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Road vehicles — Apparatus for measurement of the opacity of exhaust gas from diesel engines operating under steady state conditions

Véhicules routiers — Dispositif pour le mesurage de l'opacité des gaz d'échappement des moteurs diesel fonctionnant en régime stabilisé

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FOREWORD

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The Member Bodies of the following countries expressed disapproval of the document on technical grounds :

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Road vehicles — Apparatus for measurement of the opacity of exhaust gas from diesel engines operating under steady state conditions

1 SCOPE

This International Standard specifies the general requirements and the installation of instruments for measuring the light obscuration of exhaust gas from diesel engines for driving road vehicles, operating under steady state conditions. These instruments are generally known as "opacimeters".[1)]

Clauses 7 and 8 detail the tests which must be made to verify that a particular design of opacimeter conforms to this International Standard and the checks which must be made in service to verify that an opacimeter continues to conform to this International Standard when in use. Clause 9 gives an example of the type of test report which shall be used to record the results of the verification tests.

2 FIELD OF APPLICATION

This International Standard covers opacimeters for diesel engines for driving road vehicles. It is not intended to cover :

- free piston engines
- stationary engines
- marine engines
- engines for rail traction
- engines for aircraft
- engines for agricultural tractors and special vehicles for use in civil engineering.

3 PRINCIPLE OF OPACIMETERS

The principle of measurement is that light is transmitted through a length of the medium to be measured and the proportion of incident light which reaches a receiver (for example a photo-electric cell) is used to assess the obscuration of the medium.

4 CHARACTERISTICS OF OPACIMETERS

4.1 Basic specification

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

In determining the effective length of the light path through the gas, account shall be taken of the possible influence of devices protecting the light source and the photo-electric cell.

This effective length should be indicated on the apparatus.

The indicating dial of the opacimeter shall have two measuring scales, one in absolute units of light absorption from 0 to ∞ (m^{-1}) and the other in obscuration units from 0 to 100 % in relation to the light flux reaching the photo-electric cell; both scales shall range from 0 at total flux to full scale at complete obscuration.

The opacity of the gas shall be referred to ambient pressure and 100 °C.

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4.2 Construction specification

4.2.1 *General*

The design shall be such that in steady state operating conditions the measuring chamber is filled with smoke of uniform opacity.

This condition shall be deemed to be met if :

a) the variation of opacimeter indicator output over a period of 10 s, with smoke of constant temperature having a constant density of about 1,7 m^{-1}, measured with a recorder with a response time of 1 s, is not more than 0,075 m^{-1};

b) where the smoke chamber is divided, the mean temperature in the different sections does not differ by more than 7 °C.

1) The specification of the instrument and its installation are based originally on the C.E.C. work embodied in C.E.C. Specifications No. A-01-T-70 and A-01-M-70 which were drawn up to meet the requirements of Working Party 29 of the Economic Commission for Europe of the United Nations.

4.2.2 *Smoke chamber and opacimeter casing*

The impingement on the photo-electric cell of stray light due to internal reflections or diffusion effects shall be reduced to a minimum (for example, by finishing internal surfaces in matt black and by a suitable general layout).

The optical characteristics shall be such that the combined effect of diffusion and reflection does not exceed 0,1 m^{-1} on the opacity scale when the smoke chamber is filled with smoke having an absorption coefficient near to 1,7 m^{-1}.

4.2.3 *Light source*

The light source shall be an incandescent lamp with a colour temperature in the range from 2 800 to 3 250 K.

4.2.4 *Receiver*

The receiver shall consist of a photo-electric cell with a spectral response curve similar to the photopic curve of the human eye (maximum response in the range 550 to 570 nm, to less than 4 % of that maximum response below 430 nm and above 680 nm).

The design of the electric circuit, including the indicator, shall be such that the relationship between the photo-electric cell and the intensity of the light received does not change over the range of adjustment of the circuit and over the operating temperature range of the photo-electric cell.

4.2.5 *Measuring scales*

The light-absorption coefficient k is calculated by the formula

$$\phi = \phi_0 \times e^{-kL}$$

where

L is the effective length of the light path through the gas;

ϕ_0 is the light flux received by the photo-electric cell when the measuring chamber is filled with clean air;

ϕ is the light flux received by the photo-electric cell when the measuring chamber is full of smoke.

When the effective length L of a type of opacimeter cannot be assessed directly from its geometry, the effective length L shall be determined :

– either by the method described in 7.7.5 b)

– or by correlation with another type of opacimeter for which the effective length is known.

The relationship between the 0 to 100 obscuration scale and the absorption coefficient is given by the formula

$$k = -\frac{1}{L}\log_e\left(1 - \frac{N}{100}\right)$$

where

N is a reading on the obscuration scale;

k is the corresponding value of the absorption coefficient.

The indicating dial of the opacimeter shall enable an absorption coefficient of 1,7 m^{-1} to be read with an accuracy of 0,025 m^{-1}.

4.2.6 *Adjustment and calibration of the measuring apparatus*

The electric circuit of the photo-electric cell and of the indicator shall be adjustable so that the pointer can be reset at zero when the light flux passes through the smoke chamber filled with clean air or through a chamber having identical characteristics.

With the lamp switched off, and the electric measuring circuit open or short-circuited, the absorption-coefficient scale reading shall be set to ∞, and it shall remain at ∞ with the measuring circuit reconnected.

An intermediate check shall be carried out with the lamp switched on, by placing in the measuring chamber a screen representing a gas, whose known absorption coefficient k, measured as in 4.2.5, is between 1,6 and 1,8 m^{-1}. The value of k should be known to within 0,025 m^{-1}. The check consists in verifying that this value corresponds to within 0,05 m^{-1} of the reading obtained on the indicator when the screen is introduced between the light source and the photo-electric cell.

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4.2.7 *Pressure of the gas to be measured and of scavenging air*

The pressure of the exhaust gas in the smoke chamber shall not differ from the atmospheric pressure by more than 4 mbar. The pressure variation of the gas and the scavenging air in the smoke chamber shall not cause the absorption coefficient to vary by more than 0,05 m^{-1} in the case of a gas having an absorption coefficient of 1,7 m^{-1}.

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The opacimeter shall be equipped with appropriate devices for assessing the pressure in the smoke chamber. It shall be possible to read these with an accuracy of 0,1 mbar.

The limits of pressure variation of the gas and the scavenging air shall be stated by the manufacturer of the apparatus.

4.2.8 *Temperature of the gas to be measured*

The opacimeter shall be equipped with appropriate devices for assessing the mean temperature of the gas in the smoke chamber and the manufacturer shall specify operating limits. The mean temperature must be indicated to ± 5 °C.

At every point in the smoke chamber the temperature of the test gas at the instant of measurement of opacity shall be not less than 60 °C and the mean temperature in the chamber shall be not more than 120 °C.

Where the mean operating temperature (t °C) is other than 100 °C the opacimeter reading shall be corrected to 100 °C by the formula

$$k_{\text{corrected}} = k_{\text{observed}} \frac{(t + 273)}{373}$$

This temperature range is one in which it is considered that all the water present is in vapour form and all other

uncondensed non-solid particles (i.e. the amount of uncondensed, unburnt fuel or lubricating oil) is insignificant in normal full-load exhaust smoke. Under these conditions the correction formula for the effect of temperature is valid. If the exhaust smoke contains an abnormal amount of non-solid constituents the correction formula may not be valid and a more restricted temperature range about the 100 °C reference condition is then advised.

4.3 Design details

Any pre-chamber and relief valve before the smoke chamber must not affect the opacity characteristics of the gas entering the smoke chamber by more than 0,05 m^{-1} for gas of 1,7 m^{-1} opacity.

Where an opacimeter is designed for intermittent operation a temperature sensor shall be provided upstream of the by-pass valve controlling entry of the gas into the smoke chamber. The by-pass system flow levels should be such that when set to the manufacturer's specification the change of sample temperature between the two by-pass positions is less than 5 °C.

5 DATA AND INSTRUMENTATION REQUIREMENTS

5.1 Data to be supplied by manufacturer

5.1.1 Effective length of the smoke column under sample conditions representing the recommended lower limits of temperature and pressure of exhaust gas and the higher limit of scavenge air pressure (where relevant) and normal test-bed ambient conditions.

5.1.2 Limits of sample pressure, at the inlet to the smoke chamber.

5.1.3 Limits on scavenge air delivery (where relevant). These should include setting instructions.

5.1.4 Limits of temperature (for example ambient air and exhaust sample) giving the position of measurement and their relation to mean temperature of the sample gas in the smoke chamber.

5.1.5 Limits on leakage of scavenge air from opacimeter casing and conditions of measurement (where relevant).

5.1.6 Instructions relating to dimensional limits on fittings which may be used, giving equivalent orifices.

5.1.7 Flow data :

a) Total sample flow to the opacimeter as a function of pressure at the inlet to the smoke chamber with exit conditions in accordance with 5.1.6 and at the limits of scavenge air pressure given in 5.1.3.

b) Sample flow through the smoke chamber as a function of pressure at the inlet to the smoke chamber with exit conditions in accordance with 5.1.6 and at the limits of scavenge air pressure given in 5.1.3. This information is only required when a pressure relief valve is fitted in the opacimeter upstream of the smoke chamber.

5.1.8 Limits of operation of light source, either :

a) limits of voltage at the contacts of the light source and instructions regarding bulb life; or

b) limits of reading with a coloured calibration filter.

5.1.9 Photo-electric cell surface temperature above which photo-electric cell output characteristics change significantly.

5.1.10 Photo-electric cell spectral characteristics, including its filter if one is used.

5.1.11 Limits of supply voltage within which the opacimeter will operate satisfactorily (separate limits for lamp and blower must be given if these have separate power supplies).

5.1.12 Technical description of opacimeter including electrical circuit diagram and dimensioned drawings of smoke chamber and adjacent areas (for example passages for air and smoke), with tolerances.

5.1.13 Information on servicing of opacimeter, including intervals between cleaning, and any special operating precautions particular to the given design including whether the opacimeter is designed for continuous or intermittent operation and, in the latter case, the time for which smoke must be passed through the opacimeter before a reading may be taken.

5.2 Instrumentation requirements

5.2.1 Instruments shall be fitted to measure the following :

a) Pressure of exhaust gas at inlet to the smoke chamber.

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

c) Pressure of scavenge air (if used).

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

e) Voltage at the lamp (unless a separate method using a coloured filter is provided for checking colour temperature).

f) Output of photo-electric cell circuit (i.e. for indicating the opacity of the exhaust gas).

5.2.2 Controls shall be fitted for the following :

a) Sensitivity of photo-electric cell circuit.

b) Flow of scavenge air.

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5.2.3 Separate items for checking purposes must be provided as follows :

a) Filter for checking accuracy of the photo-electric cell and its circuit.

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

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

6 INSTALLATION OF OPACIMETERS

6.1 Sampling opacimeter

The ratio of the cross-sectional area of the probe to that of the exhaust pipe shall not be less than 0,05. Insertion of the sampling probe into the exhaust pipe shall not affect the engine performance.

The probe shall be a tube with an open end facing upstream on the axis of the exhaust pipe, or of the extension pipe if one is required. It shall be situated in a section where the distribution of smoke is approximately uniform. To achieve this, the probe shall be placed as far downstream in the exhaust pipe as possible (or, if necessary, in an extension pipe) so that, if D is the diameter of the exhaust pipe at the probe, the end of the probe is situated in a straight portion at least 6 D in length upstream of the sampling point and 3 D in length downstream. If an extension pipe is used, no air shall be allowed to enter at the joint.

The pressure in the exhaust pipe and the characteristics of the pressure drop in the sampling line shall be such that the probe collects a sample equivalent to that which would be obtained by isokinetic sampling. 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. A cooler may also be fitted. The design of the expansion tank and cooler shall not unduly disturb the composition of the exhaust gases.

A butterfly valve or other means of increasing the sampling pressure may be placed in the exhaust pipe at least 3 D downstream from the sampling probe, on condition that this does not affect the engine performance.

The connecting pipes between the probe, the cooling device, the expansion tank (if required) and the opacimeter shall be as short as possible while satisfying the pressure and temperature requirements prescribed in 4.2.7 and 4.2.8. The pipe shall be inclined upwards from the sampling point to the opacimeter, and sharp bends where soot might accumulate shall be avoided. Where the opacimeter is fitted with a water trap the sample pipe need not rise continuously providing that there are no bends where soot and water might accumulate.

A check shall be carried out during the test to ensure that the requirements of 4.2.7. concerning pressure and those of 4.2.8, concerning the temperature in the smoke chamber are observed.

6.2 Full flow opacimeter

The only general precautions to be observed are the following :

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

– Pipes connecting the exhaust with the opacimeter shall be as short as possible. The pipe system shall be inclined upwards from the exhaust pipe to the opacimeter, and sharp bends where soot might accumulate shall be avoided. Where the opacimeter is fitted with a water trap the sample pipe need not rise continuously providing that there are no bends where soot and water might accumulate.

– A check shall be carried out during the test to ensure that the requirements of 4.2.7, concerning pressure, and those of 4.2.8, concerning the temperature in the smoke chamber, are observed.

– A cooling system may also be required upstream from the opacimeter.

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7 VERIFICATION OF OPACIMETER TYPES

7.1 Scope and field of application

This clause specifies the procedures which shall be adopted in order to verify that a given opacimeter type complies with clauses 4 and 5. It covers full flow and sampling type opacimeters, and designs with and without scavenge air. 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 it is for use with continuous or intermittent operation of the instrument. Where possible each heading includes a reference to the particular sub-clause in clauses 4 and 5 to which the test refers.

7.2 General considerations

In order to verify that an opacimeter type complies with the specification it is necessary first to check that certain instruments and controls required by the specification are fitted to the opacimeter 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 claimed 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 (for example, 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-up; 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 recorder on the response or sensitivity of the circuit should be taken into account.

7.3 Definitions

The following symbols are used :

k = light absorption coefficient (opacity) of the gas in units metre^{-1} (m^{-1});

L = effective length of the opacimeter smoke column in metres (m);

N = reading on opacimeter obscuration scale in per-cent (%);

t = temperature in degrees Celsius (°C).

7.4 Data supplied by manufacturer (5.1)

Check that the data supplied by the manufacturer covers all the items required by 5.1 of the specification.

7.5 Instrumentation requirements (5.2)

Check that the instrumentation requirements of 5.2 of the specification are met by standard instruments supplied by the manufacturer.

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7.6 Verification of instrumentation

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7.6.1 *Colour temperature* (4.2.3)

Check that over the indicated conditions (for example by voltage at the contacts of the bulb or reading with a coloured checking filter) the colour temperature of the light source is between 2 800 and 3 250 K.

7.6.2 *Photo-electric cell response to different wavelengths and temperatures* (4.2.4)

Check that the combined photo-electric cell and filter characteristic has a maximum response in the range 550 to 570 nm, and less than 4 % of that maximum response below 430 nm and above 680 nm.

Check that the response of the photo-electric cell is not changed by operation at the maximum temperature specified by the manufacturer.

7.6.3 *Accuracy of measuring circuit and calibration* (4.1 and 4.2.6)

a) Check that the zero of the instrument can be satisfactorily adjusted over the range of supply voltages indicated by the manufacturer and that with the lamp switched off, the scale reading is infinity irrespective of whether the measuring circuit is connected or not.

b) Check the accuracy of the obscuration scale at at least six points between 10 % and 95 % obscuration. This check may be done on an optical bench or by using screens of neutral density, known to an accuracy of ± 0,5 %, or by other suitable equivalent methods. The obscuration scale should be accepted as satisfactory if the error of the scale is always less than 1 %. This test should be made with the normal and the maximum photo-electric cell temperature, given by the manufacturer.

NOTE — 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.

c) Check that the absorption of the calibrating screen supplied with the opacimeter, integrated over the range 430 to 680 nm in accordance with the photo-electric cell and filter characteristics, is within ± 0,025 m^{-1} of the value marked on it.

d) Check that the calibration filter supplied with the opacimeter gives an indicator reading within ± 0,05 m^{-1} of the value marked on it.

7.7 Verification of flow characteristics in relation to internal design

7.7.1 *Temperature distribution* (4.2.1 and 4.2.8)

7.7.1.1 Object

In order to determine the opacity of gas at 100 °C 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. This test also permits verification that the minimum and maximum temperatures of the gas meet those specified in 4.2.8 and, where a central entry divides the smoke chamber into two, that the temperature difference between the two halves is acceptable.

7.7.1.2 Preparation of test

For measurement of temperature distribution, arrange-ments must be made for measurement of tempera-ture at different points along the centre line of the smoke chamber. Any temperature sensor must be held in a holder which provides good heat insulation and does not unduly affect the flow of gases. An example of a satisfactory method is to traverse the centre line 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 bulb and photo-electric cell with holes drilled to allow passage of the wire. A thermocouple must also be provided for measuring the temperature of any scavenge air near where it mixes with the smoke.

7.7.1.3 Test procedure

With the opacimeter supplied with exhaust gas or heated air, measure the temperature distribution, point by point,

along the centre line of the smoke chamber and the scavenge air temperature near the mixing zone under the following stabilised 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 minimum sample flow recommended by the manufacturer (minimum sample pressure and maximum scavenge air pressure);

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

7.7.1.4 Evaluation

Plot the temperature distribution along the centre line of the smoke chamber and, for opacimeters which use scavenge air, adjust the temperature distribution for the presence of air mixing with smoke, by the method of annex A and assess as follows :

a) Calculate the mean temperature t_a, t_b and t_c under the three test conditions and verify that when expressed as absolute temperature (K) they agree within 5 °C with the temperature derived from the indicator provided by the manufacturer.

b) Verify that under test condition (7.7.1.3 a)) the temperature of the test gas before mixing with scavenge air is not less than 60 °C.

c) Calculate the mean temperature t_a and t_b under test conditions 7.7.1.3 a) and b) and verify that

$$\frac{t_b + 273}{t_a + 273} \leqslant 1{,}06$$

Verify that under test condition 7.7.1.3 c) the maximum mean temperature does not exceed 120 °C.

d) Find the distance l_m (from the point of smoke entry) on the temperature traverse for test condition 7.7.1.3 b) at which the indicated temperature equals the mean temperature. For 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. But 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 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 1.

e) For opacimeters with central entry to the smoke chamber verify that the mean temperature in the two halves does not differ by more than 7 °C under either of the test conditions.

7.7.2 *Steadiness of reading* (4.2.1)

7.7.2.1 Object

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 an unsteadiness and possible error of reading. Similarly where 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 variations of 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 and unsteadiness must, therefore, be checked on all designs.

7.7.2.2 Preparation of test

The output from the photo-electric cell shall be connected to a recorder with a frequency response of about 1 s to 90 % of full scale and with a chart speed of at least 10 mm/s. The sensitivity shall be such that 4 mm corresponds to not more than 0,05 m^{-1} at 1,7 m^{-1}. To ensure constancy of opacity, the exhaust sample shall 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 which has a firing frequency of at least 5 000 per minute.

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7.7.2.3 Test procedure

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Record the output from the photo-electric cell for about 10 s while a constant smoke of about 1,7 m^{-1} is passed through the opacimeter at the upper and lower sample pressures.

7.7.2.4 Evaluation

The steadiness shall be deemed satisfactory if the difference between the lowest and highest recorded values is less than 0,075 m^{-1} for each test condition.

7.7.3 *Internal reflectivity and diffusion* (4.2.2)

7.7.3.1 Object

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 photo-electric cell. The extent of this effect must be checked.

7.7.3.2 Preparation of test

The principle of the method is to differentiate between reflected/diffused light and direct light by focusing the direct light from the lamp 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 lamp filament, 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 lamp filament 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.[1] Preparation of test requires replacement of the photo-electric cell by a lens of focal length and diameter about equal to the diameter of the sensitive part of the photo-electric cell, provision of a matt black screen with a central hole slightly larger than the image of the lamp formed by the lens, and provision to move the photo-electric cell to collect light which comes through the hole in the screen.

Arrangements shall be made to allow measurement in two conditions :

a) The lamp, lens, screen and photo-electric cell shall be fitted in the opacimeter (for example as in figure 3) with the smoke chamber in 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, and 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.

b) The lamp, lens, screen and photo-electric cell shall be set up in the same relative positions as in arrangements a) 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 matt black and carrying out the test in a room with matt black walls.

7.7.3.3 Test procedure

a) With the lamp, lens etc., arranged as in 7.7.3.2 b) above, set the electrical circuit sensitivity to give an indicator reading of 1,7 m^{-1} when the lamp is switched on. Remove the screen and note the new reading. Repeat to give at least four pairs of readings.

b) With the opacimeter arranged as in 7.7.3.2 a) above and 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.

c) With the opacimeter arranged as in 7.7.3.2 a) above and 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 instrument 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 photo-electric cell output is also recommended.)

7.7.3.4 Evaluation

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

$\Delta_a < 0{,}1\ m^{-1}$ (this will mainly be light scattered from the lens surface)

and the opacimeter reflection and diffusion characteristics are satisfactory if :

$$\Delta_b - \Delta_a < 0{,}65\ m^{-1}$$

and

$$\Delta_c - \Delta_a < 0{,}1\ m^{-1}$$

7.7.4 *Photo-electric cell temperature* (4.2.4)

7.7.4.1 Object

Above a certain temperature the sensitivity of the photo-electric cell is changed; this temperature is given by the manufacturer and the object of the test is to verify that this is not exceeded under the most severe operating conditions of the opacimeter. For this test a thermocouple resting on the surface of the cell/filter assembly shall be deemed to indicate photo-electric cell temperature.

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7.7.4.2 Preparation of test

A thermocouple shall be placed on the surface of the photo-electric cell/filter assembly on the axis and facing the light beam. 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.

7.7.4.3 Test procedure

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

7.7.4.4 Evaluation

The specification is deemed to be met if the temperature of the photo-electric cell is below the maximum recommended by the manufacturer.

1) 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.

7.7.5 *Effective length* (4.2.5)

7.7.5.1 OBJECT

The effective length, given by the manufacturer, must 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.

7.7.5.2 COMPARISON WITH A KNOWN OPACIMETER

7.7.5.2.1 Preparation of test

The test opacimeter and known opacimeter shall be connected for simultaneous sampling. The sample to each opacimeter shall be controlled to the lower limits of temperature and 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, in the smoke chamber of the opacimeter under test in accordance with 7.7.1.

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7.7.5.2.2 Test procedure

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Simultaneous readings shall be taken on the two opacimeters with smoke at between 40 and 60 obscuration units. At least ten readings shall be made.

7.7.5.2.3 Evaluation

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

$$L = L_0 \times \frac{t + 273}{t_0 + 273} \times \frac{\log\left(1 - \frac{N}{100}\right)}{\log\left(1 - \frac{N_0}{100}\right)}$$

where L, N and t, refer to the opacimeter under test and L_0, N_0 and t_0 refer to the known opacimeter. The average of the readings shall be taken as the effective length. Verify that the average effective length is statistically valid to an accuracy of ± 1 %[1] with 95 % confidence[2]; 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 must be taken of the known accuracy of the reference opacimeter. The latter must clearly be much better than ± 1 %.

7.7.5.2.4 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 chamber 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.

7.7.5.3 COMPARISON OF RESULTS FROM ONE OPACIMETER WITH AND WITHOUT MODIFICATION OF OPERATION

7.7.5.3.1 Preparation of test

Provision must be made for rapid modification of the opacimeter from its normal operating condition (geometric effective length L) to a condition where the test gas fills a well-defined length L_0. 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 bulb and photo-electric cell. The surfaces defining the length L_0 will depend on the design of the opacimeter, they may for example be glass screens or the surface of the bulb and the surface of the photo-electric cell/filter combination. In the latter case the measurement shall be made from the surface of the bulb nearest to the photo-electric cell.

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 output from the photo-electric cell shall be connected to a recorder with a response time of less than 1,0 s and sensitivity such that 4 mm corresponds to not more than 0,05 m^{-1} for a smoke at 1,7 m^{-1}. The relation of recorder deflection to obscuration units shall be determined.

To ensure satisfactory constancy of opacity, exhaust 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 °C between the two by-pass positions.

Provision shall be made for measuring the mean temperature in the smoke chamber as described in 7.7.1. 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 bulb

1) For the present this may be increased to 2 %.

2) Annex B gives some notes on statistical tests.