TECHNICAL REPORT 4011

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Road vehicles — Apparatus for measurement of the opacity of exhaust gas from diesel engines

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

Technical Report 4011 was drawn up by Technical Committee ISO/TC 22, *Road vehicles*, and approved by the majority of its members. The reasons which led to the publication of this document in the form of a Technical Report are the following :

This Technical Report was prepared on the basis of present knowledge concerning the design and use of opacimeters intended in particular for measuring the opacity of exhaust gas from diesel engines running in free acceleration; this type of measurement is in fact a necessity when the legislation requires a control of the opacity of the smoke emitted by the vehicle in service; it is then essential that a device and a measurement method be available which allow reproducible and repeatable measurements to be made.

However, during the study, some difficulties arose in establishing with precision certain performance characteristics in relation to the response time of the device when the opacimeter is used in transient conditions.

Consequently, the type of device described below was not considered suitable for definition in an International Standard.

A study is in progress to fix the whole of the characteristics of the opacimeter.

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1 SCOPE

This Technical Report establishes the specifications for devices for measuring the opacity of exhaust gas from diesel engines for road vehicles, and for their installation. These instruments are generally known as "opacimeters". The annex deals with the installation and use of opacimeters.

2 FIELD OF APPLICATION

This Technical Report concerns opacimeters for use in steady state and free acceleration conditions for diesel engines of road vehicles. It does not cover :

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

3 REFERENCE

ISO 3173, *Road vehicles — Apparatus for measurement of the opacity of exhaust gas from diesel engines operating under steady state conditions.*

4 PRINCIPLE OF OPACIMETERS

The principle of measurement consists in passing a beam of light through a certain length of the medium to be measured. The proportion of the incident light reaching a receiver (for example, a photoelectric cell) is used to assess the opacity of this medium.

The opacimeter may be constructed to take the full flow of exhaust gas delivered by the engine (full flow opacimeter) or only a sample (sampling opacimeter).

Opacimeters are used under two types of test conditions :

- **Steady state conditions** : The engine is run at constant speed and under constant load; the opacimeter operates under steady state conditions (SS).
- **Transient conditions** : The engine is run under transient conditions of speed and/or load; the opacimeter operates under transient conditions (TC).

Opacimeters may also exist which are suitable for use only under steady state conditions. These are the subject of ISO 3173. Apparatus conforming to this Technical Report conforms *ipso facto* to ISO 3173.

5 BASIC SPECIFICATIONS FOR OPACIMETERS

5.1 The gas to be measured is passed through a chamber the internal surface of which is non-reflecting, or through an equivalent optical environment.

5.2 The effective path length of the light rays through the gas to be measured is determined taking into account the possible influence of devices for protecting the light source and the photoelectric cell. This effective length shall be indicated on the apparatus.

5.3 The measuring device shall have the following characteristics :

5.3.1 The indicator of the opacimeter shall have a measuring scale graduated in units of light absorption coefficient from 0 to 5 m^{-1} at least.

5.3.2 The indicator shall allow a light absorption coefficient to be read between 0 and 3 m^{-1} with a precision of 0,05 m^{-1} at least.

5.3.3 The measuring device (for transient conditions only) shall allow the maximum opacity to be stored for at least 5 s and allow instantaneous cancellation of the value stored. This value shall not decay by more than 1 % during this time. The peak hold device shall be able to be switched out of circuit.

5.4 The total absolute uncertainty shall be less than :

0,2 m^{-1} for a light absorption coefficient between 0 and 3 m^{-1};

0,5 m^{-1} for a light absorption coefficient between 3 and 5 m^{-1}.

6 CONSTRUCTION SPECIFICATIONS

6.1 General

The design shall be such that in steady state conditions the smoke chamber is filled with a uniform smoke and the pipes and fittings and devices for bringing the gases into the measuring chamber do not include any sharp bends where soot could accumulate.

The impingement on the receiver of stray light due to internal reflection or the effects of diffusion shall be reduced to a minimum (for example by coating the internal surfaces in matt black and by an appropriate general layout).

6.2 Measuring zone of the smoke chamber

6.2.1 The measuring zone is that part of the smoke chamber in which the measurement is made. It is bounded :

— at its two extremities by the devices for protecting the light source and the receiver, defining the effective length of the apparatus;

— parallel to the flow of gas by the lower and upper surfaces of the smoke chamber;

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

6.2.2 The speed of the gases through the measuring zone shall not differ by more than 50 % from the average speed over 90 % of the length of the measuring zone.

6.3 Light source

The light source shall have a colour temperature between 2 800 and 3 250 K within limits specified by the manufacturer for the supply voltage of the apparatus.

6.4 Receiver

6.4.1 The receiver shall be made up of a photoelectric cell with a spectral response curve similar to the photoptic curve of the human eye (maximum response in the band of 550 to 570 nm, less than 4 % of this maximum response being below 430 nm and above 680 nm).

6.4.2 The apparatus shall be so designed that :

— the rays of the light beam are parallel within 3° to the optical axis;

— the receiver does not take into consideration the direct or reflected light rays with an angle of incidence greater than 3° to the axis of the optical device.

Any system giving equivalent results will be acceptable.

6.4.3 The design of the electric measuring circuit, including the indicator, shall be such that the display value of the indicator is a monotonic function of the light absorption coefficient in the range of normal operating temperatures of the apparatus.

6.5 Measuring scale

The light absorption coefficient k (m^{-1}) is calculated according to Beer's law by the formula

$$k = \frac{\log_e(\phi_0/\phi)}{L}$$

where

L is the effective length of the light path through the gas to be measured;

ϕ_0 is the light flux received by the receiver when the measuring zone is filled with clean air;

ϕ is the light flux received by the receiver when the measuring zone is filled with smoke.

6.6 Adjustment and checking of the measuring apparatus

6.6.1 The electrical circuit of the photoelectric cell and of the indicator shall be adjustable so that the indicator can be reset at zero when the light flux passes through the measuring zone filled with clean air or through a chamber with identical characteristics.

6.6.2 Two neutral optical filters (or equivalent devices) shall provided with each opacimeter so that the accuracy and linearity of measurement of the measuring device may be checked. These filters shall have equivalent absorption coefficients as defined in 6.5, between 1,5 and 2,0 m^{-1} and between 4,5 and 5,0 m^{-1} respectively. Their values shall be known to the nearest 0,025 m^{-1}. Provision shall be made for them to be placed on the path of the light rays passing through the measuring chamber filled with clean air or through a chamber with identical characteristics. Measurement apparatus with automatic temperature compensation must simulate 100 °C during the checking tests.

6.7 Response of the opacimeter

6.7.1 *Physical response time of the opacimeter*

This is the time t necessary for a given discharge of gas, Q, to fill the volume V of the measuring zone defined in 6.2.1.

This time may be estimated with sufficient precision by means of the formula

$$t = V/Q$$

For transient conditions, the opacimeter will be satisfactory if $t \leqslant 0{,}075$ s*.

For opacimeters used only for steady state conditions, the manufacturer shall state the response time.

6.7.2 *Electrical response time*

This is the time elapsing between the moment when the light source is sealed off in less than 0,01 s, and the moment when the device recording the measuring signal reaches 90 % of the level of its final signal. For transient conditions, this electrical response time shall be equal to 0,1 ± 0,01 s*.

For opacimeters used only for steady state conditions, the manufacturer shall state the response time.

The electrical circuit shall in addition include a filtration of the measuring signal. This is obtained by means of a low-pass filter with breaking frequency of 10 Hz, possessing a frequency response curve between + 0,5 and − 1 dB up to 16,5 Hz and with a slope equal to 12 ± 6 dB/octave for frequencies greater than 16,5 Hz.

6.8 Pressure of the gas to be analysed

6.8.1 The static pressure of the exhaust gas in the smoke box shall not differ from that of the ambient air by more than 7,5 mbar.

6.8.2 The opacimeter shall be fitted with devices suitable for allowing the fitting of apparatus for measuring the static pressure in the smoke box. The readings shall be taken with an uncertainty of less than 0,1 mbar.

* Provisional values.

6.9 Temperature of the gas to be analysed

6.9.1 The opacimeter shall be fitted with the devices necessary for estimating the average temperature of the gas in the measuring chamber; the manufacturer shall specify the limits of operation. The uncertainty of measurement shall be taken into account when calculating the total measuring uncertainty of the apparatus.

6.9.2 At all points of the measuring chamber, the temperature of the test gas at the instant of measurement of opacity shall be not less than 60 °C and the average temperature in the chamber shall be not greater than 400 °C. The range of normal use shall be indicated by the manufacturer.

6.9.3 The opacimeter reading must be corrected to 100 °C by means of the formula

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

where t is the temperature, in degrees Celsius, of the test gas.

6.9.4 The thermal time-constant of the device for measuring temperature shall be

- indicated by the manufacturer;
- commensurate with the recommended operating time of the instrument for steady state use;
- less than 5 s for opacimeters used in transient conditions.

The thermal time-constant is the time necessary for the sensor to reach 63 % of the difference in temperature between the initial state and the final state in still air.

6.10 Details of design

Any devices which may be situated upstream of the measuring zone shall not affect the opacity properties of the gas entering the chamber by more than 0,05 m^{-1} for a gas with an opacity of 1,7 m^{-1}.

6.11 Total measurement uncertainty

The total measurement uncertainty Δk is given by the formula

$$\Delta k = \sqrt{\sum_i (\Delta k_i)^2}$$

where the Δk_i are principally the following uncertainties :

a) error due to the geometry of the apparatus (effective length);

b) error due to the optical and electrical devices (including soiling of lamp and photoelectric cell) :

- zero error and sensitivity error of the measuring device;
- error due to the indicator;
- error due to measurement and correction for average temperature.

Δk shall not exceed 0,2 m^{-1}.

Errors due to parameters other than those mentioned in this specification shall also be taken into account if it is considered that their influence is likely to be significant.

7 INFORMATION AND METHODS OF MEASUREMENT TO BE PROVIDED BY THE MANUFACTURER

7.1 Handbook for maintenance and use to be provided with each apparatus

This document shall deal with the following points :

7.1.1 Technical description of the opacimeter, including a diagram of the optical and electrical devices and dimensional sketches of the measuring chamber and the adjacent areas, with tolerances.

7.1.2 Information on the maintenance of the opacimeter, and in particular, the cleaning intervals and all the special operating precautions peculiar to the given model, including whether the opacimeter is designed to operate continuously or intermittently and, in the latter case, the time necessary for passing smoke through the opacimeter before a correct measurement can be taken (operating time).

List of the periodic checks which the apparatus requires.

7.1.3 Effective length of the smoke column used to calculate the light absorption coefficient.

7.1.4 Operating limits of the light source, i.e. either :

a) limits of voltage at the terminals of the light source and instructions on its life, or

b) limits of reading with a gauging colour filter provided with each opacimeter.

7.1.5 Total precision of the apparatus as defined in 6.11 and the range of corresponding ambient and exhaust gas temperatures.

7.1.6 Minimum flow of gas into the smoke chamber corresponding to the time of maximum physical response imposed in 6.7.1 and the maximum flow of gas into the smoke chamber corresponding to the maximum gas pressures allowed by the manufacturer.

7.1.7 Instructions relating to limits on fittings which may be attached to the opacimeter exit, giving equivalent orifices.

7.2 Data to be provided for the conformity check of the type of opacimeter

7.2.1 Temperature of the surface of the photoelectric cell above which its response features change significantly.

7.2.2 Relationship between the temperature indicated by the measuring device and the average temperature in the smoke chamber.

7.2.3 Nominal supply voltage limits within which the opacimeter will operate satisfactorily (separate limits must be given for each supply point where more than one exists).

7.2.4 Response time of the electric measuring circuit necessary for reaching 90 % of the level of continuous signal following sealing off of the light source in less than 0,01 s.

7.2.5 Relationship between the static pressure and the gas flow in the smoke chamber.

7.3 Methods of measurement used in the conformity check of the type of opacimeter

The opacimeter must allow the attachment of instruments necessary for measuring the following parameters :

a) static pressure of the exhaust gas in the smoke box;

b) temperature at the point specified by the manufacturer for measuring the gas temperature;

c) voltage of the lamp (unless a particular method using a colour filter is laid down for checking the colour temperature);

d) output current of the photoelectric cell.

8 VERIFICATION OF OPACIMETER TYPES

8.1 Scope

This clause gives details of the procedures to be adopted to check that an opacimeter of a given type corresponds to the requirements of clauses 5, 6 and 7. It deals with opacimeters in general. When possible, each heading includes a reference to the corresponding sub-clause of clauses 5, 6 and 7 to which the test refers. The checks cannot, however, cover all the possible models of opacimeter. It will rest therefore with the organization approving a given type of opacimeter to check the possible influence of the devices which belong to each apparatus.

8.2 General considerations

In order to verify that a particular type of opacimeter corresponds to the specification, it is necessary first to check that certain instruments and certain controls required by the specification are properly fitted on the opacimeter and that certain operational limits and certain data are properly specified by the manufacturer. The verification test consists then in checking that the properties of the instruments are as required by the specification and that, within the limits claimed by the manufacturer, the opacimeter actually satisfies the requirements of the specification. For the checking tests, certain instruments may be necessary in addition to those which are normally fitted on the opacimeter.

In fields where well-known experimental techniques already exist (aerodynamic, thermometric, optical and electrical, for example), the tests are not described in detail, but in other cases detailed instructions are given. Other methods will, however, be accepted if they are of equivalent precision and comply with the response conditions of the method described. If recording instruments are used, it is essential to take into account their influence on the response or the sensitivity of the circuit.

8.3 Definitions

The following symbols are used :

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

L : effective length of the smoke column taken into consideration in the measuring chamber;

ϕ_0 : incident light flux reaching the receiver in the absence of smoke;

ϕ : incident light flux reaching the receiver when the measuring chamber is filled by the gas to be analysed.

8.4 Information and methods of measurement (7)

Check that the information and methods of measurement provided by the manufacturer are in accordance with the requirements of clause 7 of this specification.

8.5 Basic specifications for opacimeters (5)

Check that the technical features of the opacimeter are in accordance with the requirements of clause 5 of this specification.

8.6 Verification of the components and adjustments

8.6.1 *Colour temperature* (6.3)

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

8.6.2 *Response of the photoelectric cell to different wavelengths and different temperatures* (6.4.1)

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

8.6.3 *Devices for adjusting zero and checking the measuring circuit* (6.6)

a) Check that the zero of the instrument can be adjusted satisfactorily over the whole range of supply voltages specified by the manufacturer in accordance with 7.2.3.

b) Check that the devices provided by the manufacturer for checking the operation of the measuring circuit of the opacimeter are in accordance with the requirements of 6.6.2.

8.6.4 *Indicator of the opacimeter* (5.3)

Check that the indicator of the opacimeter is in accordance with the requirements of 5.3.

8.6.5 *Static pressure measurement in the smoke chamber* (6.8.2)

Check that the opacimeter is in accordance with the requirements of 6.8.2.

8.6.6 *Optical design* (6.4.2)

Check from the technical description of the apparatus given in 7.1.1, and from actual tests, that the optical device is designated so that the opacimeter is in accordance with the requirements of 6.4.2. Check that the optical components of the opacimeter submitted for test and their dimensional position comply with the description.

8.7 Verification of the flow characteristics with respect to the internal design

8.7.1 *Temperature distribution* (6.9)

8.7.1.1 Object

In order to determine the opacity of the gas at 100 °C, it is necessary to demonstrate that the temperature gauge provided by the manufacturer does, in fact, estimate the average temperature of the gas in the measuring chamber. This is shown by comparison of the readings on the temperature gauge and the results of measurements of temperature distribution in the measuring chamber.

This test also checks that the minumum and maximum temperatures of the gas are those specified in 6.9.2.

8.7.1.2 Preparation of the test

The temperature distribution shall be measured at 11 points distributed equally along the axis of the measuring chamber over 90 % of its length. All the thermometers must be enclosed in tubes providing good thermal insulation without obstructing the flow of gas. A satisfactory method is, for example, the technique which consists in placing in the axis of the smoke chamber a thermoelectric couple the wires of which, about 0,1 mm in diameter, are connected end to end; with this system, however, it may prove necessary to use a dummy bulb and a photoelectric cell with holes in it to allow passage of the wires.

8.7.1.3 Test procedure

With the opacimeter fed with exhaust gas or hot air, measure the temperature distribution, point by point, along the axis of the measuring chamber in the following steady state conditions :

a) minimum temperature and minimum flow of gas recommended by the manufacturer;

b) maximum temperature and minimum flow of gas recommended by the manufacturer;

c) maximum temperature and maximum flow of gas recommended by the manufacturer.

8.7.1.4 Evaluation

Plot the temperature distribution along the axis of the measuring chamber, then :

a) Calculate the average absolute temperature $\overline{T}_a$, $\overline{T}_b$ and $\overline{T}_c$, in kelvins, in the three types of conditions by means of the formula

$$\overline{T} = \frac{11}{\sum_{1}^{11} (1/T)}$$

Calculate the error $\Delta k_i = 3\left[(T_m/\overline{T}) - 1\right]$ where T_m is the temperature indicated on the gauge provided by the manufacturer. This value will be required in the calculation of total uncertainty in 8.10.

b) Check that, in the three types of test conditions, at each of the 11 points of temperature measurement,

$$|1 - T/\overline{T}| \leqslant 0{,}03$$

c) Check that at no point is the measured temperature less than 60 °C, and check that $\overline{T}$ is not greater than 120 °C.

8.7.2 *Velocity distribution of the gas to be analysed* (6.2.2)

8.7.2.1 Object

It is necessary to ensure that the flow of gas in the measuring chamber is sufficiently uniform in order to avoid the mixing of the clean air in there with the puff of smoke entering. This check is carried out by comparing the velocities at different points in the flow of gas.

8.7.2.2 Preparation of test

The velocity distribution shall be measured at 11 points uniformly distributed along the axis of the measuring chamber over 90 % of its length.

8.7.2.3 Test procedure

With the opacimeter supplied with exhaust gas or with air slowed down beforehand in an expansion tank, measure the velocity distribution, point by point, along the axis of the measuring chamber and the static pressure of the gas in the smoke box in the following test conditions :

a) pressure of the gas in the smoke box as in 7.2.5 corresponding to the minimum flow D_a indicated by the manufacturer in accordance with 7.1.6;

b) pressure of the gas in the smoke box as in 7.2.5 corresponding to the maximum flow D_b indicated by the manufacturer in accordance with 7.1.6;

c) pressure of the gas in the smoke box as in 7.2.5 corresponding to an average flow of gas $D_c = (D_a + D_b)/2$.

8.7.2.4 Evaluation

Plot the velocity distribution along the axis of the measuring chamber and estimate the average velocity $\overline{v}_a$, $\overline{v}_b$ and $\overline{v}_c$ in the three types of test conditions by means of the formula

$$\overline{v} = \frac{1}{11} \sum_{1}^{11} v$$

Check that in the three types of test conditions, at each of the 11 points of velocity measurement,

$$|1 - v/\overline{v}| \leqslant 0,1$$

8.8 Response time of the opacimeter

8.8.1 *Object*

If the measuring chambers are not filled uniformly and rapidly with exhaust gas when being used in transient conditions, different types of opacimeter will then give different indications for the same test.

In addition, as the time for the smoke to pass into the measuring chamber is very short, it is necessary to ensure that the electrical measuring circuit has a short enough response time to follow the phenomenon.

8.8.2 *Physical response time* (6.7.1)

Calculate the physical response time t_{phys} of the opacimeter by means of the formula

$$t_{phys} = \frac{V}{Q}$$

where

Q is the minimum flow of gas through the smoke chamber indicated in 7.1.6;

V is the volume of the measuring zone defined in 6.2.

Check that the value calculated is less than or equal to 0,075 s.*

8.8.3 *Electrical response time* (6.7.2)

8.8.3.1 Preparation of test

To measure the receiver's response time and that of its electrical measuring circuit, it is necessary to fit the receiver on an optical bench equipped with adequate devices which work in less than 0,01 s (photographic shutter or revolving mirror, for example) and to connect the electrial measuring circuit as on the opacimeter.

The signal for measuring the light absorption and the signal for gating the light are recorded simultaneously.

The time which passes between the deflection of the light and the rising of the measuring signal to 90 % of its unbroken signal level is the response time of the electrical measuring circuit. This response time must be measured to the nearest 5 ms.

* Provisional values.

8.8.3.2 EVALUATION

The response time of the electric or electronic circuit will be considered as acceptable if it is between 0,09 and 0,11 s.*

8.9 Thermal time coefficient

8.9.1 *Object*

In transient conditions, it is difficult to measure exactly the average temperature but it is important to check that the temperature probe has a sufficiently short response time to be as close as possible to the real temperature so as to relate the measurement to the reference conditions.

8.9.2 *Preparation of test*

Connect the probe to a device recording the temperature of the probe as a function of time.

8.9.3 *Test procedure*

Heat the probe to 100 °C and immerse it suddenly in still air at room temperature the value of which is known.

8.9.4 *Evaluation*

Check that the rate of change of temperature of the probe satisfies the requirements of 6.9.4.

8.10 Determination of total measurement uncertainty (6.11)

8.10.1 *General*

The individual components of the total uncertainty must be determined according to 8.10.2 to 8.10.9, together with any other components particular to the type of opacimeter being verified. Where possible, all individual uncertainties Δk_i must be related to an opacity of 3 m^{-1}.

It must be verified that the total measuring uncertainty

$$\Delta k = \sqrt{\Sigma (\Delta k_i)^2} \leqslant 0{,}2 \text{ m}^{-1}$$

8.10.2 *Stability of zero setting*

8.10.2.1 EFFECT OF SUPPLY VOLTAGE (7.2.3)

Set the zero at the nominal supply voltage indicated by the manufacturer and note the "zero reading" (k_r) at five evenly spaced voltages between the allowed limits. Then

$$\Delta k_i = \frac{1}{2} \sqrt{\sum_1^5 (k_r)^2} \text{ m}^{-1}$$

8.10.2.2 EFFECT OF OPERATING TIME

Set the zero after an operating period of 8 min, then note the "zero reading" (k_r) at five evenly spaced points over 40 min with the opacimeter operated according to the manufacturer's instructions. Then

$$\Delta k_i = \frac{1}{2} \sqrt{\sum_1^5 (k_r)^2} \text{ m}^{-1}$$

* Provisional values.

8.10.3 *Stability of sensitivity*

Similar measurements shall be made as in 8.10.2 but with a calibrating screen equivalent to a k-value (k_c) between 1,5 and 3 m^{-1}. For each test the instrument shall be set to read k_c and the reading k_r noted at five evenly spaced points. Then

$$\Delta k_i = \frac{3}{2\,k_c}\sqrt{\sum_1^5 (k_r - k_c)^2}\ m^{-1}$$

8.10.4 *Accuracy of optical-electrical system*

Note the reading of the opacimeter (k_r) with five neutral density calibrating screens spaced approximately uniformly between equivalent k-values (k_c) of 0,25 and 3,0 m^{-1}. Then

$$\Delta k_i = \frac{1}{2}\sqrt{\frac{\sum_1^5 k_c\,(k_r - k_c)^2}{\sum_1^5 k_c}}\ m^{-1}$$

8.10.5 *Accuracy of mean temperature measuring device* (6.9.1)

This is as given in 8.7.1.

8.10.6 *Accuracy of temperature correction* (6.9.3)

When correction for temperature is performed automatically in the instrument, this system must be checked. This check shall be made at the zero setting and with a calibrating screen of equivalent opacity between 1,5 and 3,0 m^{-1}.

Set the zero with the temperature sensor at 100 °C and then note the zero reading (k_r) at five evenly spaced temperatures (at the sensor) over the range of smoke temperature specified by the manufacturer. Then

$$\Delta k_i = \frac{1}{2}\sqrt{\sum_1^5 (k_r)^2}\ m^{-1}$$

Repeat with the calibrating screen of equivalent opacity k_c. Then

$$\Delta k_i = \frac{3}{2\,k_c}\sqrt{\sum_1^5 (k_r - k_c)^2}\ m^{-1}$$

8.10.7 *Effect of temperature on optical electrical system and photoelectric cell output*

Supply the opacimeter with air (simulating smoke) or exhaust gas at controlled temperature and check the ambient air temperature. Set the zero with an exhaust gas temperature of 100 °C in the measuring zone and an ambient temperature of 20 °C.

Note the zero reading (k_r) at five evenly spaced temperature combinations between the lowest exhaust and ambient temperatures and the highest exhaust and ambient temperatures. Then

$$\Delta k_i = \frac{1}{2}\sqrt{\sum_1^5 (k_r)^2}\ m^{-1}$$

Repeat with a calibrating screen of equivalent opacity k_c. Then

$$\Delta k_i = \frac{3}{2\,k_c}\sqrt{\sum_1^5 (k_r - k_c)^2}\ m^{-1}$$