle depositing in the sampling hose.

In case FSN values, that were measured with an unheated AVL Smoke Meter 415, are supposed to be compared with values of a Smoke Meter 415S, an unheated 415S is to be used. The same sampling probes and the same sampling lines (material, length) are supposed to be used as are used for the AVL Smoke Meter 415.

Absolute FSN difference for a comparison between the Smoke Meter models AVL 415S unheated / AVL 415 unheated / AVL 415S heated at a level of (a) ~0.4 FSN, (b) ~0.8 FSN and (c) ~2 FSN for an optimal sampling time

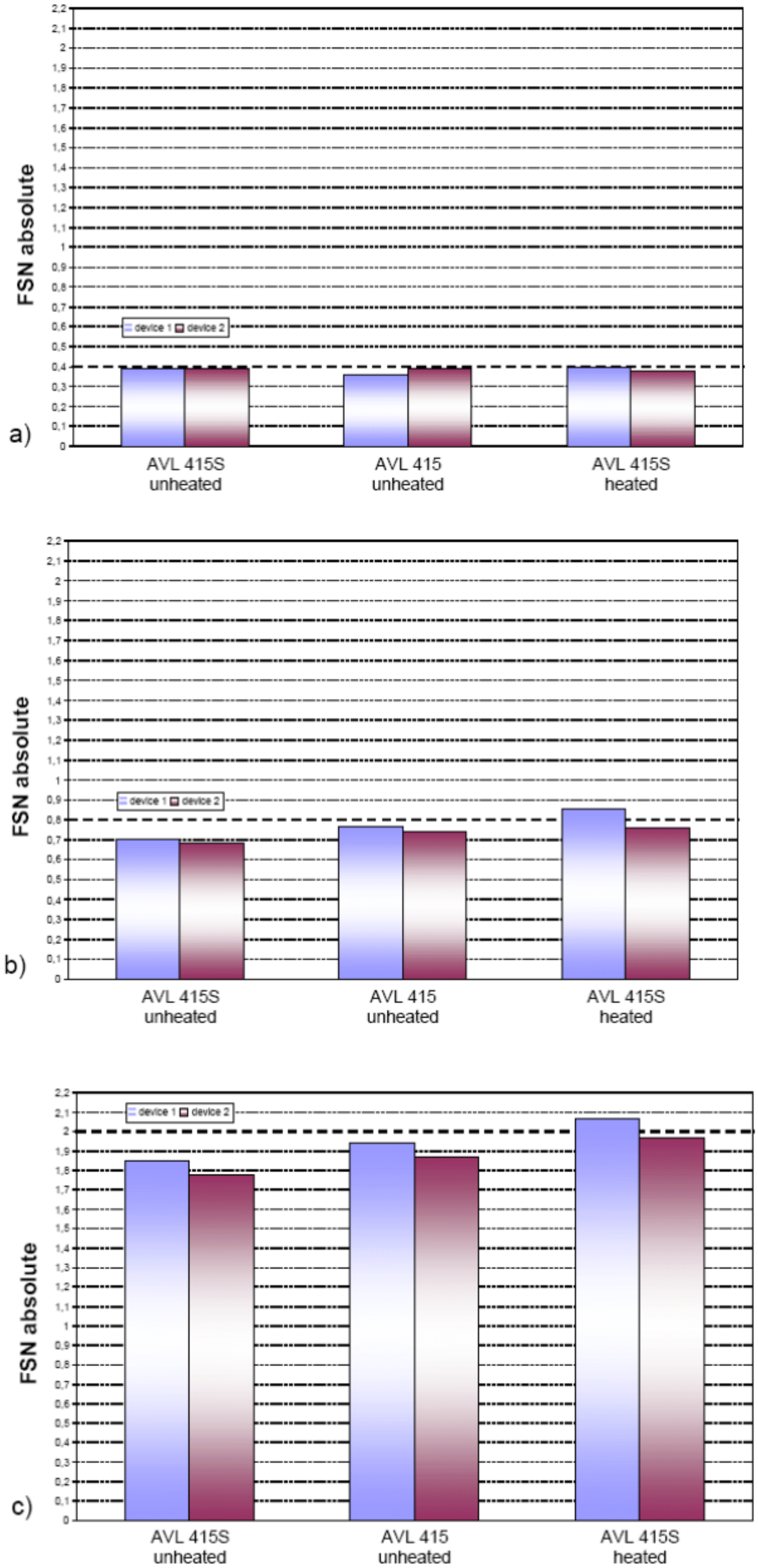


Fig. 22

5.3.3 AVL 415 / AVL 415S Device Comparison (unheated)

Because the AVL Smoke Meters 415S G001 and G002, as the AVL Smoke Meter 415 use, for unheated measurements, the same correlation curve for the calculation of the blackening number, there are no measurement result differences.

5.3.4 Device Comparison AVL 415S G001/ AVL 415S G002

If measurements with the unheated AVL Smoke Meter 415S are done, both device types use the same (old) correlation curve for the calculation of the blackening number.

For this reason there should not be any different measurement results between the AVL Smoke Meter 415S G001 (unheated) and the AVL Smoke Meter 415S G002 (unheated).

For "heated" measurements the AVL Smoke Meter 415S G002 uses a different (new) correlation curve than the AVL Smoke Meter 415S G001. This curve was developed out of the fact that less particles deposit in the sampling lines if they are heated. Thus more particles reach the filter paper and the blackening number is higher.

A new correlation between FSN and soot loading ($^{mg}/_{m^3}$) of the exhaust gases was needed. More precise, the correlation curve represents a connection between paper blackening (PB), measuring volume, FSN and soot loading.

It was found for the heated Smoke Meter 415S that the indicated FSN value depends on the former correlation of the sampled volume. Therefore it became necessary to come up with a "new" correlation which indicates a constant FSN value for heated tests with different test volumes.

When comparing the AVL Smoke Meter G001 and G002 the calculation with the new curve for the G002 device shows, in most cases (but not in all), lower FSN values than with the old correlation in the G001 - system. However still more than with unheated measurements.

Due to the fact, that the correlation is based on mathematics the possibility to convert FSN values that were found with the old curve from FSN values that were found through the new correlation exists. For that the paper blackening (PB) must be known. Unfortunately these values are not always known.

When using the "Auto Range" function the values, however, can be approximately converted very easy, because the "Auto Range" function uses a value of around PB = 2.5 ± 1.

Differences for different FSN values

"old" → "new"		Difference		"new" → "old"		Difference
1	0.92	8.0 %		1	1.08	8.0 %
2	1.92	4.0 %		2	2.08	4.0 %
3	2.89	3.7 %		3	3.12	4.0 %
4	3.85	3.8 %		4	4.16	4.0 %
5	4.82	3.6 %		5	5.18	3.6 %

Tab. 4

The following section contains tables for the conversion between the old and new FSN values.

Comparison/correlation of the FSN values:

FSN old function (for unheated system) with FSN new function (for heated system)

The correlation data was calculated under the following considerations:

- Identical measurement settings for AVL Smoke Meter 415S with the same settings:
- Same probe, same sampling point, same length of sampling line
- Always heated measurements
- One measurement with the old, the other with the new function
- The set point for the Presample Check is a paper blackening degree of PB of 2.5

Important: The here shown comparison/correlation is only valid for measurements done in "Presample Auto Range" mode.

"Standard Presample Auto Range":

mode with standard limits of 0.5 liters minimal and of 5 liters of maximum sampled volume

Calculation/Fit functions:

Calculation accuracy of +/- 0.01 FSN for bandwidths of 0 to 6 and for bandwidths of +/- 0.03 FSN

For "Standard Auto Range":

Please note that these are non linear functions. The limits for the calculating bandwidths (for example 0 to 6.2) must be mentioned.

Num.	**for calculations of FSN old (y) from FSN new (=x):**	
(1)	from FSN 0 to FSN 6:	y = (a + c*x + e*x^2 + g*x^3)/(1 + b*x + d*x^2 + f*x^3)
(2)	from FSN 6 to 10:	y =(a + b*x + c*x^2 + d*x^3 + e*x^4)
	for calculations of FSN new (y) from FSN old (=x):	
(3)	from FSN 0 to FSN 6.2:	y = (a + c*x + e*x^2 + g*x^3)/(1 + b*x + d*x^2 + f*x^3)
(4)	from FSN 6.2 to 10:	y = [(a + c*x + e*x^2)/(1 + b*x + d*x^2 + f*x^3)]^2

Fit function no.:	(1)	(2)	(3)	(4)
Parameters:				
a	-0.0044456	-93.099.775	0.003655612	1.807.437
b	-10.347.996	49.466.055	-10.944.798	-0.29456416
c	1.172.588	-92.928.208	0.85538965	-0.45910517
d	0.90592598	0.77953234	0.78728895	0.027119458
e	-12.113.938	-0.02418909	-0.94762894	0.030390954
f	0.0053316		-0.00413149	-0.00068582
g	0.9889387		0.72208241	

Tab. 5

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN old function	FSN old function
0.00	-0.004	0.50	0.567	1.00	1.079
0.01	0.007	0.51	0.578	1.01	1.089
0.02	0.019	0.52	0.589	1.02	1.099
0.03	0.031	0.53	0.600	1.03	1.108
0.04	0.042	0.54	0.611	1.04	1.118
0.05	0.054	0.55	0.621	1.05	1.128
0.06	0.066	0.56	0.632	1.06	1.138
0.07	0.077	0.57	0.643	1.07	1.148
0.08	0.089	0.58	0.653	1.08	1.157
0.09	0.101	0.59	0.664	1.09	1.167
0.10	0.112	0.60	0.675	1.10	1.177
0.11	0.124	0.61	0.685	1.11	1.187
0.12	0.136	0.62	0.696	1.12	1.197
0.13	0.147	0.63	0.706	1.13	1.207
0.14	0.159	0.64	0.717	1.14	1.216
0.15	0.171	0.65	0.727	1.15	1.226
0.16	0.182	0.66	0.738	1.16	1.236
0.17	0.194	0.67	0.748	1.17	1.246
0.18	0.205	0.68	0.758	1.18	1.256
0.19	0.217	0.69	0.769	1.19	1.265
0.20	0.229	0.70	0.779	1.20	1.275
0.21	0.240	0.71	0.789	1.21	1.285
0.22	0.252	0.72	0.800	1.22	1.295
0.23	0.263	0.73	0.810	1.23	1.305
0.24	0.275	0.74	0.820	1.24	1.315
0.25	0.286	0.75	0.830	1.25	1.325
0.26	0.298	0.76	0.840	1.26	1.334
0.27	0.309	0.77	0.850	1.27	1.344
0.28	0.321	0.78	0.861	1.28	1.354
0.29	0.332	0.79	0.871	1.29	1.364
0.30	0.344	0.80	0.881	1.30	1.374
0.31	0.355	0.81	0.891	1.31	1.384
0.32	0.366	0.82	0.901	1.32	1.394
0.33	0.378	0.83	0.911	1.33	1.404
0.34	0.389	0.84	0.921	1.34	1.414

Tab. 6

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN old function	FSN old function
0.35	0.400	0.85	0.931	1.35	1.424
0.36	0.412	0.86	0.941	1.36	1.434
0.37	0.423	0.87	0.951	1.37	1.443
0.38	0.434	0.88	0.961	1.38	1.453
0.39	0.446	0.89	0.971	1.39	1.463
0.40	0.457	0.90	0.980	1.40	1.473
0.41	0.468	0.91	0.990	1.41	1.483
0.42	0.479	0.92	1.000	1.42	1.493
0.43	0.490	0.93	1.010	1.43	1.503
0.44	0.501	0.94	1.020	1.44	1.513
0.45	0.512	0.95	1.030	1.45	1.523
0.46	0.523	0.96	1.040	1.46	1.533
0.47	0.534	0.97	1.049	1.47	1.543
0.48	0.545	0.98	1.059	1.48	1.553
0.49	0.556	0.99	1.069	1.49	1.563

Tab. 6

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN new function	FSN old function
1.50	1.573	2.00	2.082	2.50	2.599
1.51	1.583	2.01	2.092	2.51	2.609
1.52	1.593	2.02	2.103	2.52	2.620
1.53	1.603	2.03	2.113	2.53	2.630
1.54	1.614	2.04	2.123	2.54	2.641
1.55	1.624	2.05	2.134	2.55	2.651
1.56	1.634	2.06	2.144	2.56	2.661
1.57	1.644	2.07	2.154	2.57	2.672
1.58	1.654	2.08	2.164	2.58	2.682
1.59	1.664	2.09	2.175	2.59	2.693
1.60	1.674	2.10	2.185	2.60	2.703
1.61	1.684	2.11	2.195	2.61	2.713
1.62	1.694	2.12	2.206	2.62	2.724
1.63	1.704	2.13	2.216	2.63	2.734
1.64	1.714	2.14	2.226	2.64	2.744
1.65	1.725	2.15	2.237	2.65	2.755
1.66	1.735	2.16	2.247	2.66	2.765
1.67	1.745	2.17	2.257	2.67	2.776
1.68	1.755	2.18	2.268	2.68	2.786
1.69	1.765	2.19	2.278	2.69	2.796
1.70	1.775	2.20	2.288	2.70	2.807
1.71	1.785	2.21	2.299	2.71	2.817
1.72	1.796	2.22	2.309	2.72	2.828
1.73	1.806	2.23	2.319	2.73	2.838
1.74	1.816	2.24	2.330	2.74	2.848
1.75	1.826	2.25	2.340	2.75	2.859
1.76	1.836	2.26	2.350	2.76	2.869
1.77	1.847	2.27	2.361	2.77	2.879
1.78	1.857	2.28	2.371	2.78	2.890
1.79	1.867	2.29	2.381	2.79	2.900
1.80	1.877	2.30	2.392	2.80	2.911
1.81	1.887	2.31	2.402	2.81	2.921
1.82	1.898	2.32	2.412	2.82	2.931
1.83	1.908	2.33	2.423	2.83	2.942
1.84	1.918	2.34	2.433	2.84	2.952

Tab. 7

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN new function	FSN old function
1.85	1.928	2.35	2.444	2.85	2.963
1.86	1.938	2.36	2.454	2.86	2.973
1.87	1.949	2.37	2.464	2.87	2.983
1.88	1.959	2.38	2.475	2.88	2.994
1.89	1.969	2.39	2.485	2.89	3.004
1.90	1.979	2.40	2.495	2.90	3.015
1.91	1.990	2.41	2.506	2.91	3.025
1.92	2.000	2.42	2.516	2.92	3.035
1.93	2.010	2.43	2.526	2.93	3.046
1.94	2.020	2.44	2.537	2.94	3.056
1.95	2.031	2.45	2.547	2.95	3.066
1.96	2.041	2.46	2.558	2.96	3.077
1.97	2.051	2.47	2.568	2.97	3.087
1.98	2.062	2.48	2.578	2.98	3.098
1.99	2.072	2.49	2.589	2.99	3.108

Tab. 7

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN new function	FSN old function
3.00	3.118	3.50	3.637	4.00	4.155
3.01	3.129	3.51	3.648	4.01	4.165
3.02	3.139	3.52	3.658	4.02	4.175
3.03	3.150	3.53	3.668	4.03	4.186
3.04	3.160	3.54	3.679	4.04	4.196
3.05	3.170	3.55	3.689	4.05	4.206
3.06	3.181	3.56	3.700	4.06	4.217
3.07	3.191	3.57	3.710	4.07	4.227
3.08	3.202	3.58	3.720	4.08	4.237
3.09	3.212	3.59	3.731	4.09	4.247
3.10	3.222	3.60	3.741	4.10	4.258
3.11	3.233	3.61	3.751	4.11	4.268
3.12	3.243	3.62	3.762	4.12	4.278
3.13	3.253	3.63	3.772	4.13	4.289
3.14	3.264	3.64	3.782	4.14	4.299
3.15	3.274	3.65	3.793	4.15	4.309
3.16	3.285	3.66	3.803	4.16	4.320
3.17	3.295	3.67	3.813	4.17	4.330
3.18	3.305	3.68	3.824	4.18	4.340
3.19	3.316	3.69	3.834	4.19	4.351
3.20	3.326	3.70	3.844	4.20	4.361
3.21	3.337	3.71	3.855	4.21	4.371
3.22	3.347	3.72	3.865	4.22	4.382
3.23	3.357	3.73	3.876	4.23	4.392
3.24	3.368	3.74	3.886	4.24	4.402
3.25	3.378	3.75	3.896	4.25	4.412
3.26	3.388	3.76	3.907	4.26	4.423
3.27	3.399	3.77	3.917	4.27	4.433
3.28	3.409	3.78	3.927	4.28	4.443
3.29	3.420	3.79	3.938	4.29	4.454
3.30	3.430	3.80	3.948	4.30	4.464
3.31	3.440	3.81	3.958	4.31	4.474
3.32	3.451	3.82	3.969	4.32	4.485
3.33	3.461	3.83	3.979	4.33	4.495
3.34	3.471	3.84	3.989	4.34	4.505

Tab. 8

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN new function	FSN old function
3.35	3.482	3.85	4.000	4.35	4.515
3.36	3.492	3.86	4.010	4.36	4.526
3.37	3.503	3.87	4.020	4.37	4.536
3.38	3.513	3.88	4.031	4.38	4.546
3.39	3.523	3.89	4.041	4.39	4.557
3.40	3.534	3.90	4.051	4.40	4.567
3.41	3.544	3.91	4.062	4.41	4.577
3.42	3.554	3.92	4.072	4.42	4.587
3.43	3.565	3.93	4.082	4.43	4.598
3.44	3.575	3.94	4.093	4.44	4.608
3.45	3.586	3.95	4.103	4.45	4.618
3.46	3.596	3.96	4.113	4.46	4.629
3.47	3.606	3.97	4.124	4.47	4.639
3.48	3.617	3.98	4.134	4.48	4.649
3.49	3.627	3.99	4.144	4.49	4.659

Tab. 8

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN new function	FSN old function
4.50	4.670	5.00	5.182	5.50	5.692
4.51	4.680	5.01	5.192	5.51	5.702
4.52	4.690	5.02	5.203	5.52	5.713
4.53	4.700	5.03	5.213	5.53	5.723
4.54	4.711	5.04	5.223	5.54	5.733
4.55	4.721	5.05	5.233	5.55	5.743
4.56	4.731	5.06	5.244	5.56	5.753
4.57	4.742	5.07	5.254	5.57	5.763
4.58	4.752	5.08	5.264	5.58	5.774
4.59	4.762	5.09	5.274	5.59	5.784
4.60	4.772	5.10	5.284	5.60	5.794
4.61	4.783	5.11	5.295	5.61	5.804
4.62	4.793	5.12	5.305	5.62	5.814
4.63	4.803	5.13	5.315	5.63	5.824
4.64	4.813	5.14	5.325	5.64	5.834
4.65	4.824	5.15	5.335	5.65	5.845
4.66	4.834	5.16	5.346	5.66	5.855
4.67	4.844	5.17	5.356	5.67	5.865
4.68	4.854	5.18	5.366	5.68	5.875
4.69	4.865	5.19	5.376	5.69	5.885
4.70	4.875	5.20	5.387	5.70	5.895
4.71	4.885	5.21	5.397	5.71	5.906
4.72	4.896	5.22	5.407	5.72	5.916
4.73	4.906	5.23	5.417	5.73	5.926
4.74	4.916	5.24	5.427	5.74	5.936
4.75	4.926	5.25	5.438	5.75	5.946
4.76	4.937	5.26	5.448	5.76	5.956
4.77	4.947	5.27	5.458	5.77	5.966
4.78	4.957	5.28	5.468	5.78	5.977
4.79	4.967	5.29	5.478	5.79	5.987
4.80	4.978	5.30	5.489	5.80	5.997
4.81	4.988	5.31	5.499	5.81	6.007
4.82	4.998	5.32	5.509	5.82	6.017
4.83	5.008	5.33	5.519	5.83	6.027
4.84	5.018	5.34	5.529	5.84	6.037

Tab. 9

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN new function	FSN old function
4.85	5.029	5.35	5.539	5.85	6.048
4.86	5.039	5.36	5.550	5.86	6.058
4.87	5.049	5.37	5.560	5.87	6.068
4.88	5.059	5.38	5.570	5.88	6.078
4.89	5.070	5.39	5.580	5.89	6.088
4.90	5.080	5.40	5.590	5.90	6.098
4.91	5.090	5.41	5.601	5.91	6.108
4.92	5.100	5.42	5.611	5.92	6.118
4.93	5.111	5.43	5.621	5.93	6.129
4.94	5.121	5.44	5.631	5.94	6.139
4.95	5.131	5.45	5.641	5.95	6.149
4.96	5.141	5.46	5.651	5.96	6.159
4.97	5.152	5.47	5.662	5.97	6.169
4.98	5.162	5.48	5.672	5.98	6.179
4.99	5.172	5.49	5.682	5.99	6.189
				6.00	6.199

Tab. 9

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN new function	FSN old function
6.00	6.185	6.50	6.708	7.00	7.116
6.01	6.197	6.51	6.717	7.01	7.124
6.02	6.210	6.52	6.726	7.02	7.131
6.03	6.222	6.53	6.735	7.03	7.139
6.04	6.234	6.54	6.743	7.04	7.147
6.05	6.246	6.55	6.752	7.05	7.154
6.06	6.258	6.56	6.761	7.06	7.162
6.07	6.270	6.57	6.769	7.07	7.170
6.08	6.281	6.58	6.778	7.08	7.177
6.09	6.293	6.59	6.787	7.09	7.185
6.10	6.304	6.60	6.795	7.10	7.193
6.11	6.316	6.61	6.804	7.11	7.200
6.12	6.327	6.62	6.812	7.12	7.208
6.13	6.339	6.63	6.821	7.13	7.216
6.14	6.350	6.64	6.829	7.14	7.223
6.15	6.361	6.65	6.837	7.15	7.231
6.16	6.372	6.66	6.846	7.16	7.239
6.17	6.383	6.67	6.854	7.17	7.246
6.18	6.394	6.68	6.862	7.18	7.254
6.19	6.405	6.69	6.871	7.19	7.262
6.20	6.416	6.70	6.879	7.20	7.269
6.21	6.426	6.71	6.887	7.21	7.277
6.22	6.437	6.72	6.895	7.22	7.285
6.23	6.447	6.73	6.903	7.23	7.293
6.24	6.458	6.74	6.911	7.24	7.300
6.25	6.468	6.75	6.920	7.25	7.308
6.26	6.478	6.76	6.928	7.26	7.316
6.27	6.489	6.77	6.936	7.27	7.323
6.28	6.499	6.78	6.944	7.28	7.331
6.29	6.509	6.79	6.952	7.29	7.339
6.30	6.519	6.80	6.960	7.30	7.347
6.31	6.529	6.81	6.968	7.31	7.354
6.32	6.539	6.82	6.976	7.32	7.362
6.33	6.549	6.83	6.983	7.33	7.370
6.34	6.559	6.84	6.991	7.34	7.378

Tab. 10

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN new function	FSN old function
6.35	6.568	6.85	6.999	7.35	7.385
6.36	6.578	6.86	7.007	7.36	7.393
6.37	6.588	6.87	7.015	7.37	7.401
6.38	6.597	6.88	7.023	7.38	7.409
6.39	6.607	6.89	7.031	7.39	7.417
6.40	6.616	6.90	7.038	7.40	7.425
6.41	6.626	6.91	7.046	7.41	7.432
6.42	6.635	6.92	7.054	7.42	7.440
6.43	6.644	6.93	7.062	7.43	7.448
6.44	6.653	6.94	7.070	7.44	7.456
6.45	6.663	6.95	7.077	7.45	7.464
6.46	6.672	6.96	7.085	7.46	7.472
6.47	6.681	6.97	7.093	7.47	7.480
6.48	6.690	6.98	7.101	7.48	7.488
6.49	6.699	6.99	7.108	7.49	7.496

Tab. 10

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN new function	FSN old function
7.50	7.504	8.00	7.930	8.50	8.417
7.51	7.512	8.01	7.939	8.51	8.427
7.52	7.520	8.02	7.948	8.52	8.438
7.53	7.528	8.03	7.958	8.53	8.448
7.54	7.536	8.04	7.967	8.54	8.459
7.55	7.544	8.05	7.976	8.55	8.469
7.56	7.552	8.06	7.985	8.56	8.479
7.57	7.560	8.07	7.995	8.57	8.490
7.58	7.568	8.08	8.004	8.58	8.500
7.59	7.577	8.09	8.013	8.59	8.511
7.60	7.585	8.10	8.023	8.60	8.521
7.61	7.593	8.11	8.032	8.61	8.532
7.62	7.601	8.12	8.041	8.62	8.542
7.63	7.609	8.13	8.051	8.63	8.553
7.64	7.618	8.14	8.060	8.64	8.563
7.65	7.626	8.15	8.070	8.65	8.574
7.66	7.634	8.16	8.079	8.66	8.584
7.67	7.643	8.17	8.089	8.67	8.595
7.68	7.651	8.18	8.098	8.68	8.606
7.69	7.659	8.19	8.108	8.69	8.616
7.70	7.668	8.20	8.118	8.70	8.627
7.71	7.676	8.21	8.127	8.71	8.638
7.72	7.685	8.22	8.137	8.72	8.648
7.73	7.693	8.23	8.147	8.73	8.659
7.74	7.701	8.24	8.156	8.74	8.670
7.75	7.710	8.25	8.166	8.75	8.680
7.76	7.719	8.26	8.176	8.76	8.691
7.77	7.727	8.27	8.186	8.77	8.702
7.78	7.736	8.28	8.195	8.78	8.713
7.79	7.744	8.29	8.205	8.79	8.723
7.80	7.753	8.30	8.215	8.80	8.734
7.81	7.761	8.31	8.225	8.81	8.745
7.82	7.770	8.32	8.235	8.82	8.756
7.83	7.779	8.33	8.245	8.83	8.766
7.84	7.787	8.34	8.255	8.84	8.777

Tab. 11

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN new function	FSN old function
7.85	7.796	8.35	8.265	8.85	8.788
7.86	7.805	8.36	8.275	8.86	8.799
7.87	7.814	8.37	8.285	8.87	8.810
7.88	7.823	8.38	8.295	8.88	8.820
7.89	7.831	8.39	8.305	8.89	8.831
7.90	7.840	8.40	8.315	8.90	8.842
7.91	7.849	8.41	8.325	8.91	8.853
7.92	7.858	8.42	8.335	8.92	8.864
7.93	7.867	8.43	8.345	8.93	8.875
7.94	7.876	8.44	8.356	8.94	8.886
7.95	7.885	8.45	8.366	8.95	8.896
7.96	7.894	8.46	8.376	8.96	8.907
7.97	7.903	8.47	8.386	8.97	8.918
7.98	7.912	8.48	8.397	8.98	8.929
7.99	7.921	8.49	8.407	8.99	8.940

Tab. 11

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function
9.00	8.951	9.50	9.481
9.01	8.962	9.51	9.491
9.02	8.972	9.52	9.501
9.03	8.983	9.53	9.511
9.04	8.994	9.54	9.520
9.05	9.005	9.55	9.530
9.06	9.016	9.56	9.540
9.07	9.027	9.57	9.550
9.08	9.038	9.58	9.560
9.09	9.048	9.59	9.569
9.10	9.059	9.60	9.579
9.11	9.070	9.61	9.589
9.12	9.081	9.62	9.598
9.13	9.092	9.63	9.608
9.14	9.102	9.64	9.617
9.15	9.113	9.65	9.627
9.16	9.124	9.66	9.636
9.17	9.135	9.67	9.646
9.18	9.146	9.68	9.655
9.19	9.156	9.69	9.664
9.20	9.167	9.70	9.673
9.21	9.178	9.71	9.682
9.22	9.189	9.72	9.692
9.23	9.199	9.73	9.701
9.24	9.210	9.74	9.710
9.25	9.221	9.75	9.718
9.26	9.231	9.76	9.727
9.27	9.242	9.77	9.736
9.28	9.253	9.78	9.745
9.29	9.263	9.79	9.754
9.30	9.274	9.80	9.762
9.31	9.284	9.81	9.771
9.32	9.295	9.82	9.779
9.33	9.305	9.83	9.788
9.34	9.316	9.84	9.796

Tab. 12

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function
9.35	9.326	9.85	9.804
9.36	9.337	9.86	9.813
9.37	9.347	9.87	9.821
9.38	9.358	9.88	9.829
9.39	9.368	9.89	9.837
9.40	9.379	9.90	9.845
9.41	9.389	9.91	9.853
9.42	9.399	9.92	9.860
9.43	9.409	9.93	9.868
9.44	9.420	9.94	9.876
9.45	9.430	9.95	9.883
9.46	9.440	9.96	9.891
9.47	9.450	9.97	9.898
9.48	9.460	9.98	9.906
9.49	9.470	9.99	9.913
		10.00	9.920

Tab. 12

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN old function	FSN new function	FSN old function	FSN new function	FSN old function	FSN new function
0.00	0.004	0.50	0.439	1.00	0.920
0.01	0.012	0.51	0.448	1.01	0.930
0.02	0.021	0.52	0.457	1.02	0.940
0.03	0.029	0.53	0.466	1.03	0.950
0.04	0.038	0.54	0.475	1.04	0.960
0.05	0.047	0.55	0.484	1.05	0.971
0.06	0.055	0.56	0.493	1.06	0.981
0.07	0.064	0.57	0.502	1.07	0.991
0.08	0.072	0.58	0.512	1.08	1.001
0.09	0.081	0.59	0.521	1.09	1.011
0.10	0.090	0.60	0.530	1.10	1.021
0.11	0.098	0.61	0.539	1.11	1.032
0.12	0.107	0.62	0.549	1.12	1.042
0.13	0.115	0.63	0.558	1.13	1.052
0.14	0.124	0.64	0.567	1.14	1.062
0.15	0.132	0.65	0.577	1.15	1.072
0.16	0.141	0.66	0.586	1.16	1.082
0.17	0.150	0.67	0.596	1.17	1.093
0.18	0.158	0.68	0.605	1.18	1.103
0.19	0.167	0.69	0.614	1.19	1.113
0.20	0.176	0.70	0.624	1.20	1.123
0.21	0.184	0.71	0.634	1.21	1.133
0.22	0.193	0.72	0.643	1.22	1.143
0.23	0.201	0.73	0.653	1.23	1.154
0.24	0.210	0.74	0.662	1.24	1.164
0.25	0.219	0.75	0.672	1.25	1.174
0.26	0.227	0.76	0.682	1.26	1.184
0.27	0.236	0.77	0.691	1.27	1.194
0.28	0.245	0.78	0.701	1.28	1.204
0.29	0.253	0.79	0.711	1.29	1.215
0.30	0.262	0.80	0.721	1.30	1.225
0.31	0.271	0.81	0.730	1.31	1.235
0.32	0.279	0.82	0.740	1.32	1.245
0.33	0.288	0.83	0.750	1.33	1.255
0.34	0.297	0.84	0.760	1.34	1.265

Tab. 13

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN old function	FSN new function	FSN old function	FSN new function	FSN old function	FSN new function
0.35	0.306	0.85	0.770	1.35	1.275
0.36	0.314	0.86	0.780	1.36	1.286
0.37	0.323	0.87	0.790	1.37	1.296
0.38	0.332	0.88	0.799	1.38	1.306
0.39	0.341	0.89	0.809	1.39	1.316
0.40	0.349	0.90	0.819	1.40	1.326
0.41	0.358	0.91	0.829	1.41	1.336
0.42	0.367	0.92	0.839	1.42	1.346
0.43	0.376	0.93	0.849	1.43	1.356
0.44	0.385	0.94	0.859	1.44	1.366
0.45	0.394	0.95	0.869	1.45	1.376
0.46	0.403	0.96	0.880	1.46	1.386
0.47	0.412	0.97	0.890	1.47	1.396
0.48	0.421	0.98	0.900	1.48	1.406
0.49	0.430	0.99	0.910	1.49	1.416

Tab. 13

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN old function	FSN new function	FSN old function	FSN new function	FSN old function	FSN new function
1.50	1.427	2.00	1.920	2.50	2.405
1.51	1.437	2.01	1.930	2.51	2.414
1.52	1.447	2.02	1.940	2.52	2.424
1.53	1.457	2.03	1.949	2.53	2.434
1.54	1.467	2.04	1.959	2.54	2.443
1.55	1.477	2.05	1.969	2.55	2.453
1.56	1.487	2.06	1.979	2.56	2.462
1.57	1.497	2.07	1.988	2.57	2.472
1.58	1.506	2.08	1.998	2.58	2.482
1.59	1.516	2.09	2.008	2.59	2.491
1.60	1.526	2.10	2.018	2.60	2.501
1.61	1.536	2.11	2.027	2.61	2.511
1.62	1.546	2.12	2.037	2.62	2.520
1.63	1.556	2.13	2.047	2.63	2.530
1.64	1.566	2.14	2.056	2.64	2.540
1.65	1.576	2.15	2.066	2.65	2.549
1.66	1.586	2.16	2.076	2.66	2.559
1.67	1.596	2.17	2.086	2.67	2.568
1.68	1.606	2.18	2.095	2.68	2.578
1.69	1.616	2.19	2.105	2.69	2.588
1.70	1.626	2.20	2.115	2.70	2.597
1.71	1.636	2.21	2.124	2.71	2.607
1.72	1.645	2.22	2.134	2.72	2.617
1.73	1.655	2.23	2.144	2.73	2.626
1.74	1.665	2.24	2.153	2.74	2.636
1.75	1.675	2.25	2.163	2.75	2.645
1.76	1.685	2.26	2.173	2.76	2.655
1.77	1.695	2.27	2.182	2.77	2.665
1.78	1.705	2.28	2.192	2.78	2.674
1.79	1.715	2.29	2.202	2.79	2.684
1.80	1.724	2.30	2.211	2.80	2.694
1.81	1.734	2.31	2.221	2.81	2.703
1.82	1.744	2.32	2.231	2.82	2.713
1.83	1.754	2.33	2.241	2.83	2.722
1.84	1.764	2.34	2.250	2.84	2.732

Tab. 14

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN old function	FSN new function	FSN old function	FSN new function	FSN old function	FSN new function
1.85	1.773	2.35	2.260	2.85	2.742
1.86	1.783	2.36	2.270	2.86	2.751
1.87	1.793	2.37	2.279	2.87	2.761
1.88	1.803	2.38	2.289	2.88	2.771
1.89	1.813	2.39	2.298	2.89	2.780
1.90	1.823	2.40	2.308	2.90	2.790
1.91	1.832	2.41	2.318	2.91	2.799
1.92	1.842	2.42	2.327	2.92	2.809
1.93	1.852	2.43	2.337	2.93	2.819
1.94	1.862	2.44	2.347	2.94	2.828
1.95	1.871	2.45	2.356	2.95	2.838
1.96	1.881	2.46	2.366	2.96	2.848
1.97	1.891	2.47	2.376	2.97	2.857
1.98	1.901	2.48	2.385	2.98	2.867
1.99	1.910	2.49	2.395	2.99	2.876

Tab. 14

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN old function	FSN new function	FSN old function	FSN new function	FSN old function	FSN new function
3.00	2.886	3.50	3.368	4.00	3.850
3.01	2.896	3.51	3.377	4.01	3.860
3.02	2.905	3.52	3.387	4.02	3.870
3.03	2.915	3.53	3.396	4.03	3.879
3.04	2.925	3.54	3.406	4.04	3.889
3.05	2.934	3.55	3.416	4.05	3.899
3.06	2.944	3.56	3.425	4.06	3.908
3.07	2.953	3.57	3.435	4.07	3.918
3.08	2.963	3.58	3.445	4.08	3.928
3.09	2.973	3.59	3.454	4.09	3.937
3.10	2.982	3.60	3.464	4.10	3.947
3.11	2.992	3.61	3.474	4.11	3.957
3.12	3.002	3.62	3.483	4.12	3.966
3.13	3.011	3.63	3.493	4.13	3.976
3.14	3.021	3.64	3.503	4.14	3.986
3.15	3.030	3.65	3.512	4.15	3.995
3.16	3.040	3.66	3.522	4.16	4.005
3.17	3.050	3.67	3.531	4.17	4.015
3.18	3.059	3.68	3.541	4.18	4.025
3.19	3.069	3.69	3.551	4.19	4.034
3.20	3.079	3.70	3.560	4.20	4.044
3.21	3.088	3.71	3.570	4.21	4.054
3.22	3.098	3.72	3.580	4.22	4.063
3.23	3.107	3.73	3.589	4.23	4.073
3.24	3.117	3.74	3.599	4.24	4.083
3.25	3.127	3.75	3.609	4.25	4.092
3.26	3.136	3.76	3.618	4.26	4.102
3.27	3.146	3.77	3.628	4.27	4.112
3.28	3.156	3.78	3.638	4.28	4.121
3.29	3.165	3.79	3.647	4.29	4.131
3.30	3.175	3.80	3.657	4.30	4.141
3.31	3.184	3.81	3.667	4.31	4.151
3.32	3.194	3.82	3.676	4.32	4.160
3.33	3.204	3.83	3.686	4.33	4.170
3.34	3.213	3.84	3.696	4.34	4.180

Tab. 15

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN old function	FSN new function	FSN old function	FSN new function	FSN old function	FSN new function
3.35	3.223	3.85	3.705	4.35	4.189
3.36	3.233	3.86	3.715	4.36	4.199
3.37	3.242	3.87	3.725	4.37	4.209
3.38	3.252	3.88	3.734	4.38	4.218
3.39	3.262	3.89	3.744	4.39	4.228
3.40	3.271	3.90	3.754	4.40	4.238
3.41	3.281	3.91	3.763	4.41	4.248
3.42	3.290	3.92	3.773	4.42	4.257
3.43	3.300	3.93	3.783	4.43	4.267
3.44	3.310	3.94	3.792	4.44	4.277
3.45	3.319	3.95	3.802	4.45	4.286
3.46	3.329	3.96	3.812	4.46	4.296
3.47	3.339	3.97	3.821	4.47	4.306
3.48	3.348	3.98	3.831	4.48	4.316
3.49	3.358	3.99	3.841	4.49	4.325

Tab. 15

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN old function	FSN new function	FSN old function	FSN new function	FSN old function	FSN new function
4.50	4.335	5.00	4.822	5.50	5.311
4.51	4.345	5.01	4.832	5.51	5.321
4.52	4.354	5.02	4.841	5.52	5.331
4.53	4.364	5.03	4.851	5.53	5.341
4.54	4.374	5.04	4.861	5.54	5.351
4.55	4.384	5.05	4.871	5.55	5.360
4.56	4.393	5.06	4.881	5.56	5.370
4.57	4.403	5.07	4.890	5.57	5.380
4.58	4.413	5.08	4.900	5.58	5.390
4.59	4.422	5.09	4.910	5.59	5.400
4.60	4.432	5.10	4.920	5.60	5.409
4.61	4.442	5.11	4.929	5.61	5.419
4.62	4.452	5.12	4.939	5.62	5.429
4.63	4.461	5.13	4.949	5.63	5.439
4.64	4.471	5.14	4.959	5.64	5.449
4.65	4.481	5.15	4.968	5.65	5.459
4.66	4.491	5.16	4.978	5.66	5.468
4.67	4.500	5.17	4.988	5.67	5.478
4.68	4.510	5.18	4.998	5.68	5.488
4.69	4.520	5.19	5.008	5.69	5.498
4.70	4.529	5.20	5.017	5.70	5.508
4.71	4.539	5.21	5.027	5.71	5.518
4.72	4.549	5.22	5.037	5.72	5.527
4.73	4.559	5.23	5.047	5.73	5.537
4.74	4.568	5.24	5.056	5.74	5.547
4.75	4.578	5.25	5.066	5.75	5.557
4.76	4.588	5.26	5.076	5.76	5.567
4.77	4.598	5.27	5.086	5.77	5.577
4.78	4.607	5.28	5.096	5.78	5.586
4.79	4.617	5.29	5.105	5.79	5.596
4.80	4.627	5.30	5.115	5.80	5.606
4.81	4.637	5.31	5.125	5.81	5.616
4.82	4.646	5.32	5.135	5.82	5.626
4.83	4.656	5.33	5.145	5.83	5.636
4.84	4.666	5.34	5.154	5.84	5.645

Tab. 16

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN old function	FSN new function	FSN old function	FSN new function	FSN old function	FSN new function
4.85	4.676	5.35	5.164	5.85	5.655
4.86	4.685	5.36	5.174	5.86	5.665
4.87	4.695	5.37	5.184	5.87	5.675
4.88	4.705	5.38	5.194	5.88	5.685
4.89	4.715	5.39	5.203	5.89	5.695
4.90	4.724	5.40	5.213	5.90	5.705
4.91	4.734	5.41	5.223	5.91	5.714
4.92	4.744	5.42	5.233	5.92	5.724
4.93	4.754	5.43	5.243	5.93	5.734
4.94	4.763	5.44	5.252	5.94	5.744
4.95	4.773	5.45	5.262	5.95	5.754
4.96	4.783	5.46	5.272	5.96	5.764
4.97	4.793	5.47	5.282	5.97	5.774
4.98	4.802	5.48	5.292	5.98	5.783
4.99	4.812	5.49	5.301	5.99	5.793
				6.00	5.803

Tab. 16

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN new function	FSN old function
6.00	5.803	6.50	6.286	7.00	6.846
6.01	5.813	6.51	6.296	7.01	6.858
6.02	5.823	6.52	6.306	7.02	6.871
6.03	5.833	6.53	6.316	7.03	6.883
6.04	5.843	6.54	6.326	7.04	6.896
6.05	5.852	6.55	6.336	7.05	6.908
6.06	5.862	6.56	6.347	7.06	6.921
6.07	5.872	6.57	6.357	7.07	6.933
6.08	5.882	6.58	6.367	7.08	6.946
6.09	5.892	6.59	6.378	7.09	6.959
6.10	5.902	6.60	6.388	7.10	6.971
6.11	5.912	6.61	6.399	7.11	6.984
6.12	5.922	6.62	6.409	7.12	6.997
6.13	5.931	6.63	6.420	7.13	7.009
6.14	5.941	6.64	6.430	7.14	7.022
6.15	5.951	6.65	6.441	7.15	7.035
6.16	5.961	6.66	6.452	7.16	7.048
6.17	5.971	6.67	6.463	7.17	7.061
6.18	5.981	6.68	6.474	7.18	7.074
6.19	5.991	6.69	6.485	7.19	7.086
6.20	6.001	6.70	6.495	7.20	7.099
6.21	6.015	6.71	6.506	7.21	7.112
6.22	6.024	6.72	6.518	7.22	7.125
6.23	6.032	6.73	6.529	7.23	7.138
6.24	6.041	6.74	6.540	7.24	7.151
6.25	6.050	6.75	6.551	7.25	7.164
6.26	6.059	6.76	6.562	7.26	7.177
6.27	6.068	6.77	6.574	7.27	7.190
6.28	6.077	6.78	6.585	7.28	7.203
6.29	6.086	6.79	6.596	7.29	7.216
6.30	6.095	6.80	6.608	7.30	7.229
6.31	6.104	6.81	6.619	7.31	7.242
6.32	6.113	6.82	6.631	7.32	7.255
6.33	6.123	6.83	6.642	7.33	7.269
6.34	6.132	6.84	6.654	7.34	7.282

Tab. 17

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN new function	FSN old function
6.35	6.141	6.85	6.666	7.35	7.295
6.36	6.150	6.86	6.677	7.36	7.308
6.37	6.160	6.87	6.689	7.37	7.321
6.38	6.169	6.88	6.701	7.38	7.334
6.39	6.179	6.89	6.713	7.39	7.347
6.40	6.188	6.90	6.725	7.40	7.360
6.41	6.198	6.91	6.737	7.41	7.373
6.42	6.207	6.92	6.749	7.42	7.386
6.43	6.217	6.93	6.761	7.43	7.399
6.44	6.227	6.94	6.773	7.44	7.412
6.45	6.236	6.95	6.785	7.45	7.425
6.46	6.246	6.96	6.797	7.46	7.438
6.47	6.256	6.97	6.809	7.47	7.451
6.48	6.266	6.98	6.821	7.48	7.464
6.49	6.276	6.99	6.834	7.49	7.477

Tab. 17

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN new function	FSN old function
7.50	7.490	8.00	8.090	8.50	8.582
7.51	7.503	8.01	8.101	8.51	8.591
7.52	7.516	8.02	8.112	8.52	8.600
7.53	7.529	8.03	8.123	8.53	8.609
7.54	7.542	8.04	8.133	8.54	8.618
7.55	7.554	8.05	8.144	8.55	8.627
7.56	7.567	8.06	8.154	8.56	8.636
7.57	7.580	8.07	8.165	8.57	8.645
7.58	7.593	8.08	8.175	8.58	8.654
7.59	7.605	8.09	8.186	8.59	8.663
7.60	7.618	8.10	8.196	8.60	8.672
7.61	7.631	8.11	8.207	8.61	8.681
7.62	7.643	8.12	8.217	8.62	8.690
7.63	7.656	8.13	8.227	8.63	8.699
7.64	7.668	8.14	8.237	8.64	8.708
7.65	7.681	8.15	8.248	8.65	8.717
7.66	7.693	8.16	8.258	8.66	8.726
7.67	7.706	8.17	8.268	8.67	8.735
7.68	7.718	8.18	8.278	8.68	8.744
7.69	7.730	8.19	8.288	8.69	8.753
7.70	7.743	8.20	8.298	8.70	8.762
7.71	7.755	8.21	8.308	8.71	8.771
7.72	7.767	8.22	8.318	8.72	8.780
7.73	7.779	8.23	8.327	8.73	8.789
7.74	7.792	8.24	8.337	8.74	8.798
7.75	7.804	8.25	8.347	8.75	8.807
7.76	7.816	8.26	8.357	8.76	8.816
7.77	7.828	8.27	8.367	8.77	8.825
7.78	7.840	8.28	8.376	8.78	8.834
7.79	7.852	8.29	8.386	8.79	8.843
7.80	7.863	8.30	8.395	8.80	8.852
7.81	7.875	8.31	8.405	8.81	8.861
7.82	7.887	8.32	8.415	8.82	8.870
7.83	7.899	8.33	8.424	8.83	8.879
7.84	7.910	8.34	8.434	8.84	8.888

Tab. 18

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function	FSN new function	FSN old function
7.85	7.922	8.35	8.443	8.85	8.897
7.86	7.934	8.36	8.452	8.86	8.906
7.87	7.945	8.37	8.462	8.87	8.915
7.88	7.957	8.38	8.471	8.88	8.924
7.89	7.968	8.39	8.481	8.89	8.933
7.90	7.979	8.40	8.490	8.90	8.942
7.91	7.991	8.41	8.499	8.91	8.951
7.92	8.002	8.42	8.508	8.92	8.960
7.93	8.013	8.43	8.518	8.93	8.969
7.94	8.024	8.44	8.527	8.94	8.978
7.95	8.035	8.45	8.536	8.95	8.988
7.96	8.047	8.46	8.545	8.96	8.997
7.97	8.058	8.47	8.554	8.97	9.006
7.98	8.068	8.48	8.564	8.98	9.015
7.99	8.079	8.49	8.573	8.99	9.024

Tab. 18

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function
9.00	9.033	9.50	9.520
9.01	9.043	9.51	9.530
9.02	9.052	9.52	9.541
9.03	9.061	9.53	9.551
9.04	9.070	9.54	9.562
9.05	9.080	9.55	9.572
9.06	9.089	9.56	9.583
9.07	9.098	9.57	9.593
9.08	9.108	9.58	9.604
9.09	9.117	9.59	9.614
9.10	9.126	9.60	9.625
9.11	9.136	9.61	9.636
9.12	9.145	9.62	9.646
9.13	9.155	9.63	9.657
9.14	9.164	9.64	9.668
9.15	9.173	9.65	9.679
9.16	9.183	9.66	9.690
9.17	9.192	9.67	9.700
9.18	9.202	9.68	9.711
9.19	9.212	9.69	9.722
9.20	9.221	9.70	9.733
9.21	9.231	9.71	9.744
9.22	9.240	9.72	9.755
9.23	9.250	9.73	9.766
9.24	9.260	9.74	9.777
9.25	9.269	9.75	9.788
9.26	9.279	9.76	9.800
9.27	9.289	9.77	9.811
9.28	9.299	9.78	9.822
9.29	9.308	9.79	9.833
9.30	9.318	9.80	9.844
9.31	9.328	9.81	9.856
9.32	9.338	9.82	9.867
9.33	9.348	9.83	9.878
9.34	9.358	9.84	9.890

Tab. 19

FSN with "Standard Presample Auto Range"		FSN with "Standard Presample Auto Range"	
FSN new function	FSN old function	FSN new function	FSN old function
9.35	9.368	9.85	9.901
9.36	9.378	9.86	9.913
9.37	9.388	9.87	9.924
9.38	9.398	9.88	9.936
9.39	9.408	9.89	9.947
9.40	9.418	9.90	9.959
9.41	9.428	9.91	9.970
9.42	9.438	9.92	9.982
9.43	9.448	9.93	9.994
9.44	9.458	9.94	10.006
9.45	9.469	9.95	10.017
9.46	9.479	9.96	10.029
9.47	9.489	9.97	10.041
9.48	9.499	9.98	10.053
9.49	9.510	9.99	10.065
		10.00	10.077

Tab. 19

5.4 FSN-Opacity Correlation

FSN and opacity of the exhaust gas of a combustion engine are based mainly on particle emissions. Particles of the combustion have a complex construction of elementary carbon ("C", "black soot"), condensed hydrocarbons (HC), sulfur particles (SO_4; main sulfuric acid and attached water) and ashes (Metallic oxides, etc.). Schematically this is shown in the following illustration.

Particle emissions and their reference to different measuring principals

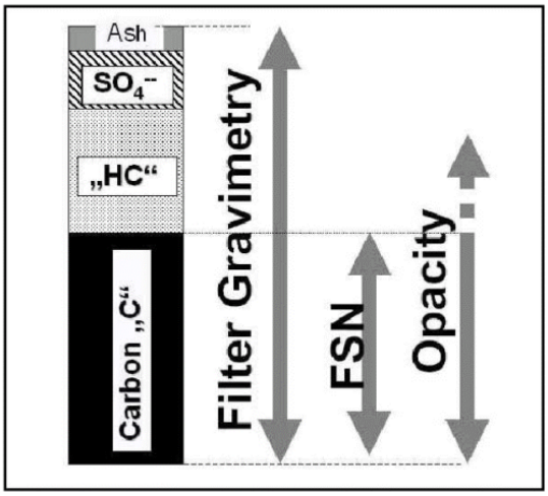


Fig. 23

It was shown, that the Filter Smoke Number, measured with a Smoke Meter as the AVL 415S, represents the "C" part of the particles. This is expressed through the correlation equation:

$$\text{"C" (mg/m}^3\text{)} = \frac{1}{0.405} \cdot 4.95 \cdot FSN \cdot \exp(0.38 \cdot FSN)$$

From the physical principle it is clear that the opacity N [%] which is the attenuation of the strength of a ray of light is also mainly influenced by "C". Because of that it is logical to asume that also a correlation between FSN and opacity exists. Experiments around this assumption were performed in order to verify it. The results of the experiments are encouraging: a quite good correlation that was confirmed from several laboratories was found.

Relationship between FSN and opacity (measured in 5 different laboratories)

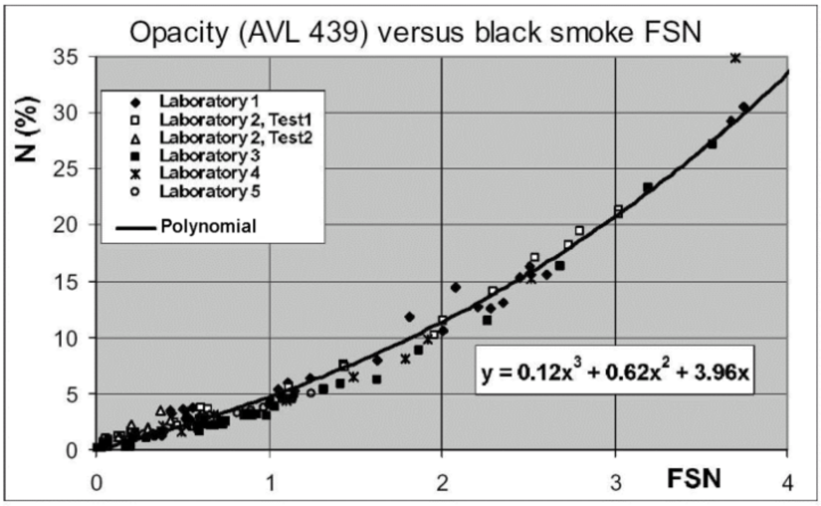


Fig. 24

Some questions remain, however:

1. What is the background for this correlation?
2. Is this correlation valid in all cases?
3. If yes, what are the statistical characteristics of this correlation?
4. If not, are there FSN/opacity -range, where this correlation is always valid?
5. If not, for which case is the correlation definitely not valid?

The answers are:

1. The background for the correlation is the fact, that FSN is virtually only, and opacity is mainly influenced by "black soot", "C". The specific light attenuation, for example the attenuation per metering unit, is for "C" many times higher than for example for "HC".
2. The correlation can not be guaranteed for all cases. The correlation is an empirical discovery which is only valid for a certain number of engines, and is for example not restricted to a certain particle property. But some combustion procedures can produce particles for which the correlation is not valid anymore. Physical backgrounds for effects, that can influence the correlation will be shown further down.
3. A statistical evaluation of the measuring data does not make sense, since no strict physical-mathematical relationship between FSN and opacity exists. The measured values of these two parameters have indeed a common physical basis, but there are also differences.

4. From the physical basics which are explained further down it is clear that a deviation from the shown correlation is basically possible over the whole range of the relation between FSN and opacity.

5. From Fig. 25 on page 95 it becomes clear that the inaccuracy of the relationship between FSN and opacity for values of FSN ≤ 1, or N ≤ 5 % increases. That has a simple reason: the low soot emissions (low FSN) are usually connected to high parts of HC. Opacity, unlike FSN, reacts sensitively on certain parameters to condensed HC particles. The opacity signal of a certain mass of HC particles will turn out considerably smaller, than the signal of the same mass of "C". But for great amounts of "HC" it can not be neglected. This is also shown by Fig. 24 on page 93.

Yet more: it must be taken into account that N is influenced by **every** exhaust gas component which absorbs or scatters light. There is one gaseous component in the exhaust gas which absorbs light, NO_2. Usually the concentration is low, because the nitrogen oxides are emitted to 95 % as NO. In spite of that the concentrations can become, after a catalytic transformation, so high, that a opacity of up to a few percent can occur. And that although, the **specific** absorption of NO_2 is many times smaller than the specific absorption of "C".

SO_4^{2-} -particles can weaken light through scattering. However, the effect is, due to the fact that SO_4^{2-} -particles are very small, negligible, except when fuels with a high sulfur content are used, as for some marine applications.

Validity at low smoke values

With the Combustion Aerosol Standard ("CAST") of the Swiss institute for metrology comparisons were done between FSN and opacity with the AVL Smoke Meter 415S, and the AVL 439 Opacimeter.

The CAST supplies particles which are similar to diesel particles. Some particles that were found exist of soot, and also of condensed hydrocarbons with a percentage by weight of hydrocarbons of up 85 %.

The correlation is shown by the next diagram.

Relationship between FSN and opacity for low soot emissions generated with CAST

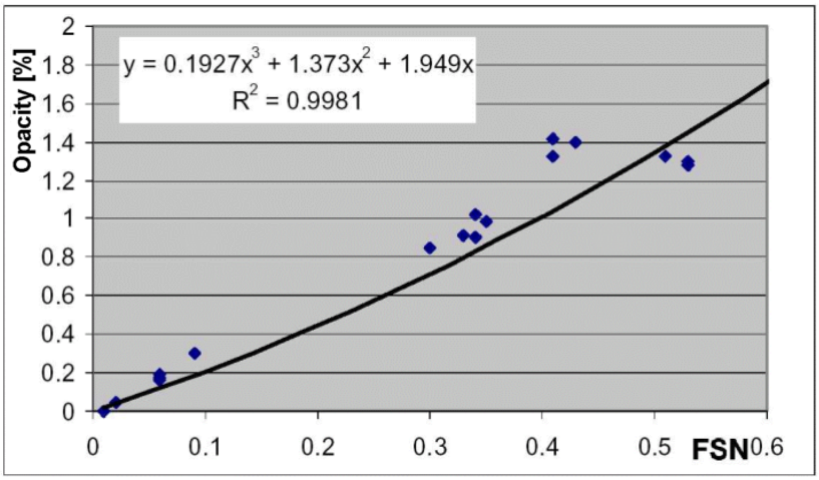


Fig. 25

The coefficients of the best polynomial adaptation differ from those, which were measured from the engine. The opacity values of this adaptation are among those from Fig. 24 on page 93, and the curves intersect each other at FSN = 2.

We assume, that this, rather than the small interference of light scattering particles, could be a reason for the boundaries of the measuring accuracy, because data that shows the almost same correlation with low diesel soot concentrations exist.

6 Smoke Value Measurement of Large Engines

6.1 Recommendations

When performing measurements on large engines attention has to be paid concerning the use of fuels with high sulfur or ash content, water injection and the appearance of large particles respectively aerosol fragments, to guidelines for the test setup in order to avoid measurement errors or even the destruction of the measuring device.

Sampling probe:

- Use the sampling probe with the screw cap (sampling probe of the AVL 415) whereas it is supposed to be mounted.

Sampling lines:

- Use only the material Viton for the sampling lines. This material is much more resistant against acidic exhaust gas components than silicone. An AVL 415S Viton sampling line with an especially smooth inner surface, an internal diameter of 4 mm and a wall thickness of 2 mm, is recommended.
- Always choose the maximum length of the sampling lines, which is necessary, to receive a reproducible result. With exhaust gases with a high sulfur content a minimum length of 4 m is recommended (however not longer than 7 or 8 m), in order to already completely condense all sulfate acidic parts in the line.
- Use an unheated and not isolated sampling line so that all unwanted substances (sulfuric acid, ash, water) are already taken out at this point.
- Always use the same set of sampling lines even if different smoke meter models are used.
- Never mix different probes and sampling lines, when doing comparison measurement at different sampling points or sites.

Smoke Meter:

- Use the Smoke Meter in an unheated condition. Comparisons between measuring data of heated and unheated measurements are not possible.
  The heating is supposed to prevent the condensing of water vapor (and the adherence of particles to these water droplets) and particularly condensation at the filter paper. A high sulfur content of more than 1 percent of the weight has, however, a great influence on the dew point of the steam. It can exceed temperatures of over 130 °C. Since for hardware reasons temperatures of more than 65 °C may not be reached with the heating system (cotton paper, detector,…) a standard heating would be counterproductive. High ash concentrations could, together with water vapor and acidic components, form big particle agglomerates. In connection with some carbon these can also have an influence on the absorptive effect of these particles. Also similar effects can occur if water vapor condenses within the device and reaches the filter paper (a slightly gray paper always appears darker when wet than when dry). Components of sulphate acid (whether with or without water and/or ash content) are very aggressive and may not in any case reach the measuring device. The condensation is supposed to occur in the sampling line and the line is supposed to be cleaned regularly. It is supposed to be avoided that water droplets can reach the probe of the Smoke Meter.
- Use the same device-model – if possible –, when comparison measurements are supposed to be carried out at different sites.
- Use the same test setup, if the same device is used for comparison purposes at different sites.
- Clean the lines at least once a day when using fuels with high sulphur or ash content. This is supposed to happen at a certain point in time.
- Prefer the "Auto Range" function or define the same sampling time, or the same sampled volume. When, however, you want to compare measurement values of AVL 409 with those of AVL 415, respectively 415S (both unheated), you should use a constant sampled volume of 1 liter for measurements with the AVL 415.

Important: Use the same sampling lines.

- Use the purging-function as often as possible, but always at the same test points(for example: before or after a measurement).

6.2 Influences on the Measurement

Ambient conditions:

- Lower ambient temperatures cause more condensate in the unheated lines, and particle losses are therefore higher.
- The humidity has besides high ambient temperatures a great influence on the amount of particles.

Engine state:

- The temperature, the pressure and the moisture of the air sucked up by the engine can have great influence on the particle output of an engine.
- The fuel composition (sulfur and ash content) have together with the water vapor an influence on the particle composition, cluster formation and the particle size distribution. High sulfur contents have, in addition, a great influence on the dew point of the vapor.

Transportation conditions:

- The type of the probe does usually not have any influence on the measuring results at particle sizes under 200 nm. At sizes above 400 nm, however, the effect can be dominant, because such big particle agglomerates are usually sucked into the probe with the screw cap.
- With unheated sampling lines condensation can occur. The amount of condensation mainly depends on the following conditions:
  - Dew point of the water vapor (depends on the engine state, kind of fuel and on the sulfur content)
  - Ambient temperature
  - Humidity
  - Heat transportation of the measured gas to the surroundings (mainly dependent on the line wall thickness).
- With sampling lines heated at 65 °C the above-mentioned effects occur to a smaller extent, except when fuels with a high sulfur or ash content are used.
- If the sampling line is isolated, but not heated, mixed effects, about which no precise statements can be made, occur.

7 Special Sampling

7.1 Special Sampling Option 415S

7.1.1 General

The standard layout of an AVL Smoke Meter 415S is designed for exhaust gas back pressures of -100 mbar to 400 mbar. Moreover the purging of ambient air into the exhaust gas system can also lead to problems. The Special Sampling option facilitates the use of the Smoke Meter through its special construction under the following crucial conditions:

- Measurements at exhaust gas back pressures of up to +750 mbar or negative pressures of up to -200 mbar at the sampling point.
- Measurements with two sampling lines (if already installed in the standard device)
- No purging into the exhaust gas
- Purging into the exhaust gas with for example nitrogen (from gas bottles or generators)
- Effective purging of the sampling probe by means of compressed air or nitrogen possible (in this case flushing into the exhaust gas tract)
- High exhaust gas temperatures of up to 600 °C (800 °C with long sampling probe)
- Exhaust gas over pressures of >900 (device turned on or in stand-by). With the Special Sampling option the system is safe-guarded up to top pressures of 1500 mbar (fixed 1000 mbar).
- Option Heating usable, respectively recommended

The Special Sampling option should only be mounted, however, if the exhaust gas shows a state (temperature, pressure) for which the standard device is not designed, or no purging air may reach the exhaust gas (for example not to influence the values of a lambda probe).

Unlike the standard sampling the sampling lines of the Special Sampling option are through their characteristic construction (valves; corrugated line and sampling probe are only purged with external compressed air if required) not suitable for highly precise measurements of very low soot concentrations (< 0.5 FSN). Moreover the obtained data can not be compared with data that was obtained without the option. Due to the deposits the measurement results can deviate up to 10 %.

7.1.2 Mode of Operation

Construction of the option at the exhaust gas system and at the measuring instrument

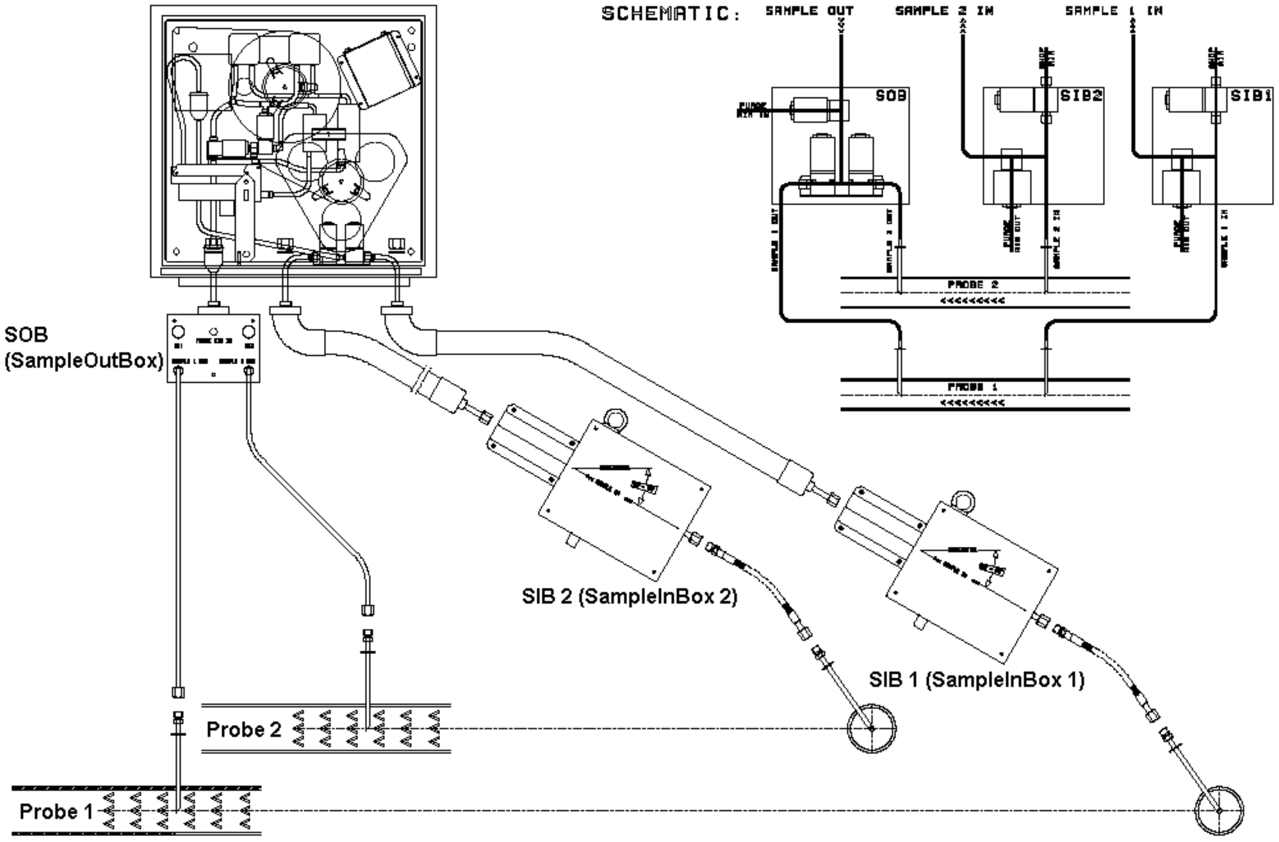


Fig. 26

Measurement at Higher Pressures

The primary function of the Special Sampling option is to increase the possible exhaust gas back pressures. This is possible through leading the exhaust gas sample back into the exhaust gas system after the measurement. Through this measure approximately the same pressure is present throughout the entire process of sampling and that way device internal and/or relative pressures are approximately kept constant. It is important that both sampling in probe and the sample out probe are mounted upstreams the pressure producing component (DPF, flaps).

Purging

To avoid ambient air being brought into the exhaust gas system the sample-in- and the sample-out box were developed. In the purging mode the valve "purging air in" is opened at the sample-out box and ambient air is sucked in. This air is then pulsated through the sampling lines and is used to purge them. The sampling probe and the flexible corrugated line are not purged in this case. This must then occur manually in regular intervals (according to soot loading) with cleaned compressed air (oil and water-free). The compressed-air inlet is available by default.

A further possibility is to purge the lines with nitrogen. This way the entire sampling line including sampling probe and corrugated line can be purged without the possible risk of influencing any exhaust gas after treatment systems that might be installed.

Possible crucial components in the exhaust line

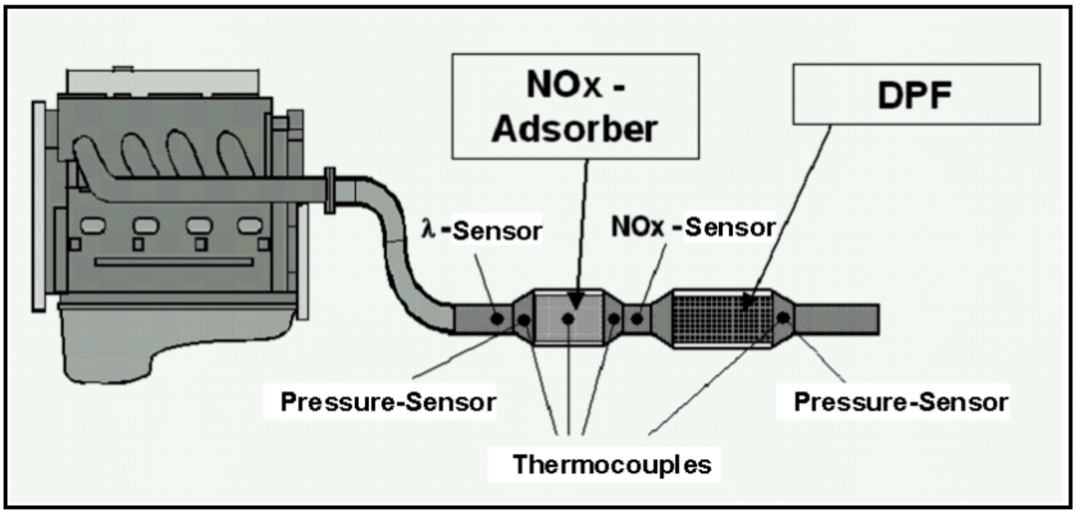


Fig. 27

7.1.3 Installation

1. Install the sampling probes same as for the standard device 415S (see device manual 415S).
2. Install the sample-out-probes in analogue to the installation of the sampling probes, at least 150 mm downstream of the sampling probes, however, in a region of approximately the same pressure. No pressure drop producing elements such as flaps, particle filters or similar things may exist between the sampling probe and the "recirculation" connection.
3. Support the sample-in box in such a way, that the flexible line can be mounted between probe and sample-in box and, that the horizontal engraved line on the box is about kept horizontally. Only this way a proper purging can be guaranteed. A strong thermal strain through radiation heat of the exhaust pipe is supposed to be avoided. If necessary attach a metallic shield between the exhaust pipe and the sample-in box.
4. Connect probe and sample-in box with the flexible line.
5. Install the sampling line.
6. Connect the compressed air (2 bar ±0.5 bar; max. 3 bar) and the power supply according to the application.
7. Install the sample-out line and probe. These are materially the same components as the sampling lines (are in most cases heated is) and -probes.

The Special Sampling option can be ordered directly with the Smoke Meter or also as a retrofit kit. The installation of the retrofit kit needs more manipulations and is described in detail in the manual.

8 Summary

In addition to the sampling time, the length of the sampling lines and the hose material, particularly the influence of the thermal conditioning and the differences between heated and unheated sampling were examined. The subsequently mentioned parameters could be identified as main influencing factors:

- Thermal conditioning of device and sampled system
- Choice of sampling time (and/or sampled volume)
- Sampling line length in unheated operation

The deposit of particles and condensate on the inside of the sampling lines can be seen as the explanation for the measuring value differences due to the told influencing factors.

The condensate formation and the resulting deviations of the measurement result are determined through parameters such as relative humidity and temperature in the device and the sampling system. With the heating also a new correlation curve between soot loading and FSN was needed. With the help of an equation it is, however, not a problem to convert the values of the individual functions if the measurements were done in the "Presample Auto Range" mode.

Unfavorable combinations of the mentioned performance-influencing factors can affect the measurement results more or less strongly. Since for example with increasing engine load the exhaust gas humidity increases and the condensate formation tendency increases with an unheated longer sampling time the combination of these two parameters can already cause noticeable measurement value differences [NÖS-00].

The accuracy of the Smoke Value measurement with small measurement values is affected both by the measuring device and by the sampling technique. The engine can have a great influence on the measurement quality through its instability, particularly in the partial load operation.

It was also shown, that for special applications, specific measurement layouts and methods are needed.

The low smoke value levels to be determined, under compliance of the described boundary conditions, in future can only be determined with a heated instrument with sufficient accuracy. In order to increase the repeatability from smoke value measurements with small FSN levels, a sampled volume increase is recommended.

Both conditions are fulfilled by the Smoke Meter 415S in the heated version.

Symbols and Indexes

SZ, SZ_B	Bosch blackness number
FSN	Filter Smoke Number
PB	Paper blackening
PL	Pollution level
s	Standard deviation (deviation, uncertainty of measurement)
n	Number of arguments
x	Value of argument (measured value difference between test and reference device)
AVL 409	Type designation of the first AVL Smoke Meter (1965)
AVL 415	Type designation of the AVL 409 succession model (1992)
AVL 415S	Type designation of the new AVL Smoke Meter (1999)
M1, M2	Measurement value (Device 1, 2)
G1, G2	Device influence on the measurement value
W	True physical value
s_D^2	Variation of the measured value difference (= square of the standard deviation)
s_{G1}^2, s_{G2}^2	Device variation
p_W	Partial pressure of steam
p_{Ws}	Saturation pressure of steam
m_W	Steam mass
m_L	Mass of dry air
x_W	Absolute humidity
x_{Ws}	Maximum absolute humidity
p	Air pressure
j	Relative humidity

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