INTERNATIONAL STANDARD

ISO 11614

First edition
1999-09-01

Reciprocating internal combustion compression-ignition engines — Apparatus for measurement of the opacity and for determination of the light absorption coefficient of exhaust gas

Moteurs alternatifs à combustion interne à allumage par compression — Appareillage de mesure de l'opacité et du coefficient d'absorption de la lumière des gaz d'échappement

Reference number
ISO 11614:1999(E)

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Printed in Switzerland

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 11614 was prepared by Technical Committee ISO/TC 22, *Road vehicles,* Subcommittee SC 5, *Engine tests*, in collaboration with ISO/TC 70, *Internal Combustion engines*, Subcommittee SC 8, *Exhaust gas emisssion measurement*.

This first edition of ISO 11614 cancels and replaces ISO 3173:1974 and ISO/TR 4011:1976, which have been technically revised.

Annex A forms a normative part of this International Standard.

Reciprocating internal combustion compression-ignition engines — Apparatus for measurement of the opacity and for determination of the light absorption coefficient of exhaust gas

1 Scope

This International Standard specifies the general requirements and the installation of apparatus for measurement of the opacity and for the determination of the light absorption coefficient of exhaust gas from internal combustion engines (not confined to road vehicles). These instruments are known as opacimeters.

2 Normative references

The following normative documents contain provisions that, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 2602:1980, *Statistical interpretation of test results — Estimation of the mean — Confidence interval.*

IEC 60068-2-1:1990, *Environmental testing — Part 2: Tests — Test A: Cold*.

IEC 60068-2-2:1974, *Environmental testing — Part 2: Tests — Test B: Dry heat*.

IEC 60068-2-3:1969, *Environmental testing — Part 2: Tests — Test Ca: Damp heat, steady state*.

IEC 60068-2-31:1969, *Environmental testing — Part 2: Tests — Test Ec: Drop and topple, primarily for equipment-type specimens*.

IEC 61000-4-2:1995, *Electromagnetic compatibility (EMC) — Part 4: Testing and measurement techniques — Section 2: Electrostatic discharge immunity test — Basic EMC publication.*

IEC 61000-4-3:1998, *Electromagnetic compatibility (EMC) — Part 4: Testing and measurement techniques — Section 3: Radiated, radio-frequency, electromagnetic field immunity test.*

IEC 61000-4-4:1995, *Electromagnetic compatibility (EMC) — Part 4: Testing and measurement techniques — Section 4: Electrical fast transient/burst immunity test — Basic EMC publication.*

CIE S 001:1986, *Colorimetric illuminants.*

3 Terms and definitions

For the purposes of this International Standard, the following terms and definitions apply.

3.1
transmittance, τ
fraction of light transmitted from a source through a smoke-obscured path, which reaches the observer or the apparatus receiver

$$\tau = \frac{I}{I_0} \times 100$$

3.2
opacity, N
fraction of light transmitted from a source through a smoke-obscured path, which is prevented from reaching the observer or the instrument receiver

$$N = 100 - \tau$$

3.3
effective optical path length, L_A
length of a light beam between the emitter and the receiver that is intersected by the exhaust gas stream, corrected as necessary for non-uniformity due to density gradients and fringe effect

3.4
light absorption coefficient, k
coefficient defined by the Beer-Lambert law:

$$k = \frac{-1}{L_A} \times \ln\left(\frac{\tau}{100}\right)$$

or

$$k = \frac{-1}{L_A} \times \ln\left(1 - \frac{N}{100}\right) \qquad (1)$$

NOTE 1 To obtain proper comparisons when making opacity measurements, the temperature and pressure prevailing in the measuring zone must be known since they influence the light absorption coefficient k. Reference conditions for these are given in 7.1.

NOTE 2 The term "light absorption coefficient" is in common use and is, therefore, used in this International Standard. However, "light extinction coefficient" would be more accurate terminology. As used, the two terms describe exactly the same parameter.

4 Symbols and units

For the purposes of this International Standard, the symbols and units given in Table 1 apply.

Table 1

Symbol	Unit	Description	Subclause concerned
d_a	dm^3/s	Minimum gas flow.	11.7.1
d_b	dm^3/s	Maximum gas flow.	11.7.1
d_c	dm^3/s	Average gas flow.	11.7.1
I	cd	Light intensity at the receiver when the measuring zone is filled with exhaust gas.	3.1
I_0	cd	Light intensity at the receiver when the measuring zone is filled with clean air.	3.1

Table 1 *(concluded)*

Symbol	Unit	Description	Subclause concerned
k	m^{-1}	Light absorption coefficient. [a]	3.4; 7
k_t	m^{-1}	Light absorption coefficient at temperature T.	7.3.7
k_{cor}	m^{-1}	Observed light absorption coefficient corrected for pressure and temperature.	7.3.7
k_{obs}	m^{-1}	Observed light absorption coefficient.	7.3.7
L_A	mm	Effective optical path length.	3.3; 7.3.4
L_{A1}	mm	Effective optical path length of an opacimeter under test.	11.6.5
L_{A2}	mm	Effective optical path length of a known opacimeter.	11.6.5
l_m	mm	Distance specifying the position in an opacimeter where the temperature equals the mean temperature in the measuring zone.	11.6.1.1
l_{m1}, l_{m2}	mm	Distances relating to separate halves of certain designs of opacimeters.	11.6.1.1
l_1, l_2	mm	Length of tube.	annex A
N	%	Opacity.	3.2; clause 6
N_1	%	Reading of an opacimeter under test.	11.6.5
N_2	%	Reading of a known or modified opacimeter.	11.6.5
P_1, P_2	dm^3/s	Extreme positions of division of flow allowed by the manufacturer.	11.6.12
p_{atm}	kPa	Atmospheric pressure.	7.3.6
p_{obs}	kPa	Observed static pressure in the measuring zone.	7.3.6
Q	dm^3/s	Rate of flow of gas through the measuring zone.	8.2.1
T	K	Temperature.	—
T_a	K	Mean temperature with minimum sample temperature and minimum sample flow.	11.6.1.1
T_b	K	Mean temperature with maximum sample temperature and maximum sample flow.	11.6.1.1
T_g	K	Temperature of the mixture.	annex A
T_m	K	Mean temperature of the gas being measured.	7.3.7
T_s	K	Scavenge air temperature.	annex A
T_1	K	Mean temperature in an opacimeter under test.	11.6.5
T_2	K	Mean temperature of known or modified opacimeter.	11.6.5
t	s	Time.	—
t_p	s	Physical response time.	8.2.1
t_e	s	Electrical response time.	8.2.2
t_o	s	Overall response time.	8.2.3
t_d	s	Physical delay time	8.3
t_T	s	Temperature response time.	8.4
V	dm^3	Volume of the measuring zone.	8.2.1
v	m/s	Gas velocity.	—
v_a	m/s	Velocity at minimum gas flow.	11.7.1
v_b	m/s	Velocity at maximum gas flow.	11.7.1
v_c	m/s	Velocity of the average gas flow.	11.7.1
τ	%	Transmittance.	3.1

a In principle, k with 5/5, means k_{cor}, unless otherwise specified.

5 Principles of opacimeters

5.1 General

The principle of measurement is that light is transmitted through a specific length of the smoke to be measured and that proportion of incident light which reaches a receiver (for example: a photoelectric device) is used to assess the light obscuration properties of the medium.

The "length of smoke" over which the opacity is measured depends on the design for the apparatus. It may be the whole exhaust in an exhaust pipe (in-line full flow opacimeter, see Figure 1) or in free air (end of line or plume type full flow opacimeter, see Figure 2) or it may be a sample of the exhaust extracted from the exhaust pipe (sampling or partial flow opacimeter).

It is important to note that opacity readings shall always be specified for a given optical path length. The value has no meaning without the optical path length for the measurement.

Also the temperature of the gas can significantly affect the reading, and this should be noted when it is not controlled or measured by the apparatus.

5.2 Measurement of light absorption coefficient

Not all apparatus which measure opacity are suitable for the measurement of the light absorption coefficient, since the effective optical path length is not always readily determined, and, with end of line (or plume-type) apparatus, the exhaust gas being measured is not in a non-reflective enclosure. The general specification to be met by all opacimeters is given in clause 6. The additional specifications for opacimeters to measure light absorption coefficient are given in clause 7.

5.3 Conditions of use

Opacimeters may be used in the following test conditions:

— steady-state conditions (SS): the engine is run at constant speed and load, under stabilized conditions;

— transient conditions (TC): the engine is run under transient conditions of speed and/or load.

Additional specifications for opacimeters for measurements under transient conditions are given in clause 8.

6 Specifications of opacimeters for measurement of opacity[1)]

6.1 Basic specifications

6.1.1 The gas to be measured may be contained within the exhaust pipe (in-line apparatus) or as a free plume at the exit from the exhaust pipe (end of line apparatus) or within a specially designed chamber (taking full or partial flow of the exhaust gas).

6.1.2 The indicator shall be in opacity units and shall have a resolution of at least 0,1 % of the full scale.

6.1.3 The zero and the full-scale setting of the apparatus shall not drift more than 0,5 % opacity or 2 % of the full scale, whichever is the smaller, over 1 h or the length of the test, whichever is the shorter.

6.1.4 Any method used for keeping the light source and receiver protected (e.g. scavenge air) shall not cause the effective optical path length of the gas being measured to change by more than 2 %.

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1) Comparison of the results is only possible if the opacity is indicated for a specified effective optical path length L_A (e.g. 430 mm) and a specified smoke temperature T (e.g. 373 K).

6.1.5 Any device which may be situated upstream and downstream of the measuring zone shall not affect the opacity of the gas entering the measuring zone by more than 0,5 % opacity or 2 % of the full scale, whichever is the smaller, for a gas of approximately 50 % of the full scale.

6.1.6 The opacimeter shall be capable of being used for a period sufficient to take measurements without soiling of the light source or receiver. This is considered satisfactory if the overall drift of the apparatus is less than 0,5 % opacity or 2 % of the full scale, whichever is the smaller, over 1 h or the length of the test, whichever is the less.

6.1.7 All maintenance of the apparatus, specified by the manufacturer (see 10.2.13) shall be performed by the user in an easy way and without risk of impairing the correct functioning of the apparatus.

6.1.8 The preconditioning of the apparatus (warming-up and stabilizing) shall not be longer than 15 min. During this time, measurements with the smoke meter shall be inhibited.

6.1.9 The apparatus shall have an adequate insensitivity to the following influences:

— climatic influences (IEC 60068-2-1, IEC 60068-2-2, IEC 60068-2-3);

— mechanical shock (IEC 60068-2-31);

— electromagnetical compatibility (IEC 61000-4-2, IEC 61000-4-3, IEC 61000-4-4);

— external sources of light.

6.1.10 Apparatus specified for use with commercial vehicles shall provide practical and safe means of connecting to standard vehicle exhaust pipe positions, including vertical exhausts and central exhausts under the chassis.

6.1.11 Those parts of the apparatus which may be used outside or are moved by the operator around the vehicle (for example, a measuring head) shall operate from a 50 V or less isolated supply unless it can be shown that the supply provided is equally safe.

6.2 Design specifications

6.2.1 Measuring zone

The measuring zone is that part of the apparatus in which the measurement is made.

6.2.1.1 Opacimeters with a measuring chamber

The measuring zone is bounded:

— at its two extremities by the devices provided for the protection of the light source and the receiver;

— parallel to the gas flow, by the limits of the smoke chamber;

— if applicable, perpendicular to the gas flow, by two imaginary planes (one of them representing the front of the incoming gas, the other the rear of the incoming gas) which form tangents to the light beam.

6.2.1.2 End of line opacimeter

The measuring zone shall be taken as a section of the plume of depth equal to the distance between two imaginary planes, one representing the front of the gas flow, the other the rear of the gas flow and parallel to the light beam. The path length of the plume is more difficult to define accurately and is dependent on how close to the end of the exhaust pipe the light source passes through the smoke plume. Because of the difficulty of accurately defining the effective optical path length, the conversion of the measurement to k should only be made with reservations.

6.2.2 Light source

The light source shall be an incandescent lamp with a colour temperature in the range of 2 800 K to 3 250 K (conforming to CIE S 001) or a green light emitting diode (LED) with a spectral peak between 550 nm and 570 nm.

6.2.3 Receiver

The receiver shall be a photocell or a photo diode (with filter if necessary) which in the case when the light source is an incandescent lamp shall have a spectral response similar to the photopic curve of the human eye (maximum response) in the range 550 nm to 570 nm, to less than 4 % of that maximum response below 430 nm and above 680 nm.

6.2.4 Combined light source and receiver characteristics

6.2.4.1 The apparatus shall be so designed that:

— the rays of the light beam shall be parallel within a tolerance of 3° of the optical axis;

— the receiver is not affected by direct or reflected light rays with an angle of incidence greater than 3° to the optical axis.

Any system giving equivalent results will be acceptable.

6.2.4.2 The design of the electrical circuit, including the indicator, shall be such that the relationship between indicator reading and the intensity of the light received remains linear within ± 0,5 % over the range of adjustment of the circuit and over the operating temperature range of the light source and receiver.

6.2.5 Adjustment and calibration of the measuring apparatus

6.2.5.1 The electric circuit of the light source and receiver shall be adjustable so that the readout can be reset to zero when the light flux passes through the measuring zone filled with clean air or an equivalent zone. The indication of negative values and values above full scale shall be provided.

The apparatus shall provide means of setting and checking full scale (e.g. by the use of a screen or neutral optical density filter perpendicular to the light beam or, in the case of apparatus which read to 100 % opacity, by turning off or blocking the light source completely). The apparatus shall have an automatic or semi-automatic sequence to ensure that the apparatus is correctly adjusted for zero and span before the measurement begins.

6.2.5.2 An intermediate check shall be carried out with a screen or neutral optical density filter perpendicular to the light beam representing a gas opacity between 15 % and 80 % of full scale and known to an accuracy of ± 1 % opacity. This neutral optical density filter shall not be an integral part of the apparatus.

Provision shall be made for placing the filter in the path of the light beam passing through the measuring zone filled with clean air. This test shall be applicable without any tools and without the need to open the case of the apparatus.

The indicator reading, with the filter inserted between the light source and the receiver, shall be within 2 % opacity of the known value of the filter.

6.2.6 Recorder output terminal

The apparatus shall provide, along with a visual readout, a recorder output terminal.

7 Additional specifications for opacimeters to measure light absorption coefficient

7.1 Reference conditions

For practical engine testing, it is convenient to use a reference pressure of ambient and a reference temperature of 373 K. This is because visible emissions of smoke are at ambient pressure and because, in current practice, opacimeters measure at approximately ambient pressure. Also, the smoke correction factors, which include the effect of atmospheric changes on smoke-producing performance of the engine as well as the effect of atmospheric pressure on smoke, have been derived from smoke measurements made at atmospheric pressure and a reference temperature of 373 K.

However, if absolute comparison of two exhaust gases is required (ignoring any effects of conditions on engine performance) then a reference pressure of 100 kPa and a reference temperature of 373 K shall be used. It should be noted that, at the reference conditions for engine performances given in ISO 1585 and ISO 3046-1 (engine air inlet pressure of 100 kPa), the absolute and the practical units coincide.

7.2 Basic specifications

7.2.1 The gas to be measured shall be confined in or passed through an enclosure having a non-reflective internal surface, or equivalent optical environment.

7.2.2 In determining the effective optical path length, L_A, through the gas, account shall be taken of the possible influence of devices used for protecting the light source and the receiver.

7.2.3 The effective optical path length should be indicated on the apparatus and specified in the manufacturer's data.

7.2.4 Unless the manufacturer specifically states that the opacimeter is only suitable for measuring very low light absorption coefficients, the indicator of the opacimeter shall have a scale in absolute units of the light absorption coefficient k from 0 m^{-1} to at least 10 m^{-1} (in addition to the opacity scale according to 6.1.2).

7.2.5 The indicator scale for the light absorption coefficient, k, shall have a resolution of at least 0,01 m^{-1}.

7.2.6 The zero and the full-scale setting of the apparatus shall not drift more than 0,025 m^{-1} or 2 % of the full scale, whichever is the smaller, over 1 h or the length of the test, whichever is the shorter.

7.3 Design specifications

7.3.1 General

7.3.1.1 The design shall be such that under steady-state (SS) operating conditions the measuring chamber is filled with smoke of uniform opacity, except for fringe effects. This condition shall be considered to be met if in addition to the flow requirements of 6.2.1.1, the requirements of 7.3.1.2 and 7.3.1.3 are met. Unless it is shown by the manufacturer that the measuring chamber is always flushed by the sample, a check of flow shall be performed in order to prevent sample oscillations in the apparatus.

7.3.1.2 The variation of the opacimeter indicator output over a period of 10 s, with smoke at constant temperature, having a constant light absorption coefficient k of approximately 1,7 m^{-1} (or about 90 % of full scale, if the opacimeter full scale is less than 2 m^{-1}), and measured with a recorder having a response time of 1 s, is not more than $\pm$ 0,075 m^{-1} (or $\pm$ 4% of the full scale if the opacimeter full scale is less than 2 m^{-1}).

7.3.1.3 Where the smoke chamber is divided, any inequality of flow between the two halves shall not affect the reading by more than 0,05 m^{-1} when measuring smoke with an absorption of about 1,7 m^{-1}.

7.3.2 Light source and receiver

These shall be in accordance with 6.2.2, 6.2.3 and 6.2.4. However, 7.3.3 may be used as an alternative to 6.2.4.1.

7.3.3 Smoke chamber and opacimeter casing

The impingement of stray light on the receiver due to internal reflections or diffusion effects shall be reduced to a minimum (for example by finishing internal surfaces in matte black or a suitable general layout).

Where all surfaces are not matte black, or the light beam is not collimated according to 6.2.4, the optical general layout shall be such that the combined effect on diffusion and reflection shall not exceed 0,075 m^{-1} on the k scale when the smoke chamber is filled with smoke having a light absorption coefficient of approximately 1,7 m^{-1} (or shall not exceed 4 % of the full scale with smoke of about 90 % of full scale if the opacimeter full scale is less than 2m^{-1}).

7.3.4 Determination of the effective optical path length, L_A

When the effective optical path length, L_A, of a type of opacimeter cannot be assessed directly from its geometry, it may be determined either:

- by the method described in 11.6.5.3;
- by correlation with another type of opacimeter for which L_A is known (see 11.6.5.2);
- by other equivalent methods.

7.3.5 Adjustment and calibration of the measuring apparatus

In addition to the requirements of 6.2.5.2, an additional intermediate check shall be provided if the intermediate check screen required in 6.2.5.2 does not have an opacity equivalent to an absorption coefficient (as defined in 3.4) of between 1,5 m^{-1} and 2 m^{-1} calculated with the effective optical path length of the specified apparatus. This additional intermediate check shall be in the form of a screen or neutral optical density filter having an opacity equivalent to an absorption coefficient of between 1,5 m^{-1} and 2 m^{-1}, known to an accuracy of $\pm$ 0,05 m^{-1}. The indicator reading with the filter inserted between the light source and the receiver shall be within $\pm$ 0,15 m^{-1} of the equivalent absorption coefficient of the filter.

Apparatus with automatic gas temperature compensation shall be set to simulate 373 K during this check.

7.3.6 Pressure of the gas to be measured and of scavenging air

7.3.6.1 The pressure of the exhaust gas in the smoke chamber shall not differ from the atmospheric pressure by more than 0,75 kPa (7,5 mbar). The pressure variation of the gas and the scavenging air in the smoke chamber shall not cause the light absorption coefficient, k, to vary by more than 0,05 m^{-1} in the case of a gas having an absorption coefficient of approximately 1,7 m^{-1} (or in the case of opacimeters having a full-scale reading of less than 2 m^{-1}, by more than 2 % of the full-scale reading).

7.3.6.2 Unless it can be shown that, by design, the pressure in the smoke chamber cannot differ from atmospheric pressure by more than 0,75 kPa (with the opacimeter operating within its specified limits), the opacimeter shall be equipped with appropriate devices for measuring the pressure in the smoke chamber. Such devices shall have an accuracy of at least 0,2 kPa and a resolution of 0,1 kPa). The apparatus shall provide means of calibrating the device for measuring the pressure with an external instrument.

Where it is not possible to make measurements at atmospheric pressure (e.g. in-line measurements distant from the exhaust pipe outlet), the opacimeter reading shall be corrected to atmospheric pressure by the formula:

$$k_{\text{cor}} = k_{\text{obs}} \times \frac{p_{\text{atm}}}{p_{\text{obs}}} \qquad (2)$$

7.3.6.3 The limits of pressure variations of the gas and of the scavenging air shall be automatically checked by the apparatus.

7.3.6.4 Unless it can be shown that, by design, the effective optical length, L_A, cannot change more than 2 % by the method for keeping the light source and receiver protected (see 6.1.4), the opacimeter shall be equipped with appropriate devices for checking whether the method is working within the specified limits. The apparatus shall provide means of calibrating the devices with an external instrument.

Where an engine is tested in a controlled atmosphere (e.g. decompression chamber), it is essential to ensure that the opacimeter is located in an area where the ambient pressure is the same as the ambient pressure to which the engine is subject. When this is not done, the opacimeter reading shall be corrected for the difference in pressure between the engine and the opacimeter.

7.3.7 Temperature of the gas to be measured

7.3.7.1 To prevent condensation, the temperature of the exhaust gas shall be sufficiently above the dew point temperature at any point in the exhaust and measuring system (e.g. upstream of the fitted probe, while passing the probe and the measuring apparatus). This condition shall be regarded as fulfilled if gas at 373 K leaving the exhaust pipe arrives in the measuring cell with a temperature above 343 K.

Where the wall temperature of the gas containing system up to the exit of the measurement system would be lower, the system shall be heated to an appropriate temperature (e.g. 373 K).

7.3.7.2 The apparatus shall prohibit the measurements if the temperature of the gas or the chamber temperature (if applicable) drops below its limit.

The opacimeter shall be equipped with appropriate devices for assessing the mean temperature of the gas in the smoke chamber, T_{m}, and the manufacturer shall specify operating limits. The mean temperature must be indicated to an accuracy of 5 K. The apparatus shall provide means of calibrating the device for measuring the temperature of the gas with an external instrument.

Where the mean temperature corrected T_{m} is other than 373 K, the opacimeter reading shall (within the limits defined below) be converted to 373 K by the formula:

$$k_{\text{cor}} = k_{\text{obs}} \times \frac{T_{\text{m}}}{373} \qquad (3)$$

When correction is not possible, k at a given temperature shall be written k_{xxx} (example: k_{500}).

7.3.7.3 The temperature of the exhaust gas at all points of the measuring chamber shall be between 343 K and 553 K for use of the above formula. If the temperatures are outside this range, the readings shall be recorded without correction but with the temperatures noted.

The above temperature range is one in which it is considered that all the water present is in the dry vapour form and all other uncondensed non-solid particles (i.e. the amount of uncondensed, unburnt fuel or lubricating oil) are insignificant in normal full-load exhaust smoke. Under these conditions the conversion formula for the effect of temperature is valid. If the exhaust gas contains an abnormal proportion of non-solid constituents, the conversion formula may not be valid. For example, the formula will not apply to exhaust gases from engines operating on heavy fuel oil having a high sulfur content when the exhaust gas at 373 K may include condensed acidic sulfur droplets. In these cases, it is necessary for comparative purposes to measure with a more restrictive temperature range of about 373 K or, if it is required to avoid measuring these droplets, then the exhaust gas of these engines shall be kept above 413 K and, if required, corrected to 373 K to give a nominal reference value for comparison.

8 Measurement of transients

8.1 General

It is necessary to be clear what is being measured. The measurement can either be the *time* smoke resides at the end of the exhaust pipe, or with gas velocity taken into account, it can be an indication of the *amount* of smoke emitted.

Normally the *amount* of smoke emitted will be regarded as the more significant measurement. The difference can be considerable for turbo vehicles which may give out a short puff of smoke at low speed before the engine accelerates the turbo to correct the air/fuel mixture. An example of a time measurement system is a full-flow opacimeter mounted directly at the end of an exhaust pipe. A small near stationary puff of smoke would be read as a wide pulse, giving the same reading as a large fast moving smoke output, although with much less volume of smoke. The shape of the smoke against time curve is distorted by the changing speed of the gas in, for example, a free acceleration test.

If this opacimeter is mounted at the end of a long extension pipe such that the gas is moving at maximum speed before the smoke passes through the opacimeter (see "delay time t_d" in 8.3), then this will remove the effect of changing gas velocity, and the wave form can be used to measure the *amount* of smoke.

Opacimeters are particularly suitable for the measurement of opacity and light absorption coefficient under transient conditions but they will only give accurate readings if the response of the opacimeter is adequate in duration compared with the transient to be measured.

For measurement of transient, two possibilities exist, as follows.

a) To define the curve of smoke versus time. For this, the overall response time must be at least five times shorter than the time of the transient. Gas velocity must be considered to avoid "turbo puff" transients being given a high weighting because of initial low gas velocity in, for example, a free acceleration test.

b) To define an average value of the transient (see, for example, EEC Directive 72/306 or UN/ECE Regulation No. 24)[2)] so that a peak reading may be taken. Gas velocity must be considered to avoid "turbo puff" transients being given a high weighting because of low gas velocity. Note that it is of little value to measure the peak value of a transient pulse without knowing something about its width. Damping is added so that the peak reading gives a measure of the amount of smoke in the transient.

For this, the overall response time, t_0 (see 8.2.4) or the physical and electrical response time, t_p and t_e (see 8.2.2 and 8.2.3), shall be fixed at given values and characteristics with tolerance. Also the physical delay time t_d (see 8.3) shall be fixed at a given value . All transient readings of different opacimeters can only be compared if they have similar values and characteristics of t_0 and t_d. In defining t_0, it should be noted that many opacimeters of established designs cannot achieve a t_p of less than about 0,4 s.

8.2 Response of the opacimeter

8.2.1 General

The overall response time, t_0, has two parts: the physical response time, t_p, and the electrical response time, t_e.

a) The physical response time, t_p, consists of the actual filling time of the measuring zone with smoke and inherent analogue response times (such as the response of the light detector, and signal conditioning). These are an integral part of the so-called raw opacity signal.

   For evaluation of t_p, this signal needs to be converted to the scale of the light absorption coefficient. This converted signal without further corrections is called the raw *k*-signal.

b) The electrical response time, t_e, consists of the filtering which may be analog filtering (for example a simple resistor/capacitor circuit for an exponential response) or digital filtering (for example a moving average applied to digitized samples). The filtering may be applied to the raw opacity, the opacity after conversion to that equivalent for a different effective optical path length, or after conversion from opacity to light absorption coefficient (raw *k*-signal). Note that where the filter is applied (referring to the three positions detailed above) can make a significant change to the reading, especially for fast transient signals.

Added filtering is normally included to meet a specific legislative response time.

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2) For in-service measurement of smoke during free acceleration, a physical response time of less than 0,4 s and an electrical response time between 0,9 s and 1,1 s have been defined in UN-ECE Regulation No. 24 and Directive 72/306/EEC for control of smoke from diesel engines. In ISO 8178-9, a response time of less than 0,2 s is specified for non-road engine applications.

8.2.2 Physical response time, t_p

This is the difference between the times when the raw k-signal reaches 10 % and 90 % of the full deviation when the light absorption coefficient of the gas being measured is changed in less than 0,01 s.

The physical response time of the sampling opacimeter is defined with the probe and sample line. For instruments with different systems of probe and sample lines (several probes), the physical response time shall be given for all combinations.

For opacimeters such as certain full flow types, where the measuring zone is in a straight section of a pipe of uniform diameter, the physical response can be estimated by the formula:

$$t_p = 0{,}8\ V/Q \qquad (4)$$

and indicated by the manufacturer as "calculated physical response time" [3].

For such apparatus, the speed of the gas through the measuring zone shall not differ by more than 50 % from the average speed over 90 % of the length of the measuring zone.

For all other opacimeters, the physical response time and characteristics[4] shall be determined by experiment (see 11.7.2).

8.2.3 Electrical response time, t_e

8.2.3.1 General

A given opacimeter will have more than one electrical output (e.g. recorder output, analog display, digital display).

When used in a given application, the electrical response will be that corresponding to whichever mode of output is used (e.g. when measuring transients, the peak hold of digital display may be used and the response as defined in 8.2.2.4 will be relevant).

Indicating electrical response time, it is important to specify the output, the scale (opacity or light absorption coefficient), the effective optical path length L_A, and the characteristics of the response.

8.2.3.2 Recorder output response time

The recorder output will normally be the raw opacity signal (without additional filtering and transformation). If the output is in the k-scale, it is the physical response time.

The recorder output response time is the difference between the times when the apparatus recorder output signal goes from 10 % to 90 % of full deviation, when the opacity or the light absorption coefficient is changed in less than 0,01 s.

8.2.3.3 Analog display response time

Where the output is also indicated on an analog display, the "analog display response" is defined as the time taken for the display indication to go from 10 % to 90 % of full deviation when the opacity or the light absorption coefficient is changed less than 0,01 s.

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3) The factor 0,8 is used to give a response time value more comparable to that which might be determined experimentally where the rise time from 10 % to 90 % is used.

4) Long response times and different characteristics may influence the result.

8.2.3.4 Digital display response time

Digital displays are not considered suitable for displaying transient readings except to display captured peaks. The peak will be that of the signal with any additional filtering applied. The digital response time is the difference between the times when result goes from 10 % to 90 % of the full deviation when the opacity or the light absorption coefficient is changed in less than 0,01 s.

For numerical filtering, different algorithms can be used, for example first-order recursive filter, second-order recursive filter (as Bessel filter), moving arithmetic average. The filter can consist of two parts: a primary filter to adjust for different physical response times, and the main electrical filter. The specific design of the filter, the scale (opacity, light absorption coefficient with or without corrections due to temperature and pressure) in which the filtering is applied, and the filter parameters (type, constants) shall be indicated.

8.2.4 Overall response time, t_0

This is the combined physical and electrical response time and can be estimated by the formula:

$$t_0 = \sqrt{{t_p}^2 + {t_e}^2} \qquad (5)$$

The response time, t_0, defines the fastest transient for which the apparatus should be used for making measurements of the opacity peak or variation with time.

8.3 Physical delay time, t_d

In apparatus with a measuring chamber, the smoke passes through the probe, the sample line and sometimes a valve before it enters the measuring zone. The physical delay time, t_d, defined here is the difference between the times when smoke enters the probe and when it arrives in the measuring zone.

The physical delay time, t_d, depends on the exhaust diameter, gas velocity, probe diameter and sample line design. When the gas velocity changes rapidly (e.g. in free acceleration test), the physical delay time may affect the peak value of a transient test. For example, for a very short delay time the meter will be sensitive to the *time* the smoke is at the sample point; for a long delay time the gas may be at constant velocity when the smoke passes through the measurement chamber and the meter will be sensitive to the *amount* of smoke.

8.4 Temperature response time, t_T

When an opacimeter is declared suitable for transient tests, and when the conversion of the light absorption coefficient k to 373 K is required, it is important that the temperature transient of the gas in the measuring chamber be adequately known.

Using temperature sensors, the temperature response time, t_T, is characterized by the thermal time constant of the device for measuring temperature and the gas velocity. This thermal time constant is the time for the temperature indicator to read from 10 % to 90 % of the difference between the initial and the final state when, with a representative amount of air flowing through the apparatus instead of exhaust gas, a sudden change of temperature of this air is made (e.g. by switching between air flows of different temperatures). The amount of gas shall be less than or equal to the amount of exhaust gas during the test. The temperature response time shall not be above the overall response time, t_0.

As an alternative to a rapid response temperature sensor, the temperature of the exhaust gas entering the opacimeter may be controlled to be constant to ± 5 K. For example, in the case of a sampling-type opacimeter, suitable heating or cooling of the sample line may stabilize the temperature of the sample entering the opacimeter. Such heating or cooling shall not cause significant separation of soot from the sample.

8.5 Peak hold

For transient conditions, the apparatus shall provide for the maximum opacity, or k reading, to be stored for at least 5 s and allow instantaneous cancellation of the value stored. This value stored shall not decay by more than 1 % during this time. The peak hold control shall be able to be switched out of the circuit.

9 Specifications concerning specific opacimeters and their installation

9.1 Sampling opacimeter

9.1.1 Probes and sampling pipes

9.1.1.1 Only the probes and sampling pipes provided by the manufacturer of the opacimeter shall be used. If several probes are necessary, precautions shall be taken to ensure that the user utilizes the appropriate probes and pipes.

9.1.1.2 The probes shall be equipped with systems to fix them at the exhaust pipe.

9.1.1.3 It is recommended to install the probe in a straight section of the exhaust pipe, with the straight part of the exhaust pipe upstream of the probe entrance corresponding to at least six times the diameter of the pipe, and downstream at least three times the diameter of the pipe with a minimum of 300 mm. If this recommendation is not followed, it shall be demonstrated that the instrument is receiving a valid sample of smoke.

The entrance of the probes shall be introduced in the exhaust pipe with a minimum distance of 50 mm. The probe shall be a tube with an open end facing upstream, on or near to the axis of the exhaust pipe.

In the case of large exhaust pipe (e.g. of more than about 250 mm diameter), it may be difficult to respect the requirements concerning the length of straight pipe. In such cases an alternative sampling arrangement may be used provided it has been established that the alternative ensures a representative sample.

9.1.1.4 The sample probe shall have a diameter which ensure a representative sampling and a correct flow through the opacimeter

9.1.1.5 For smoke measurement on vehicles, the probe may be installed off the axis of the tail pipe, but the clearance with the wall of the tail pipe shall be at least 5 mm or 10 % of the inner diameter of the probe equivalent diameter, whichever is the larger.

9.1.1.6 The connection of the opacimeter to the exhaust pipe shall not affect the engine performance; this shall be deemed to be achieved if the increase of the back pressure by the probe is less than 1 kPa.

9.2 In-line full-flow opacimeter

Sharp bends should be avoided to prevent the accumulation of soot.

It is recommended that no change in the exhaust diameter be allowed within three exhaust diameters before and after the measuring zone and that within six exhaust diameters upstream of the measuring zone no change in exhaust diameter may exceed a 12° half angle.

A pipe gradually convergent before the measuring zone is advisable to accelerate and stabilize the flow lines. Pipes with divergent cross-sections before the convergent section and/or after the measuring zone are acceptable providing that changes in exhaust diameters do not exceed a 12° half angle.

Should a convergent pipe be used before the measuring zone, then a smooth convergence of greater than 12° half angle is allowed.

Generally, it is not convenient to use a cooler. If a cooler is not used, the reading should be corrected for temperature or the temperature of the exhaust recorded.

Convergent sections shall not affect the engine performance. This shall be deemed to be achieved if the increase of the back pressure by the probe is less than 1 kPa .

9.3 End of line (plume-type) opacimeter

The opacimeter shall be mounted centrally to the plume as close to the end of the pipe as possible. The centre of the light beam shall not be more than 20 mm or 1/3 pipe diameters (whichever is the smaller) from the end of the pipe. The distance of the light beam from the end of the pipe shall be recorded.

Plume-type opacimeters are not recommended for use with tailpipes of more than 150 mm diameter.

Other general precautions to be observed are the following:

— the opacimeter should be mounted so as to minimize vibrations;

— precautions should be taken to avoid influencing the shape of the plume (e.g. by any exhaust extraction systems).

9.4 Opacimeter for free-acceleration tests

9.4.1 Free-acceleration test

The complete free-acceleration test typically consists of six phases. A brief non-exhaustive outline of these phases is as follows.

a) Preparation of vehicle: The engine is at normal temperature, all settings of the engine are correct (e.g. low idle and maximum speed), exhaust pipe has no leaks, the gear is set at neutral and all other consumers of energy are turned off (e.g. air conditioning, light).

b) Preparation of apparatus: The apparatus has passed all necessary checks, apparatus is stabilized, zero and full scale are adjusted, the apparatus is connected to one exhaust pipe.

c) Conditioning of the exhaust system: The conditioning consists of free-acceleration cycles or specified phases with constant speed; the smoke shall pass through the measuring chamber.

d) Free-acceleration cycles: The free-acceleration cycles shall be performed until one of the following completion criteria is fulfilled:

   — the arithmetical difference of a certain number of results from each cycle (in k or N) does not exceed a limit;

   — the certain number of cycles has been achieved;

   — the user interrupts the procedure;

   — the apparatus detects an error (e.g. communication, temperature).

e) Validation of the test:

   — the cycles were completed correctly;

   — zero has not drifted;

   — results of the test are calculated;

   — results are compared with default values, if applicable.

f) Reporting the result: The results and/or a decision are shown and printed as a test report. The test report contains at least the following data: place, date and time at which the measurement is performed; the identification of the apparatus (serial number, engine or vehicle); the identification of the engine; the results of the measurement.

The numerical details are defined in 10.1.6.

9.4.2 Free-acceleration cycle

The free-acceleration cycle consists of five phases. Briefly, these phases are as follows.

a) Rest period: The apparatus demands the engine to keep idle speed for a certain time.

b) Start an acceleration: The measurement of smoke starts. The user is instructed to push the throttle fast for full speed within 5 s. If no acceleration is recognized the cycle is aborted.

c) Accelerating: The engine rapidly increases speed, a smoke peak is produced in the engine and passes through the exhaust pipe into the opacimeter.

d) Constant maximum speed: The speed stabilizes as the engine governor acts. Maximum speed shall be maintained for a certain period. Smoke measurement is terminated after a defined period.

e) Return to idle speed: The user is instructed to release the throttle. The result (e.g. peak value) is calculated from the measured smoke data.

9.5 Installation of opacimeters in a test bench

9.5.1 General

A butterfly valve or other means of increasing the sampling pressure may be placed in the exhaust pipe downstream from the sampling probe, on the condition that this does not affect the engine performance. Should the latter not be the case, a sufficient length of a larger-diameter exhaust pipe shall be provided for installation. The recommended minimum length between the probe entrance and the valve is three pipe diameters.

The connection of the opacimeter to the exhaust pipe shall not affect the engine performances. This shall be deemed to be achieved if the increase of the back pressure by the probe is less than 1 kPa. The wall temperature of the whole gas-containing system up to and including the measuring chamber shall be sufficiently above the dew point of the exhaust gas to prevent condensation.

The exhaust gas temperature will usually be above the dew point but caution may be necessary when the exhaust and/or ambient temperatures are low, the engine is not fully warmed up, or the sulfur content of the fuel is high. Also, where a heat exchanger is fitted as part of the engine installation, the exhaust gas after the heat exchanger may need to be heated to vaporize any condensed droplets.

If necessary, an expansion tank of sufficient capacity to damp the pulsations, and of compact design, may be incorporated in the sampling line as near to the probe as possible.

The design of the expansion tank and of the whole sampling system shall not unduly disturb the composition of the exhaust gases.

The connecting pipes between the probe, the expansion tank (if required) and the opacimeter should be as short as possible. The temperature and pressure requirements specified in 7.3.6 and 7.3.7 should be satisfied.

The material of the connecting pipes and the opacimeter shall withstand the temperatures prevailing and shall not emit parasitic smoke.

A check should be carried out during the test to ensure that the requirements of 7.3.6, concerning the pressure and those of the 7.3.7, concerning the temperature in the smoke chamber, are satisfied, if necessary.

Sharp bends or other components where soot might accumulate shall be avoided.

If necessary, the exhaust pipe shall be extended.

Joints in the connecting pipes between the exhaust pipe and the opacimeter shall not allow air to enter from outside.

It is recommended that the pipe system be inclined upwards from the exhaust pipe to the opacimeter.

NOTE Considering the size of the particulate component of the smoke (equivalent average size of 0,3 µm), the behaviour of these particulates is like gas; for these reasons, considerations concerning dimensions and pipe systems are not mandatory.

9.5.2 Specifications concerning transient tests

When an opacimeter is used for transient tests (particularly for sample-type apparatus), additional precautions may need to be taken to ensure that the manufacturer's specified limits are respected (e.g. pressure, physical response time, dew point). Precautions shall also be taken in terms of sample line length, diameter and presence (or otherwise) of a damping chamber, since these may significantly affect the overall response of the system (physical response time and delay).

10 Data and instrumentation requirements

10.1 Example of specific requirements for sampling opacimeters

Unless alternative requirements are specified by national authorities, the following requirements are recommended for use.

10.1.1 Physical response time, t_p (see 8.2.2)

— $t_p < 0{,}4$ s with a gas velocity of 20 m/s in all exhaust pipe diameters (range 40 mm to 100 mm),

— $t_p < 0{,}3$ s with a gas velocity of 40 m/s.

10.1.2 Electrical response time, t_e (see 8.2.3)

A numerical filter shall be performed with a recursive first-order filter in the opacity scale with optical path length of 430 mm and a response time of $t_e = 0{,}9$ s. A primary electrical filter shall be superimposed with an electrical time constant $t_e < 0{,}4$ s in the opacity scale with $L_A = 430$ mm. This primary filter shall be chosen to adjust for fast physical response times.

10.1.3 Overall response time, t_0 (see 8.2.4)

Requirements should only be defined if physical and electrical response time are not defined.

10.1.4 Physical delay time, t_d (see 8.3)

The delay time for apparatus used for transient conditions shall be greater than 1 s for any probe and pipe configuration and 20 m/s in exhaust tubes.

10.1.5 Periodicity of in use-checks

a) Calibration with a screen or neutral optical density filter shall be demanded at least every 7,5 days (see 6.2.5.2 and 7.3.5).

b) Calibration of the device for measuring pressure and temperature shall be required every 6 months (see 7.3.6 and 7.3.7).

c) A check of the device for protecting the optics and defining the effective optical path length shall be required every 6 months (see 7.3.6).

10.1.6 Procedure of free-acceleration test

The following parameters define the free-acceleration test procedure [the letters a) to f) refer to 9.4.1].

a) The checks listed are performed.

b) The checks listed are performed

c) For cleaning, two free-acceleration cycles shall be performed.

d) Additional parameters for the free-acceleration cyle: The rest period lasts between 15 and 30 s. The maximum speed time lasts between 1 s and 3 s and, if it is too short, the cycle is not accepted. The result of the cycle is a peak reading of light absorption coefficient.

Additional completion criterias: The arithmetical difference between the highest an lowest of last four peak light absorption coefficients (span) does not exceed 0,25 m^{-1} if the average coefficient is less than 2 m^{-1} and 12,5 % of the average coefficient if the average coefficient is greater than 2 m^{-1}. The maximum number of accelerations is less than 15.

e) Additional validation criterion: Zero drift shall be less than 0,05 m^{-1}.

f) The result of the test consists of the average light absorption coefficient of the four last values. The results from each cycle and the arithmetic average of the last four results shall be printed. If the validation criteria are not fulfilled, a report with the invalid test results shall be printed.

10.2 Data requirements

Data to be supplied by the manufacturer (if applicable) are as follows.

a) The effective optical path length of the smoke column under partial or full-flow conditions representing the recommended lower limits of temperature and pressure of the exhaust gas and the higher limit of the scavenge air pressure (if applicable) and normal test-bed ambient conditions.

b) Limits of sample pressure at the inlet to the smoke chamber and limits of pressure in the measuring zone of in-line instruments.

c) Limits of scavenge air delivery (if applicable). These should include setting instructions.

d) Limits of temperature (e.g. ambient air and exhaust sample) giving the position of temperature measurement and their relation to the mean temperature of the exhaust gas in the smoke chamber.

e) Limits of leakage of the scavenge air from the opacimeter casing and the conditions of measurement (if applicable).

f) Instructions relating to dimensional limits on fittings which may be used, giving equivalent orifices (if applicable).

g) The flow data are:

   1) in the case of a sampling opacimeter:

      i) total sample flow to the opacimeter, as a function of pressure at the inlet to the smoke chamber with exit conditions in accordance with 10.2 a) and at the limits of scavenge air pressure given in 10.2 c),

      ii) sample flow through the smoke chamber, as a function of pressure at the inlet to the smoke chamber with exit conditions in accordance with 10.2 a) and at the limits of scavenge air pressure given in 10.2 c). This information is only required when a pressure relief valve is fitted in the opacimeter upstream of the smoke chamber;

   2) in the case of a full-flow opacimeter: maximum and minimum flow rates for correct operation.

h) Limits of operation of light source (limits of voltage at the contacts of the light source and instructions regarding lamp life).

i) Light source and receiver temperature above or below which the output characteristics change significantly.

j) Light source and receiver spectral characteristics, including its filter (if applicable).

k) Limits of supply voltage within which the opacimeter will operate satisfactorily and will have the required accuracy. Separate limits for lamp and blower shall be given if these have separate power supplies.

l) Technical description of the opacimeter, including an electrical circuit diagram and dimensioned drawings of the smoke chamber and adjacent areas (e.g. passages for air and smoke) with tolerances where necessary (e.g. where there are adjustable elements).

m) Information on servicing of the opacimeter, including recommended intervals between cleaning. Any special operating precautions particular to the given design including whether the opacimeter is designed for continuous or intermittent operation. In the latter case, the time for which smoke must be passed through the opacimeter before a reading may be taken and the maximum test time for which smoke may be passed without a "zero" check.

n) Physical response times in terms of:

   1) sampling opacimeter: physical response times corresponding to gas velocities at the exhaust tubes defined according to 10.1.1 for the appropriate probes and sample lines designed by the manufacturer;

   2) full-flow opacimeter: physical response time as a function of gas flow.

o) Electrical response time, algorithm or electrical circuit diagram with all their parameters and (if applicable) display response time (for specification see 8.2.3).

p) Temperature response time (for apparatus measuring light absorption coefficient; see 8.4).

10.3 Instrumentation requirements

10.3.1 Apparatus shall (if applicable) be fitted to measure the following.

a) Pressure of exhaust gas at inlet to the smoke chamber or in the smoke chamber as applicable.

b) Temperature at the point specified by the manufacturer for measurement of gas temperature.

c) Pressure of scavenge air (if applicable).

d) Temperature of exhaust gas upstream of the by-pass (if applicable).

e) Voltage at the lamp (not required when a green LED is used).

f) Output of the receiver circuit (i.e. for indicating the opacity of the exhaust gas).

10.3.2 Controls shall be fitted for the following (if applicable).

a) Sensitivity of the receiver circuit.

b) Flow of scavenge air (direct or indirect measurement).

10.3.3 Separate items for checking purposes must be provided as follows.

a) Neutral density filter for checking the accuracy of the apparatus.

b) Orifice (or equivalent) for checking leakage (when scavenge air is used).

c) Orifice (or equivalent) for checking pressure drop of waste pipes.

11 Verification of opacimeter types

11.1 Introduction

This clause specifies the procedures which shall be adopted in order to verify that a given opacimeter type complies with clauses 6 to 10. All parts do not apply to all opacimeters and the applicability of any given clause will depend on the details of the opacimeter design including whether the opacimeter is:

- full flow or sampling;
- for measurement of opacity only or for measurement of the light absorption coefficient;
- for steady-state measurement or also for transients.

Where possible each heading includes a reference to the particular clause in clauses 6 to 10 to which the text refers.

11.2 General considerations

In order to verify that an opacimeter type complies with the specifications, it is necessary first to check that certain instruments and controls required by the specification are fitted to the opacimeters and that certain operational limits and data are specified by the manufacturer. The verification test then consists of checking that the characteristics of the instruments are as required by the specification and that, within the limits specified by the manufacturer, the opacimeter does, in fact, satisfy the performance requirements of the specification. For the verification tests, certain instruments may be needed in addition to those normally fitted to the opacimeter.

In areas where well-known experimental techniques already exist (e.g. optical and electrical), the tests are not described in detail, but in other cases detailed instructions are given. These instructions may not, however, cover all possible designs of opacimeters and test set-ups; alternative methods will, therefore, be accepted provided that they are equivalent in accuracy and comply with the response requirements of the described method. Wherever recorders are used, it is essential that any effect of the circuit be taken into account.

A type of opacimeter which does not comply with some of the specifications of this International Standard can be accepted if this non-compliance is compensated for. This compensation shall be checked either by calculation or by comparison with a reference opacimeter.

For a specific application, an opacimeter type may not comply with some particular specifications of this International Standard if these specifications are not necessary for that specific application.

11.3 Data supplied by the manufacturer

Check that the data supplied by the manufacturer covers the items required by 10.2 of the specification.

11.4 Instrumentation requirements

Check that the instrumentation requirements of 10.3 of the specification are met by the instruments from the manufacturer.

11.5 Instrument verification

11.5.1 Resolution and scale (see 6.1.2 and 7.2)

Check that the resolution and the scale of the indicator(s) meets the requirements of 6.1.2, 7.2.4 and 7.2.5, as appropriate.

11.5.2 Light source (see 6.2.2)

Check that over the indicated conditions (e.g. the voltage at the contacts of the light source) the colour temperature of the light source is between 2 800 K and 3 250 K, or verify that a green LED is used by checking the spectral peak (colour).

11.5.3 Light receiver response to different wavelengths and temperatures (see 6.2.3)

Check that the combined receiver and filter characteristics have a maximum response in the range 550 nm to 570 nm, and less than 4 % of that maximum response below 430 nm and above 680 nm, or verify that a green LED is used in conjunction with a photodiode; since the wavelength is set by the green LED, it is not necessary to check the photodiode when used with a green LED.

Check that the response of the light source/receiver is not changed by operation at the maximum temperature specified by the manufacturer.

11.5.4 Accuracy of measuring circuit and calibration (see 6.1.3, 6.2.5, 7.2.6 and 7.3.5)

11.5.4.1 Check that the zero of the apparatus can be satisfactorily adjusted, that negative values are indicated and that, for example, with the light source switched off, the opacity indicator reading is 100 % irrespective of whether the measuring circuit is connected or not. The zero adjustment should be checked over the range of supply voltages indicated by the manufacturer.

11.5.4.2 Confirm that the zero setting drifts less than 0,5 % or 0,025 m^{-1} over 60 min or over the test time specified by the manufacturer, whichever is less.

11.5.4.3 Check the accuracy of the opacity scale at a minimum of three points approximately uniformly spaced between, 5 % and 60 % opacity. Recommended values are approximately 10 %, 25 % and 50 %. Repeat this test with the apparatus adjusted at different levels of light intensity (simulation of soiled optics).

This check may be done on an optical bench or by using screens of neutral density, know to an accuracy of 1 % opacity, or by other suitable equivalent methods. The opacity scale should be accepted as satisfactory if the error of the scale is always less than 2 % opacity. Care shall be exercised to make sure the screen is perfectly clean with no scratches. This test should be made with the normal and the maximum receiver temperatures given by the manufacturer.

For apparatus where the full scale represents less than 60 % opacity, the three intermediate screens should be approximately uniformly spaced between zero and full scale for the particular apparatus.

NOTE When using screens with a known density, account should be taken of the fact that the light passing through the screen is not exactly proportional to its density, since it is also influenced by reflection on the two borders of the screen between glass and air.

11.5.4.4 Confirm that the k-reading of the apparatus without the temperature and pressure corrections (see 7.3.5) conforms to the opacity reading modified by the effective optical path length of the opacimeter per the formula in 3.4 to within 0,05 m^{-1} at each of the three points checked in 11.5.4.3.

11.5.5 Optical design (see 6.2.4)

Check, from the technical description of the apparatus given in 10.2 l) and from actual tests, that the optical device is designed so that the opacimeter is in accordance with the requirement of 6.2.4. Check that the optical components of the opacimeter submitted for test and their dimensional positions comply with the description.

11.5.6 Preconditioning (see 6.1.8)

The test given in 11.5.4.3 should be performed immediately after preconditioning.

11.5.7 Electromagnetic and climatic compatibility (see 6.1.9)

Tests according the standards mentioned in 6.1.9 should be performed. The requirements of 11.5.4.3 shall be applied.

11.6 Verification of basic and design specifications

11.6.1 Temperatures checks (see 7.3.7)

11.6.1.1 Evaluation of temperature distribution in sampling type opacimeters

11.6.1.1.1 Objective

In order to determine the light absorption coefficient of exhaust gas at 373 K, it is necessary to show that the temperature indicator provided by the manufacturer does in fact assess the mean temperature of the gas in the measuring chamber. This can be shown by comparing the reading of the temperature indicator with the results of measurements of temperature distribution within the smoke chamber.

11.6.1.1.2 Preparation for test

For measurement of temperature distribution, arrangements shall be made for measurement of temperature a different points along the centreline of the smoke chamber. Any temperature sensor shall be held in a holder which provides good heat insulation and does not unduly affect the flow gases. An example of a satisfactory method is to traverse the centreline of the smoke chamber with a thermocouple where the wires, of about 0,1 mm diameter, are joined end to end. With this system, however, it may be necessary to use a dummy light source and receiver with holes drilled to allow passage of the wire.

11.6.1.1.3 Test procedure

With the opacimeter supplied with exhaust gas or heated air, measure the temperature distribution, point by point, along the centreline of the smoke chamber, including the scavenge air temperature near the mixing zone, at sufficient points to establish the temperature distribution under the following stabilized conditions:

a) minimum sample temperature and minimum sample flow recommended by the manufacturer (minimum sample pressure and maximum scavenge air pressure);

b) maximum sample temperature and maximum sample flow recommended by the manufacturer (maximum sample pressure and minimum scavenge air pressure).

11.6.1.1.4 Evaluation

a) Plot the temperature distribution along the centreline of the smoke chamber and, for opacimeters which use scavenge air, adjust the temperature distribution for the presence of air mixing with the smoke by the method given in annex A and assess as follows.

b) Calculate the mean temperature, T_a and T_b, under the two test conditions and verify that they agree within 5 K with the temperature derived from the indicator provided by the manufacturer.

c) Verify that, under the test conditions of 11.6.1.1.3, the temperature of the test gas before mixing with scavenge air is not less than 343 K.

d) Verify that, under the test condition of 11.6.1.1.3, the maximum mean temperature does not exceed 553 K.

e) Find the distance, l_m (from the point of smoke entry), on the temperature traverse for test conditions according to 11.6.1.1.3, at which the indicated temperature equals the mean temperature. For the purposes of other parts of the verification test, the temperature at this point will be deemed to be equal to the mean temperature of the sample gas in the smoke chamber. However, for opacimeters with a central entry to the smoke chamber, determine l_{m1} and l_{m2} for the two halves of the smoke chamber separately. For the purposes of other parts of the verification test, the mean temperature in the smoke chamber will be deemed to be the mean reading of two thermocouples, one in each half, mounted at a distance $0,5(l_{m1} + l_{m2})$ from the centre. A suitable design of thermocouple is given in Figure 3.

11.6.1.2 Evaluation of temperature distribution in full-flow opacimeters

11.6.1.2.1 Objective

In order to determine the light absorption coefficient of exhaust gas at 373 K, it is necessary to show that the temperature indicator provided by the manufacturer does in fact assess the mean temperature of the gas in the measuring chamber. This can be shown by comparing the reading of the temperature indicator with the results of measurements of temperature distribution within the smoke chamber.

11.6.1.2.2 Preparation for test

For measurement of temperature distribution, arrangements shall be made for measurement of temperature at different points along the centreline of the smoke chamber. Any temperature sensor shall be held in a holder which provides good heat insulation and does not unduly affect the flow of gases.

11.6.1.2.3 Test procedure

With the opacimeter supplied with exhaust gas or heated air with a temperature between 373 K and 553 K, measure the temperature, point by point, along the centreline of the smoke chamber, including the scavenge air, at sufficient points to establish the temperature distribution under the following stabilized conditions:

a) minimum gas pressure and maximum scavenge air pressure (if applicable);

b) maximum gas pressure and minimum scavenge air pressure (if applicable).

11.6.1.2.4 Evaluation

Plot the temperature distribution along the centreline of the smoke chamber and, for opacimeters which use scavenge air, adjust the temperature distribution for the presence of air mixing with the smoke by the method given in annex A. Calculate the mean temperatures, T_a and T_b, under the two test conditions and verify that they agree to within 5 K with the temperature derived from the indicator provided by the manufacturer.

11.6.1.3 Temperature of sampling line and housing of sampling-type opacimeters

11.6.1.3.1 Objective

In order to prevent condensation and excessive soot deposition, it is necessary to show that the temperature in the probe, in the sampling pipe and in the measuring chamber were sufficiently above the dew point. For steady-state applications this can be shown by measuring the minimum sample temperature in the measuring system at the minimum sample pressure and a specified sample temperature. Also, for measuring transients, the time between the start of sampling and achieving the minimum temperature shall be considered.

11.6.1.3.2 Preparation for test

Thermoelements shall be fitted at the point of lowest sample temperature between the probe and the smoke chamber. They shall be connected to a recorder or equivalent instrument with frequency response of about 1 s and a chart speed of at least 1 mm/s. The probe shall be connected to a three-way valve. Exposure of the sample line to wind shall be prevented. Hot air at a temperature of 373 °C at a flow rate for a velocity of 30 m/s in the corresponding exhaust tube shall be available at the three-way valve.

11.6.1.3.3 Test procedure

The sample line shall be at a temperature of 293 K. The temperature shall be continuously recorded. On switching the three-way valve, the hot air flushes the sample line and the smoke chamber until the temperature of the whole system is stabilized.

11.6.1.3.4 Evaluation

The temperature curves shall be characterized by two parameters. First, the temperature of the stabilized system, which shall be above 343 K. Second, the time between start and reaching a temperature of 343 K. This time shall be shorter than 60 s or the time the instrument demands for preconditioning before each measurement, whichever is the shorter.

11.6.2 Steadiness of reading (see 7.3.1)

11.6.2.1 Objective

In opacimeters using scavenge air, there may be a relatively large region of mixing of air and exhaust gas at the ends of the smoke chamber. This mixing may cause vorticity and a variation of effective length, leading to unsteadiness and possible error of reading. Similarly, when flow in the smoke chamber is divided, for example by a central entry, there is a possibility of a variation of flow between the two halves of the chamber which will also lead to variation in opacimeter readings. The extent of these effects shall be checked. Other designs of opacimeter, for example full-flow designs, may also exhibit unsteadiness of reading. Therefore, unsteadiness shall be checked for on all designs.

11.6.2.2 Preparation for test

The signal from the output terminal (see 6.2.6) shall be connected to a recorder or equivalent instrument with a frequency response of about 1 s to 90 % of the full scale and a chart speed of at least 10 mm/s. The sensitivity shall be such that 4 mm corresponds to not more than 0,5 % opacity at approximately 20 % opacity. To ensure a constant opacity (for sampling apparatus) the exhaust sample may be passed through a damping chamber with a volume of at least 20 times the flow through the sample line in 1 s and shall be drawn from an engine that has a firing frequency of at least 5 000 periods per minute.

Full-flow apparatus may be run under steady-state conditions without the damping chamber.

11.6.2.3 Test procedure

Record the signal from the output terminal for about 10 s under steady-state conditions while constant smoke is passed through the opacimeter (for sample apparatus, operate at the upper and lower sample pressures). For apparatus which only measure opacity, the smoke should correspond to about 20 % opacity. For apparatus which measure the light absorption coefficient, the smoke should correspond to about 1,7 m^{-1} or 90 % of the full scale if the full scale is less than 2 m^{-1}.

11.6.2.4 Evaluation

The steadiness shall be deemed satisfactory if the difference between the lowest and highest recorded values is less than 1 % opacity or 0,15 m^{-1} or 8 % of the full scale if the full scale is less than 2 m^{-1}.

11.6.3 Internal reflection and diffusion (see 7.3.3)

11.6.3.1 Objective

If the internal surfaces of the smoke chamber are reflective or not sufficiently closed to external light, then unwanted reflected or diffused light will be received by the receiver. The extent of this effect shall be checked by the method given in 11.6.3.2 or an equivalent method.

11.6.3.2 Preparation for test

11.6.3.2.1 The principle of the method is to differentiate between reflected or diffused light and direct light by focusing the direct light from the light source with a lens. Light from diffusion and reflection effects may then be defined as the light which crosses the plane of focus outside the area covered by the focused image of the light source. For example, if the image is a 10 mm diameter circle, any light crossing the focal plane outside of the 10 mm diameter circle must be reflected or diffused light. A screen, placed at the plane of focus, with a central hole slightly larger than the light source image, will allow the light forming the image to pass but will stop most of the reflected and diffused light. Measurement of the light with and without the screen gives, by difference, the reflected and diffused light[5]. Preparation for the test requires replacement of the receiver by a lens of focal length and diameter about equal to the diameter of the sensitive part of the receiver, provision of a matt black screen with a central hole slightly larger than the image of the light source formed by the lens, and provision to move the receiver to collect light which comes through the hole in the screen. Arrangements shall be made to allow measurement under the two following conditions.

11.6.3.2.2 The light source, lens, screen and light receiver shall be fitted in the opacimeter (for example as in Figure 4) with the smoke chamber in the normal condition (this should not be a "new" condition, but the inside surfaces of the smoke chamber should be "conditioned" by passing smoke through the opacimeter in normal operation). Arrangements should be made for easy removal of the screen from the light path. It may be necessary to modify the opacimeter casing so that the screen and photo-electric cell can be accommodated inside the opacimeter casing and the opacimeter can be operated normally in terms of passage of smoke and (where relevant) scavenge air.

11.6.3.2.3 The light source, lens, screen and light receiver shall be set-up in the same relative positions as in 11.6.3.2.2 but in a non-reflecting environment. In a sampling-type opacimeter this may be achieved by removing the smoke tube and part of the casing, painting the inside of the remainder of the casing matte black and carrying out the rest in a room with matte black walls.

11.6.3.3 Test procedure

11.6.3.3.1 With the light source, lens and screen arranged as in 11.6.3.2.3, set the electrical circuit sensitivity to give and indicator reading of 1,7 m^{-1} units when the lamp is switched on. Remove the screen and note the new reading. Repeat to give at least four pairs of readings.

11.6.3.3.2 With the opacimeter arranged as in 11.6.3.2.1 and the screen in position, set the electrical circuit sensitivity to give an indicator reading of 1,7 m^{-1} units. Remove the screen and note the new reading. Repeat to give at least four pairs of readings.

11.6.3.3.3 With the opacimeter arranged as in 11.6.3.2.3 and the screen in position, set the sensitivity to give an indicator reading of zero when the smoke chamber is filled with clean air. Pass smoke of about 1,7 m^{-1} through the apparatus and note the indicator reading. Remove the screen and note the new readings. Repeat to give at least four pairs of readings. For this test a large damping volume may be required in the sample line to smooth out effects of engine variations. Recording of the receiver output is also recommended.

11.6.3.4 Evaluation

If the change of readings under the three conditions are Δa, Δb and Δc (each an average of at least four values) then the test set-up is satisfactory if:

$$\Delta a < 0{,}1\ m^{-1}$$

NOTE This will mainly be light scattered from the lens surface.

The opacimeter reflection and diffusion characteristics are satisfactory if:

$$\Delta b - \Delta a < 0{,}65\ m^{-1} \text{ and}$$

$$\Delta c - \Delta a < 0{,}1\ m^{-1}$$

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5) It should be noted that this light does not only come from reflection and diffusion effects in the opacimeter but may also come from light scattering at the surface of the lens. This scattered light may be reduced by use of a bloomed lens but some remains as a baseline which has to be taken into account during calculation.

11.6.4 Light receiver temperature (see 6.2.3 and 6.2.4)

11.6.4.1 Objective

Above a certain temperature the sensitivity of the receiver/light source combination may change. This temperature is given by the manufacturer and the objective of this test is to verify that the maximum temperature specified by the manufacturer is not exceeded under the most severe operating conditions of the opacimeter. For this test, a thermocouple resting on the surface of the receiver assembly shall be deemed to indicate the receiver temperature.

11.6.4.2 Preparation for test

A thermocouple shall be placed on the surface of the receiver as indicated in 11.6.4.1. Arrangements shall be made to supply the opacimeter with exhaust gas or air at the highest temperature and pressure recommended by the manufacturer. Arrangements shall be made to heat the scavenge air supply to the maximum recommended by the manufacturer (if applicable).

11.6.4.3 Test procedure

The exhaust gas or hot air shall be passed through the opacimeter, otherwise operating normally, until the temperature of the receiver has stabilized. This temperature shall be measured together with the temperature and pressure of the gas and the temperature of the scavenge air.

11.6.4.4 Evaluation

The specification is deemed to be met if the temperature of the receiver is below the maximum recommended by the manufacturer.

NOTE Some opacimeters are equipped with the ability to water cool the receivers and light sources. These may be employed if necessary by supplying the water temperature and flow recommended by the manufacturer.

11.6.5 Effective optical path length, L_A (see 7.2.2 and 7.3.4)

11.6.5.1 Objective

The effective length, given by the manufacturer, shall be checked to verify the absolute calibration of the opacimeter. It can be obtained either by comparison with an opacimeter for which the effective length is known, or by comparison of readings taken with the opacimeter operating normally and when modified so that the smoke fills a known length. In both cases it is necessary also to know the average temperature of the gas in the smoke chamber in order to permit corrections for the difference in temperature between the opacimeter operating normally and the reference or modified opacimeter.

11.6.5.2 Comparison with a known opacimeter

11.6.5.2.1 Preparation for test

The test opacimeter and known opacimeter shall be connected for simultaneous sampling. The sample to each opacimeter shall be controlled within the lower limits of temperature and the minimum sample flow recommended by the manufacturer (minimum sample pressure and maximum scavenge air pressure). Provision shall be made for measuring the mean temperature, T_1, in the smoke chamber of the opacimeter under test in accordance with 11.6.1.

11.6.5.2.2 Test procedure

Simultaneous readings shall be taken on the two opacimeters with smoke between 40 % and 60 % opacity. At least 10 readings shall be made.

11.6.5.2.3 Evaluation

For each opacity reading calculate the effective length by the formula:

$$L_{A1} = L_{A2} \times \frac{T_1}{T_2} \times \left[\ln\left(1 - \frac{N_1}{100}\right) \Big/ \ln\left(1 - \frac{N_2}{100}\right) \right] \qquad (6)$$

where L_{A1}, N_1 and T_1 refer to the opacimeter under test and L_{A2}, N_2 and T_2 refer to the known opacimeter.

The average of the L_{A1} values shall be taken as the effective length. Verify that the average effective length is statistically valid to an accuracy of ± 1 % with 95 % confidence (see ISO 2602). If this degree of confidence is not attained, then further tests shall be made until the statistical requirement is satisfied. In calculating the confidence limits, account shall be taken of the known accuracy of the reference opacimeter. The latter shall be better than ± 1 %.

11.6.5.2.4 Alternative

When it is not possible to control the sample temperature to the desired values, measurements should be made separately of the average temperature in the smoke chambers of both opacimeters. The opacimeter readings should then be corrected for the difference between the measured temperature and the average temperature in the smoke chamber corresponding to the minimum sample temperature specified by the manufacturer.

11.6.5.3 Comparison of results from one opacimeter with and without modification of operation

11.6.5.3.1 Preparation for test

Provision shall be made for rapid modification of the opacimeter from its normal operating condition (geometric effective length L_{A1}) to a condition where the test gas fills a well-defined length, L_{A2}.

With an opacimeter using scavenge air to contain the smoke column, a convenient method of modification is merely to block the scavenge air inlet so that the test gas fills the space between the light source and receiver. The surfaces defining the length, L_{A2}, will depend on the design of the opacimeter. They may, for example, be glass screens or the surface of the light source and the surface on the receiver/filter combination. In the latter case, the measurement shall be made from the surface of the light source nearest to the receiver.

For the actual test, the opacimeter should be supplied with exhaust gas of constant opacity at the lower limit of temperature and sample flow (lowest sample pressure and highest scavenge air pressure) specified by the manufacturer. The signal from the output terminal from the photo-electric cell shall be connected to a recorder or equivalent instrument with a response time of less than 1 s and sensitivity such that 4 mm corresponds to not more than 0,05 m^{-1} for smoke of opacity equal at 1,7 m^{-1}. The relationship between recorder deflection and opacity shall be determined.

To ensure satisfactory constancy of opacity, exhaust gas samples shall be passed through a damping chamber of at least 20 times the flow through the sample line in 1 s. This sampling system may require a heater to ensure satisfactory sample temperature. If not already provided, a by-pass shall be fitted to the opacimeter with the outlet adjusted so that the temperature of the sample at the by-pass is not changed by more than 5 K between the two by-pass positions.

Provision shall be made for measuring the mean temperature in the smoke chamber as described in 11.6.1. Where the modification to fill a known length involves any modification of scavenge air flow, a check should be made to ensure that this modification does not affect the light source performance (i.e. the modification does not affect zero reading) or a separate power supply to the light source shall be provided. Where the ratio $L_{A2}/L_{A1} \leqslant 1{,}25$, the mean temperature sensor position derived from 11.6.1 can also be taken as indicating the mean temperature of the smoke in both the modified and unmodified opacimeter conditions. But, when $L_{A2}/L_{A1} > 1{,}25$ the temperature indicated by the temperature sensor shall be converted to true mean temperature over the length L_{A2} by use of separately obtained data. Such data can, for example, be obtained by comparing the sensor temperature with the temperature indicated by a resistance wire cage spanning the full length L_{A2}. It is essential, however, that the comparative data be obtained under the same sequence of test conditions as used in the measurement of effective length, for example, scavenge air blanked for 10 s or 15 s following a stabilized period of normal operation.

11.6.5.3.2 Test procedure

Calibration lines should be recorded corresponding to two convenient points. Recording should then be made while test gases of different opacities are passed through the opacimeter and the opacimeter is switched from working normally to working as modified with the effective length L_{A2}. For each test, the modified conditions should be held for at least 10 s or for a time greater than the response time of the mean temperature indicator, whichever is the longer. At the end of each period of modification, check the "zero" setting with clean air.

In order to protect the receiver surface from excessive temperatures, a shield may be placed in front of it during the initial period of each modification. This shield should not be more than 1 mm from the surface of the receiver and should be completely removed during all periods of measurement. If the "zero" recorded between tests increases to more than 0,4 m^{-1}, the light source and receiver should be cleaned before further tests are made. Readings should be made with exhaust densities corresponding to levels of between 1 m^{-1} and 2 m^{-1} and at least ten readings (each reading comprising a comparison of modified and unmodified conditions) should be made.

11.6.5.3.3 Evaluation

For each recording determine:

— N_1 reading with unmodified opacimeter referred to the "zero" immediately before admitting the smoke sample;

— T_1 average temperature in the smoke chamber corresponding to opacimeter reading N_1;

— N_2 reading with opacimeter modified, taken immediately after the modification, and referred to the "zero" obtained immediately before admitting the smoke sample;

— T_2 average temperature in the smoke chamber corresponding to opacimeter reading N_2.

The effective length is then given by equation (6).

Verify that the average effective length is statistically valid to an accuracy of ± 1 % with 95 % confidence. If this degree of confidence is not attained, then further tests shall be made until the statistical requirement is satisfied.

11.6.6 Effect of sample and scavenge air pressure (see 6.1.4 and 7.3.6)

11.6.6.1 Objective

The effective length of the opacimeter may be changed by changes of sample pressure and scavenge air (where used). The operating limits claimed by the manufacturer should be verified. This test also enables a check to be made on the pressure in the measuring chamber.

11.6.6.2 Preparation for test

The same test method should be used as for the measurement of effective length (see 11.6.5). Additionally arrangements should be made to measure the maximum pressure/depression in the smoke chamber. This latter provision may be omitted if it can be shown from consideration of the sample and scavenge air pressures that the pressure in the smoke chamber does not differ from the atmospheric pressure by more than 1 kPa.

11.6.6.3 Test procedure

The effective length shall be determined by the method given in 11.6.5 with the opacimeter supplied with exhaust gas of a light absorption coefficient of about 1,7 m^{-1} and at the maximum flow (maximum sample pressure and minimum scavenge air pressure) and minimum temperature specified by the manufacturer. At least 10 readings shall be made. Note the pressure of gas in the measuring chamber unless such measurement is not required under 11.6.6.2.

11.6.6.4 Evaluation

The sample pressure and scavenge air limits claimed by the manufacturer are satisfactory if:

$$1{,}00 \leqslant \frac{\text{Effective length at maximum sample flow}}{\text{Effective length at minimum sample flow}} \leqslant 1{,}03 \qquad (7)$$

Equation (7) shall be satisfied to a statistical confidence limit of 95 %. If this degree of confidence is not attained then further tests shall be made until the statistical requirements is satisfied. The pressure in the smoke chamber is satisfactory if it does not differ from atmospheric pressure by more than 1 kPa.

11.6.7 Gas tightness of opacimeter (see 6.2.5 and 10.2.5)

11.6.7.1 Gas tightness of the by-pass valve (if applicable)

11.6.7.1.1 Objective

If the by-pass valve leaks, then, depending on the design of the opacimeter, the "zero" of the apparatus will be affected and incorrect opacimeter readings obtained. The efficiency of the by-pass valve shall, therefore, be checked.

11.6.7.1.2 Test with reduced pressure at the by-pass valve

Arrangements shall be provided for reducing the smoke pressure at the by-pass valve to below the pressure in the opacimeter. For engines connected to an exhaust main operating at ambient pressure or a slight depression, it will be sufficient to stop the engine. In other cases it may be necessary to disconnected the sample line from the probe or opacimeter, or fit (for this test only) a valve in the sample line which can be positively closed.

The by-pass valve should be set in the position so that the exhaust gas by-passes the smoke chamber. Reduce the pressure on the sample side of the by-pass until it is below the pressure on the smoke chamber side and set the opacimeter "zero". Then allow the pressure on the sample side of the valve to return to normal and pass smoke with a light absorption coefficient of about 1,7 m^{-1} through the sample system and by-pass valve (but not through the measuring zone) at a rate corresponding to the maximum sample pressure when the opacimeter is operating normally. Note the "zero" reading.

11.6.7.1.3 Test with increased pressure at the by-pass valve

Smoke with a light absorption coefficient of about 1,7 m^{-1} and a neutral optical density filter are used.

The test shall be performed in a mode where temperature compensation is turned off, because neutral optical density filter is used. The test consists of six steps, as follows.

a) Remove the probe from the exhaust, zero the opacimeter and read the value of the neutral optical density filter.

b) Connect the probe to the exhaust and flush the instrument with smoke with a light absorption coefficient of about 1,7 m^{-1}.

c) Leaving probe in the exhaust; zero the opacimeter.

d) Remove the probe from the exhaust and wait until the displayed value returns to zero.

e) Without zeroing, read the value of the neutral optical density filter.

f) For evaluation, compare the two values for the neutral optical density filter [step a) and step e)].

Repeat twice for each probe.

11.6.7.1.4 Evaluation

The by-pass valve is satisfactory if the change of reading between the two conditions is less than 0,01 m^{-1} with a statistical confidence of 95 %.

11.6.7.2 Gas tightness of the casing

11.6.7.2.1 Objective

In opacimeters using scavenge air or using a sample pressure in the measuring chamber that differs more than 1 kPa from ambient pressure, leakage of the air through joints and clearances around controls may alter the effective length. The manufacturer specifies a limit for this leakage, and it shall be verified that this amount of leakage does not alter the effective length.

11.6.7.2.2 Preparation for test

An opacimeter shall be prepared in which all joints and clearances are sealed. An adjustable "leak" shall then be provided in the casing near the waste outlet of the housing. With the leak valve shut, find the scavenge air system setting, S_1, to give the maximum allowable scavenge air flow.

Then, find the scavenge air system setting, S_2, and leak valve setting, S_v, such that the maximum leakage allowed by the manufacturer is obtained with a scavenge air flow equal to the maximum allowed by the manufacturer.

11.6.7.2.3 Test procedure

Pass smoke with a light absorption coefficient of about 1,7 m^{-1} at minimum sample pressure through the opacimeter and note the reading with leakage valve shut and scavenge air system setting S_1, and then with leakage valve setting S_v and scavenge air system setting S_2. Repeat at least four times. For ease of reading the opacimeter, the sample system shall include a damping chamber of at least five times the volume passing through the sample line in 1 s.

11.6.7.2.4 Evaluation

Average the readings with and without the leak. The difference shall not be greater than 0,025 m^{-1} with a statistical confidence of 95 %. If this degree of confidence is not attained, then further tests shall be made until the statistical requirement is satisfied.

11.6.8 Waste exit conditions (see 6.1.5 and 10.2.6)

11.6.8.1 Objective

The manufacturer has to state limits on the waste exit conditions, for example, length of pipe(s), pressure characteristics of pipes, limitation of back pressure or extraction pressure permissible on any standard pipes provided. The effect of these limits shall be tested.

11.6.8.2 Preparation for test

Arrangements shall be made so that the waste exit conditions can be rapidly varied between the limits specified by the manufacturer.

11.6.8.3 Test procedure

Pass smoke of a light absorption coefficient of about 1,7 m^{-1} through the opacimeter and note the readings with the waste exit conditions alternated between the limits. For ease of reading the opacimeter, the sample system shall include a damping volume of at least five times the volume passing through the sample line in 1 s.

11.6.8.4 Evaluation

The change of reading between the two conditions should not be greater than 0,025 m^{-1} with a statistical confidence of 95 %.

11.6.9 Effect of pre-chamber and pressure relief valve design (if applicable, see 6.1.5)

11.6.9.1 Objective

Certain opacimeters may have a pressure relief valve in a pre-chamber just upstream of the smoke chamber. This item, if in-correctly designed, could result in a modification of the exhaust gas sample by unequal division of soot by the valve. The possible occurrence of this shall be checked.

11.6.9.2 Preparation for test

The test set-up shall be as shown in Figure 5, and, to ensure satisfactory constancy of opacity of exhaust samples, the damping chamber shall have a volume of at least 20 times the volume passing through the sample line in 1 s. The need for the heater will depend on the temperature and insulation of the sampling system. Means shall be provided so that the relief valve can quickly be shut or opened.

The butterfly valve in the exhaust system shall be adjusted so that, with the relief valve operating normally, the maximum sample pressure is obtained at the opacimeter with valve A closed and valve B fully open. With the relief valve shut, find positions of valves A and B such that the sample pressure at the opacimeter is unchanged and the pressure in the damping chamber is unchanged.

The valve in the exhaust system shall not be altered. Note the positions of valves A and B. Arrangement shall be made to record the receiver output and the mean temperature in the smoke chamber (as defined in 11.6.1).

11.6.9.3 Test of procedure

With the opacimeter supplied with exhaust gas of a light absorption coefficient of about 1,7 m^{-1} and the maximum sample pressure, record the opacimeter reading and mean temperature in the smoke chamber with the relief valve operating normally (valve A shut and valve B fully open) and with it closed and valves A and B adjusted as described above. Repeat at least four times (see this operation in 11.6.9.4).

11.6.9.4 Evaluation

Correct the readings of the opacimeter for any changes of mean temperature in the smoke chamber. The pressure relief valve and pre-chamber shall be deemed to be satisfactory if the average difference between the corrected readings of the opacimeter with the valve operating and shut is less than 0,05 m^{-1} with a statistical confidence of 95 % (see 11.6.9.3).

11.6.10 Flow characteristics (if applicable, see 9.1. and 10.2.7)

11.6.10.1 Objective

This test is to measure the flow of sample gas to an opacimeter and, where a relief valve is fitted upstream of the measuring chamber, to also measure the flow of gas through the measuring chamber. This information is useful for calculating the gas velocity at the sampling probe and hence, determine the extent to which the sampling is isokinetic.

11.6.10.2 Preparation for test

The sample inlet to the opacimeter shall be connected to a supply of air sufficient to maintain the maximum pressure at the opacimeter recommended by the manufacturer. A gasmeter or orifice shall be provided for temporarily closing all relief valves fitted to the sample inlet to the opacimeter.

11.6.10.3 Test procedure

With the correct waste exit conditions and at the upper and lower limits of scavenge air pressure, measure the flow of air to the sample inlet, as a function of pressure at the entrance to the opacimeter, between the operating limits specified by the manufacturer. If a relief valve is fitted, measurements shall be made under the two following conditions:

a) with the relief valve operating normally; and

b) with the relief valve locked shut.

Record the flow of the scavenge air for information.

11.6.10.4 Evaluation

The results shall be presented as a graph of sample pressure in kilopascals against air flow in cubic decimetres per second. The temperature to which the results are referred should be stated on the graph.

11.6.11 Soiling of the light source and receiver (see 6.1.6)

11.6.11.1 Objective

Use of an opacimeter may in time lead to deposition of soot on the light source and receiver and this will affect the reading.

The manufacturer shall state the necessary intervals between cleaning, and it shall be verified that the opacimeter can be satisfactorily operated for this period without cleaning.

11.6.11.2 Test procedure

11.6.11.2.1 Opacimeters designed for continuous use: Test with constant smoke

Clean the light source and receiver. With the receiver output connected to a recorder or equivalent instrument, adjust the sensitivity of the latter to give a deflection such that a change of 0,5 % can be assessed. Pass smoke of a light absorption coefficient of about 1,7 m^{-1} or an approximately equivalent opacity at maximum allowable pressure through the opacimeter (with scavenge air, where used, set to minimum pressure) for 1 h or for whatever shorter period is claimed by the manufacturer. Stop the flow of smoke, fill the smoke chamber with clean air and note the recorder "zero" reading.

11.6.11.2.2 Opacimeters designed for intermittent use: Test with constant smoke

Clean the light source and receiver. With the receiver output connected to a recorder or equivalent instrument, adjust the sensitivity of the latter to give a deflection such that a change of 0,5 % can be assessed. Pass smoke of a light absorption coefficient of about 1,7 m^{-1} or an approximately equivalent opacity at maximum allowable pressure, through the opacimeter (with scavenge air, where used, set to minimum pressure) for at least 10 s or for the time necessary to take a reading (whichever is the longer). Stop the flow of smoke, fill the smoke chamber with clean air as for a normal zero check and note the recorder reading. Repeat the cycle of passing smoke and checking the zero throughout the interval claimed by the manufacturer, or for 12 readings (whichever is the longer).

11.6.11.2.3 Opacimeters designed for intermittent use: Test with smoke peaks

Clean the light source and receiver. Pass smoke in a similar way to a transient test procedure (e.g. free acceleration) through the opacimeter (with maximum sample pressure and minimum scavenge air). The area under the t-k plot shall be larger than 8 s/m. Repeat the cycle of passing a smoke peak and checking the zero throughout the maximum number of peak measurements in a measuring series claimed by the manufacturer, or for 12 cycles (whichever is the longer).

11.6.11.3 Evaluation

The freedom of the light source and receiver from soiling shall be deemed satisfactory in the change of zero reading during the test is less than 0,5 % opacity or 0,025 m^{-1}.

11.6.12 Division of flow (see 7.3.1.2)

11.6.12.1 Objective

In opacimeters with a central entry to the smoke chamber or when scavenging air is used on both sides of the measuring zone, it is necessary to check that the sample flow divides sufficiently equally between the two halves of the smoke chamber.

11.6.12.2 Preparation for test

Devise means (if not already provided) for altering the division of flow between the two halves of the smoke chamber or for altering the scavenging air supply to one and the other side (e.g. an adjustable vane or regulable current supply of the fans).

11.6.12.3 Test procedure

With the opacimeter supplied with exhaust gas of about 1,7 m^{-1} light absorption coefficient, note the opacimeter reading and the device setting with the opacimeter operating normally and when the division of flow is altered with the device under the following conditions:

a) minimum sample temperature and minimum sample flow recommended by the manufacturer (minimum sample pressure and maximum scavenge air pressure);

b) maximum sample temperature and maximum sample flow recommended by the manufacturer (maximum sample pressure and minimum scavenge air pressure).

For condition a), the device shall be moved over a sufficient range to include the extremes of division of flow allowed by the manufacturer (e.g. maximum difference of temperature between the two halves of the sample chamber). For condition b), the device shall be moved over the same physical range required for a).

11.6.12.4 Evaluation

From the plot of opacimeter readings against device position for condition a), determine the maximum opacimeter reading and the device positions, P_1 and P_2, which correspond to the extremes of division of flow allowed by the manufacturer. Check that the opacimeter readings at P_1 and P_2 are not more than 0,05 m^{-1} lower than the maximum reading. From the plot of opacimeter readings against device position for condition b), determine the opacimeter readings for the same physical device positions P_1 and P_2 found with condition a) and check that these reading are not more than 0,05 m^{-1} lower than the maximum opacimeter reading with condition b).

11.6.13 Specifications concerning specific opacimeters

Check that the instrument covers the specifications in clause 9 and 10.1 (if applicable).

11.7 Verification of response characteristics

In measuring transients, the most important requirements of the opacimeter are the electrical, physical and temperature responses times.

11.7.1 Velocity distribution (see 8.2.1)

11.7.1.1 Objective

Where equation (4) is used for the calculation of physical response time, it is necessary to ensure that the flow of gases in the measuring chamber is sufficiently uniform. This check is carried out by comparing the velocities at different points in the gas flow.

11.7.1.2 Preparation of test

The velocity shall be measured at five points uniformly distributed across the axis of the measuring chamber over the central 90 % of its width.

11.7.1.3 Test procedure

With the opacimeter supplied with exhaust gas or with air, measure the velocity distribution, point by point, across the axis of the measuring chamber and the static pressure of the gas in the smoke chamber under the following test conditions.

a) Pressure of the gas at the inlet to the smoke chamber corresponds to the minimum flow, d_a, indicated by the manufacturer in accordance with 10.2.7.

b) Pressure of the gas at the inlet to the smoke chamber corresponds to the maximum flow, d_b, indicated by the manufacturer in accordance with 10.2.7.

c) Pressure of the gas at the inlet to the smoke chamber corresponds to an average flow of gas

$$d_c = (d_a + d_b)/2 \qquad (8)$$

11.7.1.4 Evaluation

Plot the velocity distribution along the axis of the measuring chamber and estimate the average velocity v_a, v_b and v_c in the three types of test conditions by means of the formula:

$$\bar{v} = \frac{1}{5}\sum_{1}^{5} v \qquad (9)$$

Check that under the three types of test conditions, at each to the five points of velocity measurement:

$$\left|1 - \frac{v}{\bar{v}}\right| \leqslant 0{,}5 \qquad (10)$$

11.7.2 Physical response time (see 8.2.1 and 10.1.1)

11.7.2.1 Objective

Where the physical response time is to be measured, the method below with constant flow shall be used.

11.7.2.2 Preparation for test

Arrange that the opacimeter can be switched suddenly (in less than 0,1 s or less than 1/10 of the expected response time, whichever is the less) from a flow of clean, hot air to a flow of smoke with a light absorption coefficient of about 1,7 m^{-1} or an approximately equivalent opacity of about 90 % of the full scale if the opacimeter full scale is less than 2 m^{-1} step function). The temperature of the clean air and smoke should be similar. The reading of the opacimeter (excluding any electrical response) and a fast opacimeter as reference (e.g. full flow, with a physical response time less than 0,1 s or 1/10 of the expected t_p) shall be recorded with a response of less than 0,1 s or 1/10 of the expected physical response time, whichever is the less.

11.7.2.3 Test procedure

Record the output at the opacimeter while the flow of gas is switched from clean air to smoke. This test shall be performed at minimum and maximum gas velocity in the exhaust pipes. Recommended gas velocities are 10 m/s to 50 m/s. Recommended diameters of exhaust pipes are 40 mm to 100 mm.

11.7.2.4 Evaluation

If the smoke cannot switched from one level to the other fast enough, or if the smoke levels are not constant, the physical response time shall be calculated as follows.

a) The smoke curve at the exhaust (raw curve) is measured with an fast instrument (full flow). It is recorded with the same sampling rate as the opacimeter (opacimeter curve). The physical response time is considered as constant during the measurement, if the flow rate is constant.

b) A numerical damping algorithm is used to simulate the instrument's response. It consists of a time shift and physical damping. The dominant part in the damping algorithm is a gliding arithmetical mean in the scale of light extinction coefficient (k). The parameters of the time shift and the damping algorithm shall be applied to the raw curve. They are optimized in order to minimize the sum of the squared difference to the opacimeter curve. These parameters shall be applied for damping a theoretical step function in order to evaluate the step answer.

c) Check that the time for the step response to rise from 10 % to 90 % of the final light absorption value fulfils the requirements of 10.1.1.

11.7.3 Electrical and display responses times (see 8.2.2 and 10.1.2)

11.7.3.1 Test details

11.7.3.1.1 General

There were two ways to realise and check an electrical response time: electronic circuit or numerical treatment of the raw signal.

a) Electronic circuit: To measure the instrument's electrical response time, it is necessary to fit the optical system on an optical bench equipped with adequate devices to rapidly block or extinguish the light which work in less than 0,01 s (photographic shutter for example) and to connect the optical system to the opacimeter measuring system. In the case of a green LED, sufficiently rapid extinction of the light can be obtained by merely switching it off.

b) Numerical treatment: The A-D transformation and recording time interval must be known. The manufacturer specifies in detail the numerical algorithm with all constants.

11.7.3.1.2 Recorder output signal

The recorder or equivalent instrument output of the opacimeter should be viewed on an oscilloscope of at least 10 MHz band pass. The electrical response time is then the time taken for the output to go from 10 % to 90 % of its final value; this time shall be measured to the nearest 5 ms.

11.7.3.1.3 Analog meter output

Where an analog output (e.g. moving coil meter) is also fitted, the "display response" shall be measured by photographing the display with a camera or video recorder of sufficiently high speed to enable a time response graph to be derived. The display response is the time for the display to go from 10 % to 90 % of its final value; this time shall be measured to the nearest 20 ms.

11.7.3.1.4 Digital meter output (unless numerical raw signal treatment)

Where a digital peak hold indicator is fitted, arrangements shall be made for the shutter or other light extinction device to extinguish the light for a known and adjustable time interval.

The test then consists of noting the time interval, as it is increased, at which the displayed peak reaches 80 %[6)] of the value for full extinction. This time interval is the electrical response time of the digital display system.

11.7.3.2 Evaluation

Verify that the measured electrical and (if applicable) display response covers the specifications in 10.1.2.

11.7.4 Physical delay time (see 8.3 and 10.1.4)

11.7.4.1 Objective

In applications of transient measurements, the physical response time may change rapidly during the test. The physical delay time, t_d, then determines the actual physical response time of the arrival of a smoke peak in the measuring chamber and therefore indirectly determines the width, the area in the *t*-*k* plot and the height of the peak.

11.7.4.2 Preparation for test

A smoke detector shall be installed in the exhaust pipe (e.g. simple version of a full-flow opacimeter). The time for the smoke to go from this smoke detector position to the position of the inlet of the opacimeters shall not exceed 0,05 s. The signal from the smoke detector and the output terminal shall be connected to a recorder.

11.7.4.3 Test procedure

Fast smoke transients shall be performed for different sample flows (from lowest to highest sample pressure) and both smoke curves shall be recorded.

11.7.4.4 Evaluation

The start of the smoke shall be defined as the rising of the smoke signal over 10 % of the full deviation. The delay time is the difference between the start times of the smoke detection and the opacimeter. Check that the delay times for the sample flows is within the range of flows specified.

11.7.5 Temperature response time (see 8.4)

11.7.5.1 Objective

When using the temperature of the exhaust gas in the evaluation of the test, it is important to know the response time of the temperature measuring device.

This check is to verify that the temperature measuring device has a sufficiently short response time to follow the gas temperature being measured.

11.7.5.2 Preparation for test

Determine from the design and flow characteristics of the opacimeter (or by a practical test) the minimum gas velocity to which the temperature probe is subjected in normal operation of the opacimeter.

Arrange for the probe to be immersed in a flow of air at the minimum gas velocity at ambient temperature, then switch (in less than 0,1 s) to a gas flow with a temperature of about 100 K above ambient.

Arrange for the recording of the temperature as a function of time.

11.7.5.3 Test procedure

Switch the probe from ambient temperature to heated temperature and record the time. Repeat twice.

---

6) If the electrical response is a simple exponential one, then t_e is 1,6 times the time constant (of the simple exponential).

11.7.5.4 Evaluation

Check that the time for the temperature indication to reach from 10 % to 90 % of the difference between the heated and ambient covers the specifications of the electrical response time t_e in 10.1.2.

The temperature probe may be mounted in the opacimeter or a separate rig, but, in the latter, the probe shall be mounted in a equivalent position (protrusion into the air stream and similar heat conductance conditions).

12 Verification of in-service conformity of opacimeters

12.1 General

This clause gives the minimum checks which shall be made in service to verify than an opacimeter of a type which has been verified in accordance with clause 11 continues to conform to the specification when in use.

12.2 Items to be checked

In service, it is necessary to check that the following items are correct, if applicable:

a) colour temperature of light source (e.g. by voltage) or verify green LED is used;

b) receiver circuit setting and accuracy;

c) sample pressure indicator;

d) scavenge air setting:

- setting of blower or pressure,
- performance characteristics of blower, if not covered by a);

e) sample temperature sensor;

f) pipe fittings (e.g. waste pipes, probes);

g) gas tightness of casing;

h) gas tightness of by-pass valve;

i) mechanical and chemical conditions of all moving parts and installation items;

j) division of flow (occasional check for opacimeters with central entry to the smoke chamber).

12.3 Details of checks

12.3.1 General

Most of the items can be checked against the list of operating limits provided by the manufacturer, but it should be verified that the necessary instruments and fittings (voltmeters, manometers, controls, and offices) are supplied as standard equipment with the opacimeter. The accuracy of the temperature sensor should periodically be checked by standard methods.

12.3.2 Receiver circuit setting and accuracy

To satisfy the second item of 12.2, the zero setting (with light source switched on) and 100 % opacity (with light source switched or blocked) should be checked frequently and reset if necessary. An intermediate scale check of accuracy should be made using the calibration filter (see 10.3.3) provided by the manufacturer. Different, but equivalent checks, may be required with some designs of smoke meter.

12.3.3 Division of flow (if applicable)

At intervals of about 1 month (or in accordance with the recommendation of the manufacturer), with normal usage, opacimeters with central smoke entries should be checked to ensure that the division of flow between the two halves is within the limits recommended by the manufacturer.

13 Test report of opacimeter verification

NOTE These are examples of the type of headings and layout which may be used. Where equivalent methods apply, different headings and layout may be more appropriate.

Opacimeter manufacturer ....

Type .... Model number ....

Serial number ....

13.1 Data and instrumentation requirements

13.1.1 Data supplied by the manufacturer (see 11.3)

Establish the list.

13.1.2 Instrumentation requirements (see 11.4)

Establish the list instruments fitted or supplied.

13.2 Results of instrument verification

13.2.1 Resolution and scale (see 11.5.1)

Opacity resolution and scale .... %

Light absorption resolution and scale .... m^{-1}

13.2.2 Light source (see 11.5.2)

13.2.2.1 Incandescent light source

Light source type ....

Operating limits .... V to .... V (given by manufacturer)

Corresponding colour temperature .... K to .... K

13.2.2.2 Green LED light source

Colour verified to be green ....

13.2.3 Receiver response (see 11.5.3)

13.2.3.1 Receiver for an incandescent light source

Photocell type ....

Filter type (if applicable) ....

Table 2

Receiver characteristics (including filter if applicable)		Temperature conditions	
		Ambient temperature	Maximum temperature[a]
Receiver temperature	K		
Wavelength for maximum response	nm		
Response at 430 nm	% of max.		
Response at 680 nm	% of max.		

[a] Receiver at maximum temperature specified by manufacturer. Tests to be made as applicable to type of opacimeter.

13.2.3.2 Receiver for green LED light source

Photodiode type ....

13.2.4 Accuracy of measuring circuit and calibration (see 11.5.4)

13.2.4.1 Power variation and zero stability (see 11.5.4.1)

Minimal light intensity level for accepted adjustment: ....

Error message at to low light level: ....

13.2.4.2 Zero stability (see 11.5.4.2)

Voltage setting V

Indicator reading with:

— lamp switched off or blocked, circuit disconnected 100 %;

— lamp switched off or blocked, circuit connected %.

Zero drift ....% over .... min

13.2.4.3 Scale accuracy (see 11.5.4.3)

Zero light intensity: ....

Receiver temperature: .... K

Table 3

Test No.	Calibrator value		Opacimeter reading		Error	
	%	m^{-1}	%	m^{-1}	%	m^{-1}
1						
2						
3						

13.2.4.4 Conformity of scales (see 11.5.4.4)

Table 4

Reading on opacity scale %	**Reading on *k* scale** m^{-1}	**Calculated *k* scale** m^{-1}	**Difference** m^{-1}

13.2.5 Verification of optical design (see 11.5.5)

Optical design verified ....

13.2.6 Preconditioning (see 11.5.6)

Use a table similar to that in 13.2.4.3.

13.2.7 Electromagnetic and climatic compatibility (see 11.5.7)

Use a table similar to that in 13.2.4.3.

13.3 Results of verification of basic and design specifications (see 11.6)

13.3.1 Temperature conditions (see 11.6.1)

13.3.1.1 Temperature distribution in sampling type opacimeters (see 11.6.1.1)

13.3.1.1.1 Test conditions

Table 5

Specifications		**Test conditions**	
		a)	b)
Sample temperature [a]	K	$T_{a'}$:	$T_{b'}$:
Sample pressure	kPa		
Scavenge air pressure	kPa		
Stabilizing time	min		
[a] Mean temperature in the smoke chamber assessed from the sample temperature indicator provided by the manufacturer.			

13.3.1.1.2 Test results

See Figure 6 for an example.

Minimum temperature of test gas (before mixing scavenge air) .... K

Maximum temperature of test gas in smoke chamber .... K

Table 6

Specifications	Test conditions			
	a)		b)	
Mean sample temperature calculated from temperature distribution K	T_a:	$T_{a'}$:	T_b:	$T_{b'}$: .....

Distance, l_m (from the point of smoke entry), for condition B at which the measured temperature equals the mean temperature:

For an opacimeter with smoke entry at one end of tube: l_m .... mm

For an opacimeter with central smoke entry:

l_{m1} (left of entry) [7] .... mm

l_{m2} (right of entry) [7] .... mm

0,5 (l_{m1} + l_{m2}) .... mm

maximum difference between calculated (T_a, T_b) and assessed temperature ($T_{a'}$, $T_{b'}$) .... K

13.3.1.2 Temperature distribution in full-flow opacimeters (see 11.6.1.2)

13.3.1.2.1 Temperature as measured by the temperature measuring device supplied by the manufacturer:

Temperature .... K

13.3.1.2.2 Temperature as determined by measuring at five points in the measuring zone as described in 11.6.1.2.3, see Table 7.

Table 7

Position	**10 %**	**30 %**	**50 %**	**70 %**	**90 %**
T_a					
T_b					

13.3.1.2.3 Mean temperature T_a and T_b as calculated in annex A:

T_a .... K

T_b .... K

Confirm that the indicated temperatures are within ± 5 K of T_a and T_b mean values.

7) Viewed from entry.

13.3.1.3 Temperature of sampling line and housing of sampling type opacimeters (see 11.6.1.3)

Table 8

Probe identification		Probe 1	Probe 2	Probe 4
Ambient temperature	K			
Temperature of hot air	K			
Flow rate of hot air	l/min			
Probe diameter	mm			
Max. gas velocity in probe	m/s			
Position of temperature sensor (brief description)				
Preconditioning time (stated by manufacturer)	s			
Temperature of stabilized system	K			
Time taken to reach 343 K	s			

13.3.2 Steadiness of reading (see 11.6.2)

13.3.2.1 Test conditions

Recorder characteristics:

— response .... s to 90 % full scale

— sensitivity .... m^{-1}/mm (at test opacity)

— chart speed ....mm/s

Smoke measuring system (brief description):..

Table 9

Specifications		Test conditions max. [a]	Sample pressure min. [a]
Opacity of test gas	m^{-1}		
Sample pressure	kPa		
Scavenge air pressure	kPa		
Sample temperature	K		
[a] Delete if not applicable.			

13.3.2.2 Test results

See Figures 7a) and 7b).

Unsteadiness over 10 s .... m^{-1}(range)

13.3.3 Internal reflection and diffusion (see 11.6.3)

13.3.3.1 Test conditions

Diameter of sensitive area of receiver .... mm

Diameter of lens .... mm

Distance from lens to screen .... mm

Diameter of central hole of screen .... mm

Distance from screen to receiver .... mm

Test gas opacity .... m^{-1}

13.3.3.2 Test results[8)]

a) Reading with screen in position .... m^{-1}

Reading with screen removed .... m^{-1}

a .... m^{-1}

b) Reading with screen in position .... m^{-1}

Reading with screen removed .... m^{-1}

b .... m^{-1}

c) Reading with screen in position[9)] .... m^{-1}

Reading with screen removed .... m^{-1}

c .... m^{-1}

13.3.4 Light receiver temperature (see 11.6.4)

13.3.4.1 Test conditions

Sample pressure (if applicable) .... kPa

Scavenge air pressure (if applicable) .... kPa

Sample or exhaust temperature .... K

Stabilizing time .... min

Scavenge air temperature .... K

13.3.4.2 Test results

Receiver temperature .... K

13.3.5 Effective optical path length, L_A (see 11.6.5)

13.3.5.1 Comparison with known opacimeter (see 11.6.5.2)

Reference opacimeter manufacturer ....

Type ....

8) Delete if not applicable.

9) With smoke passing through the smoke chamber.

Number ....

Effective optical path length, L_A .... mm

Table 10

Reference opacimeter				Opacimeter under test				
Sample pressure kPa	**Sample temperature** K	**Opacimeter reading** %	**Corrected opacimeter reading[a]** %	**Sample pressure** kPa	**Sample temperature** K	**Opacimeter reading** %	**Corrected opacimeter reading[a]** %	**Calculated effective optical path length** mm
					Average			
					Standard deviation			
					95 % confidence limits [b]			

[a] This correction is to bring the reading to the reference temperature.
[b] Taking into account the known accuracy of the reference opacimeter.

Accuracy of effective optical path length, L_A: ± ...... mm at 95 % confidence.

Scavenge air pressure (delete if not applicable):

— reference opacimeter.. kPa

— opacimeter under test.. kPa

— sampling system (brief detail)...

13.3.5.2 Comparison of results from one opacimeter with and without modification of operation (see 11.6.5.3)

Table 11

Modification opacimeter				Opacimeter operating normally			
Sample pressure kPa	**Sample temperature [a]** K	**Opacimeter reading [b]** %	**Effective optical path length** mm	**Sample pressure** kPa	**Sample temperature [a]** K	**Opacimeter reading [c]** %	**Calculated effective optical path length** mm
				Average			
				Standard deviation			
				95 % confidence limits			

[a] If these temperatures differ by more than 40 K, then experimental data shall be given validating the adjustment for the differences in temperature in the method of calculating effective optical path length.
[b] Relative to "zero" after the modification is made.
[c] Relative to "zero" before the modification is made.

Scavenge air pressure with opacimeter operating normally .... kPa

$$\frac{\text{Effective optical path length as modified}}{\text{Effective optical path length operating normally}} = \ldots\ldots\ldots\ldots$$

Where the ratio is greater than 1,25, separate data shall be given to validate the sample temperature measurements with the modified opacimeter.

Modification (brief details) ....

Sample temperature measurement position: ....

Opacimeter operating normally ....

Opacimeter modified ....

Recordings of readings during the test shall be included in the test report.

13.3.6 Effect of sample and scavenge air pressure (see 11.6.6)

13.3.6.1 Test conditions

Maximum sample pressure .... kPa

Normal scavenge air pressure .... kPa

Minimal scavenge air pressure .... kPa

Sample temperature .... K

Smoke opacity .... m^{-1}

13.3.6.2 Test results

A table of results similar to that in 13.3.5 shall be provided depending on the method of measuring effective optical path length.

Number of readings ....

Average effective optical path length .... mm

Standard deviation .... %

95 % confidence limits on average .... mm... %

$$\frac{\text{Effective optical path length at maximum sample pressure}}{\text{Effective optical path length at minimum sample pressure}} = \ldots\ldots\ldots\ldots$$

Maximum pressure/depression in smoke chamber .... kPa

Position of measurement ....

13.3.7 Gas tightness of opacimeter (see 11.6.7)

13.3.7.1 Gas tightness of by-pass valve with reduced pressure

Sample pressure .... kPa

Scavenge air pressure .... kPa

Sample temperature .... K

Smoke opacity .... m^{-1}

Table 12

Specifications	Individual readings m^{-1}	Average m^{-1}
Smoke by-passing normally		
Reduced pressure at by-pass valve		

Method of obtaining reduced pressure at by-pass valve ....

13.3.7.2 Gas tightness of by-pass valve with increased pressure

Probe description ....

Sample gas velocity in exhaust tube: .... m/s

Sample temperature .... K

Smoke opacity .... m^{-1}

Table 13

Step	Action	Test 1	Test 2
1	Adjustment without smoke, without filter Measurement of filter		
2	Measurement of smoke		
3	Adjustment with smoke at probe and automatically closed valve		
4	Without smoke at probe, without adjustment Measurement of "zero"		
5	Measurement of filter		
6	Difference between values from steps 1 and 5		

13.3.7.3 Gas tightness of casing (see 11.6.7.2)

Sample pressure .... kPa

Scavenge air pressure .... kPa

Sample temperature .... K

Smoke opacity .... m^{-1}

Leak capacity ....dm^3/s

Leak position .... dm^3/s

Leakage of casing before sealing .... dm^3/s

Table 14

Specifications	Individual readings m^{-1}	Average m^{-1}
Smoke with leakage valve closed and scavenge air setting S_1		
Smoke with leakage valve setting S_v and scavenge air setting S_2		
Difference in readings		

13.3.8 Waste exit condition (see 11.6.8)

Opacity of test gas .... m^{-1}

Change of opacimeter with change of waste condition .... m^{-1}

13.3.9 Effect of pre-chamber and pressure relief valve design (see 11.6.9)

13.3.9.1 Test conditions

Table 15

Test conditions		Relief valve inoperative	Relief valve operative
Sample pressure	kPa		
Scavenge air pressure	kPa		

13.3.9.2 Test results

Table 16

Test No.	Corrected opacimeter reading m		
	Relief valve inoperative a	Relief valve operative b	Difference $b - a$
1			
2			
3			
4			

13.3.10 Flow characteristics (see 11.6.10)

Brief description of test installation ....

....

Test results: see Figure 8.

13.3.11 Soiling of the light source and receiver (see 11.6.11)

13.3.11.1 Test with constant smoke

Smoke opacity .... m^{-1}

Sample gas velocity in exhaust tube: .... m/s

Sample pressure (if applicable) .... kPa

Scavenge air pressure (if applicable) .... kPa

Duration of test .... min

Change of zero during test .... % opacity

13.3.11.2 Test with smoke peaks

Probe description ....

Sample pressure, range (if applicable) .... kPa

Sample velocity in exhaust tube, range (if applicable) .... m/s

Smoke opacity .... m^{-1}

Smoke peak area (opacity-time): .... s/m

Scavenge air pressure (if applicable) .... kPa

Number of repetitions ....

Change of zero during test .... % opacity or m^{-1}

13.3.12 Division of flow (see 11.6.12)

Table 17

Test conditions	**Opacimeter reading** m^{-1}			**Difference of reading from maximum**	
	At setting P_1	Maximum	At setting P_2	At setting P_1	At setting P_2
a)					
b)					

13.4 Verification of response characteristics (see 11.7)

13.4.1 Velocity distribution (see 11.7.1)

Give a brief description of test arrangement with a plan of the measuring positions.

Table 18

Position No.	**Distance from wall** %	**Measured velocity** m/s	**Velocity deviation**	
			$\bar{v} - v$	$\left(1 - \frac{v}{\bar{v}}\right)$ [a]
1	10			
2	30			
3	50			
4	70			
5	90			

[a] Mean velocity in metres per second.

13.4.2 Physical response time (see 11.7.2)

For each probe and for different sample gas velocities:

Probe description ....

Exhaust diameter: .... mm

Sample gas velocity in exhaust tube: .... m/s

Manufacturer's stated physical response time, t_p .... s

Sample temperature .... K

Smoke opacity before step .... m^{-1}

Smoke temperature before step .... K

Smoke opacity after step .... m^{-1}

Smoke temperature after step .... K

Sampling frequency: Opacimeter .... Hz

Sampling frequency: Reference .... Hz

Damping algorithm: ....

Physical response time, t_p: .... s

13.4.3 Electrical and display response times (see 11.7.3)

Type of electrical response:

Recorder, analog meter output, digital meter output

— Manufacturer's stated response time, t_e .... s

— Measured response time, t_e .... s

— Damping algorithm (if applicable) ....

13.4.4 Physical delay time (see 11.7.4)

Test for each probe and different exhaust gas velocities:

— probe description: ....

— sample gas velocity in exhaust tube: .... m/s

— distance between smoke detection position and probe entrance: .... m

— delay time between smoke detection position and probe entrance: .... s

— delay time, t_d: .... s

13.4.5 Temperature response time (see 11.7.5)

Manufacturer's stated response time, t_T .... s

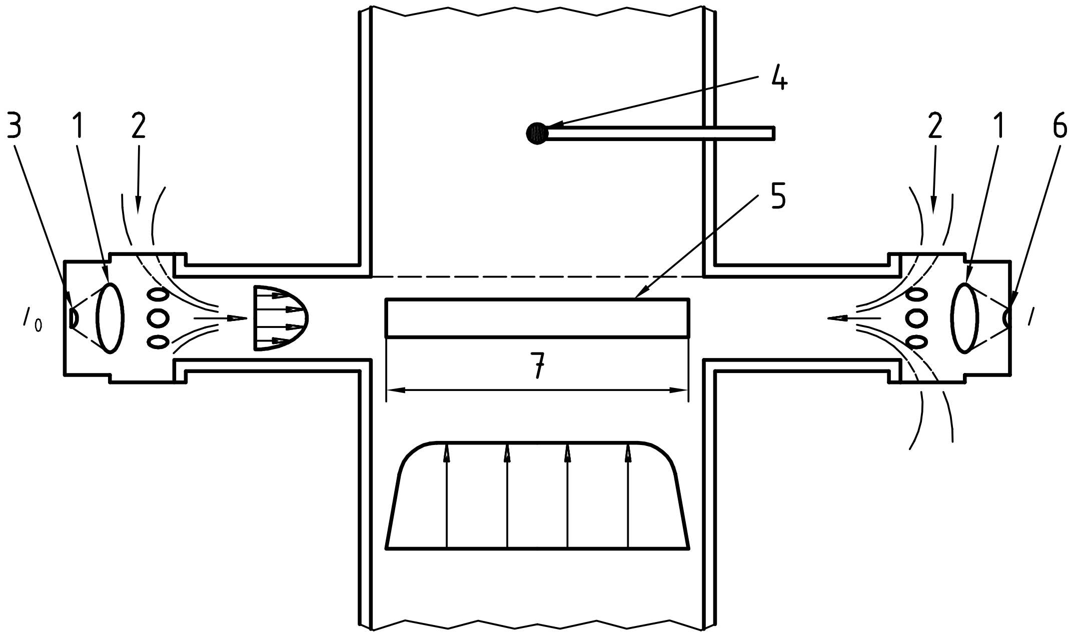
Probe description ....

Sample gas velocity in exhaust tube: .... m/s

Sample temperature before step .... K

Sample temperature after step .... K

Temperature response time, t_T: .... s

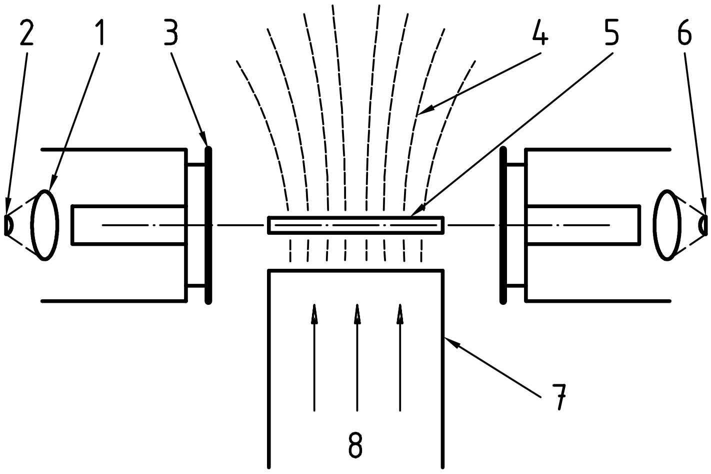


Key

1 Collimating lens
2 Air
3 Light source
4 Measuring device
5 Smoke measuring zone
6 Receiver
7 Smoke path length, L_A

NOTE The basic principle utilized by the opacimeter in measuring smoke density is the attenuation of the intensity of a collimated light beam by smoke aerosol absorption and scattering. The LED light source of intensity, I_0, and collimating lens produce a collimated light beam which passes through the centre of the smoke column where some of the light is absorbed or scattered by smoke aerosols, thus reducing the intensity of the light which reaches the receiver focusing lens and the photo diode to the intensity, I.

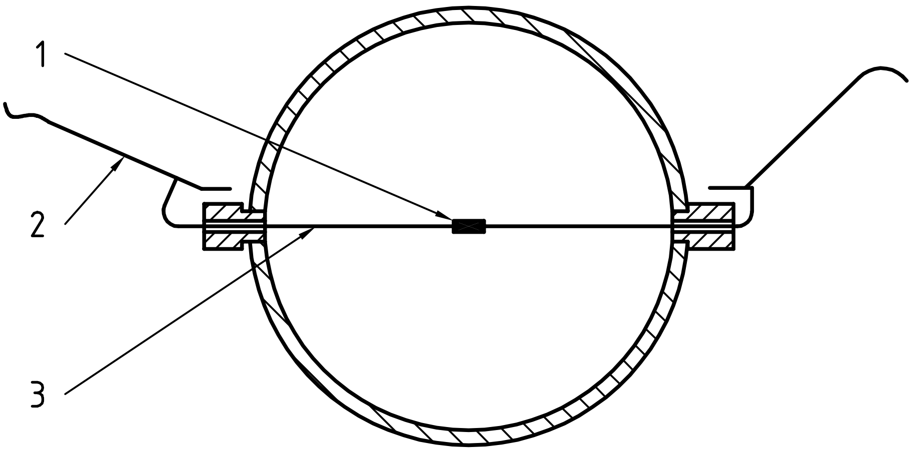
Figure 1 — Example of in-line full-flow opacimeter (see 5.1)



Key

1 Collimating lens
2 Light source
3 Screen
4 Exhaust plume
5 Measuring zone
6 Receiver
7 Exhaust pipe
8 Exhaust

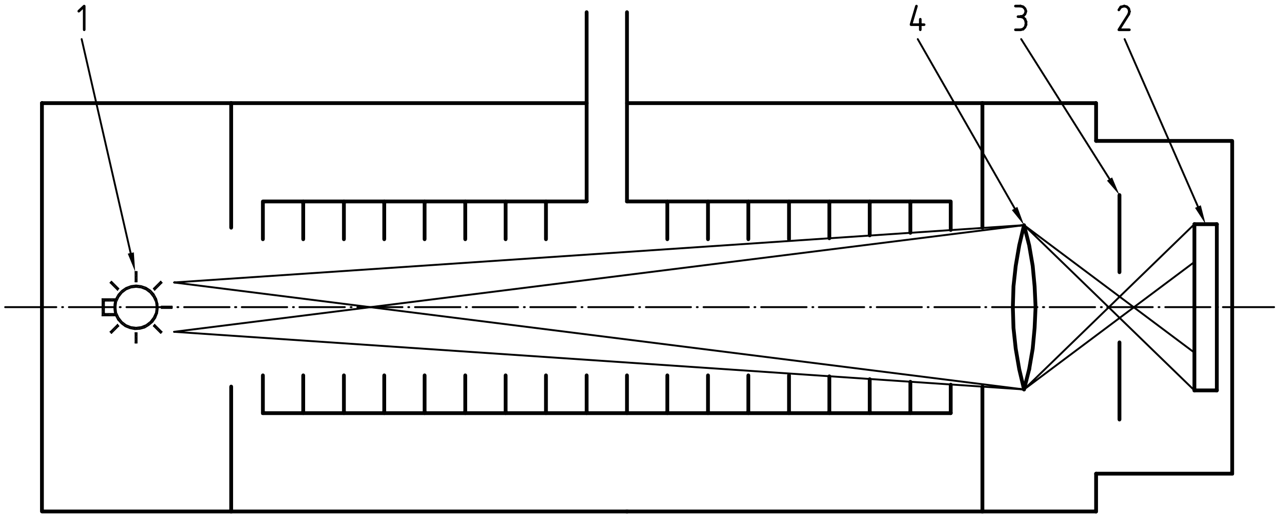
Figure 2 — Example of end of line or plume-type full-flow opacimeter (see 5.1)



Key

1 Thermocouple joint
2 Wire, diameter 0,7 mm approx.
3 Wire, diameter 0,12 mm approx.

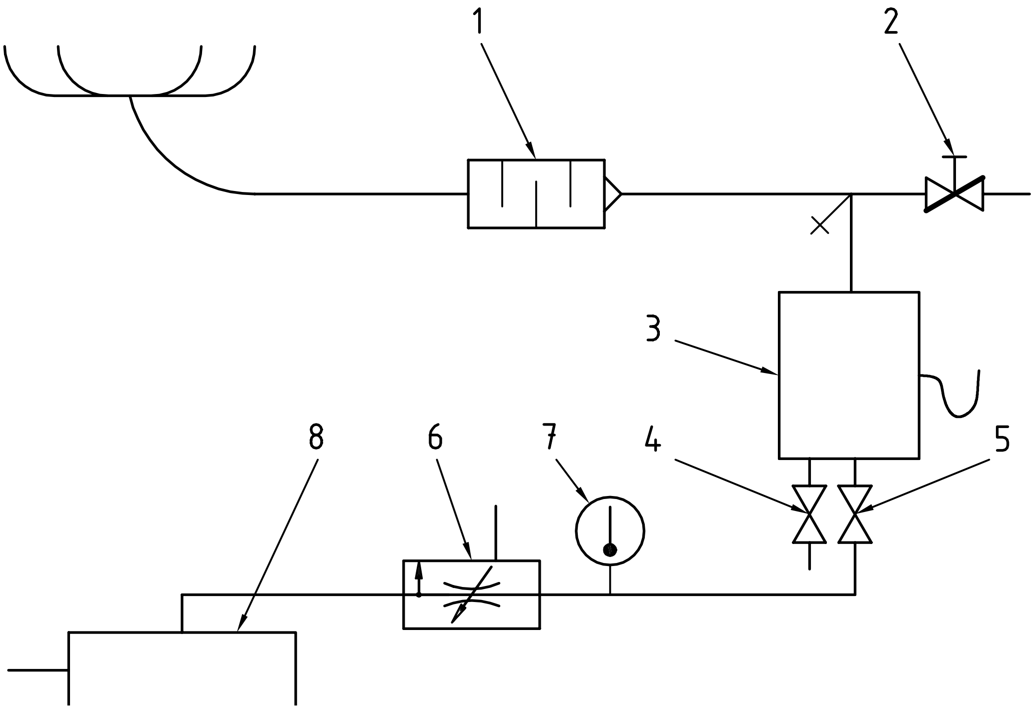
Figure 3 — Diametral thermocouple (see 11.6.1.1)



Key

1 Light source
2 Light receiver
3 Screen
4 Lens

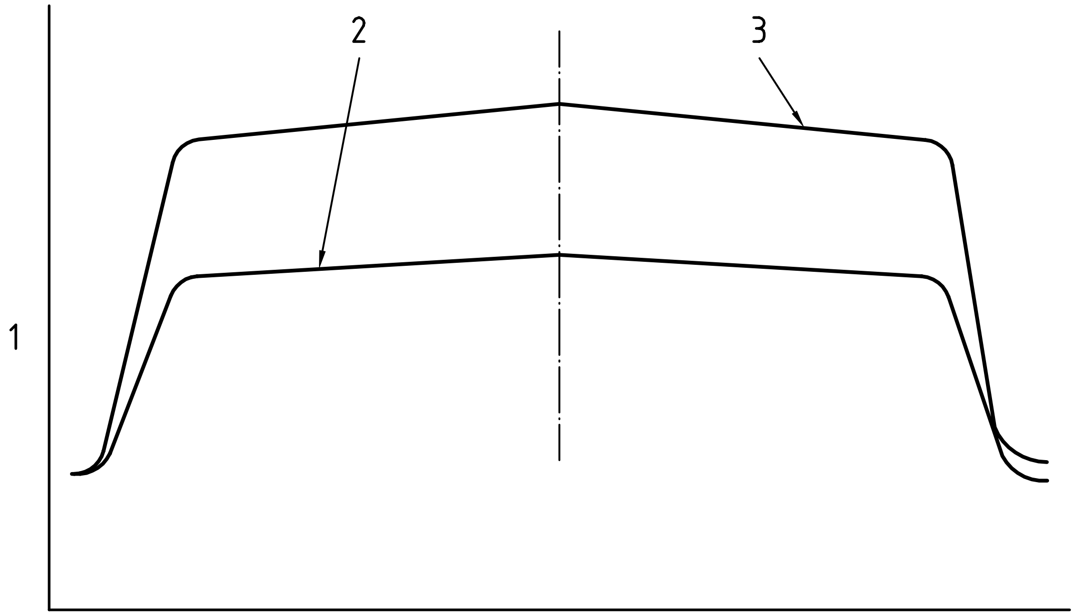
Figure 4 — Opacimeter with incandescent light (see 11.6.3)



Key

1 Silencer
2 Butterfly valve
3 Damping chamber with heater
4 Valve A
5 Valve B
6 By-pass
7 Temperature sensor
8 Opacimeter

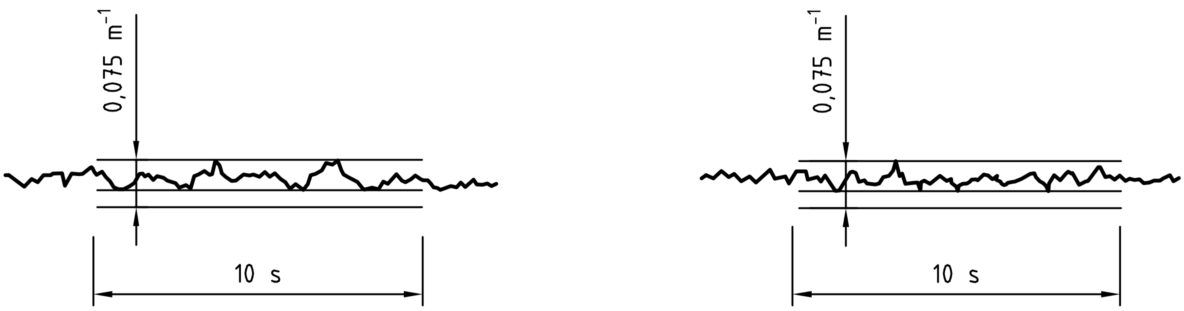
Figure 5 — Test installation for sampling opacimeter (see 11.6.9)



Key

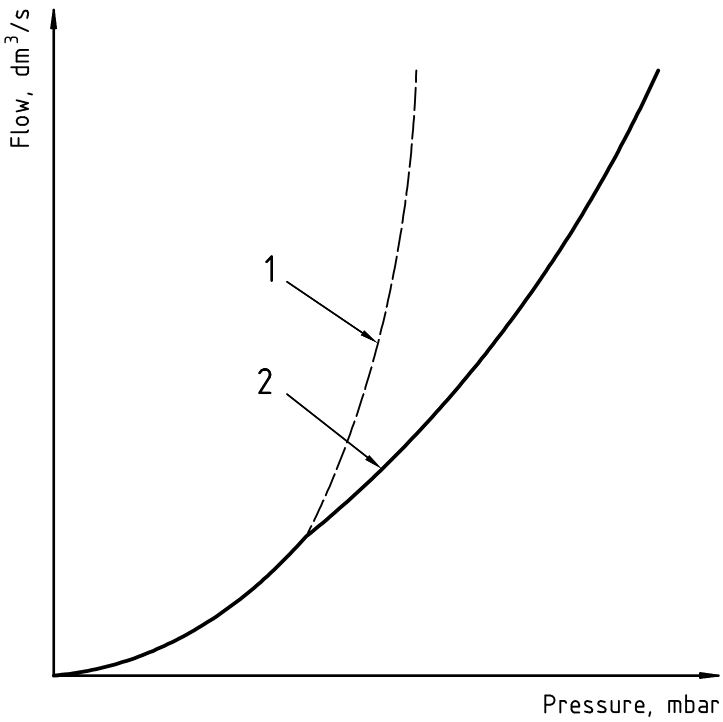
1 Temperature
2 Condition a)
3 Condition b)

Figure 6 — Position along smoke chamber (central entry) (see 13.3.1.1.2)



a) Sample pressure 0,2 kPa (0,2 mbar) b) Sample pressure 0,3 kPa (0,3 mbar)

Figure 7 — Unsteadiness of reading (see 13.3.2.2)



Key

1 Relief valve open
2 Relief valve shut

Figure 8 — Flow characteristics (see 13.3.10)

Annex A
(normative)

Determination of the "mean exhaust gas temperature" in the smoke chamber of an air-scavanged opacimeter

This annex shows how the mean exhaust gas temperature can be determined from the temperature distribution measured over the length of the smokemeter. An opacimeter with central inlet to the smoke chamber is used as an example.

Figure A.1 shows the usual temperature curve for the left half of the tube. The distances of each measuring point from the gas inlet are on the abscissa, the temperatures on the ordinate.

The temperature in the tube decreases regularly over the length, l_1, through radiation and conduction, from the inlet temperature, T_1, to a temperature T_2.

With the distance from the gas inlet increasing further, the temperature in the tube decreases more rapidly, which can be explained by intermixture with the scavenge air entering through the end of the tube.

The temperature decreases further and eventually reaches, at a certain distance from the end of the tube, and before the photoelectric cell, the scavenge air temperature, T_s. The tube length l_1 thus contains only exhaust gas and with increasing distance from the gas inlet there is a mixture with a growing proportion of air.

With the exhaust gas temperature T_a, the scavenge air temperature, T_s and the temperature of the mixture T_g, the gas/air ratio as a given cross-section can be calculated, neglecting the differences in specific heat.

If X is the proportion of exhaust gas then:

$$X = \frac{T_g - T_s}{T_a - T_s}$$

T_g and T_s are known. The exhaust gas temperature in the region of intermixture can be determined with sufficient accuracy, if the decrease in the exhaust gas temperature from the inlet is extended linearly beyond length l_1 (see Figure A.1).

If this calculation is carried our for the rest of the length, i.e. for l_2, a curve is obtained which shows the proportion of exhaust gas in the mixture. It begins with $X = 1$ (pure exhaust) and ends with $X = 0$ (pure air).

For calculating the mean exhaust gas temperature, only the exhaust gases can be used not the air with which they are mixed, since a temperature change of air has no effect on the light absorption coefficient k.

Distance l_2 is therefore divided into as many small sections Δl as possible. To each of these sections there belongs a calculated exhaust gas proportion, X, and a measured temperature, T_g.

If the air and exhaust gas in each Δl are considered separately, exhaust gas and air have the same temperature, T_g. The section within Δl which is filled with exhaust gas can be taken as $X\ \Delta l$.

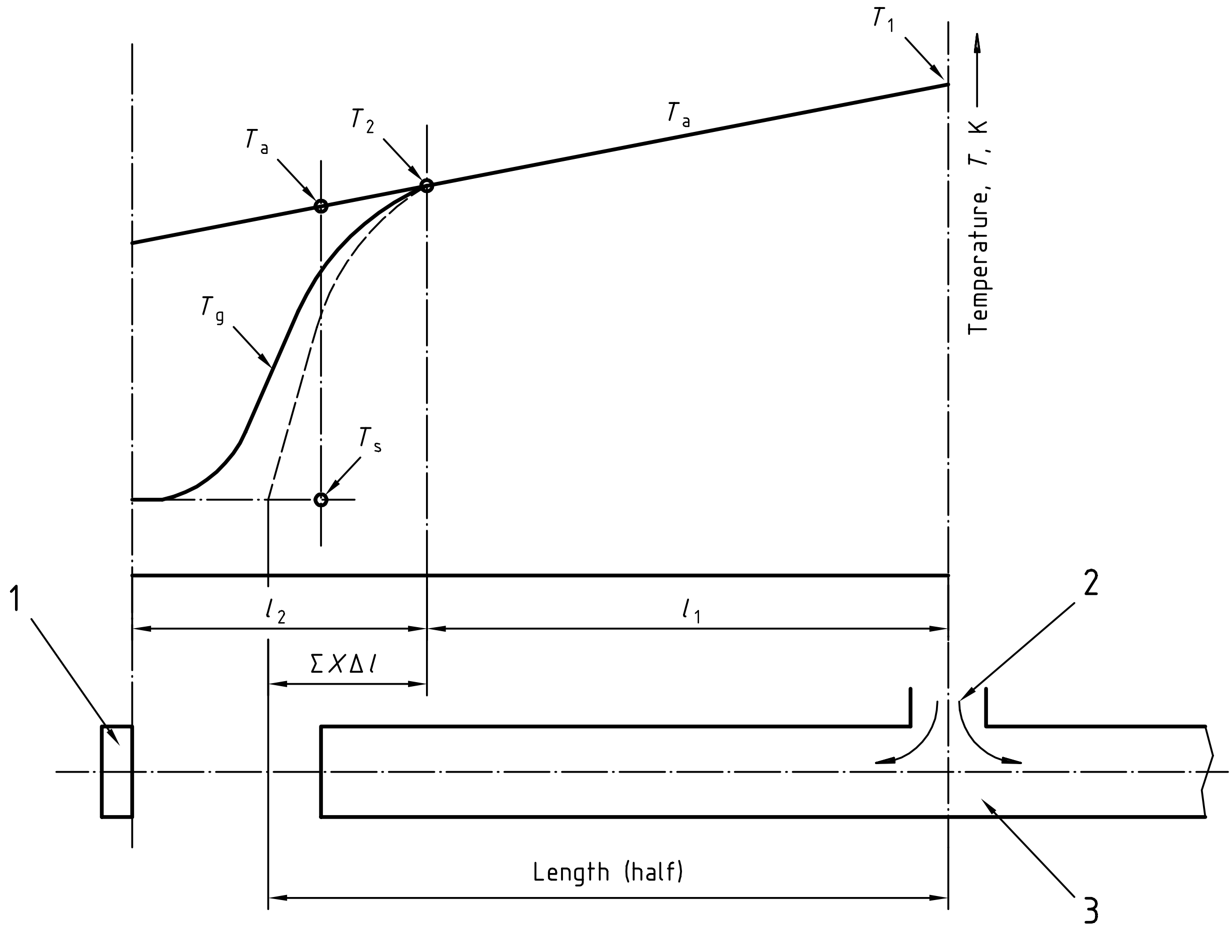
Over the whole distance l_2 sections are obtained which can be imagined as being alternately filled with exhaust gas or air. All sections $(1 - X)\ \Delta l$, which are filled with air, are now taken out and the sections $X\Delta l$ are put together and added to l_1. The result is $l_1 + X\ \Delta l$. The temperature, T_g, which are associated with each Δl from the curve for the mixture temperature T_g, are now plotted over each section $X\Delta l$.

The mean exhaust gas temperature can now be calculated over the length $l_1 + \Sigma X\Delta l$ by planimetry.

Figure A.2 shows the calculation of a practical example using the method described. The diagram also shows the exhaust proportion, X, for each position. Within the range of l_1, $X = 1$; at the end of l_2, $X = 0$.

The mean exhaust gas temperature over length l_1 is T_{m1}; over length $X\Delta l$ it is T_{m2}.

The mean temperature for the resulting length $l_1 + \Sigma X\Delta l$ is T_m.



Key

1 Light receiver
2 Exhaust inlet
3 Measuring chamber

Figure A.1 — Sampling opacimeter with central entry

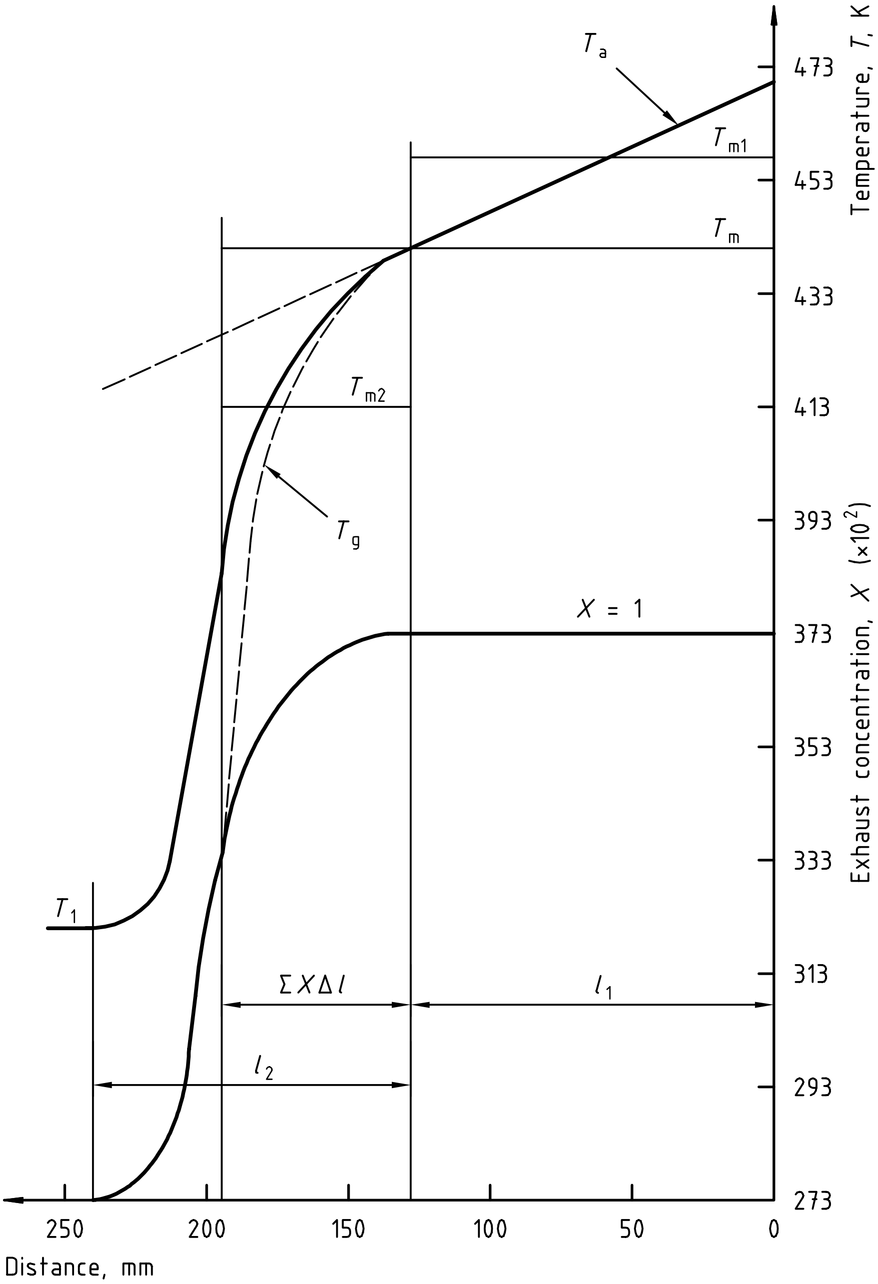


Figure A.2 — Calculation of a practical example using this method

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ICS 13.040.50; 43.180

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