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Reciprocating internal combustion engines — Exhaust emission measurement —

Part 1:
Test-bed measurement of gaseous and particulate exhaust emissions

Moteurs alternatifs à combustion interne — Mesurage des émissions de gaz d'échappement —

Partie 1: Mesurage des émissions de gaz et de particules au banc d'essai

Reference number
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Contents

Page

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 2.

The main task of technical committees is to prepare International Standards. 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.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 8178-1 was prepared by Technical Committee ISO/TC 70, *Internal combustion engines*, Subcommittee SC 8, *Exhaust gas emission measurement*.

This second edition cancels and replaces the first edition (ISO 8178-1:1996), which has been technically revised.

ISO 8178 consists of the following parts, under the general title *Reciprocating internal combustion engines — Exhaust emission measurement*:

- *Part 1: Test-bed measurement of gaseous and particulate exhaust emissions*
- *Part 2: Measurement of gaseous and particulate exhaust emissions at site*
- *Part 3: Definitions and methods of measurement of exhaust gas smoke under steady-state conditions*
- *Part 4: Test cycles for different engine applications*
- *Part 5: Test fuels*
- *Part 6: Report of measuring results and test*
- *Part 7: Engine family determination*
- *Part 8: Engine group determination*
- *Part 9: Test cycles and test procedures for test bed measurement of exhaust gas smoke emissions from compression ignition engines operating under transient conditions*
- *Part 10: Test cycles and test procedures for field measurement of exhaust gas smoke emissions from compression ignition engines operating under transient conditions*
- *Part 11: Test-bed measurement of gaseous and particulate exhaust emissions from engines used in nonroad mobile machinery under transient test conditions*

Introduction

This part of ISO 8178 is intended for use as a measurement procedure to determine the gaseous and particulate emission levels of reciprocating internal combustion (RIC) engines for non-automotive use. Its purpose is to provide a map of an engine's emissions characteristics which, through use of the proper weighting factors, can be used as an indication of that engine's emission levels under various applications. The emission results are expressed in units of grams per kilowatt-hour and represent the mass rate of emissions per unit of work accomplished.

Although this part of ISO 8178 is designed for non-automotive engines, it shares many principles with particulate and gaseous emission measurements that have been in use for many years for on-road engines. One test procedure that shares many of these principles is the full-flow dilution method as currently specified for certification of 1985 and later heavy-duty truck engines in the USA. Another is the procedure for direct measurement of the gaseous emissions in the undiluted exhaust gas, as currently specified for the certification of heavy-duty truck engines in Japan and Europe.

Many of the procedures described in this part of ISO 8178 are detailed accounts of laboratory methods, since determining an emissions value requires performing a complex set of individual measurements, rather than obtaining a single measured value. Thus, the results obtained depend as much on the process of performing the measurements as they depend on the engine and test method.

Evaluating emissions from off-road engines is more complicated than the same task for on-road engines due to the diversity of off-road applications. For example, on-road applications primarily consist of moving a load from one point to another on a paved roadway. The constraints of the paved roadways, maximum acceptable pavement loads and maximum allowable grades of fuel, narrow the scope of on-road vehicle and engine sizes. Off-road engines and vehicles include a wider range of size, including the engines that power the equipment. Many of the engines are large enough to preclude the application of test equipment and methods that were acceptable for on-road purposes. In cases where the application of dynamometers is not possible, the tests must be made at site or under appropriate conditions.

Reciprocating internal combustion engines — Exhaust emission measurement —

Part 1:
Test-bed measurement of gaseous and particulate exhaust emissions

1 Scope

This part of ISO 8178 specifies the measurement and evaluation methods for gaseous and particulate exhaust emissions from reciprocating internal combustion (RIC) engines under steady-state conditions on a test bed, necessary for determining one weighted value for each exhaust gas pollutant. Various combinations of engine load and speed reflect different engine applications (see ISO 8178-4).

This part of ISO 8178 is applicable to RIC engines for mobile, transportable and stationary use, excluding engines for motor vehicles primarily designed for road use. This part of ISO 8178 may be applied to engines used, for example, for earth-moving machines, generating sets and for other applications.

In limited instances, the engine can be tested on the test bed in accordance with ISO 8178-2, the field test document. This can only occur with the agreement of the parties involved. It should be recognized that data obtained under these circumstances may not agree completely with previous or future data obtained under the auspices of this part of ISO 8178. Therefore, it is recommended that this option be exercised only with engines built in very limited quantities such as very large marine or generating set engines.

For engines used in machinery covered by additional requirements (e.g. occupational health and safety regulations, regulations for powerplants), additional test conditions and special evaluation methods may apply.

Where it is not possible to use a test bed or where information is required on the actual emissions produced by an in-service engine, the site test procedures and calculation methods specified in ISO 8178-2 are appropriate.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 31-0:1992, *Quantities and units — Part 0: General principles*

ISO 3046-1:2002, *Reciprocating internal combustion engines — Performance — Part 1: Declarations of power, fuel and lubricating oil consumptions, and test methods — Additional requirements for engines for general use*

ISO 5167-1:2003, *Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full — Part 1: General principles and requirements*

ISO 5725-1, *Accuracy (trueness and precision) of measurement methods and results — Part 1: General principles and definitions*

ISO 5725-2:1994, *Accuracy (trueness and precision) of measurement methods and results — Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method*

ISO 8178-4:1996, *Reciprocating internal combustion engines — Exhaust emission measurement — Part 4: Test cycles for different engine applications*

ISO 8178-5:1997, *Reciprocating internal combustion engines — Exhaust emission measurement — Part 5: Test fuels*

ISO 8178-6:2000, *Reciprocating internal combustion engines — Exhaust emission measurement — Part 6: Report of measuring results and test*

ISO 9000:2005, *Quality management systems — Fundamentals and vocabulary*

ISO 9096:2003, *Stationary source emissions — Manual determination of mass concentration of particulate matter*

ISO 14396:2002, *Reciprocating internal combustion engines — Determination and method for the measurement of engine power — Additional requirements for exhaust emission tests in accordance with ISO 8178*

ISO 15550:2002, *Internal combustion engines — Determination and method for the measurement of engine power — General requirements*

ISO 16183:2002, *Heavy duty engines — Measurement of gaseous emissions from raw exhaust gas and of particulate emissions using partial flow dilution systems under transient test conditions*

SAE J 1088:1993, *Test procedure for the measurement of gaseous exhaust emissions from small utility engines*

SAE J 1151:1991, *Methane measurement using gas chromatography*

3 Terms and definitions

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

3.1
particulates
material collected on a specified filter medium after diluting exhaust gases with clean, filtered air to a temperature of greater than 315 K (42 °C) and less than or equal to 325 K (52°C), as measured at a point immediately upstream of the primary filter

NOTE 1 Particulates consist primarily of carbon, condensed hydrocarbons, and sulfates and associated water.

NOTE 2 Particulates defined in this part of ISO 8178 are substantially different in composition and weight from particulates or dust sampled directly from the undiluted exhaust gas using a hot filter method (e.g. ISO 9096). Particulates measurement as described in this part of ISO 8178 is conclusively proven to be effective for fuel sulphur levels up to 0,8 %.

NOTE 3 The filter temperature requirement has been changed compared to ISO 8178-1:1996 to reflect the latest legal requirements in the USA and European Union. Existing systems built in compliance with the requirements of ISO 8178-1:1996 may still be used.

3.2
partial-flow dilution method

process of separating a part of the raw exhaust from the total exhaust flow, then mixing with an appropriate amount of dilution air prior to passing through the particulate sampling filter

NOTE See 17.2.1, Figures 10 to 18.

3.3
full-flow dilution method

process of mixing dilution air with the total exhaust flow prior to separating a fraction of the diluted exhaust stream for analysis

NOTE It is common in many full-flow dilution systems to dilute this fraction of pre-diluted exhaust a second time to obtain appropriate sample temperatures at the particulate filter (see 17.2.2, Figure 19).

3.4
isokinetic sampling

process of controlling the flow of the exhaust sample by maintaining the mean sample velocity at the probe equal to the exhaust stream mean velocity

3.5
non-isokinetic sampling

process of controlling the flow of the exhaust sample independently of the exhaust stream velocity

3.6
multiple-filter method

process of using one pair of filters for each of the individual test cycle modes

NOTE The modal weighting factors are accounted for after sampling during the data evaluation phase of the test.

3.7
single-filter method

process of using one pair of filters for all test cycle modes

NOTE Modal weighting factors must be accounted for during the particulate sampling phase of the test cycle by adjusting sample flow rate and/or sampling time. This method dictates that particular attention be given to sampling duration and flow rates.

3.8
specific emissions

mass emissions expressed in grams per kilowatt-hour

NOTE For many engine types within the scope of this part of ISO 8178, the auxiliaries which will be fitted to the engine in service will not be known at the time of manufacture or certification.

When it is not appropriate to test the engine in the conditions as defined in ISO 14396 (e.g. if the engine and transmission form a single integral unit), the engine can only be tested with other auxiliaries fitted. In this case the dynamometer settings should be determined in accordance with 5.3 and 12.5. The auxiliary losses should not exceed 5 % of the maximum observed power. Losses exceeding 5 % must be approved by the parties involved prior to the test.

3.9
brake power

observed power measured at the crankshaft or its equivalent, the engine being equipped only with the standard auxiliaries necessary for its operation on the test bed

NOTE See 5.3 and ISO 14396.

3.10
auxiliaries

equipment and devices listed in ISO 14396

4 Symbols and abbreviations

4.1 General symbols

Symbol	Term	Unit
A/F_{st}	Stoichiometric air-to-fuel ratio	1
A_{p}	Cross-sectional area of the isokinetic sampling probe	m^2
A_{r}	Atomic mass	g
A_{x}	Cross-sectional area of the exhaust pipe	m^2
c_{c}	Background corrected concentration	ppm % (V/V)
c_{d}	Concentration in the dilution air	ppm % (V/V)
c_{x}	Concentration in the exhaust (with suffix of the component nominating)	ppm % (V/V)
D	Dilution factor	1
E_{CO2}	CO_2 quench of NO_x analyser	%
E_{E}	Ethane efficiency	%
E_{H2O}	Water quench of NO_x analyser	%
E_{M}	Methane efficiency	%
E_{NOx}	Efficiency of NO_x converter	%
e_{PT}	Particulate emission	g/kW·h
e_{x}	Gas emission (with subscript denoting compound)	g/kW·h
λ	Excess air factor ([kg dry air] / ([kg fuel] * [A/F_{st}]))	1
λ_{Ref}	Excess air factor at reference conditions	1
f_{a}	Laboratory atmospheric factor	1
f_{c}	Carbon factor	1
f_{fd}	Fuel specific factor for exhaust flow calculation on dry basis	1
f_{fh}	Fuel specific factor used for the calculations of wet concentrations from dry concentrations	1
f_{fw}	Fuel specific factor for exhaust flow calculation on wet basis	1
H_{a}	Absolute humidity of the intake air (g water / kg dry air)	g/kg
H_{d}	Absolute humidity of the dilution air (g water / kg dry air)	g/kg
i	Subscript denoting an individual mode	1
k_f	Fuel specific factor for the carbon balance calculation	1
k_{hd}	Humidity correction factor for NO_x for diesel engines	1
k_{hp}	Humidity correction factor for NO_x for gasoline (petrol) engines	1
k_{p}	Humidity correction factor for particulates	1
k_{wa}	Dry to wet correction factor for the intake air	1
k_{wd}	Dry to wet correction factor for the dilution air	1
k_{we}	Dry to wet correction factor for the diluted exhaust gas	1
k_{wr}	Dry to wet correction factor for the raw exhaust gas	1
M	Percent torque related to the maximum torque for the test engine speed	%
M_{r}	Molecular mass	g
m_{d}	Mass of the dilution air sample passed through the particulate sampling filters	kg
$m_{\mathrm{f,d}}$	Particulate sample mass of the dilution air collected	mg
m_{f}	Particulate sample mass collected	mg
m_{sep}	Mass of the diluted exhaust sample passed through the particulate sampling filters	kg
P_{A}	Absolute outlet pressure at pump outlet	kPa

Symbol	Term	Unit
p_a	Saturation vapour pressure of the engine intake air	kPa
p_b	Total barometric pressure	kPa
p_d	Saturation vapour pressure of the dilution air	kPa
p_r	Water vapour pressure after cooler	kPa
p_s	Dry atmospheric pressure	kPa
P	Uncorrected brake power	kW
P_aux	Declared total power absorbed by auxiliaries fitted for the test and not required by ISO 14396	kW
P_m	Maximum measured or declared power at the test engine speed under test conditions (see 12.5)	kW
$q_{m\mathrm{ad}}$	Intake air mass flow rate on dry basis	kg/h
$q_{m\mathrm{aw}}$	Intake air mass flow rate on wet basis	kg/h
$q_{m\mathrm{dw}}$	Dilution air mass flow rate on wet basis	kg/h
$q_{m\mathrm{edf}}$	Equivalent diluted exhaust gas mass flow rate on wet basis	kg/h
$q_{m\mathrm{ew}}$	Exhaust gas mass flow rate on wet basis	kg/h
$q_{m\mathrm{f}}$	Fuel mass flow rate	kg/h
$q_{m\mathrm{dew}}$	Diluted exhaust gas mass flow rate on wet basis	kg/h
$q_{m\mathrm{gas}}$	Emission mass flow rate of individual gas	g/h
$q_{m\mathrm{PT}}$	Particle mass flow rate	g/h
r_d	Dilution ratio	1
r_a	Ratio of cross-sectional areas of isokinetic probe and exhaust pipe	1
R_a	Relative humidity of the intake air	%
R_d	Relative humidity of the dilution air	%
r_h	FID response factor	1
r_m	FID response factor for methanol	1
r_x	Ratio of the SSV throat to inlet absolute, static pressure	1
r_y	Ratio of the SSV throat diameter, d, to the inlet pipe inner diameter	1
ρ	Density	$\mathrm{kg/m^3}$
S	Dynamometer setting	kW
T_a	Absolute temperature of the intake air	K
T_d	Absolute dewpoint temperature	K
T_ref	Absolute reference temperature (of combustion air: 298 K)	K
T_c	Absolute temperature of the intercooled air	K
T_cref	Absolute intercooled air reference temperature	K
V_m	Molar volume	l
W_f	Weighting factor	1
W_fe	Effective weighting factor	1

4.2 Symbols for fuel composition

w_ALF	H content of fuel, % mass
w_BET	C content of fuel, % mass
w_GAM	S content of fuel, % mass
w_DEL	N content of fuel, % mass

w_{EPS}	O content of fuel, % mass
α	molar ratio (H/C)
β	molar ratio (C/C)
γ	molar ratio (S/C)
δ	molar ratio (N/C)
ε	molar ratio (O/C)

NOTE The conversion between mass content and molar ratio is given in Equations A.3 to A.12 of Annex A.

4.3 Symbols and abbreviations for the chemical components

ACN	acetonitrile
C1	carbon 1 equivalent hydrocarbon
CH_4	methane
C_2H_6	ethane
C_3H_8	propane
CH_3OH	methanol
CO	carbon monoxide
CO_2	carbon dioxide
DNPH	dinitrophenyl hydrazine
DOP	dioctyl phthalate
HC	hydrocarbons
HCHO	formaldehyde
H_2O	water
NH_3	ammonia
NMHC	non-methane hydrocarbons
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	oxides of nitrogen
N_2O	dinitrogen oxide
O_2	oxygen
RME	rapeseed oil methylester
SO_2	sulphur dioxide
SO_3	sulphur trioxide

4.4 Abbreviations

CFV	critical flow venturi
CLD	chemiluminescent detector
CVS	constant volume sample
ECS	electrochemical sensor
FID	flame ionization detector
FTIR	Fourier transform infrared analyser
GC	gas chromatograph
HCLD	heated chemiluminescent detector
HFID	heated flame ionization detector
HPLC	high-pressure liquid chromatograph
NDIR	non-dispersive infrared analyser
NMC	non-methane cutter
PDP	positive displacement pump
PMD	paramagnetic detector
PT	particulates
UVD	ultraviolet detector
ZRDO	zirconium dioxide sensor

5 Test conditions

5.1 Engine test conditions

5.1.1 Test condition parameter

The absolute temperature T_a of the engine intake air expressed in Kelvin and the dry atmospheric pressure p_s expressed in kilopascals shall be measured, and the parameter f_a shall be determined according to the following provisions.

a) Compression-ignition engines

Naturally aspirated and mechanically pressure-charged engines:

$$f_a = \left(\frac{99}{p_s}\right) \times \left(\frac{T_a}{298}\right)^{0,7} \quad (1)$$

Turbocharged engines with or without cooling of the intake air:

$$f_a = \left(\frac{99}{p_s}\right)^{0,7} \times \left(\frac{T_a}{298}\right)^{1,5} \quad (2)$$

b) Spark-ignition engines

$$f_a = \left(\frac{99}{p_s}\right)^{1,2} \times \left(\frac{T_a}{298}\right)^{0,6} \qquad (3)$$

NOTE Formulae (1) to (3) are identical with the exhaust emissions legislation from ECE, EEC and EPA, but different from the ISO power correction formulae.

5.1.2 Test validity

For a test to be recognized as valid, the parameter f_a shall be such that

$$0,93 \leqslant f_a \leqslant 1,07 \qquad (4)$$

Tests should be conducted with the parameter f_a between 0,96 and 1,06.

5.2 Engines with charge air cooling

The charge air temperature shall be recorded and shall be, at the speed of the declared rated power and full load, within ± 5 K of the maximum charge air temperature specified by the manufacturer. The temperature of the cooling medium shall be at least 293 K (20 °C).

If a test shop system or external blower is used, the charge air temperature shall be set to within ± 5 K of the maximum charge air temperature specified by the manufacturer at the speed of the declared rated power and full load. Coolant temperature and coolant flow rate of the charge air cooler at the above set point shall not be changed for the whole test cycle. The charge air cooler volume shall be based upon good engineering practice and typical vehicle/machinery applications.

5.3 Power

The basis of specific emissions measurement is uncorrected brake power as defined in ISO 14396. The engine shall be submitted with auxiliaries needed for operating the engine (e.g. fan, water pump). If it is impossible or inappropriate to install the auxiliaries on the test bench, the power absorbed by them shall be determined and subtracted from the measured engine power.

Certain auxiliaries necessary only for the operation of the machine and which may be mounted on the engine should be removed for the test. The following incomplete list is given as an example:

- air compressor for brakes,
- power steering compressor,
- air conditioning compressor,
- pumps for hydraulic actuators.

For further details, see 3.9 and ISO 14396.

Where auxiliaries have not been removed, the power absorbed by them at the test speeds shall be determined in order to calculate the dynamometer settings in accordance with 12.5, except for engines where such auxiliaries form an integral part of the engine (e.g. cooling fans for air-cooled engines).

5.4 Specific test conditions

5.4.1 Engine air inlet system

An engine air intake system or a test shop system shall be used, presenting an air intake restriction within ± 300 Pa of the maximum value specified by the manufacturer for a clean air cleaner at the speed of rated power and full load.

If the engine is equipped with an integral air inlet system, it shall be used for testing.

NOTE The restrictions are to be set at rated speed and full load.

5.4.2 Engine exhaust system

An engine exhaust system or a test shop system shall be used, presenting an exhaust backpressure within ± 650 Pa of the maximum value specified by the manufacturer at the speed of rated power and full load. The exhaust system shall conform to the requirements for exhaust gas sampling, as set out in 7.5.5, 17.2.1, EP and 17.2.2, EP.

If the engine is equipped with an integral exhaust system, it shall be used for testing.

If the engine is equipped with an exhaust aftertreatment device, the exhaust pipe shall have the same diameter as found in use for at least four pipe diameters upstream to the inlet of the beginning of the expansion section containing the aftertreatment device. The distance from the exhaust manifold flange or turbocharger outlet to the exhaust aftertreatment device shall be the same as in the vehicle configuration or within the distance specifications of the manufacturer. The exhaust backpressure or restriction shall follow the same criteria as above, and may be set with a valve. The aftertreatment container may be removed during dummy tests and during engine mapping, and replaced with an equivalent container having an inactive catalyst support.

NOTE The restrictions are to be set at rated speed and full load.

5.4.3 Cooling system

An engine cooling system with sufficient capacity to maintain the engine at normal operating temperatures prescribed by the manufacturer shall be used.

5.4.4 Lubricating oil

Specifications of the lubricating oil used for the test shall be recorded and presented with the results of the test.

5.4.5 Adjustable carburettors

For engines with limited adjustable carburettors, test of the engines shall be performed at both extremes of the adjustment.

5.4.6 Crankcase breather

When it is required to measure the crankcase emissions of an open crankcase system as part of the total emissions from the engine, they shall be introduced into the exhaust system downstream of any aftertreatment system, if used, and upstream of the sampling point. Sufficient distance shall be allowed to ensure mixing of the crankcase emissions with the exhaust gas.

6 Test fuels

Fuel characteristics influence the engine exhaust gas emission. Therefore, the characteristics of the fuel used for the test should be determined, recorded and presented with the results of the test. Where fuels designated in ISO 8178-5 as reference fuels are used, the reference code and the analysis of the fuel shall be provided; for all other fuels, the characteristics to be recorded are those listed in the appropriate universal data sheets in ISO 8178-5.

The fuel temperature shall be in accordance with the manufacturer's recommendations.The fuel temperature shall be measured at the inlet to the fuel injection pump or as specified by the manufacturer, and the location of measurement recorded.

The selection of the fuel for the test depends on the purpose of the test. Unless otherwise agreed by the parties involved, the fuel shall be selected in accordance with Table 1. When a suitable reference fuel is not available, a fuel with properties very close to the reference fuel may be used. The characteristics of the fuel shall be declared.

Table 1 — Selection of fuel

Test purpose	Interested parties	Fuel selection
Type approval (Certification)	1. Certification body 2. Manufacturer or supplier	Reference fuel, if one is defined Commercial fuel if no reference fuel is defined
Acceptance test	1. Manufacturer or supplier 2. Customer or inspector	Commercial fuel as specified by the manufacturer [a]
Research/development	One or more of the following: manufacturer, research organization, fuel and lubricant supplier, etc.	To suit the purpose of the test.

[a] Customers and inspectors should note that the emission tests carried out using commercial fuel will not necessarily comply with limits specified when using reference fuels.

7 Measurement equipment and data to be measured

7.1 General

The emission of gaseous and particulate components by the engine submitted for testing shall be measured by the methods described in Clauses 16 and 17. These clauses describe the recommended analytical systems for the gaseous emissions (Clause 16) and the recommended particulate dilution and sampling systems (Clause 17).

Other systems or analysers may be accepted if they yield equivalent results. The determination of system equivalency shall be based on a seven-sample pair (or larger) correlation study between the system under consideration and one of the accepted systems of this part of ISO 8178. "Results" refers to the specific cycle weighted emissions value. The correlation testing is to be performed at the same laboratory, test cell, and on the same engine. The tests should be run concurrently. The test cycle to be used shall be the appropriate cycle as found in ISO 8178-4, or the C1 cycle as found in ISO 8178-4. The equivalency of the sample pair averages shall be determined by F-test and t-test statistics (see Annex D), with outliers excluded, obtained under the laboratory cell and the engine conditions described above. The systems to be used for correlation testing shall be declared prior to the test and shall be agreed upon by the parties involved.

For introduction of a new system into the standard, the determination of equivalency shall be based upon the calculation of repeatability and reproducibility, as described in ISO 5725-1 and ISO 5725-2.

The following equipment shall be used for emissions tests of engines on engine dynamometers. This part of ISO 8178 does not contain details of flow, pressure, and temperature measuring equipment. Instead, only the accuracy requirements of such equipment necessary for conducting an emissions test are given in 7.4.

7.2 Dynamometer specification

An engine dynamometer with adequate characteristics to perform the appropriate test cycle described in ISO 8178-4 shall be used.

The instrumentation for torque and speed measurement shall allow the measurement accuracy of the shaft power within the given limits. Additional calculations may be necessary. The accuracy of the measuring equipment shall be such that the maximum tolerances of the figures given in 7.4 are not exceeded.

7.3 Exhaust gas flow

7.3.1 General

The exhaust gas flow shall be determined by one of the methods given in 7.3.2 to 7.3.6.

7.3.2 Direct measurement method

Direct measurement of the exhaust flow may be done by systems such as the following:

- pressure differential devices, like flow nozzle (see ISO 5167);
- ultrasonic flowmeter;
- vortex flowmeter.

Precautions shall be taken to avoid measurement errors which will impact on emission value errors. Such precautions include the careful installation of the device in the engine exhaust system according to the instrument manufacturers' recommendations and to good engineering practice. In particular, engine performance and emissions shall not be affected by the installation of the device.

The flowmeters shall meet the accuracy specifications of 7.4.

7.3.3 Air and fuel measurement method

This involves measurement of the air flow and the fuel flow. Air flowmeters and fuel flowmeters with an accuracy defined in 7.4 shall be used. The calculation of the exhaust gas flow is as follows:

$$q_{m\mathrm{ew}} = q_{m\mathrm{aw}} + q_{m\mathrm{f}} \tag{5}$$

7.3.4 Fuel flow and carbon balance method

This involves exhaust mass calculation from fuel consumption, fuel composition and exhaust gas concentrations using the carbon balance method, as given with the following formulae (see A.3.2.3.1):

$$q_{m\mathrm{ew}} = q_{m\mathrm{f}} \times \left(\left(\frac{w_{\mathrm{BET}} \times w_{\mathrm{BET}} \times 1{,}4}{\dfrac{\left(\dfrac{1{,}4 \times w_{\mathrm{BET}}}{f_{\mathrm{c}}} + w_{\mathrm{ALF}} \times 0{,}089\,36 - 1 \right) \times \dfrac{1}{1{,}293} + f_{\mathrm{fd}}}{f_{\mathrm{c}} \times f_{\mathrm{c}}}} + w_{\mathrm{ALF}} \times 0{,}089\,36 - 1 \right) \times \left(1 + \frac{H_{\mathrm{a}}}{1\,000} \right) + 1 \right) \tag{6}$$

where

f_{fd} is according to Equations A.20 to A.23;

H_{a} is the g water per kg dry air;

f_c is according to Equation A.64:

$$f_c = \left(c_{\mathrm{CO2d}} - c_{\mathrm{CO2ad}}\right) \times 0{,}544\,1 + \frac{c_{\mathrm{COd}}}{18\,522} + \frac{c_{\mathrm{HCw}}}{17\,355} \qquad (7)$$

where

c_{CO2d} is the dry CO_2 concentration in the raw exhaust [%];

c_{CO2ad} is the dry CO_2 concentration in the ambient air [%];

c_{COd} is the dry CO concentration in the raw exhaust [ppm];

c_{HCw} is the wet HC concentration in the raw exhaust [ppm].

NOTE Optionally, the oxygen balance method may be used. See A.3.3.

7.3.5 Tracer measurement method

This involves measurement of the concentration of a tracer gas in the exhaust.

A known amount of an inert gas (e.g. pure helium) shall be injected into the exhaust gas flow as a tracer. The gas is mixed and diluted by the exhaust gas, but shall not react in the exhaust pipe. The concentration of the gas shall then be measured in the exhaust gas sample.

In order to ensure complete mixing of the tracer gas, the exhaust gas sampling probe shall be located at least 1 m or 30 times the diameter of the exhaust pipe – whichever is larger – downstream of the tracer gas injection point. The sampling probe may be located closer to the injection point if complete mixing is verified by comparing the tracer gas concentration with the reference concentration when the tracer gas is injected upstream of the engine.

The tracer gas flow rate shall be set so that the trace gas concentration after mixing becomes lower than the full scale of the trace gas analyser.

The calculation of the exhaust gas flow is as follows:

$$q_{m\mathrm{ew}} = \frac{q_{\mathrm{rt}} \times \rho_{\mathrm{ew}}}{60 \times \left(c_{\mathrm{mix}} - c_{\mathrm{a}}\right)} \qquad (8)$$

where

$q_{m\mathrm{ew}}$ is the exhaust mass flow [kg/s];

q_{rt} is the tracer gas flow rate [cm^3/min];

c_{mix} is the concentration of the tracer gas after mixing [ppm];

ρ_{ew} is the density of the exhaust gas [kg/m^3];

c_{a} is the background concentration of the tracer gas in the intake air [ppm].

The background concentration of the tracer gas (c_{a}) may be determined by averaging the background concentration measured immediately before the test run and after the test run.

When the background concentration is less than 1 % of the concentration of the tracer gas after mixing (c_{mix}) at maximum exhaust flow, the background concentration may be neglected.

The total system shall meet the accuracy specifications for the exhaust gas flow, and shall be calibrated according to 8.6.

7.3.6 Air flow and air-to-fuel ratio measurement method

This involves exhaust mass calculation from the air flow and the air-to-fuel ratio. The calculation of the instantaneous exhaust gas mass flow is as follows:

$$q_{m\mathrm{ew}} = q_{m\mathrm{aw}} \times \left(1 + \frac{1}{A/F_{\mathrm{st}} \times \lambda}\right) \tag{9}$$

where

$$A/F_{\mathrm{st}} = \frac{138{,}0 \times \left(\beta + \frac{\alpha}{4} - \frac{\varepsilon}{2} + \gamma\right)}{12{,}011 \times \beta + 1{,}007\,94 \times \alpha + 15{,}999\,4 \times \varepsilon + 14{,}006\,7 \times \delta + 32{,}065 \times \gamma} \tag{10}$$

$$\lambda = \frac{\beta \times \left(100 - \frac{c_{\mathrm{CO}} \times 10^{-4}}{2} - c_{\mathrm{HC}} \times 10^{-4}\right) + \left(\frac{\alpha}{4} \times \frac{1 - \frac{2 \times c_{\mathrm{CO}} \times 10^{-4}}{3{,}5 \times c_{\mathrm{CO2}}}}{1 + \frac{c_{\mathrm{CO}} \times 10^{-4}}{3{,}5 \times c_{\mathrm{CO2}}}} - \frac{\varepsilon}{2} - \frac{\delta}{2}\right) \times \left(c_{\mathrm{CO2}} + c_{\mathrm{CO}} \times 10^{-4}\right)}{4{,}764 \times \left(\beta + \frac{\alpha}{4} - \frac{\varepsilon}{2} + \gamma\right) \times \left(c_{\mathrm{CO2}} + c_{\mathrm{CO}} \times 10^{-4} + c_{\mathrm{HC}} \times 10^{-4}\right)} \tag{11}$$

where

A/F_{st}	is the stoichiometric air-to-fuel ratio [kg/kg];
λ	is the excess air ratio;
c_{CO2}	is the dry CO_2 concentration [%];
c_{CO}	is the dry CO concentration [ppm];
c_{HC}	is the HC concentration [ppm].

NOTE Fuel composition $C_{\beta}H_{\alpha}S_{\gamma}N_{\delta}O_{\varepsilon}$ with $\beta = 1$. For fuels without carbon (e.g. hydrogen) Equations (10) and (11) cannot be used.

The air flowmeter shall meet the accuracy specifications of 7.4, the CO_2 analyser used shall meet the specifications of 7.5.4.2, and the total system shall meet the accuracy specifications for the exhaust gas flow.

Optionally, air-to-fuel ratio measurement equipment, such as a zirconia-type sensor, which meets the specifications of 7.5.4.12 may be used for the measurement of the excess air ratio.

7.3.7 Total dilute exhaust gas flow

When using a full-flow dilution system, the total flow of the dilute exhaust ($q_{m\mathrm{dew}}$) shall be measured with a PDP or CFV (see 17.2.2). The accuracy shall conform to the provisions of 9.2.

7.4 Accuracy

The calibration of all measuring instruments shall be traceable to national (international) standards and comply with the requirements given in Tables 2 and 3.

NOTE Calibration requirements for analysers are given in 8.5.

The instruments shall be calibrated as required by internal audit procedures, by the instrument manufacturer or in accordance with ISO 9000 requirements. The deviations given in Tables 2 and 3 refer to the final recorded value, which includes the data acquisition system.

Table 2 — Permissible deviations of instruments for engine-related parameters

No.	Measurement instrument	Permissible deviation
1	Engine speed	± 2 % of reading or ± 1 % of engine's max. value, whichever is larger
2	Torque	± 2 % of reading or ± 1 % of engine's max. value, whichever is larger
3	Fuel consumption [a]	± 2 % of engine's max. value
4	Air consumption [a]	± 2 % of reading or ± 1 % of engine's max. value, whichever is larger
5	Exhaust gas flow [a]	± 2,5 % of reading or ± 1,5 % of engine max. value, whichever is larger

[a] The calculations of the exhaust emissions as described in this part of ISO 8178 are, in some cases, based on different measurement and/or calculation methods. Because of limited total tolerances for the exhaust emission calculation, the allowable values for some items, used in the appropriate equations, must be smaller than the allowed tolerances given in ISO 15550:2002, Table 4.

Table 3 — Permissible deviations of instruments for other essential parameters

No.	Parameter	Permissible deviation
1	Temperatures $\leqslant$ 600 K	± 2 K absolute
2	Temperatures > 600 K	± 1% of reading
3	Exhaust gas pressure	± 0,2 kPa absolute
4	Intake air depressions	± 0,05 kPa absolute
5	Atmospheric pressure	± 0,1 kPa absolute
6	Other pressures	± 0,1 kPa absolute
7	Relative humidity	± 3 % absolute
8	Absolute humidity	± 5 % of reading
9	Dilution air flow	± 2 % of reading
10	Diluted exhaust gas flow	± 2 % of reading

7.5 Determination of the gaseous components

7.5.1 General analyser specifications

7.5.1.1 General specifications

The analysers shall have a measuring range appropriate for the accuracy required to measure the concentrations of the exhaust gas components (see 7.5.1.2). The analysers should be operated such that the measured concentration falls between 15 % and 100 % of full scale.

If the full-scale value is 155 ppm (or ppmC) or less or if read-out systems (computers, data loggers) that provide sufficient accuracy and resolution below 15 % of full scale are used, concentrations below 15 % of full scale are also acceptable. In this case, additional calibrations are to be made to ensure the accuracy of the calibration curves.

The electromagnetic compatibility (EMC) of the equipment shall be at a level so as to minimize additional errors.

7.5.1.2 Accuracy

The analyser shall not deviate from the nominal calibration point by more than ± 2 % of the reading over the whole measurement range (except zero) or ± 0,3 % of full scale, whichever is larger. The accuracy shall be determined according to the calibration requirements laid down in 8.5.5.

NOTE For the purposes of this part of ISO 8178, accuracy is defined as the deviation of the analyser reading from the nominal calibration values using a calibration gas (= true value).

7.5.1.3 Precision

The precision, defined as 2,5 times the standard deviation of 10 repetitive responses to a given calibration or span gas, shall be no greater than ± 1 % of full-scale concentration for each range used above 100 ppm (or ppmC) or ± 2 % of each range used below 100 ppm (or ppmC).

7.5.1.4 Noise

The analyser peak-to-peak response to zero and calibration or span gases over any 10-second period shall not exceed 2 % of full scale on all ranges used.

7.5.1.5 Zero drift

Zero response is defined as the mean response, including noise, to a zero gas during a 30 s time interval. The drift of the zero response during a 1 h period shall be less than 2 % of full scale on the lowest range used.

7.5.1.6 Span drift

Span response is defined as the mean response, including noise, to a span gas during a 30 s time interval. The drift of the span response during a 1 h period shall be less than 2 % of full scale on the lowest range used.

7.5.2 Gas drying

Exhaust gases may be measured wet or dry. A gas-drying device, if used, shall have a minimal effect on the composition of the measured gases. Chemical driers are not an acceptable method of removing water from the sample.

7.5.3 Analysers

7.5.3.1 General

7.5.3.2 to 7.5.3.12 define the measurement principles to be used. A detailed description of the measurement systems is given in Clause 16. The gases to be measured shall be analysed with the following instruments. For non-linear analysers, the use of linearizing circuits is permitted.

7.5.3.2 Carbon monoxide (CO) analysis

The carbon monoxide analyser shall be of the non-dispersive infrared (NDIR) absorption type.

7.5.3.3 Carbon dioxide (CO_2) analysis

The carbon dioxide analyser shall be of the non-dispersive infrared (NDIR) absorption type.

7.5.3.4 Oxygen (O_2) analysis

Oxygen analysers shall be of the paramagnetic detector (PMD), zirconium dioxide (ZRDO) or electrochemical sensor (ECS) type.

Zirconium dioxide sensors should not be used when HC and CO concentrations are high, such as for lean-burn spark-ignited engines.

Electrochemical sensors shall compensate for CO_2 and NO_x interference.

7.5.3.5 Hydrocarbon (HC) analysis

The hydrocarbon analyser shall be of the heated flame ionization detector (HFID) type with detector, valves, pipework, etc. heated so as to maintain a gas temperature of 463 K ± 10 K (190 °C ± 10 °C). For methanol-fuelled engines, the temperature requirements of 7.5.3.12.3 apply. Optionally, for gas-fuelled engines and for the dilute testing of spark-ignition engines, the hydrocarbon analyser may be of the non-heated flame ionization detector (FID) type.

7.5.3.6 Non-methane hydrocarbon (NMHC) analysis

7.5.3.6.1 General

Depending on the methane (CH_4) concentration, this method is more relevant for gaseous than for liquid fuels.

7.5.3.6.2 Gas chromatographic (GC) method

Non-methane hydrocarbons shall be determined by subtraction of the methane analysed with a gas chromatograph (GC) conditioned at 423 K (150 °C) from the hydrocarbons measured according to 7.5.3.5.

7.5.3.6.3 Non-methane cutter (NMC) method

The determination of the non-methane fraction shall be performed with an NMC operated in line with an FID as per 7.5.3.5 by subtraction of the methane from the hydrocarbons.

7.5.3.7 Oxides of nitrogen (NO_x) analysis

The oxides of nitrogen analyser shall be of the chemiluminescent detector (CLD) or heated chemiluminescent detector (HCLD) type with an NO_2/NO converter, if measured on a dry basis. If measured on a wet basis, an HCLD with converter maintained above 328 K (55 °C) shall be used, provided the water quench check (see 8.9.3.2) is satisfied. For both CLD and HCLD, the sampling path shall be maintained at a wall temperature of 328 K to 473 K (55 °C to 200 °C) up to the converter for dry measurement, and up to the analyser for wet measurement.

7.5.3.8 Sulphur dioxide (SO_2) analysis

The SO_2 emission shall be calculated from the sulphur content of the fuel used, since experience has shown that using the direct measurement method for SO_2 does not give more precise results:

$$q_{m\mathrm{SO2}} = q_{m\mathrm{f}} \times w_{\mathrm{GAM}} \times 20 \qquad (12)$$

NOTE The application of the calculation method for SO_2 assumes a 100 % sulphur conversion and is limited to engines without aftertreatment systems. In this case SO_2 may be measured in accordance with the instructions of the instrument suppliers. Since SO_2 measurement is a difficult task and has not been fully demonstrated for exhaust measurements, prior agreement of the parties involved is required.

7.5.3.9 Ammonia (NH_3) analysis

Ammonia shall be determined with a CLD, as described in 7.5.3.7, by using two different converters. For the total amount of NO_x and NH_3, a high-temperature converter of 973 K (700 °C) shall be used.

For the NO_x only, a low-temperature converter of 573 K (300 °C) shall be used. The difference between these measurements is the ammonia concentration. This method has a long response time (approx. 10 min).

Alternatively, an FTIR (Fourier transform infrared) analyser or NDUVR (non-dispersive ultraviolet resonance) analyser may be used in accordance with the instrument supplier's instructions. Since the technology has not been fully demonstrated for exhaust measurements, prior agreement of the parties involved is required. The response time of this method is considerably shorter than with the double converter method.

7.5.3.10 Dinitrogen oxide (N_2O) analysis

An FTIR analyser or an NDIR (non-dispersive infrared) analyser may be used in accordance with the instrument supplier's instructions. Since the technology has not been fully demonstrated for exhaust measurements, prior agreement of the parties involved is required.

7.5.3.11 Formaldehyde (HCHO) analysis

Formaldehyde shall be determined by passing an exhaust sample, preferably from the diluted exhaust gas, through an impinger containing an acetonitrile (ACN) solution of DNPH reagent or through a silica cartridge coated with 2,4-DNPH. The sample collected shall be analysed by a high-pressure liquid chromatograph (HPLC) using UV detection at 365 nm.

Optionally, an FTIR analyser may be used in accordance with the instrument supplier's instructions.

7.5.3.12 Methanol (CH_3OH) analysis

7.5.3.12.1 General

An FTIR analyser may be used in accordance with the instrument supplier's instructions. Since the technology has not been fully demonstrated for exhaust measurements, prior agreement of the parties involved is required.

7.5.3.12.2 Gas chromatographic (GC) method

Methanol shall be determined by passing an exhaust sample through an impinger containing de-ionized water. The sample shall be analysed by a GC with FID.

7.5.3.12.3 HFID method

The HFID calibrated on propane shall be operated at 385 K ± 10 K (112 °C ± 10 °C). The methanol response factor shall be determined at several concentrations in the range of concentrations in the sample, according to 8.8.5.

7.5.3.13 Air-to-fuel measurement

The air-to-fuel measurement equipment used to determine the exhaust gas flow as specified in 7.3.6 shall be a wide range air-to-fuel ratio sensor or lambda sensor of zirconia type.

The sensor shall be mounted directly on the exhaust pipe where the exhaust gas temperature is high enough to eliminate water condensation.

The accuracy of the sensor with incorporated electronics shall be as follows:

± 3 % of reading for	$\lambda < 2$
± 5 % of reading for	$2 \leqslant \lambda < 5$
± 10 % of reading for	$5 \leqslant \lambda$

To fulfil the accuracy specified above, the sensor shall be calibrated as specified by the instrument manufacturer.

7.5.4 Sampling for gaseous emissions

The gaseous emissions sampling probes shall be fitted at least 0,5 m or three times the diameter of the exhaust pipe – whichever is the larger – upstream of the exit of the exhaust gas system but sufficiently close to the engine so as to ensure an exhaust gas temperature of at least 343 K (70 °C) at the probe.

In the case of a multi-cylinder engine with a branched exhaust manifold, the inlet of the probe shall be located sufficiently far downstream so as to ensure that the sample is representative of the average exhaust emissions from all cylinders. In multi-cylinder engines having distinct groups of manifolds, such as in a “V” engine configuration, it is permissible to acquire a sample from each group individually and calculate an average exhaust emission. Other methods which have been shown to correlate with the above methods may be used. For exhaust emission calculation the total exhaust mass flow shall be used.

If the composition of the exhaust gas is influenced by any exhaust aftertreatment system, the exhaust sample shall be taken downstream of this device.

For spark-ignition engines the exhaust sampling probe should be in a high-pressure side of the muffler, but as far from the exhaust port as possible. To ensure complete mixing of the engine exhaust before sample extraction, a mixing chamber may be optionally inserted between the muffler outlet and the sample probe. The internal volume of the mixing chamber shall be not less than 10 times the cylinder displacement of the engine under test and should be roughly equal dimensions in height, width and depth. The mixing chamber size should be kept as small as practicable and should be coupled as close as possible to the engine. The exhaust line leaving the mixing chamber should extend at least 610 mm beyond the sample probe location and be of sufficient size to minimize back pressure. The temperature of the inner surface of the mixing chamber shall be maintained above the dew point of the exhaust gases and a minimum temperature of 65 °C is recommended.

For marine engines the inlet of the probe shall be located so as to avoid ingestion of water which is injected into the exhaust system for the purpose of cooling, tuning or noise reduction.

When a full-flow dilution system is used for the determination of the particulates, the gaseous emissions may also be determined in the diluted exhaust gas. The sampling probes shall be close to the particulate sampling probe in the dilution tunnel (see 17.2.2, Figure 19, DT and PSP).

For compression-ignition engines, HC and NO_x shall be measured by direct sampling from the dilution tunnel. CO and CO_2 may optionally be determined by direct measurement or by sampling into a bag and subsequent measurement of the concentration in the sampling bag.

For spark-ignition engines and gas-fuelled engines, all components may optionally be measured directly in the dilution tunnel, or by sampling into a bag and subsequent measurement of the concentration in the sampling bag.

7.6 Particulate determination

7.6.1 General

The determination of the particulates requires a dilution system. Dilution shall be accomplished by a partial-flow or a full-flow dilution system. The flow capacity of the dilution system shall be large enough to completely eliminate water condensation in the dilution and sampling systems, and maintain the temperature of the diluted exhaust gas between 315 K (42 °C) and 325 K (52 °C) immediately upstream of the filter holders. Humidity control of the dilution air before entering the dilution system is permitted; dehumidification, in particular, is useful if dilution air humidity is high. The temperature of the dilution air shall be higher than 288 K (15 °C) in close proximity to the entrance into the dilution tunnel.

Existing systems established in accordance with ISO 8178-1:1996 do not have to comply with the above filter temperature requirements.

For a partial-flow dilution system, the particulate sampling probe shall be fitted close to and upstream of the gaseous probe as defined in 7.5.4 and in accordance with 17.2.1, Figures 10 to 18, EP and SP.

The partial-flow system shall be designed to extract a raw exhaust sample from the engine exhaust stream, introduce dilution air into this sample and subsequently measure the particulates in the diluted sample. From that it is essential that the dilution ratio be determined very accurately. Different sampling methods can be applied, whereby the type of sampling used dictates the hardware and procedures to be used (see 17.2.1).

To determine the mass of the particulates, a particulate sampling system, particulate sampling filters, a microgram balance, and a temperature- and humidity-controlled weighing chamber are required. For particulate sampling, the following two methods may be applied.

The multiple-filter method dictates that one pair of filters (see 7.6.2.3) is used for each of the individual modes of the test cycle. This method allows more lenient sample procedures but uses more filters.

The single-filter method uses one pair of filters (see 7.6.2.3) for all modes of the test cycle. Considerate attention shall be paid to sampling times and flows during the sampling phase of the test; however, only one pair of filters will be required for the test cycle.

7.6.2 Particulate sampling filters

7.6.2.1 Filter specification

Fluorocarbon coated glass-fibre filters or fluorocarbon membrane filters are required. All filter types shall have a 0,3 µm DOP (di-octylphthalate) collection efficiency of at least 95 % at a gas face velocity of 35 cm/s and at least 99 % at 100 cm/s. When performing correlation tests between laboratories or between a manufacturer and a regulatory agency, filters of identical quality shall be used.

7.6.2.2 Filter size

Particulate filters shall have a minimum diameter of 47 mm (37 mm stain diameter). Larger diameter filters are acceptable (see 7.6.2.5).

7.6.2.3 Primary and back-up filters

The diluted exhaust shall be sampled during the test sequence by one filter if the collection efficiency is > 99 % (see 7.6.2.1), or a pair of filters placed in series (one primary and one back-up filter) if the collection efficiency is between 95 % and 99 %. The back-up filter shall be located no more than 100 mm downstream of the primary filter and shall not be in contact with the primary filter. The filters may be weighed separately or as a pair with the filters placed stain side to stain side.

7.6.2.4 Filter face velocity

A gas face velocity through the filter of 35 cm/s to 100 cm/s shall be achieved. The pressure-drop increase between the beginning and the end of the test shall be no more than 25 kPa.

7.6.2.5 Filter loading

The filter loading should be 0,338 µg/mm^2 filter area for the single-filter method. The required minimum filter loading shall be 0,065 µg/mm^2 filter area. For the most common filter sizes the values are given in Table 4.

For the multiple-filter method, the filter loading for the sum of all filters is the product of the appropriate value above and the square root of the total number of modes.

Table 4 — Minimum filter loading

Filter diameter mm	Recommended loading mg	Required minimum loading mg
47	0,6	0,11
70	1,3	0,25
90	2,1	0,41
110	3,2	0,62

7.6.3 Weighing chamber and analytical balance specifications

7.6.3.1 Weighing chamber conditions

The temperature of the chamber (or room) in which the particulate filters are conditioned and weighed shall be maintained to within 295 K ± 3 K (22 °C ± 3 °C) during all filter conditioning and weighing. The humidity shall be maintained to a dewpoint of 282,5 K ± 3 K (9,5 °C ± 3 °C) and a relative humidity of 45 % ± 8 %.

7.6.3.2 Reference filter weighing

The chamber (or room) environment shall be free of any ambient contaminants (such as dust) that would settle on the particulate filters during their stabilization. Disturbances to weighing room specifications as outlined in 7.6.3.1 will be allowed if the duration of the disturbances does not exceed 30 min. The weighing room should meet the required specifications prior to personal entrance into the weighing room. At least two unused reference filters or reference filter pairs shall be weighed within 4 h of (but preferably at the same time as) the sample filter (pair) weighings. They shall be the same size and material as the sample filters.

If the average mass of the reference filters or reference filter pairs changes between sample filter weighings by more than 10 µg + 5 % of particulate loading at the actual test with an absolute upper limit of 40 µg, then all sample filters shall be discarded and the emissions test repeated. Optionally, the cycle may be repeated on the same filter to get a higher particulate loading with correspondingly higher reference filter tolerances.

If the weighing room stability criteria outlined in 7.6.3.1 are not met, but the reference filter (pair) weighings meet the above criteria, the engine manufacturer has the option of accepting the sample filter masses or voiding the tests, fixing the weighing room control system and rerunning the test.

7.6.3.3 Analytical balance

The analytical balance used to determine the masses of all filters shall have a precision (standard deviation) of 20 µg and a resolution of 10 µg (1 digit = 10 µg). For filters less than 70 mm in diameter, the precision and resolution shall be 2 µg and 1 µg, respectively.

7.6.3.4 Elimination of static electricity effects

To eliminate the effects of static electricity, the filters shall be neutralized prior to weighing, e.g. by a polonium neutralizer or a device of similar effect.

7.6.4 Additional specifications for particulate measurement

All parts of the dilution system and the sampling system from the exhaust pipe up to the filter holder, which are in contact with raw and diluted exhaust gas, shall be designed to minimize deposition or alteration of the particulates. All parts shall be made of electrically conductive materials that do not react with exhaust gas components, and shall be electrically grounded to prevent electrostatic effects.

8 Calibration of the analytical instruments

8.1 General requirements

Each analyser shall be calibrated as often as necessary to fullfil the accuracy requirements of this part of ISO 8178. The calibration method that shall be used is described below for the analysers indicated in 7.5.3.

8.2 Calibration gases

8.2.1 General

The shelf life of all calibration gases shall be respected.

The expiry date of the calibration gases stated by the manufacturer shall be recorded.

8.2.2 Pure gas

The required purity of the gases is defined by the contamination limits given below. The following gases shall be available for operation:

- purified nitrogen (contamination $\leqslant$ 1 ppmC, $\leqslant$ 1 ppmCO, $\leqslant$ 400 ppmCO_2, $\leqslant$ 0,1 ppmNO);
- purified oxygen (purity > 99,5 % vol. O_2);
- hydrogen–helium mixture (40 % ± 2 % hydrogen, balance helium) (contamination $\leqslant$ 1 ppmC, $\leqslant$ 400 ppmCO_2);
- purified synthetic air (contamination $\leqslant$ 1 ppmC, $\leqslant$ 1 ppmCO, $\leqslant$ 400 ppmCO_2, $\leqslant$ 0,1 ppmNO) (oxygen content 18 % – 21 % vol.).

8.2.3 Calibration and span gases

Mixtures of gases having the following chemical compositions shall be available:

- C_3H_8 and purified synthetic air (see 8.2.2);
- CO and purified nitrogen;
- NO_x and purified nitrogen (the amount of NO_2 contained in this calibration gas shall not exceed 5 % of the NO content);
- O_2 and purified nitrogen;
- CO_2 and purified nitrogen;
- CH_4 and purified synthetic air;
- C_2H_6 and purified synthetic air.

NOTE Other gas combinations are allowed provided the gases do not react with one another.

The true concentration of a calibration and span gas shall be within ± 2 % of the nominal value. All concentrations of calibration gas shall be given on a volume basis (volume percent or volume ppm).

8.2.4 Use of gas dividers

The gases used for calibration and span may also be obtained by means of precision blending devices (gas dividers), diluting with purified N_2 or with purified synthetic air. The accuracy of the mixing device shall be such that the concentration of the blended calibration gases is accurate to within ± 2 %. This accuracy implies that primary gases used for blending must be known to an accuracy of at least ± 1 %, traceable to national or international gas standards. The verification shall be performed at between 15 % and 50 % of full scale for each calibration incorporating a blending device.

Optionally, the blending device may be checked with an instrument which by nature is linear, e.g. using NO gas with a CLD. The span value of the instrument shall be adjusted with the span gas directly connected to the instrument. The blending device shall be checked at the used settings and the nominal value shall be compared to the measured concentration of the instrument. This difference shall in each point be within ± 1 % of the nominal value. But this linearity check of the gas divider shall not be performed with a gas analyser which was previously linearized with the same gas divider.

8.2.5 Oxygen interference gases

Oxygen interference check gases shall contain propane with 350 ppmC ± 75 ppmC hydrocarbon. The concentration value shall be determined to calibration gas tolerances by chromatographic analysis of total hydrocarbons plus impurities or by dynamic blending. Nitrogen shall be the predominant diluent with the balance oxygen. Blends required for gasoline-fuelled and diesel engine testing are listed in Table 5:

Table 5 — Oxygen interference check gases

Applicability	O_2 concentration	Balance
Diesel	21 (20 to 22)	Nitrogen
Diesel and gasoline	10 (9 to 11)	Nitrogen
Diesel and gasoline	5 (4 to 6)	Nitrogen
Gasoline	0 (0 to 1)	Nitrogen

8.3 Operating procedure for analysers and sampling system

The operating procedure for analysers shall follow the start-up and operating instructions of the instrument manufacturer. The minimum requirements given in 8.4 to 8.9 shall be included. For laboratory instruments such as GC and HPLC, only 8.5.4 applies.

8.4 Leakage test

A system leakage test shall be performed. The probe shall be disconnected from the exhaust system and the end plugged. The analyser pump shall be switched on. After an initial stabilization period all flow meters should read zero. If not, the sampling lines shall be checked and the fault corrected.

The maximum allowable leakage rate on the vacuum side shall be 0,5 % of the in-use flow rate for the portion of the system being checked. The analyser flows and bypass flows may be used to estimate the in-use flow rates.

Another method is the introduction of a concentration step change at the beginning of the sampling line by switching from zero to span gas. If after an adequate period of time the reading shows a lower concentration compared to the introduced concentration, this points to calibration or leakage problems.

8.5 Calibration procedure

8.5.1 Instrument assembly

Calibrate the instrument assembly and check calibrated curves against standard gases. The same gas flow rates shall be used as when sampling exhaust gas.

8.5.2 Warm-up time

The warm-up time should be according to the recommendations of the manufacturer. If not specified, a minimum of 2 h is recommended for warming up the analysers.

8.5.3 NDIR and HFID analyser

Tune the NDIR analyser as necessary, and optimize the combustion flame of the HFID analyser (see 8.8.1)

8.5.4 GC and HPCL

Calibrate both instruments according to good laboratory practice and the recommendations of the manufacturer.

8.5.5 Establishment of the calibration curve

a) Each normally used operating range shall be calibrated.

b) Using purified synthetic air (or nitrogen), the CO, CO_2, NO_x and HC analysers shall be set at zero.

c) The appropriate calibration gases shall be introduced to the analysers, the values recorded, and the calibration curve established.

d) The calibration curve shall be established by at least six calibration points (excluding zero) approximately equally spaced over the operating range. The highest nominal concentration shall be equal to or higher than 90 % of full scale.

e) The calibration curve shall be calculated by the method of least squares. A best-fit linear or non-linear equation may be used.

f) The calibration points shall not differ from the least squares best-fit line by more than ± 2 % of reading or ± 0,3 % of full scale, whichever is larger.

g) The zero setting shall be rechecked and the calibration procedure repeated, if necessary.

8.5.6 Alternative calibration methods

If it can be shown that alternative technology (computer, electronically controlled range switch, etc.) can give equivalent accuracy, then these alternatives may be used.

8.5.7 Verification of the calibration

Each normally used operating range shall be checked prior to each analysis in accordance with the following procedure.

The calibration is checked by using a zero gas and a span gas whose nominal value is more than 80 % of full scale of the measuring range.

If, for the two points considered, the value found does not differ by more than ± 4 % of full scale from the declared reference value, the adjustment parameters may be modified. Should this not be the case, the span gas shall be verified or a new calibration curve shall be established in accordance with 8.5.5.

8.6 Calibration of tracer gas analyser for exhaust flow measurement

The analyser for measurement of the tracer gas concentration shall be calibrated using the standard gas.

The calibration curve shall be established by at least six calibration points (excluding zero) approximately equally spaced over the operating range. The highest nominal concentration shall be equal to or higher than 90 % of full scale. The calibration curve is calculated by the method of least squares.

The calibration points shall not differ from the least-squares best-fit line by more than ± 2 % of reading or ± 0,3 % of full scale, whichever is larger.

The analyser shall be set at zero and spanned prior to the test run using a zero gas and a span gas whose nominal value is more than 80 % of the analyser full scale.

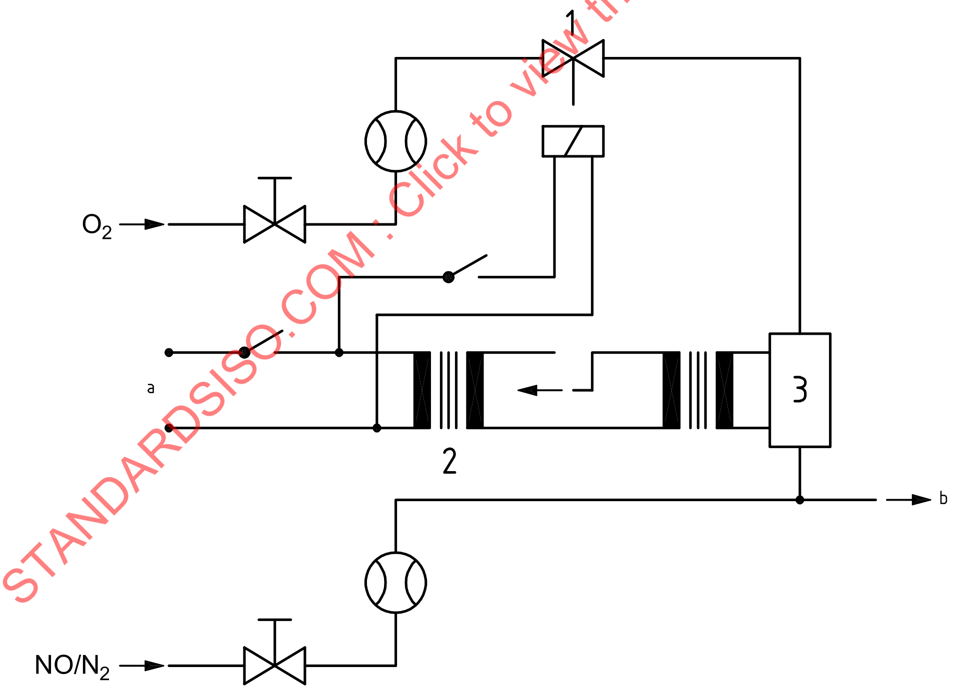
8.7 Efficiency test of the NO_x converter

8.7.1 Introduction

The efficiency of the converter used for the conversion of NO_2 into NO is tested as given in 8.7.2 to 8.7.9 (see Figure 1).

8.7.2 Test setup

Using the test setup as schematically shown in Figure 1 (see also 7.5.3.7) and the procedure below, the efficiency of converters can be tested by means of an ozonator.



Key

1 solenoid valve
2 variac
3 ozonator

a Alternating current.
b To analyser.

Figure 1 — Schematic representation of NO_2 converter efficiency device

8.7.3 Calibraton

The CLD and the HCLD shall be calibrated in the most common operating range, following the manufacturer's specifications, using zero and span gas (the NO content of which must amount to about 80 % of the operating range and the NO_2 concentration of the gas mixture to less than 5 % of the NO concentration). The NO_x analyser shall be in the NO mode so that the span gas does not pass through the converter. The indicated concentration shall be recorded.

8.7.4 Calculation

The efficiency of the NO_x converter is calculated as follows:

$$E_{\mathrm{NOx}} = \left(1 + \frac{a-b}{c-d}\right) \times 100 \tag{13}$$

where

a is the NO_x concentration according to 8.7.7;

b is the NO_x concentration according to 8.7.8;

c is the NO concentration according to 8.7.5;

d is the NO concentration according to 8.7.6.

8.7.5 Adding of oxygen

Via a T-fitting, oxygen or zero air is added continuously to the gas flow until the concentration indicated is about 20 % less than the indicated calibration concentration given in 8.7.3. (The analyser is in the NO mode.)

The indicated concentration (c) shall be recorded. The ozonator is kept deactivated throughout the process.

8.7.6 Activation of the ozonator

The ozonator is now activated to generate enough ozone to bring the NO concentration down to about 20 % (minimum 10 %) of the calibration concentration given in 8.7.3. The indicated concentration (d) shall be recorded. (The analyser is in the NO mode.)

8.7.7 NO_x mode

The NO analyser is then switched to the NO_x mode so that the gas mixture (consisting of NO, NO_2, O_2 and N_2) now passes through the converter. The indicated concentration (a) shall be recorded. (The analyser is in the NO_x mode.)

8.7.8 Deactivation of the ozonator

The ozonator is now deactivated. The mixture of gases described in 8.7.7 passes through the converter into the detector. The indicated concentration (b) shall be recorded. (The analyser is in the NO_x mode.)

8.7.9 NO mode

Switched to NO mode with the ozonator deactivated, the flow of oxygen or synthetic air is also shut off. The NO_x reading of the analyser shall not deviate by more than ± 5 % from the value measured according to 8.7.3. (The analyser is in the NO mode.)

8.7.10 Test interval

The efficiency of the converter shall be tested prior to each calibration of the NO_x analyser.

8.7.11 Efficiency requirement

The efficiency of the converter shall not be less than 90 %, but a higher efficiency of 95 % is strongly recommended.

If, with the analyser in the most common range, the NO_x converter cannot give a reduction from 80 % to 20 % according to 8.7.3, then the highest range which will give the reduction shall be used.

8.8 Adjustment of the FID

8.8.1 Optimization of the detector response

The FID shall be adjusted as specified by the instrument manufacturer. A propane-in-air span gas should be used to optimize the response on the most common operating range.

With the fuel and air flow rates set at the manufacturer's recommendations, a 350 ± 75 ppmC span gas shall be introduced to the analyser. The response at a given fuel flow shall be determined from the difference between the span gas response and the zero gas response. The fuel flow shall be incrementally adjusted above and below the manufacturer's specification. The span and zero response at these fuel flows shall be recorded. The difference between the span and zero response shall be plotted and the fuel flow adjusted to the rich side of the curve. This is the initial flow rate setting which may need further optimization depending on the results of the hydrocarbon response factors and the oxygen interference check according to 8.8.2 and 8.8.3.

If the oxygen interference or the hydrocarbon response factors do not meet the following specifications, the air flow shall be incrementally adjusted above and below the manufacturer's specifications, 8.8.2 and 8.8.3 for each flow.

The optimization may optionally be conducted using the procedures outlined in SAE Technical Paper 770141 (see Bibliography).

8.8.2 Hydrocarbon response factors

The analyser shall be calibrated using propane in air and purified synthetic air, according to 8.5.

Response factors shall be determined when introducing an analyser into service and after major service intervals. The response factor (r_h) for a particular hydrocarbon species is the ratio of the FID C1 reading to the gas concentration in the cylinder expressed by ppmC1.

The concentration of the test gas shall be at a level to give a response of approximately 80 % of full scale. The concentration shall be known to an accuracy of ± 2 % in reference to a gravimetric standard expressed in volume. In addition, the gas cylinder shall be preconditioned for 24 h at a temperature of 298 K ± 5 K (25 °C ± 5 °C).

The test gases to be used and the recommended relative response factor ranges are as follows.

- Methane and purified synthetic air: $1{,}00 \leqslant r_h \leqslant 1{,}15$.
- Propylene and purified synthetic air: $0{,}90 \leqslant r_h \leqslant 1{,}1$.
- Toluene and purified synthetic air: $0{,}90 \leqslant r_h \leqslant 1{,}1$.

These values are relative to a r_h of 1 for propane and purified synthetic air.

8.8.3 Oxygen interference check

The oxygen interference check shall be determined when introducing an analyser into service and after major service intervals.

A range shall be chosen where the oxygen interference check gases will fall in the upper 50 %. The test shall be conducted with the oven temperature set as required. The oxygen interference gases are specified in 8.2.5.

a) The analyser shall be zeroed.

b) The analyser shall be spanned with the 0 % oxygen blend for gasoline-fuelled engines. Diesel engine instruments shall be spanned with the 21 % oxygen blend.

c) The zero response shall be rechecked. If it has changed by more than 0,5 % of full scale, steps a) and b) shall be repeated.

d) The 5 % and 10 % oxygen interference check gases shall be introduced.

e) The zero response shall be rechecked. If it has changed by more than ± 1 % of full scale, the test shall be repeated.

f) The oxygen interference (%O_2int) shall be calculated for each mixture in step d) as follows:

$$\%\mathrm{O_2int} = \frac{(B - \text{analyser response})}{B} \times 100 \tag{14}$$

where

$$\text{analyser response is } \frac{A}{\%\text{FS at } A} \times \%\text{FS at } B$$

where

A is the hydrocarbon concentration in parts per million C (microlitres per litre) of the span gas used in step b),

B is the hydrocarbon concentration (ppmC) of the oxygen interference check gases used in step d).

$$(\text{ppmC}) = \frac{A}{D} \tag{15}$$

where

D is the percentage of full scale analyser response due to A.

g) The % of oxygen interference (%O_2int) shall be less than ± 3,0 % for all required oxygen interference check gases prior to testing.

h) If the oxygen interference is greater than ± 3,0 %, the air flow above and below the manufacturer's specifications shall be incrementally adjusted, repeating 8.8.1 for each flow.

i) If the oxygen interference is greater than ± 3,0 % after adjusting the air flow, the fuel flow and thereafter the sample flow shall be varied, repeating 8.8.1 for each new setting.

j) If the oxygen interference is still greater than ± 3,0 %, the analyser, FID fuel, or burner air shall be repaired or replaced prior to testing. Steps a) to i) shall then be repeated with the repaired or replaced equipment or gases.

8.8.4 Efficiency of the Non-Methane Cutter (NMC)

8.8.4.1 General

The NMC is used for the removal of the non-methane hydrocarbons from the sample gas by oxidizing all hydrocarbons except methane. Ideally, the conversion for methane is 0 %, and for the other hydrocarbons represented by ethane is 100 %. For the accurate measurement of NMHC, the two efficiencies shall be determined and used for the calculation of the NMHC emission mass flow rate (see 14.4).

8.8.4.2 Methane efficiency

Methane calibration gas shall be flowed through the FID with and without bypassing the NMC and the two concentrations recorded. The efficiency shall be determined as follows:

$$E_\mathrm{M} = 1 - \frac{c_\mathrm{wCutter}}{c_\mathrm{w/oCutter}} \tag{16}$$

where

c_wCutter is the HC concentration with CH_4 flowing through the NMC,

$c_\mathrm{w/oCutter}$ is the HC concentration with CH_4 bypassing the NMC.

8.8.4.3 Ethane efficiency

Ethane calibration gas shall be flowed through the FID with and without bypassing the NMC and the two concentrations recorded. The efficiency shall be determined as follows:

$$E_\mathrm{E} = 1 - \frac{c_\mathrm{wCutter}}{c_\mathrm{w/oCutter}} \tag{17}$$

where

c_wCutter is the HC concentration with C_2H_6 flowing through the NMC,

$c_\mathrm{w/oCutter}$ is the HC concentration with C_2H_6 bypassing the NMC.

8.8.5 Methanol response factor

When the FID analyser is to be used for the analysis of hydrocarbons containing methanol, the methanol response factor (r_m) of the analyser shall be established.

A known volume of methanol (a, in millilitres) is injected, using a microlitre syringe, into the heated mixing zone [395 K (122 °C)] of a septum injector, vapourized and swept into a tedlar bag with a known volume of zero-grade air (b, in cubic metres). The air volume(s) shall be such that the methanol concentration in the bag is representative of the range of concentrations found in the exhaust sample.

The bag sample is analysed using the FID, and the response factor is calculated as follows:

$$r_\mathrm{m} = \frac{x_\mathrm{FID}}{c_\mathrm{SAM}} \tag{18}$$

where

x_FID is the FID reading, in parts per million (microlitres per litre) of C,

c_SAM is the methanol concentration in the sample bag in ppmC, as calculated from a and b: $c_\mathrm{SAM} = 594 \times a/b$.

8.9 Interference effects with CO, CO_2, NO_x, O_2, NH_3 and N_2O analysers

8.9.1 General

Gases other than the one being analysed can interfere with the reading in several ways. Positive interference occurs in NDIR and PMD instruments where the interfering gas gives the same effect as the gas being measured, but to a lesser degree. Negative interference occurs in NDIR instruments by the interfering gas broadening the absorption band of the measured gas, and in CLD instruments by the interfering gas quenching the radiation. The interference checks in 8.9.2 and 8.9.3 shall be performed prior to an analyser's initial use and after major service intervals, but at least once per year.

8.9.2 CO analyser interference check

Water and CO_2 can interfere with the CO analyser performance. Therefore, a CO_2 span gas having a concentration of 80 % to 100 % of full scale of the maximum operating range used during testing shall be bubbled through water at room temperature and the analyser response recorded. The analyser response shall not be more than 1 % of full scale for ranges equal to or above 300 ppm or more than 3 ppm for ranges below 300 ppm.

8.9.3 NO_x analyser quench checks

The two gases of concern for CLD (and HCLD) analysers are CO_2 and water vapour. Quench responses to these gases are proportional to their concentrations, and therefore require test techniques to determine the quench at the highest expected concentrations experienced during testing.

8.9.3.1 CO_2 quench check

A CO_2 span gas having a concentration of 80 % to 100 % of full scale of the maximum operating range shall be passed through the NDIR analyser and the CO_2 value recorded as A. It shall then be diluted approximately 50 % with NO span gas and passed through the NDIR and (H)CLD, with the CO_2 and NO values recorded as B and C, respectively. The CO_2 shall then be shut off and only the NO span gas be passed through the (H)CLD and the NO value recorded as D.

The quench shall be calculated as follows:

$$E_{\mathrm{CO2}} = \left[1 - \left(\frac{(C \times A)}{(D \times A) - (D \times B)}\right)\right] \times 100 \tag{19}$$

where

A is the undiluted CO_2 concentration measured with NDIR [%],

B is the diluted CO_2 concentration measured with NDIR [%],

C is the diluted NO concentration measured with (H)CLD [ppm],

D is the undiluted NO concentration measured with (H)CLD [ppm].

Alternative methods of diluting and quantifying CO_2 and NO span gas values, such as dynamic mixing/blending, can be used.

8.9.3.2 Water quench check

This check applies to wet gas concentration measurements only. Calculation of water quench shall consider dilution of the NO span gas with water vapour and scaling of water vapour concentration of the mixture to that expected during testing.

A NO span gas having a concentration of 80 % to 100 % of full scale of the normal operating range shall be passed through the (H)CLD and the NO value recorded as D. The NO span gas shall then be bubbled through water at a temperature of 298 + 5 K (25 ± 5 °C), passed through the (H)CLD and the NO value recorded as C. The water temperature shall be determined and recorded. The mixture's saturation vapour pressure that corresponds to the bubbler water temperature (F) shall be determined and recorded as G. The water vapour concentration (H, in %) of the mixture shall be calculated as follows:

$$H = 100 \times \left(\frac{G}{p_\mathrm{b}} \right) \tag{20}$$

The expected diluted NO span gas (in water vapour) concentration (D_e) shall be calculated as follows:

$$D_\mathrm{e} = D \times \left(1 - \frac{H}{100} \right) \tag{21}$$

For diesel exhaust, the maximum exhaust water concentration (in %) expected during testing shall be estimated, under the assumption of a fuel atom H:C ratio of 1,8:1, from the maximum CO_2 concentration A in the exhaust gas as follows:

$$H_\mathrm{m} = 0{,}9 \times A \tag{22}$$

Record H, D_e and H_m.

The water quench shall be calculated as follows:

$$E_\mathrm{H2O} = 100 \times \left(\frac{D_\mathrm{e} - C}{D_\mathrm{e}} \right) \times \left(\frac{H_\mathrm{m}}{H} \right) \tag{23}$$

where

D_e is the expected diluted NO concentration [ppm];

C is the diluted NO concentration [ppm];

H_m is the maximum water vapour concentration [%];

H is the actual water vapour concentration [%].

NOTE It is important that the NO span gas contains minimal NO_2 concentration for this check, since absorption of NO_2 in water has not been accounted for in the quench calculations.

8.9.3.3 Maximum allowable quench

The maximum allowable quench shall be as follows.

- For all dry CLD analysers, it shall be demonstrated that for the highest expected water vapour concentration (i.e. "%H_2Oexp" as calculated later in this section), the water removal technique maintains CLD humidity at less than or equal to 5 g water per kg dry air (or about 0,008 % H_2O), which is 100 % RH at 3,9 °C and 101,3 kPa. This humidity specification is also equivalent to about 25 % RH at 25 °C and 101,3 kPa. This can be demonstrated by measuring the temperature at the outlet of a thermal dehumidifier, or by measuring humidity at a point just upstream of the CLD. Humidity of the CLD exhaust might also be measured as long as the only flow into the CLD is the flow of the dehumidifier.
- For raw measurement CO_2-quench according to 8.9.3.1: 2 % of full scale.
- Water quench according to 8.9.3.2: 3 % of full scale.
- For dilute measurement: 2 % combined CO_2 and water quench.

8.9.4 O_2 analyser interference

Instrument response of a PMD analyser caused by gases other than oxygen is comparatively slight. The oxygen equivalents of the common exhaust gas constituents are shown in Table 6.

Table 6 — Oxygen equivalents

Gas	O_2 equivalent %
Carbon dioxide (CO_2)	− 0,623
Carbon monoxide (CO)	− 0,354
Nitric oxide (NO)	+ 44,4
Nitrogen dioxide (NO_2)	+ 28,7
Water (H_2O)	− 0,381

The observed oxygen concentration shall be corrected by the following formula if high-precision measurements are to be done:

$$\text{Interference} = \frac{(\text{Equivalent } \% \ O_2 \times \text{Observed concentration})}{100} \tag{24}$$

For ZRDO and ECS analysers, instrument interference caused by gases other than oxygen shall be compensated for in accordance with the instrument supplier's instruction and with good engineering practice.

8.9.5 Cross-interference check compensation for NH_3 and N_2O measurement channels using IR and UV measurement techniques

8.9.5.1 Procedure for establishing the cross-interference correction for NH_3 analysers (NDUVR method)

There are cross-interferences to nitrogen oxide (NO) and nitrogen dioxide (NO_2). Both components shall be measured with the measurement equipment and a compensation shall be applied to the analyser readings, if the cross-interference exceeds 2 % full scale.

8.9.5.2 Check of the cross-interferences

NO and NO_2 calibration gases are fed into the analyser with cross-interference compensation activated. For each component, at least five different calibration gas concentrations with equidistant spacing between zero and the maximum expected interference gas concentration shall be used for the compensation check. The maximum deviation of the NH_3 reading from the zero reading shall be less than ± 2 % full scale of the commonly used range. If the deviation is higher, a new correction curve for the corresponding interference component shall be established and applied to the analyser readings. The use of single-blend gases is possible, as well as the use of gas mixtures containing two or more interference gases.

8.9.5.3 Procedure for the generation of cross-interference correction curves

8.9.5.3.1 NO cross-interference

Calibration gases with at least five different NO concentrations that have to be spread equidistantly over the used NO analyser range during measurement shall be fed into the NH_3 analyser.

The nominal NO values and the measured NH_3 concentrations have to be recorded. Using a least-squares fit for a suitable fit function (e.g. polynomial fit function) $f(\text{NO})$, a correction curve to compensate for the NO cross-interference is calculated. The number of fit points has to be higher by at least two than the number of fit parameters (e.g. polynomial of fourth order needs at least seven fit points). The correction values $\text{NH}_{3\_\text{compensated}} = \text{NH}_{3\_\text{not compensated}} - f(\text{NO})$ should be within ± 1 % full scale of the analyser zero reading.

8.9.5.3.2 NO_2 cross-interference

The procedure for NO_2 is equivalent to that for NO_2 span gases. The result is the correction curve $f(\text{NO}_2)$.

The calibration gases used for establishing the cross-interference compensation curves shall be single-blend mixtures. The use of gas mixtures with two or more interference gases is not allowed for generating the cross-interference compensation curves.

The following compensation calculation should be done by the measurement system:

$$\text{NH}_{3\_\text{compensated}} = \text{NH}_{3\_\text{not compensated}} - f(\text{N=}) - f(\text{NO}_2)$$

After the compensation curves have been established, the cross-interference compensation shall be checked by the procedures given in 8.9.5.2.

8.9.5.4 Procedure for establishing the cross-interference correction for N_2O analysers (NDIR method)

There are cross-interferences for CO_2, CO and NO and small interferences for some hydrocarbons.

8.9.5.5 Check the cross-interferences

Calibration gases for CO, CO_2, NO and C_3H_8 are fed into the analyser with cross-interference compensation activated. For each component at least five different calibration gas concentrations with equidistant spacing between zero and the maximum expected interference gas concentration shall be used for the compensation check. The maximum deviation of the NO_2 reading from the zero reading shall be less than ± 2 % full scale of the commonly used range. If the deviation is higher, a new correction curve for the corresponding interference component shall be established and applied to the analyser readings. The use of single-blend gases is allowed, as well as the use of gas mixtures containing two or more interference gases.

8.9.5.6 Procedure for the generation of cross-interference correction curves

8.9.5.6.1 CO cross-interference

Calibration gases with at least five different CO concentrations that have to be spread equidistantly over the used CO analyser range during measurement shall be fed into the N_2O analyser.

The nominal CO values and the measured N_2O concentrations shall be recorded. Using a least-squares fit for a suitable fit function (e.g. polynomial fit function) $f(\text{CO})$, a correction curve to compensate for the CO cross-interference is calculated. The number of fit points shall be higher by at least two than the number of fit parameters (e.g. polynomial of fourth order needs at least seven fit points).

The corrected values $\text{N}_2\text{O}_{\text{compensated}} = \text{N}_2\text{O}_{\text{not compensated}} - f(\text{CO})$ should be within ± 1 % full scale of the analyser zero reading.

8.9.5.6.2 CO_2, NO and C_3H_8 cross-interference

The same procedure is done for CO_2, NO and C_3H_8. The result is the correction functions $f(\text{CO}_2)$, $f(\text{NO})$, and $f(\text{C}_3\text{H}_8)$, respectively.

The calibration gases used for establishing the cross-interference compensation curves shall be single-blend mixtures. The use of gas mixtures with two or more interference gases is not allowed for generating the cross-interference compensation curves.

The following compensation calculation should be done by the measurement system:

$$N_2O_{\text{compensated}} = N_2O_{\text{not compensated}} - f(CO_2) = - f(CO) - f(NO) - f(C_3H_8)$$

After the compensation curves have been established, the cross-interference compensation shall be checked by the procedure given in 8.9.5.5.

8.10 Calibration intervals

The analysers shall be calibrated according to 8.5 at least every three months or whenever a system repair or change is made that could influence calibration

9 Calibration of the particulate measuring system

9.1 General

Each component shall be calibrated as often as necessary to fulfil the accuracy requirements of this part of ISO 8178. The calibration method to be used is described in this clause for the components indicated in 7.6 and 17.

9.2 Calibration procedure

9.2.1 Flow measurement

The calibration of gas flow meters or flow measurement instrumentation shall be traceable to international and/or national standards.

If the gas flow is determined by differential flow measurement, the maximum error of the difference shall be such that the accuracy of $q_{m\text{edf}}$ is within ± 4 % (see also 17.2.1, exhaust gas analyser explanations given below Figures 10 to 18). It can be calculated by taking the root-mean-square of the errors of each instrument.

9.2.2 Exhaust gas analysers

If CO_2 or NO_x concentration measurement is used for the determination of the dilution ratio, the exhaust gas analysers shall be calibrated in accordance with 8.5.5.

9.2.3 Carbon flow check

A carbon flow check using actual exhaust is strongly recommended for detecting measurement and control problems and verifying the proper operation of the partial-flow dilution system. The carbon flow check should be run at least each time a new engine is installed, or something significant is changed in the test cell configuration.

The engine shall be operated at peak torque load and speed or any other steady-state mode that produces 5 % or more of CO_2. The partial-flow sampling system shall be operated with a dilution factor of about 15 to 1.

If a carbon flow check is conducted, the procedure given in Annex F shall be applied. The carbon flow rates shall be calculated according to Equations F.1, F.2 and F.3. All carbon flow rates should agree to within 6 %.

9.3 Checking the partial-flow conditions

The range of the exhaust gas velocity and the pressure oscillations shall be checked and adjusted according to the requirements of 17.2.1, exhaust pipe explanations given below Figures 10 to 18, if applicable.

9.4 Calibration intervals

The flow measurement instrumentation shall be calibrated at least once per year or whenever a system repair or change is made that could influence calibration.

10 Calibration of the CVS full-flow dilution system

10.1 General

The CVS system shall be calibrated by using an accurate flowmeter and a restricting device. The flow through the system shall be measured at different restriction settings, and the control parameters of the system shall be measured and related to the flow.

Various type of flowmeter may be used, e.g. calibrated venturi, calibrated laminar flowmeter, calibrated turbinemeter.

10.2 Calibration of the Positive Displacement Pump (PDP)

10.2.1 General

All the parameters related to the pump shall be simultaneously measured, along with the parameters related to a calibration venturi which is connected in series with the pump. The calculated flow rate (in m^3/min at pump inlet, absolute pressure and temperature) shall be plotted against a correlation function which is the value of a specific combination of pump parameters. The linear equation which relates the pump flow and the correlation function shall be determined. If a CVS has a multiple-speed drive, the calibration shall be performed for each range used.

Temperature stability shall be maintained during calibration.

Leaks in all the connections and ducting between the calibration venturi and the CVS pump shall be maintained lower than 0,3 % of the lowest flow point (highest restriction and lowest PDP speed point).

10.2.2 Data analysis

The air flow rate (Q_s) at each restriction setting (minimum six settings) shall be calculated in standard m^3/min from the flowmeter data using the manufacturer's prescribed method. The air flow rate shall then be converted to pump flow (V_0) in m^3/rev at absolute pump inlet temperature and pressure as follows:

$$V_0 = \frac{Q_s}{n} \times \frac{T}{273} \times \frac{101{,}3}{p_A} \quad (25)$$

where

Q_s is the air flow rate at standard conditions (101,3 kPa, 273 K) [m^3/s];

T is the temperature at pump inlet [K];

p_A is the absolute pressure at pump inlet [kPa];

n is the pump speed [rev/s].

To account for the interaction of pressure variations at the pump and the pump slip rate, the correlation function (X_0) between pump speed, pressure differential from pump inlet to pump outlet, and absolute pump outlet pressure shall be calculated as follows:

$$X_0 = \frac{1}{n} \times \sqrt{\frac{\Delta p_\text{p}}{p_\text{A}}} \tag{26}$$

where

Δp_p is the pressure differential from pump inlet to pump outlet [kPa];

p_A is the absolute outlet pressure at pump outlet [kPa].

A linear least-squares fit shall be performed to generate the calibration equation as follows:

$$V_0 = D_0 - m \times (X_0) \tag{27}$$

D_0 and m are the intercept and slope constants, respectively, describing the regression lines.

For a CVS system with multiple speeds, the calibration curves generated for the different pump flow ranges shall be approximately parallel, and the intercept values (D_0) shall increase as the pump flow range decreases.

The calculated values from the equation shall be within ± 0,5 % of the measured value of V_0. Values of m will vary from one pump to another. Particulate influx over time will cause the pump slip to decrease, as reflected by lower values for m. Therefore, calibration shall be performed at pump start-up, after major maintenance, and if the total system verification indicates a change of the slip rate.

10.3 Calibration of the Critical-Flow Venturi (CFV)

10.3.1 General

Calibration of the CFV is based upon the flow equation for a critical-flow venturi. Gas flow (Q_s) is a function of inlet pressure and temperature:

$$Q_\text{s} = \frac{k_\text{v} \times p_\text{A}}{\sqrt{T}} \tag{28}$$

where

k_v is the calibration coefficient;

p_A is the absolute pressure at the venturi inlet [kPa];

T is the temperature at the venturi inlet [K].

10.3.2 Data analysis

The air flow rate (Q_s) at each restriction setting (minimum eight settings) shall be calculated in standard m^3/min from the flowmeter data using the manufacturer's prescribed method. The calibration coefficient shall be calculated from the calibration data for each setting as follows:

$$k_\text{v} = \frac{Q_\text{s} \times \sqrt{T}}{p_\text{A}} \tag{29}$$

where

Q_s is the air flow rate at standard conditions (101,3 kPa, 273 K) [m^3/s];

T is the temperature at the venturi inlet [K];

p_A is the absolute pressure at the venturi inlet [kPa].

To determine the range of critical flow, k_v shall be plotted as a function of venturi inlet pressure. For critical (choked) flow, k_v will have a relatively constant value. As pressure decreases (vacuum increases), the venturi becomes unchoked and k_v decreases, which indicates that the CFV is operating outside the permissible range.

For a minimum of eight points in the region of critical flow, the average k_v and the standard deviation shall be calculated. The standard deviation shall not exceed ± 0,3 % of the average k_v.

10.4 Calibration of the Subsonic Venturi (SSV)

10.4.1 General

Calibration of the SSV is based upon the flow equation for a subsonic venturi. Gas flow (Q_{SSV}) is a function of inlet pressure and temperature, pressure drop between the SSV inlet and throat, as shown below:

$$Q_{SSV} = A_0 d^2 C_d p_A \sqrt{\left[\frac{1}{T}\left(r_x^{1{,}428\,6} - r_x^{1{,}714\,3}\right)\left(\frac{1}{1 - r_y^{4} r_x^{1{,}428\,6}}\right)\right]} \qquad (30)$$

where

A_0 is a collection of constants and unit conversions

$= 0{,}006\,111$ in SI units of $\left[\frac{\mathrm{m}^3}{\mathrm{min}}\right]\left[\frac{\mathrm{K}^{\frac{1}{2}}}{\mathrm{kPa}}\right]\left[\frac{1}{\mathrm{mm}^2}\right]$;

d is the diameter of the SSV throat [m];

C_d is the discharge coefficient of the SSV;

p_A is the absolute pressure at venturi inlet [kPa];

T is the temperature at the venturi inlet [K].

r_x is the ratio of the SSV throat to inlet absolute, static pressure, $r_x = 1 - (\Delta p/p_A)$;

r_y is the ratio of d to the inlet pipe inner diameter (D), $r_y = d/D$.

10.4.2 Data analysis

The air flow rate ($q_{v\mathrm{SSV}}$) at each restriction setting (minimum 16 settings) shall be calculated in standard m^3/min from the flowmeter data using the manufacturer's prescribed method. The discharge coefficient (C_d) shall be calculated from the calibration data for each setting as follows:

$$C_\mathrm{d} = \frac{q_{v\mathrm{SSV}}}{d^2 p_\mathrm{A} \sqrt{\left[\frac{1}{T} \left(r_\mathrm{x}^{1{,}428\,6} - r_\mathrm{x}^{1{,}714\,3} \right) \left(\frac{1}{1 - r_\mathrm{y}^{4} r_\mathrm{x}^{1{,}428\,6}} \right) \right]}} \qquad (31)$$

where

$q_{v\mathrm{SSV}}$ is the air flow rate at standard conditions (101,3 kPa, 273 K) [m^3/min];

T is the temperature at the venturi inlet [K];

d is the diameter of the SSV throat [m];

r_x is the ratio of the SSV throat to inlet absolute, static pressure, $r_\mathrm{x} = 1 - (\Delta p / p_\mathrm{A})$;

r_y is the ratio of d to the inlet pipe inner diameter (D), $r_\mathrm{y} = d/D$.

To determine the range of subsonic flow, C_d shall be plotted as a function of Reynolds number (Re), at the SSV throat. The Re at the SSV throat is calculated with the following formula:

$$Re = A_1 \frac{q_{v\mathrm{SSV}}}{d \mu} \qquad (32)$$

where

A_1 is a collection of constants and units conversions

$$= 25{,}551\,52 \left(\frac{1}{\mathrm{m}^3} \right) \left(\frac{\mathrm{min}}{\mathrm{s}} \right) \left(\frac{\mathrm{mm}}{\mathrm{m}} \right);$$

$q_{v\mathrm{SSV}}$ is the air flow rate at standard conditions (101,3 kPa, 273 K) [m^3/s];

d is the diameter of the SSV throat, [m];

μ is the absolute or dynamic viscosity of the gas, calculated with the following formula:

$$\mu = \frac{b T^{3/2}}{S + T} = \frac{b T^{1/2}}{1 + \frac{S}{T}} \ \mathrm{kg/m\text{-}s} \qquad (33)$$

where

b is an empirical constant $= 1{,}458 \times 10^6 \ \frac{\mathrm{kg}}{\mathrm{msK}^{1/2}}$;

S is an empirical constant $= 110{,}4 \ \mathrm{K}$.

Because Q_{SSV} is an input to the Re formula, the calculations shall be started with an initial guess for Q_{SSV} or C_d of the calibration venturi, and repeated until Q_{SSV} converges. The convergence method shall be accurate to 0,1 % of a point or better.

For a minimum of sixteen points in the region of subsonic flow, the calculated values of C_d from the resulting calibration curve fit equation shall be within ± 0.5% of the measured C_d for each calibration point.

10.5 Total system verification

10.5.1 General

The total accuracy of the CVS sampling system and analytical system shall be determined by introducing a known mass of a pollutant gas into the system while it is being operated in the normal manner. The pollutant is analysed, and the mass calculated according to 14.5, except in the case of propane where a factor of 0,000 472 is used in place of 0,000 479 for HC. Either of the following two techniques shall be used.

10.5.2 Metering with a critical flow orifice

A known quantity of pure gas (carbon monoxide or propane) shall be fed into the CVS system through a calibrated critical orifice. If the inlet pressure is high enough, the flow rate, which is adjusted by means of the critical flow orifice, is independent of the orifice outlet pressure (critical flow). The CVS system shall be operated as in a normal exhaust emission test for about 5 min to 10 min. A gas sample shall be analysed with the usual equipment (sampling bag or integrating method), and the mass of the gas calculated. The mass so determined shall be within ± 3% of the known mass of the gas injected.

10.5.3 Metering by means of a gravimetric technique

The mass of a small cylinder filled with carbon monoxide or propane shall be determined with a precision of ± 0,01 g. For about 5 min to 10 min, the CVS system shall be operated as in a normal exhaust emission test, while carbon monoxide or propane is injected into the system. The quantity of pure gas discharged shall be determined by means of differential weighing. A gas sample shall be analysed with the usual equipment (sampling bag or integrating method), and the mass of the gas calculated. The mass so determined shall be within ± 3% of the known mass of the gas injected.

11 Running conditions (test cycles)

ISO 8178-4 applies.

12 Test run

12.1 Preparation of the sampling filters

At least one hour before the test, each filter (pair) shall be placed in a closed, but unsealed Petri dish and placed in a weighing chamber for stabilization. At the end of the stabilization period, each filter (pair) shall be weighed and the tare shall be recorded. The (pair of) filter(s) shall then be stored in a closed Petri dish or filter holder until needed for testing. If the (pair of) filter(s) is not used within 8 h of its removal from the weighing chamber, it must be reweighed before use.

12.2 Installation of the measuring equipment

The instrumentation and sample probes shall be installed as required. When using a full-flow dilution system for exhaust gas dilution, the tailpipe shall be connected to the system.

12.3 Starting the dilution system and the engine

The dilution system and the engine shall be started and warmed up until all temperatures and pressures have stabilized at full load and rated speed. (Stabilization criteria are given in ISO 15550:2002, 6.2.4.3.2.)

12.4 Adjustment of the dilution ratio

The particulate sampling system shall be started and run on bypass for the single-filter method (optional for the multiple-filter method). The particulate background level of the dilution air may be determined by passing dilution air through the particulate filters. If filtered dilution air is used, one measurement may be done at any time prior to, during, or after the test. If the dilution air is not filtered, measurements at a minimum of three points (at the beginning, at the end, and a point near the middle of the cycle) are required, and the values averaged.

The dilution air shall be set to obtain a maximum filter face temperature of 325 K (52 °C) at each mode. The total dilution ratio shall not be less than 4.

For CO_2 or NO_x concentration controlled systems, the CO_2 or NO_x content of the dilution air must be measured at the beginning and at the end of each test. The pre- and post-test background CO_2 or NO_x concentration measurements of the dilution air shall be within 100 ppm or 5 ppm of each other, respectively.

When using a dilute exhaust gas analysis system, the relevant background concentrations of the gaseous components shall be determined by sampling dilution air into a sampling bag over the complete test sequence. Continuous (non-bag) background concentration may be taken at a minimum of three points of the cycle (the beginning, the end, and at a point near the middle) and then the average value determined. At the request of the engine manufacturer, background measurements may be omitted.

12.5 Determination of test points

The settings of inlet restriction and exhaust back pressure shall be adjusted to the manufacturer's upper limits, in accordance with 5.4.1 and 5.4.2.

The maximum torque values at the specified test speeds shall be determined by experimentation in order to calculate the torque values for the specified test modes. For engines which are not designed to operate over a speed range on a full-load torque curve, the maximum torque at the test speeds shall be declared by the manufacturer.

The engine setting for each test mode shall be calculated using the following formula:

$$S = \left((P_\mathrm{m} + P_\mathrm{aux}) \times \frac{M}{100} \right) - P_\mathrm{aux} \quad (34)$$

where

S is the dynamometer setting [kW];

P_m is the maximum observed or declared power at the test speed under the test conditions (specified by the manufacturer) [kW];

P_aux is the declared total power absorbed by any auxiliaries fitted for the test and not required by ISO 14396 [kW];

M is the torque specified for the test mode [%].

12.6 Checking of the analysers

The emission analysers shall be set at zero and spanned.

12.7 Test cycles

The test cycles are defined in ISO 8178-4. This takes into account the variations in engine size and application.

12.7.1 Test sequence

The engine shall be operated in each mode in the appropriate test cycle of ISO 8178-4. The tolerances indicated below apply during the emission data acquisition, particulate and bag sampling period only.

a) For engines tested with the dynamometer speed control test configuration

During each mode of the test cycle after the initial transition period, the specified speed shall be held within ± 1 % of the rated speed or ± 3 rev·min^{-1}, whichever is greater, except for low idle which shall be within the tolerances declared by the manufacturer. The specified torque shall be held so that the average over the period during which the measurements are being taken is within ± 2 % of the maximum torque at the test speed.

b) For engines tested with the dynamometer load control test configuration

During each mode of the test cycle after the initial transition period, the specified speed should be within ± 2 % of the rated speed or ± 3 rev·min^{-1}, whichever is greater, but shall in any case be held within ± 5 %, except for low idle which shall be within the tolerances declared by the manufacturer.

During modes of the test cycle where the prescribed torque is 50 % or greater of the maximum torque at the test speed, the specified average torque over the data acquisition period shall be held within ± 5 % of the prescribed torque. During modes where the prescribed torque is less than 50 % of the maximum torque at the test speed, the specified average torque over the data acquisition period shall be held within ± 10 % of the prescribed torque or ± 0,27 N·m, whichever is greater.

12.7.2 Analyser response

The output of the analysers shall be recorded on a strip chart recorder or measured with an equivalent data acquisition system with the exhaust gas flowing through the analysers at least during the last 3 min of each mode. If bag sampling is applied for the diluted CO and CO_2 measurement (see 7.5.4), a sample shall be bagged during the last 3 min of each mode, and the bag sample analysed and recorded.

12.7.3 Particulate sampling

Particulate sampling can be done either with the single-filter method or with the multiple-filter method (see 7.6).

Since the results of the methods may differ slightly, the method used shall be declared with the results.

For the single-filter method, the modal weighting factors specified in the test cycle procedure shall be taken into account by taking a sample proportional to the exhaust mass flow for each mode of the cycle. This can be achieved by adjusting sample flow rate, sampling time and/or dilution ratio, accordingly, so that the criterion for the effective weighting factors in 15.6 is met.

Sampling shall be conducted as late as possible within each mode. The sampling time per mode shall be at least 20 s for the single-filter method and at least 60 s for the multiple-filter method. For additional information on test mode duration, see ISO 8178-4. For systems without bypass capability, the sampling time per mode shall be at least 60 s for single- and multiple-filter methods.

12.7.4 Engine conditions

The engine speed and load, intake air temperature, fuel flow and air or exhaust gas flow shall be measured at each mode once the engine has been stabilized.

If the measurement of exhaust gas flow or combustion air is not possible, they can be calculated using the carbon and oxygen balance method (see 7.3.6 and Annex A).

Any additional data required for calculation shall be recorded (see Clause 13).

12.8 Re-checking the analysers

After the emission test, a zero gas and the same span gas shall be used for re-checking. The test will be considered acceptable if the difference between the two measuring results is less than 2 %.

12.9 Test report

The test report should contain the data given in ISO 8178-6.

13 Data evaluation for gaseous and particulate emissions

13.1 Gaseous emissions

For the evaluation of the gaseous emissions, the chart reading of at least the last 60 s of each mode shall be averaged, and the average concentrations of HC, CO, CO_2, NO_x, O_2, NMHC (NMC method), NH_3 and CH_3OH (FID method) during each mode shall be determined from the average chart readings and the corresponding calibration data. The average concentrations in the sampling bag, if used, shall be determined from the bag readings and the corresponding calibration data. A different type of recording can be used if it ensures an equivalent data acquisition.

The average background concentrations, if measured, shall be determined from the bag readings of the dilution air or from the averaged continuous (non-bag) background readings and the corresponding calibration data.

When using impinger or cartridge sampling methods for CH_3OH and HCHO, the concentrations and background concentrations (if used) shall be determined from the CH_3OH/HCHO quantity in the impingers or cartridges (see Figure 7 and Figure 8) as determined by GC and HPLC analysis, and the total sample volumes through the impingers or cartridges.

13.2 Particulate emissions

For the evaluation of the particulates, the total sample masses (m_{sep}) through the filters shall be recorded for each mode.

The filters shall be returned to the weighing chamber and conditioned for at least 1 h, but not more than 80 h, and then weighed. The gross mass of the filters shall be recorded and the tare (see 12.1) subtracted.

If background correction is to be applied, the dilution air mass (m_{d}) through the filters and the particulate mass ($m_{\text{f,d}}$) shall be recorded. If more than one measurement was made, the quotient $m_{\text{f,d}}/m_{\text{d}}$ shall be calculated for each single measurement and the values averaged.

14 Calculation of the gaseous emissions

14.1 General

Figure 2 gives some guidance on the different possibilities to calculate the exhaust emissions.

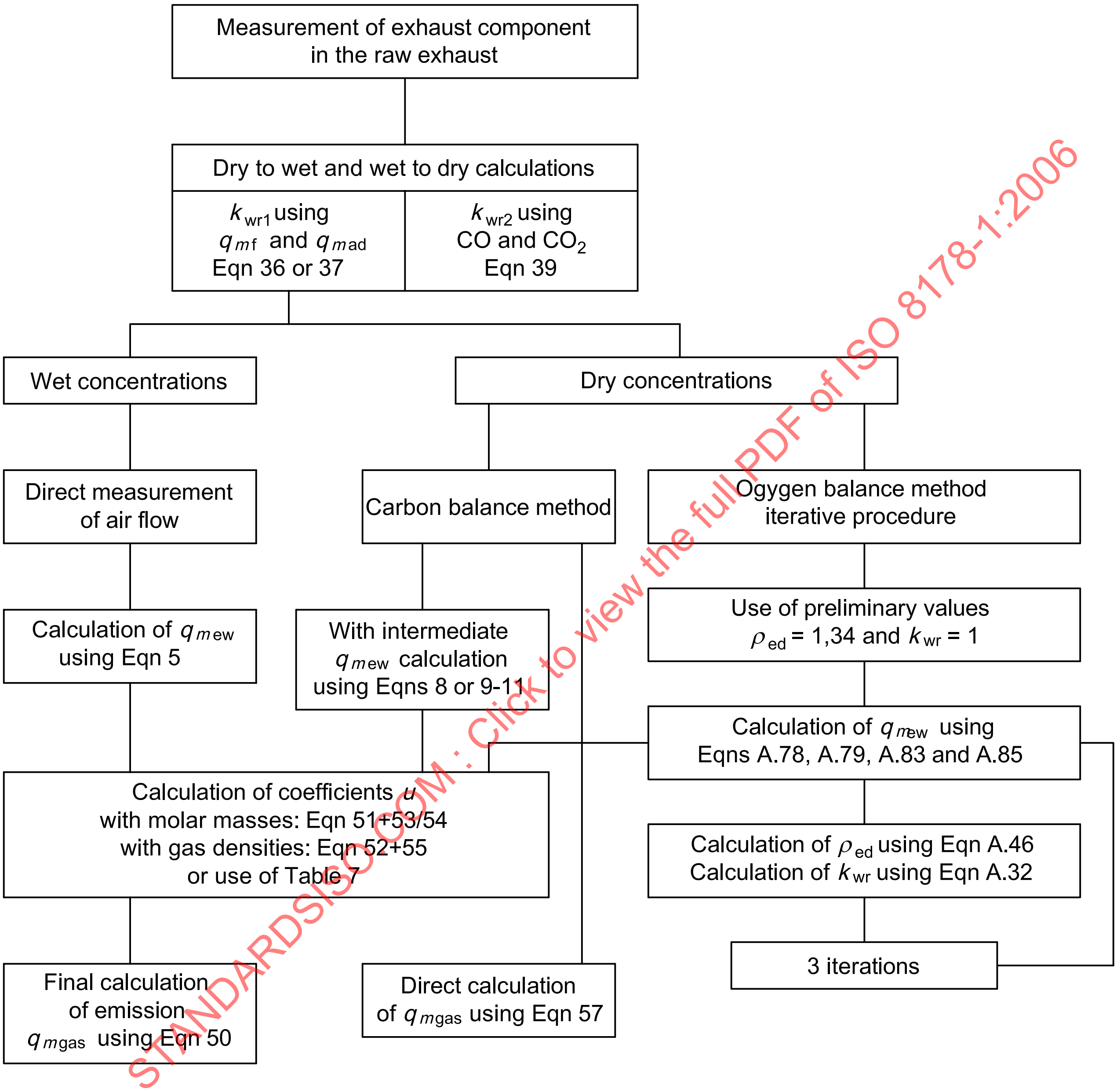


Figure 2 — Measurement of exhaust component in the raw exhaust

14.2 Determination of the exhaust gas flow

The exhaust gas flow rate (q_{mew}) shall be determined for each mode according to 7.3.2 to 7.3.7.

When using a full-flow dilution system, the total dilute exhaust gas flow rate (q_{mdew}) shall be determined for each mode according to 7.3.7.

14.3 Dry/wet correction

If the emissions are not measured on a wet basis, the measured concentration shall be converted to a wet basis according to either of the following formulae. The derivation is given in Annex A.

$$c_\mathrm{w} = k_\mathrm{w} \times c_\mathrm{d} \tag{35}$$

a) For the raw exhaust gas

1) Complete combustion

$$k_\mathrm{wr1} = \left(1 - \frac{1{,}244\,2 \times H_\mathrm{a} + 111{,}19 \times w_\mathrm{ALF} \times \dfrac{q_{m\mathrm{f}}}{q_{m\mathrm{ad}}}}{773{,}4 + 1{,}244\,2 \times H_\mathrm{a} + \dfrac{q_{m\mathrm{f}}}{q_{m\mathrm{ad}}} \times f_\mathrm{fw} \times 1\,000} \right) \times 1{,}008 \tag{36}$$

or

$$k_\mathrm{wr1} = \left(1 - \frac{1{,}244\,2 \times H_\mathrm{a} + 111{,}19 \times w_\mathrm{ALF} \times \dfrac{q_{m\mathrm{f}}}{q_{m\mathrm{ad}}}}{773{,}4 + 1{,}244\,2 \times H_\mathrm{a} + \dfrac{q_{m\mathrm{f}}}{q_{m\mathrm{ad}}} \times f_\mathrm{fw} \times 1\,000} \right) \Big/ \left(1 - \frac{p_\mathrm{r}}{p_\mathrm{b}} \right) \tag{37}$$

$$f_\mathrm{fw} = 0{,}055\,594 \times w_\mathrm{ALF} + 0{,}008\,002\,1 \times w_\mathrm{DEL} + 0{,}007\,004\,6 \times w_\mathrm{EPS} \tag{38}$$

2) Incomplete combustion

In cases of considerable amounts of not or only partly combusted components (CO, H_2) the following equation shall be used (see derivation in Annex A):

$$k_\mathrm{wr2} = \frac{1}{1 + \alpha \times 0{,}005 \times [c_\mathrm{CO2d} + c_\mathrm{COd}] - 0{,}01 \times c_\mathrm{H2d} + k_\mathrm{w2} - \dfrac{p_\mathrm{r}}{p_\mathrm{b}}} \tag{39}$$

and

$$c_\mathrm{H2d} = \frac{0{,}5 \times \alpha \times c_\mathrm{COd} \times (c_\mathrm{COd} + c_\mathrm{CO2d})}{c_\mathrm{COd} + 3 \times c_\mathrm{CO2d}} \tag{40}$$

NOTE The CO and CO_2 concentrations in Equations (39) and (40) are expressed as percentages [%].

b) For the diluted exhaust gas

$$k_\mathrm{we1} = \left(1 - \frac{\alpha \times c_\mathrm{CO2w}}{200} \right) - k_\mathrm{w1} \tag{41}$$

or

$$k_\mathrm{we2} = \left(\frac{(1 - k_\mathrm{w1})}{1 + \dfrac{\alpha \times c_\mathrm{CO2d}}{200}} \right) \tag{42}$$

c) For the dilution air

$$k_{\mathrm{wd}} = 1 - k_{\mathrm{w1}} \tag{43}$$

$$k_{\mathrm{w1}} = \frac{1{,}608 \times \left[H_{\mathrm{d}} \times \left(1 - \frac{1}{D} \right) + H_{\mathrm{a}} \times \left(\frac{1}{D} \right) \right]}{1\,000 + \left\{ 1{,}608 \times \left[H_{\mathrm{d}} \times \left(1 - \frac{1}{D} \right) + H_{\mathrm{a}} \times \left(\frac{1}{D} \right) \right] \right\}} \tag{44}$$

d) For the intake air (if different from the dilution air)

$$k_{\mathrm{wa}} = 1 - k_{\mathrm{w2}} \tag{45}$$

$$k_{\mathrm{w2}} = \frac{1{,}608 \times H_{\mathrm{a}}}{1\,000 + \left(1{,}608 \times H_{\mathrm{a}} \right)} \tag{46}$$

where

H_{a}, H_{d} are the absolute humidities of intake air and dillution air [g of water per kg of dry air].

NOTE H_{a}, H_{d} can be derived from relative humidity measurement, dewpoint measurement, vapour pressure measurement or dry/wet bulb measurement using the generally accepted formulae.

14.4 NO$_{\mathrm{x}}$ correction for humidity and temperature

As the NO$_{\mathrm{x}}$ emission depends on ambient air conditions, the NO$_{\mathrm{x}}$ concentration shall be corrected for ambient air temperature and humidity with the factors given in the following formulae. These factors are valid for a humidity range between 0 g/kg and 25 g/kg dry air.

If the parties involved agree, reference values for humidity other than 10,71 g/kg may be used and shall be reported with the results.

Other correction formulae outside the above humidity range may be used if they can be justified or validated upon agreement of the parties involved. In the following formulae, T_{a} corresponds to the ambient air temperature at the inlet to the air filter and H_{a} corresponds to the ambient air humidity at the inlet to the air filter.

Water or steam injected into the air charger (air humidification) is considered an emission control device and shall therefore not be taken into account for humidity correction. Water that condenses in the charge cooler will change the humidity of the charge air and shall therefore be taken into account for humidity correction.

a) For compression ignition engines:

$$k_{\mathrm{hd}} = \frac{1}{1 - 0{,}018\,2 \times \left(H_{\mathrm{a}} - 10{,}71 \right) + 0{,}004\,5 \times \left(T_{\mathrm{a}} - 298 \right)} \tag{47}$$

where

T_{a} is the temperature of the air [K];

H_{a} is the humidity of the intake air [g water per kg dry air].

b) For compression ignition engines with intermediate air cooler, the following alternative equation may be used:

$$k_{\text{hd}} = \frac{1}{1 - 0{,}012 \times (H_{\text{a}} - 10{,}71) - 0{,}002\,75 \times (T_{\text{a}} - 298) + 0{,}002\,85 \times (T_{\text{SC}} - T_{\text{SCRef}})} \quad (48)$$

where

T_{SC} is the temperature of the intercooled air;

T_{SCRef} is the intercooled air reference temperature – to be specified by the manufacturer.

NOTE 1 For an explanation of the other variables, see a).

c) For spark ignition engines:

$$k_{\text{hp}} = 0{,}627\,2 + 44{,}030 \times 10^{-3} \times H_{\text{a}} - 0{,}862 \times 10^{-3} \times H_{\text{a}}^2 \quad (49)$$

NOTE 2 For an explanation of the variables, see a).

14.5 Calculation of the emission mass flow rates

14.5.1 Raw exhaust gas

The emission mass flow rates for each mode shall be calculated from the raw concentrations of the pollutants, the u values from Table 7 and the exhaust mass flow in accordance with 14.5.1.1. If concentrations are measured on a dry basis, the dry/wet correction according to 14.3 shall be applied to the concentration values before any further calculation is done.

Optionally, the mass emissions may be calculated using the exact formulae of 14.5.1.2 with the prior agreement of the parties involved. The exact formulae must be used if the fuel used for the test is not specified in Table 7, under multi-fuel operation or in case of dispute.

14.5.1.1 Calculation method based on tabulated values

The following formula shall be applied:

$$q_{m\text{gas}} = u_{\text{gas}} \times c_{\text{gas}} \times q_{m\text{ew}} \quad (50)$$

where

$q_{m\text{gas}}$ is the emission mass flow rate of individual gas;

u_{gas} is the ratio between density of exhaust component and density of exhaust gas;

c_{gas} is the concentration of the respective component in the raw exhaust gas [ppm];

$q_{m\text{ew}}$ is the exhaust mass flow [kg/h].

For the calculation of NO_x, the humidity correction factor – k_{hd} or k_{hp}, as applicable and as determined according to 14.4 – shall be used.

The measured concentration shall be converted to a wet basis according to 14.3, if not already measured on a wet basis.

Values for u are given in Table 7 for selected components based on ideal gas properties and a range of fuels.

14.5.1.2 Calculation method based on exact formulae

The mass emission shall be calculated using Equation (50). Instead of using the tabulated values, the following equation shall be applied for the calculation of u_{gas}. It is assumed in the following equations that the concentration c_{gas} in Equation (50) is measured in or converted to ppm.

$$u_{\mathrm{gas}} = \frac{M_{\mathrm{rgas}}}{M_{\mathrm{r,e}} \times 1000} \tag{51}$$

or

$$u_{\mathrm{gas}} = \frac{\rho_{\mathrm{gas}}}{\rho_{\mathrm{e}} \times 1000} \tag{52}$$

where

$\rho_{\mathrm{gas}} = M_{\mathrm{rgas}} / 22{,}414$ or optionally taken from Table 7 (based on ideal gas properties).

The densities, ρ_{gas}, are given for a number of exhaust gas components in Table 7. The molecular mass of the exhaust, $M_{\mathrm{r,e}}$, shall be derived for a general fuel composition $\mathrm{C}_{\beta}\mathrm{H}_{\alpha}\mathrm{O}_{\varepsilon}\mathrm{N}_{\delta}\mathrm{S}_{\gamma}$ under the assumption of complete combustion, as follows:

$$M_{\mathrm{r,e}} = \frac{1 + \dfrac{q_{m\mathrm{f}}}{q_{m\mathrm{aw}}}}{\dfrac{q_{m\mathrm{f}}}{q_{m\mathrm{aw}}} \times \dfrac{\dfrac{a}{4} + \dfrac{\varepsilon}{2} + \dfrac{\delta}{2}}{12{,}011 \times \beta + 1{,}007\,94 \times a + 15{,}999\,4 \times \varepsilon + 14{,}006\,7 \times \delta + 32{,}065 \times \gamma} + \dfrac{\dfrac{H_{\mathrm{a}} \times 10^{-3}}{2 \times 1{,}007\,94 + 15{,}999\,4} + \dfrac{1}{M_{\mathrm{r,a}}}}{1 + H_{\mathrm{a}} \times 10^{-3}}} \tag{53}$$

or for incomplete combustion

$$\begin{aligned} M_{\mathrm{r,e}} = {} & \frac{M_{\mathrm{rHC}} \times c_{\mathrm{HCw}}}{10^6} + \frac{28{,}01 \times c_{\mathrm{COw}}}{10^6} + \frac{44{,}01 \times c_{\mathrm{CO2w}}}{10^2} + \frac{46{,}01 \times c_{\mathrm{NOxw}}}{10^6} \\ & + \frac{32 \times c_{\mathrm{O2w}}}{10^2} + \frac{2{,}016 \times c_{\mathrm{H2w}}}{10^2} + 18{,}01 \times \left(1 - k_{\mathrm{wr}}\right) \\ & + \frac{28{,}01}{100} \times \left[100 - \frac{c_{\mathrm{HCw}}}{10^4} - \frac{c_{\mathrm{COw}}}{10^4} - c_{\mathrm{CO2w}} - \frac{c_{\mathrm{NO_xw}}}{10^4} - c_{\mathrm{O2w}} - c_{\mathrm{H2w}} - 100 \times \left(1 - k_{\mathrm{wr}}\right)\right] \end{aligned} \tag{54}$$

The exhaust density ρ_{e} shall be derived, as follows:

$$\rho_{\mathrm{e}} = \frac{1000 + H_{\mathrm{a}} + 1000 \times \left(q_{m\mathrm{f}} / q_{m\mathrm{ad}}\right)}{773{,}4 + 1{,}243\,4 \times H_{\mathrm{a}} + f_{\mathrm{fw}} \times 1000 \times \left(q_{m\mathrm{f}} / q_{m\mathrm{ad}}\right)} \tag{55}$$

where

$$f_{\mathrm{fw}} = 0{,}055\,594 \times w_{\mathrm{ALF}} + 0{,}008\,002\,1 \times w_{\mathrm{DEL}} + 0{,}007\,004\,6 \times w_{\mathrm{EPS}} \tag{56}$$

When using the carbon balance method

$$q_{m\mathrm{gas}} = \frac{M_{\mathrm{rgas}} \times c_{\mathrm{gas}} \times q_{m\mathrm{f}}}{M_{\mathrm{rf}} \times \left[\left(c_{\mathrm{CO2w}} - c_{\mathrm{CO2aw}} \right) + \dfrac{c_{\mathrm{COw}} + c_{\mathrm{HCw}}}{10^4} \right] \times 10} \qquad (57)$$

where c_{CO} and c_{HC} are expressed in ppm and c_{CO2} in percentage volume.

The derivation of Equation (58) is given in A.2.2.2

$$M_{\mathrm{rf}} = \alpha \times A_{\mathrm{rH}} + \beta \times A_{\mathrm{rC}} + \gamma \times A_{\mathrm{rS}} + \delta \times A_{\mathrm{rN}} + \varepsilon \times A_{\mathrm{rO}} \qquad (58)$$

14.5.2 Dilute exhaust gas

The emission mass flow rates for each mode shall be calculated from the diluted concentrations of the pollutants, the u values from Table 8 and the diluted exhaust mass flow as follows. If concentrations are measured on a dry basis, the dry/wet correction according to 14.3 shall be applied to the concentration values before any further calculation is done.

$$q_{m\mathrm{gas}} = u_{\mathrm{gas}} \times c_{\mathrm{gas,c}} \times q_{m\mathrm{dew}} \qquad (59)$$

where

u_{gas} is the ratio between density of exhaust component and density of diluted exhaust gas (equivalent to air density);

$c_{\mathrm{gas,c}}$ is the background corrected concentration of the respective component in the diluted exhaust gas [ppm];

$q_{m\mathrm{dew}}$ is the diluted exhaust mass flow [kg/s].

Values for u are given in Table 8 for selected components based on ideal gas properties and a range of fuels.

$$c_{\mathrm{c}} = c - c_{\mathrm{d}} \times \left[1 - \frac{1}{D} \right] \qquad (60)$$

$$D = \frac{FS}{c_{\mathrm{CO2}} + \left(c_{\mathrm{CO}} + c_{\mathrm{HC}} \right) \times 10^{-4}} \qquad (61)$$

or

$$D = \frac{FS}{c_{\mathrm{CO2}}} \qquad (62)$$

where

$$FS = 100 \times \frac{1}{1 + \dfrac{\alpha}{2} + \gamma + 3{,}76 \left(1 + \dfrac{\alpha}{4} - \dfrac{\varepsilon}{2} + \gamma \right)} \qquad (63)$$

α, γ, ε means a fuel composition of $\mathrm{CH}_{\alpha}\mathrm{O}_{\varepsilon}\mathrm{S}_{\gamma}$.

For diesel fuel, $FS = 13{,}4$.

Table 7 — Coefficient u_{gas} and fuel specific parameters for raw exhaust gas

Fuel and corresponding ρ_e (kg/m^3)		Gas							
		NO_x	CO	HC	CO_2	O_2	CH_4	HCHO	CH_3OH
		ρ_{gas} (kg/m^3)							
		2,053	1,250	[a]	1,963 6	1,427 7	0,716	1,340	1,430
		Coefficient u_{gas} [b]							
Diesel	1,294 3	0,001 586	0,000 966	0,000 479	0,001 517	0,001 103	0,000 553	0,001 035	0,001 104
RME	1,295 0	0,001 585	0,000 965	0,000 536	0,001 516	0,001 102	0,000 553	0,001 035	0,001 104
Methanol	1,261 0	0,001 628	0,000 991	0,001 133	0,001 557	0,001 132	0,000 568	0,001 062	0,001 134
Ethanol	1,275 7	0,001 609	0,000 980	0,000 805	0,001 539	0,001 119	0,000 561	0,001 050	0,001 121
Natural gas[c]	1,266 1	0,001 621	0,000 987	0,000 558[d]	0,001 551	0,001 128	0,000 565	0,001 058	0,001 129
Propane	1,280 5	0,001 603	0,000 976	0,000 512	0,001 533	0,001 115	0,000 559	0,001 046	0,001 116
Butane	1,283 2	0,001 600	0,000 974	0,000 505	0,001 530	0,001 113	0,000 558	0,001 044	0,001 114
Gasoline	1,297 7	0,001 582	0,000 963	0,000 481	0,001 513	0,001 100	0,000 552	0,001 032	0,001 102

[a] Depending on fuel.

[b] At $\lambda = 2$, dry air, 273 K, 101,3 kPa.

[c] u accurate within 0,2 % for mass composition of C = 66 % – 76 %; H = 22 % – 25 %; N = 0 % – 12 %.

[d] NMHC on the basis of $CH_{2,93}$ (for total HC the u_{gas} coefficient of CH_4 shall be used).

Table 8 — Coefficient u_{gas} and fuel specific parameters for diluted exhaust gas

Fuel (ρ_e = 1,293 kg/m^3)		Gas							
		NO_x	CO	HC	CO_2	O_2	CH_4	HCHO	CH_3OH
		ρ_{gas} (kg/m^3)							
		2,053	1,250	[a]	1,963 6	1,427 7	0,716	1,340	1,430
		Coefficient u_{gas} [b]							
Diesel		0,001 588	0,000 967	0,000 480	0,001 519	0,001 104	0,000 553	0,001 036	0,001 106
RME		0,001 588	0,000 967	0,000 537	0,001 519	0,001 104	0,000 553	0,001 036	0,001 106
Methanol		0,001 588	0,000 967	0,001 105	0,001 519	0,001 104	0,000 553	0,001 036	0,001 106
Ethanol		0,001 588	0,000 967	0,000 795	0,001 519	0,001 104	0,000 553	0,001 036	0,001 106
Natural gas[c]		0,001 588	0,000 967	0,000 584[d]	0,001 519	0,001 104	0,000 553	0,001 036	0,001 106
Propane		0,001 588	0,000 967	0,000 507	0,001 519	0,001 104	0,000 553	0,001 036	0,001 106
Butane		0,001 588	0,000 967	0,000 501	0,001 519	0,001 104	0,000 553	0,001 036	0,001 106
Gasoline		0,001 588	0,000 967	0,000 483	0,001 519	0,001 104	0,000 553	0,001 036	0,001 106

[a] Depending on fuel.

[b] Assume density of diluted exhaust gas = density of air.

[c] u accurate within 0,2 % for mass composition of C = 66 % – 76 %; H = 22 % – 25 %; N = 0 % – 12 %.

[d] NMHC on the basis of $CH_{2,93}$ (for total HC the u_{gas} coefficient of CH_4 shall be used).

14.5.3 Determination of the NMHC concentration

The determination of c_{NMHC} depends on the method used (see 16.5). In both cases, the CH_4 concentration shall be determined and subtracted from the HC concentration as follows:

a) GC method

$$c_{\mathrm{NMHC}} = c_{\mathrm{HC}} - c_{\mathrm{CH_4}} \tag{64}$$

b) NMC method

$$c_{\mathrm{NMHC}} = \frac{c_{\mathrm{HC(w/oCutter)}} \times (1 - E_{\mathrm{M}}) - c_{\mathrm{HC(wCutter)}}}{E_{\mathrm{E}} - E_{\mathrm{M}}} \tag{65}$$

where

$c_{\mathrm{HC(wCutter)}}$ is the HC concentration with the sample gas flowing through the NMC;

$c_{\mathrm{HC(w/oCutter)}}$ is the HC concentration with the sample gas bypassing the NMC;

E_{M} is the methane efficiency as determined per 8.8.4.2;

E_{E} is the ethane efficiency as determined per 8.8.4.3.

14.6 Calculation of the specific emission

The emission shall be calculated for all individual components in the following way:

$$\mathrm{gas}_x = \frac{\sum_{i=1}^{i=n} \left(q_{m\mathrm{gas}i} \times W_{\mathrm{f}i} \right)}{\sum_{i=1}^{i=n} \left(P_i \times W_{\mathrm{f}i} \right)} \tag{66}$$

where

$q_{m\mathrm{gas}}$ is the emission mass flow rate of the individual gas;

$$P = P_{\mathrm{m}} + P_{\mathrm{aux}} \tag{67}$$

where

P_{m} is the measured power of the individual mode;

P_{aux} is the power of the auxiliaries fitted to the engine of the individual mode.

The weighting factors and the number of modes (n) used in the above calculation are according to the provisions of ISO 8178-4.

15 Calculation of the particulate emission

15.1 Particulate correction factor for humidity

As the particulate emission of diesel engines depends on ambient air conditions, the particulate concentration shall be corrected for ambient air humidity with the factor k_p given in the following formulae.

Reference values for humidity instead of 10,71 g/kg may be used and shall be reported with the results by agreement within the parties involved.

Other correction formulae may be used if they can be justified or validated.

$$k_p = \frac{1}{\left[1 + 0{,}013\,3 \times \left(H_a - 10{,}71\right)\right]} \tag{68}$$

where

H_a is the humidity of the intake air [g water per kg dry air].

15.2 Partial-flow dilution system

The final reported test results of the particulate emission shall be determined through the following steps. Since various types of dilution rate control may be used, different calculation methods for $q_{m\text{edf}}$ apply. All calculations shall be based upon the average values of the individual modes during the sampling period.

15.2.1 Isokinetic systems

See 17.2.1, Figures 10 and 11.

$$q_{m\text{edf}} = q_{m\text{ew}} \times r_d \tag{69}$$

with

$$r_d = \frac{q_{m\text{dw}} + \left(q_{m\text{ew}} \times r_a\right)}{q_{m\text{ew}} \times r_a} \tag{70}$$

where r corresponds to the ratio of the cross-sectional areas of the isokinetic probe A_p and the exhaust pipe A_T:

$$r_a = \frac{A_p}{A_T} \tag{71}$$

15.2.2 Systems with measurement of CO_2 or NO_x concentration

See 17.2.1, Figures 12, 14 to 16.

For $q_{m\text{edf}}$ use Equation (69) and

$$r_d = \frac{c_{\text{Ew}} - c_{\text{Aw}}}{c_{\text{Dw}} - c_{\text{Aw}}} \tag{72}$$

where

c_{Ew} is the wet concentration of the tracer gas in raw exhaust;

c_{Dw} is the wet concentration of the tracer gas in the diluted exhaust;

c_{Aw} is the wet concentration of the tracer gas in the dilution air.

Concentrations measured on a dry basis shall be converted to a wet basis according to 14.3.

15.2.3 Systems with CO_2 measurement and carbon balance method

See 17.2.1, Figure 13.

Calculation of $q_{m\mathrm{edf}}$ with

$$q_{m\mathrm{edf}} = \frac{k_{\mathrm{f}} \times q_{m\mathrm{f}}}{c_{(\mathrm{CO_2})\mathrm{D}} - c_{(\mathrm{CO_2})\mathrm{A}}} \tag{73}$$

where

$c_{(\mathrm{CO2})\mathrm{D}}$ is the CO_2 concentration of the diluted exhaust;

$c_{(\mathrm{CO2})\mathrm{A}}$ is the CO_2 concentration of the dilution air.

Concentrations are in volume per cent on wet basis.

Therefore,

$$r_{\mathrm{d}} = \frac{k_{\mathrm{f}} \times q_{m\mathrm{f}}}{q_{m\mathrm{ew}} \times \left[c_{(\mathrm{CO_2})\mathrm{D}} - c_{(\mathrm{CO_2})\mathrm{A}} \right]} \tag{74}$$

In the above equation, k_{f} can be determined as given in A.4, with the following final equation:

$$k_{\mathrm{f}} = w_{\mathrm{BET}} \times 2{,}412\,9 \tag{75}$$

15.2.4 Systems with flow measurement

See 17.2.1, Figures 17 and 18.

For $q_{m\mathrm{edf}}$ see Equation (69).

$$r_{\mathrm{d}} = \frac{q_{m\mathrm{dew}}}{q_{m\mathrm{dew}} - q_{m\mathrm{dw}}} \tag{76}$$

15.3 Full-flow dilution system

The reported test results of the particulate emission shall be determined through the following steps.

All calculations shall be based upon the average values of the individual modes during the sampling period. For full-flow dilution systems $q_{m\mathrm{dew}}$ is used as $q_{m\mathrm{edf}}$.

15.4 Calculation of the particulate mass flow rate

The particulate mass flow rate shall be calculated as follows.

a) For the single-filter method

$$q_{m\mathrm{PT}} = \frac{m_\mathrm{f}}{m_\mathrm{sep}} \times \frac{\overline{q_{m\mathrm{edf}}}}{1000} \tag{77}$$

$$\overline{q_{m\mathrm{edf}}} = \sum_{i=1}^{i=n} q_{m\mathrm{edf}i} \times W_{\mathrm{f}i} \tag{78}$$

$$m_\mathrm{sep} = \sum_{i=1}^{i=n} M_{\mathrm{sep}i} \tag{79}$$

$i = 1, \ldots n$

b) For the multiple-filter method

$$q_{m\mathrm{PT}i} = \frac{M_{\mathrm{f}i}}{m_{\mathrm{sep}i}} \times \frac{q_{m\mathrm{edf}i}}{1000} \tag{80}$$

$i = 1, \ldots n$

PT_mass is determined over the test cycle by summation of the average values of the individual modes during the sampling period.

The particulate mass flow rate may be background-corrected (see 12.4) as follows.

c) For the single-filter method with background correction

$$q_{m\mathrm{PT}} = \left\{ \frac{m_\mathrm{f}}{m_\mathrm{sep}} - \left[\frac{m_\mathrm{f,d}}{m_\mathrm{d}} \times \sum_{i=1}^{i=n} \left(1 - \frac{1}{Di} \right) \times W_{\mathrm{f}\,\mathrm{i}} \right] \right\} \times \frac{\overline{q_{m\mathrm{edf}}}}{1000} \tag{81}$$

d) For the multiple-filter method with background correction

$$q_{m\mathrm{PT}i} = \left\{ \frac{m_{\mathrm{f}i}}{m_{\mathrm{sep}i}} - \left[\frac{m_\mathrm{f,d}}{m_\mathrm{d}} \times \left(1 - \frac{1}{D} \right) \right] \right\} \times \frac{q_{m\mathrm{edf}i}}{1000} \tag{82}$$

where D is calculated according to Equations (61) and (62). Optionally, the dilution ratio r_d, as determined according to 15.2.1 to 15.2.4, may be used instead of D for partial-flow dilution systems, if the dilute $\mathrm{CO_2}$ concentration is not measured.

If more than one measurement is made, $m_\mathrm{f,d} / m_\mathrm{d}$ shall be replaced with $\overline{m_\mathrm{f,d} / m_\mathrm{d}}$.

15.5 Calculation of the specific emissions

The particulate emission shall be calculated in the following way.

a) For the single-filter method

$$e_{\mathrm{PT}} = \frac{q_{m\mathrm{PT}}}{\sum_{i=1}^{i=n} P_i \times W_{\mathrm{f}i}} \tag{83}$$

b) For the multiple-filter method

$$e_{\mathrm{PT}} = \frac{\sum_{i=1}^{i=n} q_{m\mathrm{PT}i} \times W_{\mathrm{f}i}}{\sum_{i=1}^{i=n} P_i \times W_{\mathrm{f}i}} \tag{84}$$

where

$$P_i = P_{\mathrm{m}i} + P_{\mathrm{aux}i} \tag{85}$$

Cf. Equation (39).

15.6 Effective weighting factor

For the single-filter method, the effective weighting factor, $W_{\mathrm{fe}i}$, for each mode shall be calculated in the following way.

$$W_{\mathrm{fe}i} = \frac{m_{\mathrm{sep}i} \times \overline{q_{m\mathrm{edf}}}}{m_{\mathrm{sep}} \times q_{m\mathrm{edf}i}} \tag{86}$$

$i = 1, \ldots n$

The value of the effective weighting factors shall be within ± 0,005 (absolute value) of the weighting factors listed in ISO 8178-4.

16 Determination of the gaseous emissions

16.1 General

16.2 to 16.6 and Figures 3 to 10 contain detailed descriptions of the recommended sampling and analysing systems. Since various configurations can produce equivalent results, exact conformance with these figures is not required. Additional components such as instruments, valves, solenoids, pumps, and switches may be used to provide additional information and coordinate the functions of the component systems. Other components which are not needed to maintain the accuracy on certain systems may be excluded if their exclusion is based upon good engineering judgement.

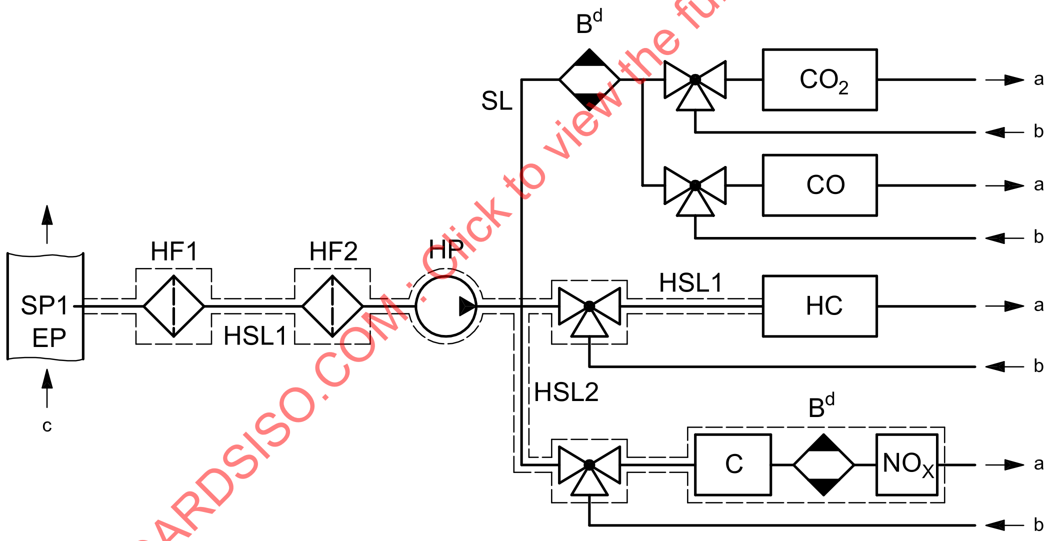
16.2 Main exhaust components CO, CO_2, HC, NO_x, O_2

An analytical system for the determination of the gaseous emissions in the raw or diluted exhaust gas is described, based on the use of

- HFID or FID for the measurement of hydrocarbons;
- NDIRs for the measurement of carbon monoxide and carbon dioxide;
- HCLD, CLD or equivalent for the measurement of nitrogen oxides;
- PMD, ECS or ZRDO for the measurement of oxygen.

For the raw exhaust gas (see Figure 3), the sample for all components may be taken with one sampling probe or with two sampling probes located in close proximity and internally split to the different analysers. Care must be taken that no condensation of exhaust components (including water and sulphuric acid) occurs at any point of the analytical system.

For the diluted exhaust gas (see Figure 4), the sample for the hydrocarbons shall be taken with a sampling probe other than that used with the sample for the other components, unless a common sample pump is used for all analysers and the sample line system design reflects good engineering practice. Care must be taken that no condensation of exhaust components (including water and sulphuric acid) occurs at any point of the analytical system.



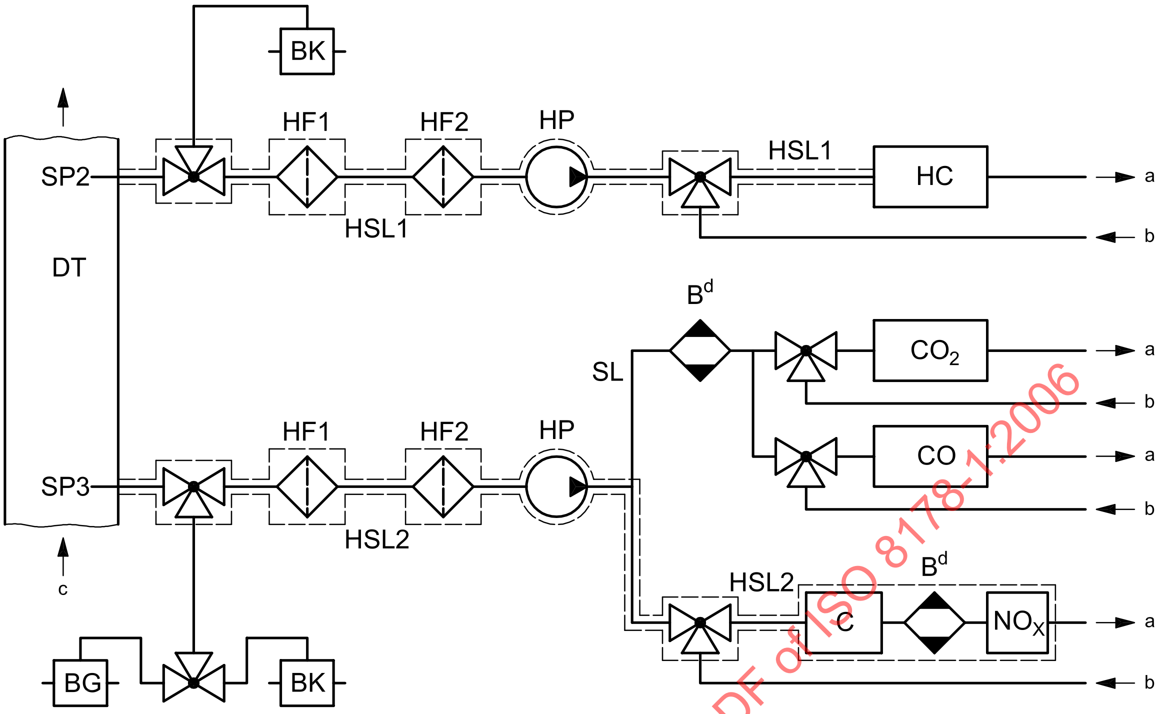
a Vent.

b Zero, span gas.

c Exhaust.

d Optional.

Figure 3 — Flow diagram of raw exhaust gas analysis system for CO, CO_2, NO_x, HC and O_2



a Vent.

b Zero, span gas.

c Diluted exhaust.

d Optional.

Figure 4 — Flow diagram of diluted exhaust gas analysis system for CO, CO_2, NO_x, HC and O_2

Components of Figures 3 and 4

General

All components in the sampling gas path shall be maintained at the temperatures specified for the respective systems.

EP — exhaust pipe (Figure 3 only)

DT — dilution tunnel (Figure 4 only)

For details, see 17.2.2.

SP1 — raw exhaust gas sampling probe (Figure 3 only)

A stainless steel, straight, closed-end, multi-hole probe is recommended. The inside diameter shall not be greater than the inside diameter of the sampling line. The wall thickness of the probe shall not be greater than 1 mm. There shall be a minimum of three holes in three different radial planes sized to sample approximately the same flow. The probe shall extend across at least 80 % of the diameter of the exhaust pipe.

NOTE If exhaust pulsations or engine vibrations are likely to change the sampling probe, the wall thickness of the probe may be enlarged with the agreement of the parties involved.

SP2 — dilute exhaust gas HC sampling probe (Figure 4 only)

The probe shall

- be defined as the first 254 mm to 762 mm of the heated sampling line HSL1;
- have a 5 mm minimum inside diameter;
- be installed in the dilution tunnel DT (see 17.2.2, Figure 19) at a point where the dilution air and exhaust gas are well mixed (i.e. approximately 10 tunnel diameters downstream of the point where the exhaust enters the dilution tunnel);
- be sufficiently distant (radially) from other probes and the tunnel wall so as to be free from the influence of any wakes or eddies;
- be heated so as to increase the gas stream temperature to 463 K ± 10 K (190 °C ± 10 °C) at the exit of the probe, or to 385 K ± 10 K (112 °C ± 10 °C) for methanol-fuelled engines;
- be non-heated in case of FID measurement (cold).

SP3 — dilute exhaust gas CO, CO_2, NO_x sampling probe (Figure 4 only)

The probe shall

- be in the same plane as SP2;
- be sufficiently distant (radially) from other probes and the tunnel wall so as to be free from the influence of any wakes or eddies;
- be heated and insulated over its entire length to a minimum temperature of 328 K (55 °C) to prevent water condensation.

HSL1 — heated sampling line

The sampling line provides a gas sample from a single probe to the split point(s) and the HC analyser.

The sampling line shall

- have a 5 mm minimum and a 13,5 mm maximum inside diameter;
- be made of stainless steel or PTFE.

a) For non-methanol-fuelled engines

If the temperature of the exhaust gas at the sampling probe is equal to or below 463 K (190 °C), maintain a wall temperature of 463 K ± 10 K (190 °C ± 10 °C) as measured at every separately controlled heated section.

If the temperature of the exhaust gas at the sampling probe is above 463 K (190 °C), maintain a wall temperature greater than 453 K (180 °C).

Immediately before the heated filter F2 and the HFID, maintain a gas temperature of 463 K ± 10 K (190 °C ± 10°C).

b) For methanol-fuelled engines

If the temperature of the exhaust gas at the sampling probe is equal to or below 385 K (112 °C), maintain a wall temperature of 385 K ± 10 K (112 °C ± 10 °C) as measured at every separately controlled heated section.

If the temperature of the exhaust gas at the sampling probe is above 385 K (112 °C), maintain a wall temperature greater than 375 K (102 °C).

Immediately before the heated filter F2 and the HFID, maintain a gas temperature of 385 K ± 10 K (112 °C ± 10 °C).

HSL2 — heated NO_x (and NH_3) sampling line

The sampling line shall

— maintain a wall temperature of 328 K to 473 K (55 °C to 200 °C), up to the converter C when using a cooling bath B, and up to the analyser when a cooling bath B is not used;

— be made of stainless steel or PTFE.

NOTE Since the sampling line need only be heated to prevent condensation of water and sulphuric acid, the sampling line temperature will depend on the sulphur content of the fuel.

SL — sampling line for CO, (CO_2, O_2)

The line shall be made of PTFE or stainless steel. It may be heated or unheated.

BK — background bag (optional; Figure 4 only)

For the measurement of the background concentrations.

BG — sample bag (optional; Figure 4, CO and CO_2 only)

For the measurement of the sample concentrations.

HF1 — heated pre-filter (optional)

The temperature shall be the same as HSL1 or HSL2.

HF2 — heated filter

The filter shall extract any solid particles from the gas sample before the analyser. The temperature shall be the same as HSL1 or HSL2. The filter shall be changed as needed.

HP — heated sampling pump

The pump shall be heated to the temperature of HSL1 or HSL2.

HC

Heated-flame ionization detector (HFID) for the determination of the hydrocarbons. The temperature shall be kept at 453 K to 473 K (180 °C to 200 °C) for non-methanol-fuelled engines, and at 375 K to 395 K (102 °C to 122 °C) for methanol-fuelled engines.

CO, CO_2

NDIRs for the determination of carbon monoxide and carbon dioxide.

NO

CLD or HCLD for the determination of the oxides of nitrogen. If an HCLD is used, it shall be kept at a temperature of 328 K to 473 K (55 °C to 200 °C).

C — converter

A converter shall be used for the catalytic reduction of NO_2 to NO prior to analysis in the CLD or HCLD.

O_2

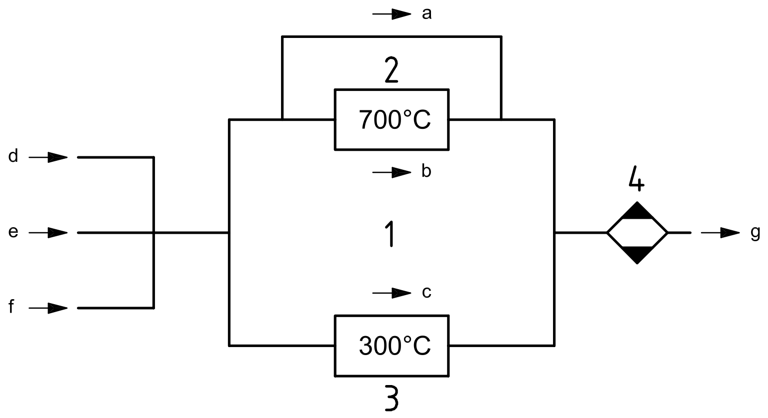
PMD, ZRDO or ECS for the determination of oxygen.

B — cooling bath

To cool and condense water from the exhaust sample. The bath shall be maintained at a temperature of 273 K to 277 K (0 °C to 4 °C) by ice or refrigerator. It is optional whether the analyser is free from water vapour interference as determined in 8.9.2 and 8.9.3. If water is removed by condensation, the sample gas temperature or dew point shall be monitored either within the water trap or downstream. The sample gas temperature or dew point shall not exceed 280 K (7 °C). Chemical driers are not allowed for removing water from the sample.

16.3 Ammonia analysis

In cases where ammonia (NH_3) is present in the exhaust gas (for instance from NH_3 sources in SCR – Selective Catalytic Reduction – equipment), the measurement system described in Figure 5 is recommended. The high-temperature converter C1 oxidizes NH_3 to NO and the measured value “C” is the sum of NH_3 and NO_x. The low-temperature converter C2 does not oxidize NH_3 but reduces NO_2 to NO. The measured value “A” is NO_x. The difference between C and A corresponds to the NH_3 value. The system can be integrated into the analytical system described in 16.2, Figures 3 and 4 by adding a second converter and associated piping. The calculation procedure is identical to the other exhaust components and is given in 14.5.



Key

1 HSL2
2 C1
3 C2
4 B (optional)

a	B (NO measurement).
b	C ($NO_x + NH_3$ measurement).
c	A (NO_x measurement).
d	Sample gas.
e	Zero.
f	Span gas.
g	To analyser.

NOTE $A - B$ = NO_2 content; $C - A$ = NH_3 content.

Figure 5 — Flow diagram of a converter system for NO_x/NH_3 measurement

Components of Figure 5

C1 — high-temperature converter

The temperature of C1 shall be kept at 953 K to 993 K (680 °C to 720 °C).

C2 — low-temperature converter

The temperature of C2 shall be kept at 553 K to 593 K (280 °C to 320 °C).

B — cooling bath (optional)

To cool and condense water from the exhaust sample. The bath shall be maintained at a temperature of 273 K to 277 K (0 °C to 4 °C) by ice or refrigeration. It is optional whether the analyser is free from water vapour interference as determined in 8.9.2 and 8.9.3. Chemical driers are not allowed for removing water from the sample.

16.4 Methane analysis

The methane (CH_4) analysis can be done in two ways.

16.4.1 Gas chromatographic (GC) method (Figure 6)

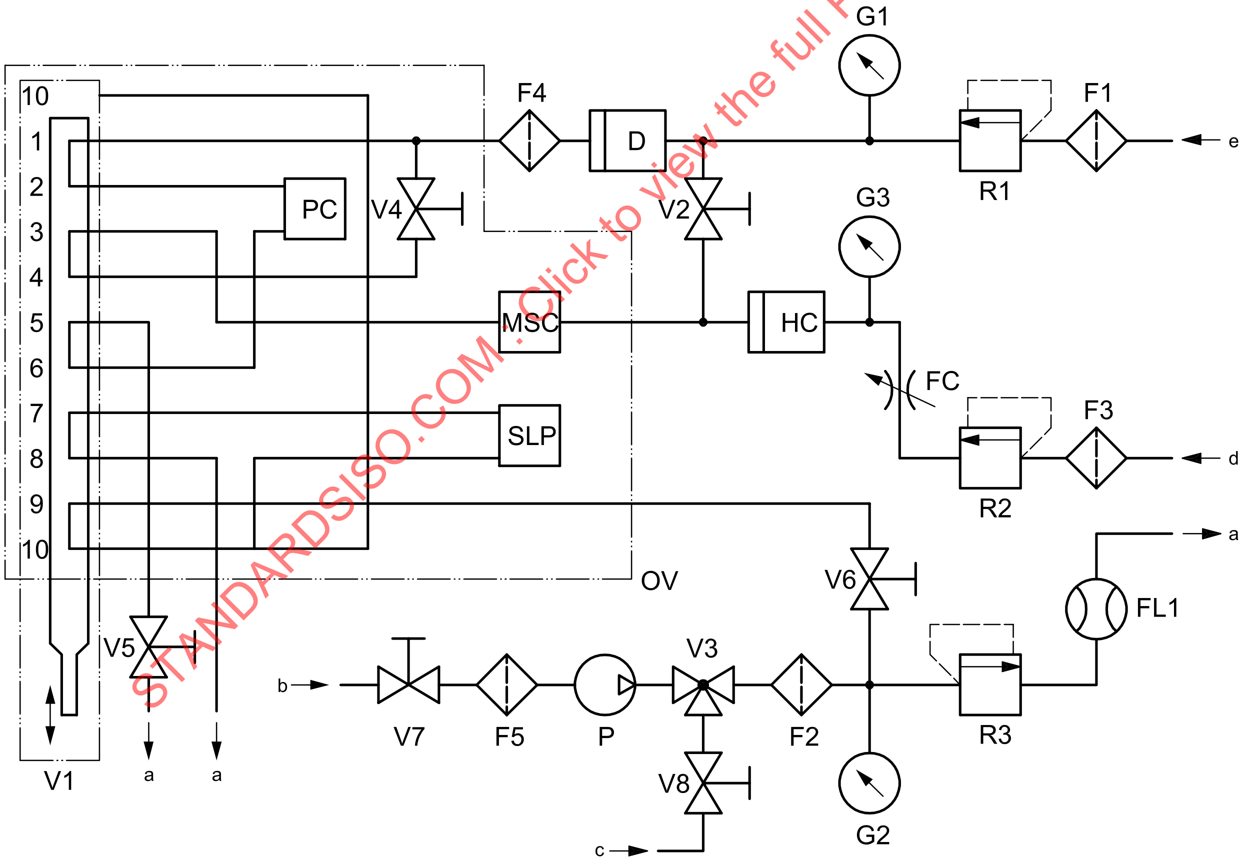
For details of this method see SAE J 1151.

When using the GC method, a small measured volume of a sample is injected into an analytical column through which it is swept by an inert carrier gas. The column separates various components according to their boiling points so that they elute from the column at different times. They then pass through a detector which gives an electrical signal that depends on their concentration. This is not a continuous analysis technique.

For CH_4 an automated GC with a FID shall be used. The exhaust gas is sampled into a sampling bag from which a part is taken and injected into the GC. The sample is separated into two parts (CH_4/air/CO and NMHC/CO_2/H_2O) on the Porapak column. The molecular sieve column separates CH_4 from the air and CO before passing it to the FID. A complete cycle from injection of one sample to injection of a second can be made in 30 s.

Figure 6 shows a typical GC assembled to routinely determine CH_4.

Other GC methods can also be used based on good engineering judgement.



a Vent.
b Sample.
c Span gas.
d Air inlet.
e Fuel inlet.

Figure 6 — Flow diagram for methane analysis (GC method)

Components of Figure 6

PC — Porapak column

Porapak N, 180/300 µm (50/80 mesh), 610 mm length × 2,16 mm ID shall be used and conditioned for at least 12 h at 423 K (150 °C) with carrier gas prior to initial use.

MSC — molecular sieve column

Type 13X, 250/350 µm (45/60 mesh), 1220 mm length × 2,16 mm ID shall be used and conditioned for at least 12 h at 423 K (150 °C) with carrier gas prior to initial use.

OV — oven

To maintain columns and valves at a stable temperature for analyser operation, and to condition the columns at 423 K (150 °C).

SLP — sample loop

A sufficient length of stainless steel tubing to obtain approximately 1 cm^3 volume.

P — pump

To bring the sample to the gas chromatograph.

D — drier

To remove water and other contaminants which might be present in the carrier gas; contains a molecular sieve.

HC — flame ionization detector (FID)

To measure the concentration of methane.

V1 — sample injection valve

To inject the sample. It shall be low dead volume, gas-tight, and heatable to 423 K (150 °C).

V3 — selector valve

To select span gas, sample or no flow.

V2, V4, V5, V6, V7, V8 — needle valves

To set the flows in the system.

R1, R2, R3 — pressure regulators

To control the flow rate of the fuel (i.e. carrier gas), the sample and the air, respectively.

FC — flow capillary

To control the rate of air flow to the FID.

G1, G2, G3 — pressure gauges

To monitor the flow of the fuel (i.e. carrier gas), the sample and the air, respectively.

F1, F2, F3, F4, F5 — filters

Sintered metal filters to prevent grit from entering the pump or the instrument.

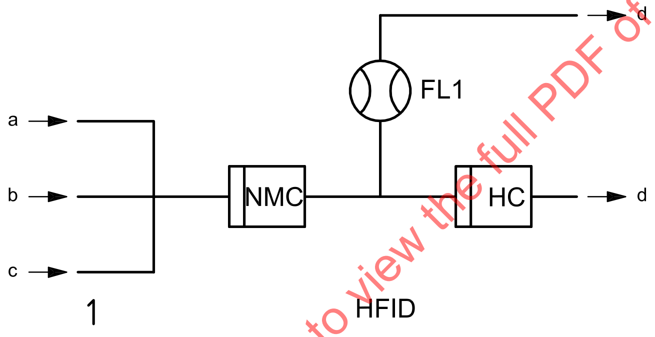
FL1 — flowmeter

To measure the sample bypass flow rate.

16.4.2 Non-methane cutter (NMC) method (Figure 7)

The cutter oxidizes all hydrocarbons except CH_4 to CO_2 and H_2O, so that by passing the sample through the NMC only CH_4 is detected by the HFID. The usual HC sampling train (see 16.2, Figures 3 and 4) shall be equipped with a flow diverter system with which the flow can be alternatively passed through or around the cutter. During non-methane testing, both values shall be observed on the FID and recorded.

The cutter shall be characterized at or above 600 K (327 °C) prior to test work with respect to its catalytic effect on CH_4 and CH_2H_6 at H_2O values representative of exhaust stream conditions. The dewpoint and O_2 level of the sampled exhaust stream shall be known. The non-methane fraction shall not be evaluated for previously collected (bagged) samples. The relative response of the FID to CH_4 shall be recorded.



Key

1 HSL1

[a] Zero.

[b] Span gas.

[c] Sample.

[d] Vent.

Figure 7 — Flow diagram for methane analysis (NMC method)

Components of Figure 7

NMC — non-methane cutter

To oxidize all hydrocarbons except methane.

HC

Heated flame ionization detector (HFID) to measure the HC and CH_4 concentrations. The temperature shall be kept at 453 K to 473 K (180 °C to 200 °C).

FL1 — flowmeter

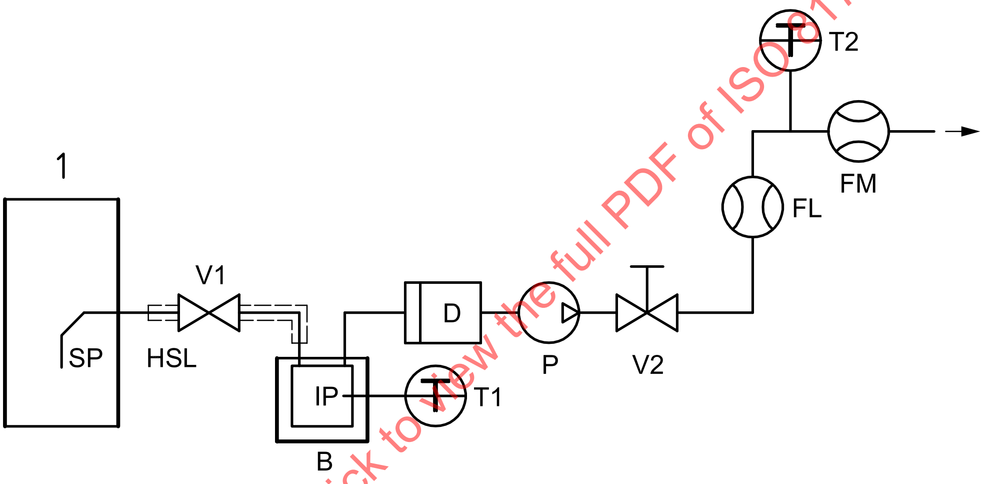
To measure the sample bypass flow rate.

16.5 Methanol analysis

Among the methanol analysis methods described in 7.5.3.12, this section describes the gas chromatographic (GC) method (see Figure 8).

The exhaust sample is passed through two ice-cooled impingers placed in series containing deionized water. Sampling time and flow rate shall be such that a recommended CH_3OH concentration of at least 1 mg/l be reached in the primary impinger. The CH_3OH concentration in the second impinger shall not be more than 10 % of the total amount collected. These requirements do not apply to background measurements.

A sample from the impingers is injected into the GC, preferably not later than 24 h after the test in accordance with established gas chromatographic procedures. If it is not possible to perform the analysis within 24 h, the sample should be stored in a dark cold environment of 277 K to 283 K (4 °C to 10 °C) until analysis. CH_3OH is separated from the other components and detected with an FID. The GC is calibrated with known amounts of CH_3OH standards.



Key

1 exhaust pipe or dilution tunnel

Figure 8 — Flow diagram for methanol analysis

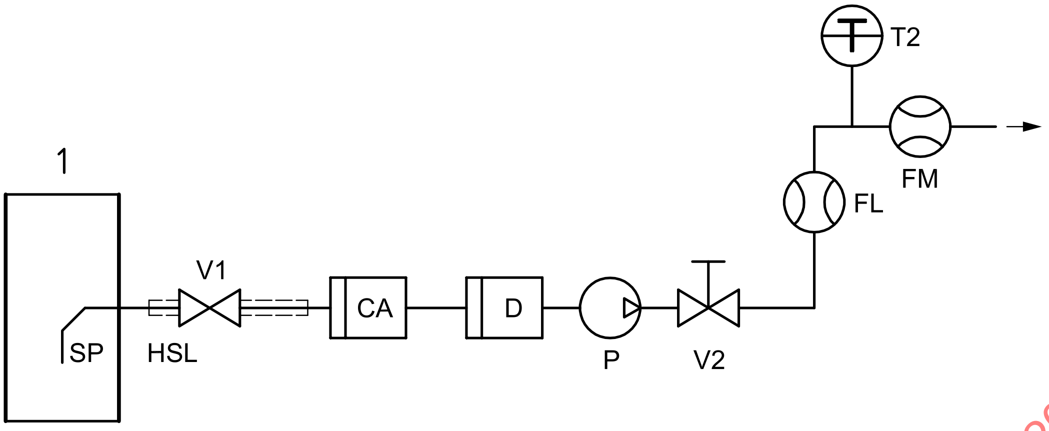
16.6 Formaldehyde analysis

See Figure 9.

In the HPLC (High Pressure Liquid Chromatograph), a small measured volume of the sample is injected into an analytical column through which it is swept by an inert liquid under pressure. Separation, elution and detection of the components follow the same general rules as with the GC. Like the GC, it is not a continuous analysis technique.

The exhaust sample is passed through two ice-cooled impingers placed in series containing an ACN solution of DNPH reagent or through a silica cartridge coated with 2,4-DNPH. An HCHO concentration in the collectors of at least 1 mg/l is recommended.

A sample from the collector is injected into the HPLC preferably not later than 24 h after the test. If it is not possible to perform the analysis within 24 h, the sample should be stored in a dark, cold environment of 277 K to 283 K (4 °C to 10 °C) until analysis. HCHO is separated from the other carbonyl components by gradient elution (Figure 9) and detected with a UV detector at 365 nm. The HPLC is calibrated with standards of CHO-DNPH derivatives.



Key

1 exhaust pipe or dilution tunnel

Figure 9 — Flow diagram for formaldehyde analysis

Components of Figures 8 and 9

SP — sampling probe

For the raw exhaust gas, a stainless steel, straight, closed-end, multi-hole probe is recommended. The inside diameter shall not be greater than the inside diameter of the sampling line. The wall thickness of the probe shall not be greater than 1 mm. There shall be a minimum of three holes in three different radial planes sized to sample approximately the same flow. The probe must extend across at least 80 % of the diameter of the exhaust pipe. The probe shall be fitted close to the HC/CO/NO_x/CO_2/O_2 sampling probe as defined in 7.5.4.

For the diluted exhaust gas, the probe shall be in the same plane of the dilution tunnel DT (see 17.2.2, Figure 19) as the HC, CO/NO_x/CO_2 and particulate sampling probes, but sufficiently distant from other probes and the tunnel wall to be free from the influence of any wakes or eddies.

HSL — heated sampling line

The temperature of the HSL shall be between the maximum dewpoint of the mixture and 394 K (121 °C). Heating of the HSL may be omitted, provided the sample collection system (IP) be close coupled to the SP, thereby preventing loss of sample due to cooling and resulting condensation in the HSL.

IP — impinger (optional for formaldehyde)

To collect the methanol or formaldehyde in the sample. The impingers should be cooled with ice or a refrigeration unit.

CA — cartridge collector (formaldehyde only; optional)

To collect the formaldehyde in the sample.

B — cooling bath

To cool the impingers.

D — drier (optional)

To remove water from the sample.

P — sampling pump

V1 — solenoid valve

To direct the sample to the collection system.

V2 — needle valve

To regulate the sample flow through the collection system.

T1 — temperature sensor

To monitor the temperature of the cooling bath.

T2 — temperature sensor (optional)

To monitor the temperature of the sample.

FL — flowmeter (optional)

To measure the sample flow rate through the collection system.

FM — flow measurement device

Gas meter or other flow instrumentation to measure the flow through the collection system during the sampling period.

17 Determination of the particulates

17.1 General

17.2 and 17.3 and Figures 10 to 21 contain detailed descriptions of the recommended dilution and sampling systems. Since various configurations can produce equivalent results, exact conformance with these figures is not required. Additional components such as instruments, valves, solenoids, pumps and switches may be used to provide additional information and coordinate the functions of the component systems. Other components, which are not needed to maintain the accuracy on certain systems, may be excluded if their exclusion is based upon good engineering judgment.

17.2 Dilution system

17.2.1 Partial-flow dilution system (Figures 10 to 18)

A dilution system is described based upon the dilution of a part of the exhaust stream. Splitting of the exhaust stream and the following dilution process may be done by different dilution system types. For subsequent collection of the particulates, the entire dilute exhaust gas or only a portion of the dilute exhaust gas is passed to the particulate sampling system (see 17.3, Figure 20). The first method is referred to as total-sampling type, the second method as fractional-sampling type.

The calculation of the dilution ratio depends upon the type of system used. The following types are recommended.

Isokinetic systems (Figures 10 and 11)

With these systems, the flow into the transfer tube is matched with the bulk exhaust flow in terms of gas velocity and/or pressure, thus requiring an undisturbed and uniform exhaust flow at the sampling probe. This is usually achieved by using a resonator and a straight approach tube upstream of the sampling point. The split ratio is then calculated from easily measurable values such as tube diameters. It should be noted that isokinesis is only used for matching the flow conditions and not for matching the size distribution. The latter is not typically necessary, as the particle dimension is small such that the particles follow the fluid streamlines.

Flow controlled systems with concentration measurement (Figures 12 to 16)

With these systems, a sample is taken from the bulk exhaust stream by adjusting the dilution air flow and the total dilute exhaust flow. The dilution ratio is determined from the concentrations of tracer gases, such as CO_2 or NO_x, naturally occurring in the engine exhaust. The concentrations in the dilute exhaust gas and in the dilution air are measured, whereas the concentration in the raw exhaust gas can be either measured directly or determined from fuel flow and the carbon balance equation, if the fuel composition is known. The systems may be controlled by the calculated dilution ratio (Figures 12 and 13) or by the flow into the transfer tube (Figures 14 to 16).

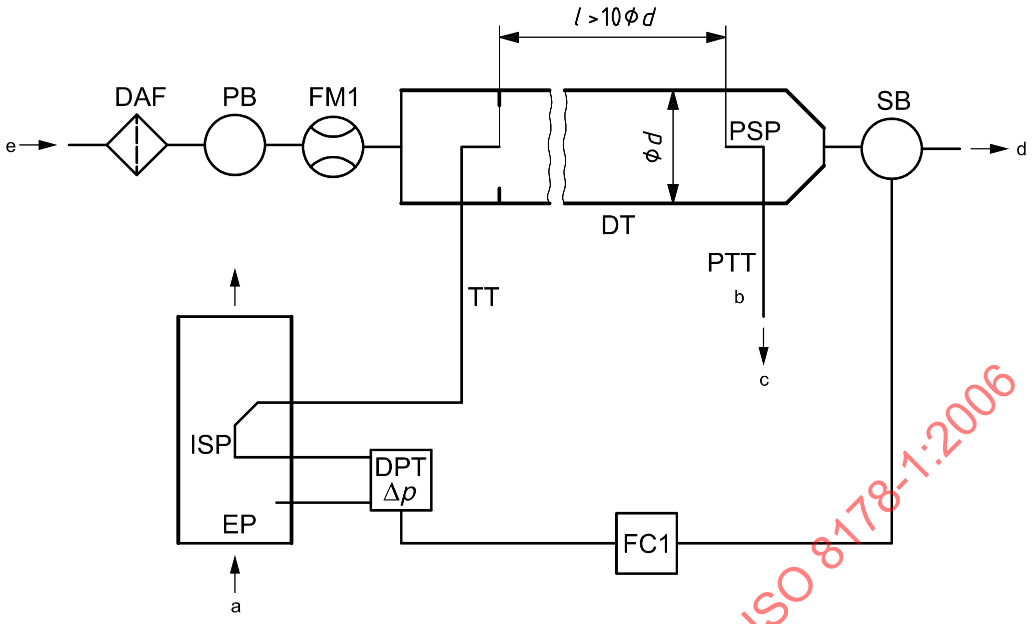
Flow controlled systems with flow measurement (Figures 17 and 18)

With these systems, a sample is taken from the bulk exhaust stream by setting the dilution air flow and the total dilute exhaust flow. The dilution ratio is determined from the difference of the two flow rates. Accurate calibration of the flowmeters relative to one another is required, since the relative magnitude of the two flow rates can lead to significant errors at higher dilution ratios (of 15 and above). Flow control is very straightforward and is maintained by keeping the dilute exhaust flow rate constant and varying the dilution air flow rate, if needed.

NOTE Partial-flow dilution systems are recommended not only because they are more cost-effective than full-flow dilution systems, but also because of the impossibility of realizing full-flow dilution for “medium and large” engine testing on the test bed and at site, and because of site constraints for other engines.

In order to realize the advantages of partial-flow dilution systems, attention must be paid to avoiding the potential problems of loss of particulates in the transfer tube, ensuring that a representative sample is taken from the engine exhaust and determination of the split ratio.

The systems described take into account these critical areas.



a Exhaust.

b See Figure 20.

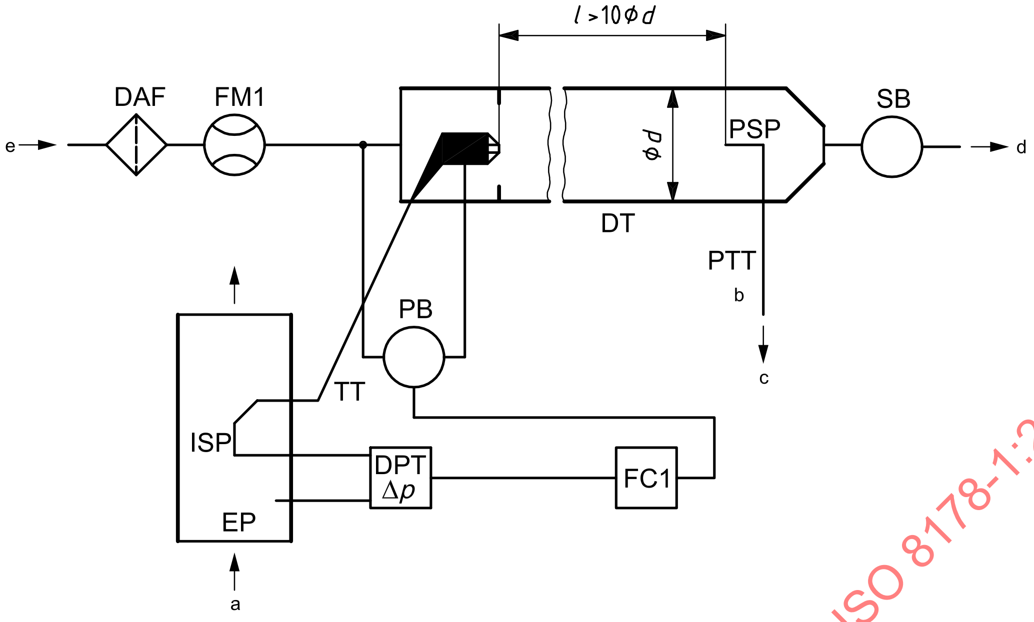
c To particulate sampling system.

d Vent.

e Dilution air.

Raw exhaust gas is transferred from the exhaust pipe EP to the dilution tunnel DT through the isokinetic sampling probe ISP and the transfer tube TT. The differential pressure of the exhaust gas between exhaust pipe and inlet to the probe is measured with the pressure transducer DPT. This signal is transmitted to the flow controller FC1 that controls the suction blower SB to maintain a differential pressure of zero at the tip of the probe. Under these conditions, exhaust gas velocities in EP and ISP are identical, and the flow through ISP and TT is a constant fraction (split) of the exhaust gas flow. The split ratio is determined from the cross-sectional areas of EP and ISP. The dilution air flow rate is measured with the flow measurement device FM1. The dilution ratio is calculated from the dilution air flow rate and the split ratio.

Figure 10 — Partial-flow dilution system with isokinetic probe and fractional sampling (SB control)



a Exhaust.

b See Figure 20.

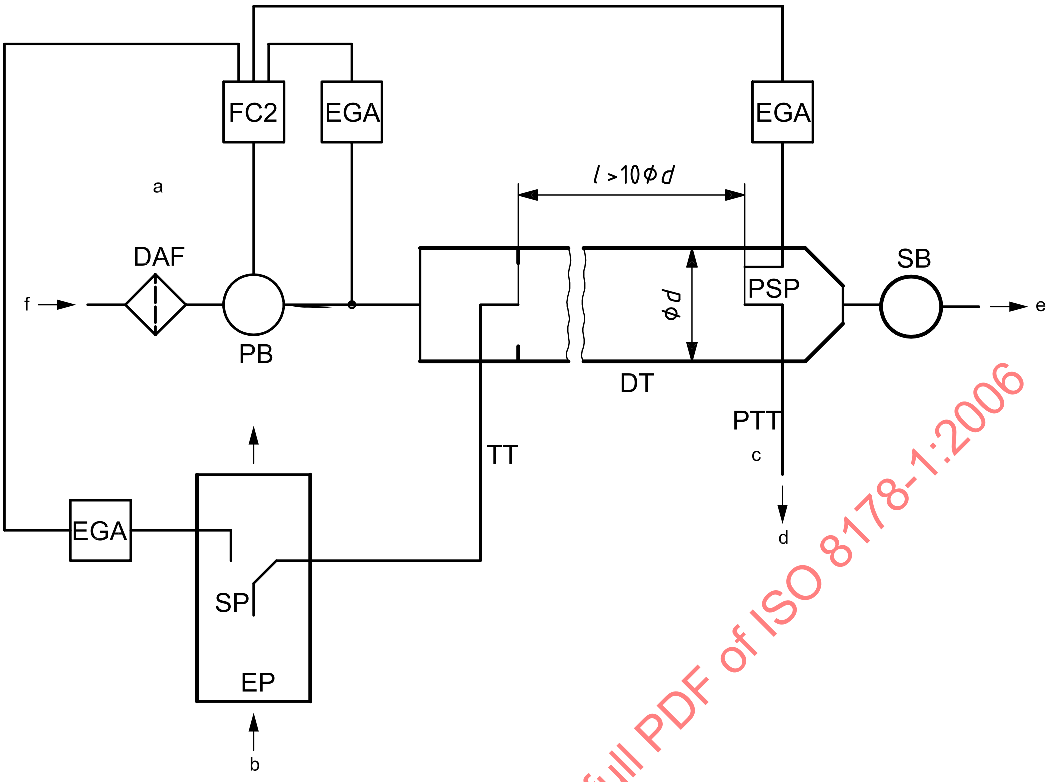
c To particulate sampling system.

d Vent.

e Dilution air.

Raw exhaust gas is transferred from the exhaust pipe EP to the dilution tunnel DT through the isokinetic sampling probe ISP and the transfer tube TT. The differential pressure of the exhaust gas between exhaust pipe and inlet to the probe is measured with the pressure transducer DPT. This signal is transmitted to the flow controller FC1 that controls the pressure blower SB to maintain a differential pressure of zero at the tip of the probe. This is done by taking a small fraction of the dilution air whose flow rate has already been measured with the flow measurement device FM1, and feeding it to TT by means of a pneumatic orifice. Under these conditions, exhaust gas velocities in EP and ISP are identical, and the flow through ISP and TT is a constant fraction (split) of the exhaust gas flow. The split ratio is determined from the cross-sectional areas of EP and ISP. The dilution air is sucked through DT by the suction blower SB, and the flow rate is measured with FM1 at the inlet to DT. The dilution ratio is calculated from the dilution air flow rate and the split ratio.

Figure 11 — Partial-flow dilution system with isokinetic probe and fractional sampling (PB control)



a Optional to PB or SB.

b Exhaust.

c See Figure 20.

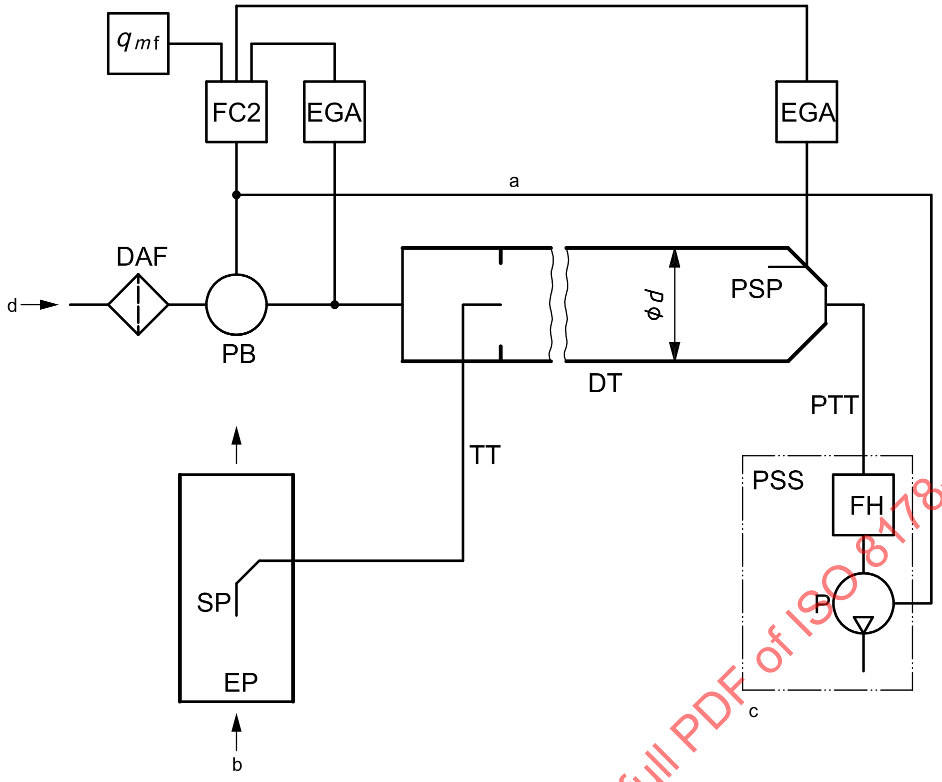
d To particulate sampling system.

e Vent.

f Dilution air.

Raw exhaust gas is transferred from the exhaust pipe EP to the dilution tunnel DT through the sampling probe SP and the transfer tube TT. The concentrations of a tracer gas (CO_2 or NO_x) are measured in the raw and diluted exhaust gases as well as in the dilution air using the exhaust gas analyser(s) EGA. These signals are transmitted to the flow controller FC2 that controls either the pressure blower PB or the suction blower SB to maintain the desired exhaust split and dilution ratio in DT. The dilution ratio is calculated from the tracer gas concentrations in the raw exhaust gas, the diluted exhaust gas and the dilution air.

Figure 12 — Partial-flow dilution system with CO_2 or NO_x concentration measurement and fractional sampling



[a] Optional to P.

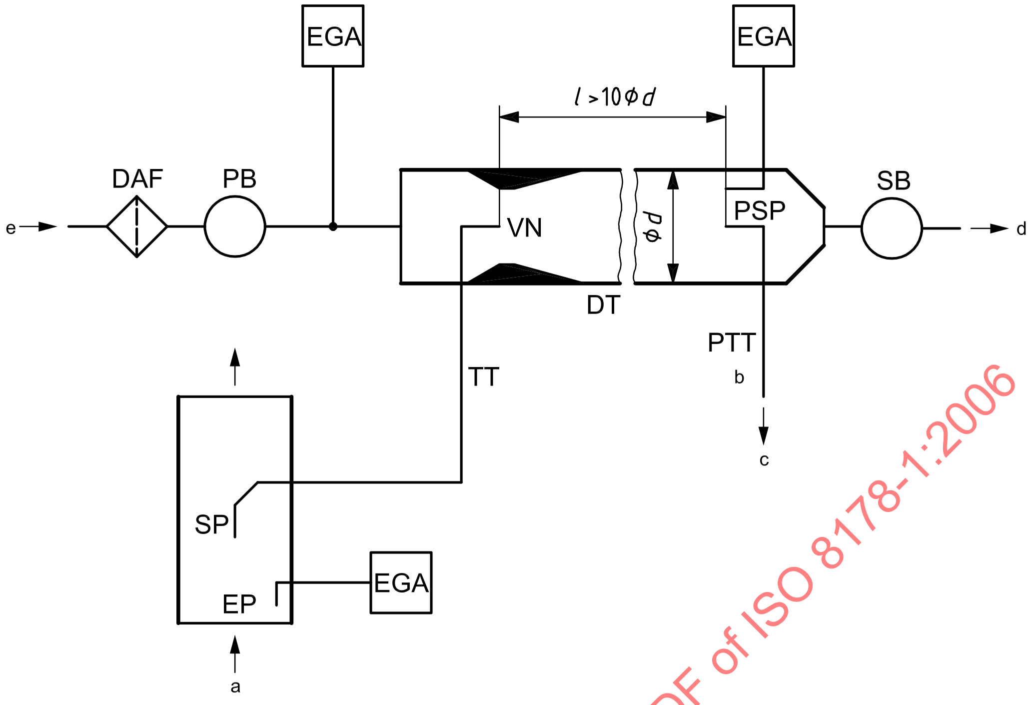
[b] Exhaust.

[c] See Figure 20.

[d] Dilution air.

Raw exhaust gas is transferred from the exhaust pipe EP to the dilution tunnel DT through the sampling probe SP and the transfer tube TT. The CO_2 concentrations are measured in the diluted exhaust gas and in the dilution air using the exhaust gas analyser(s) EGA. The CO_2 and fuel flow q_{mf} signals are transmitted either to the flow controller FC2 or to the flow controller FC3 of the particulate sampling system (see Figure 20). FC2 controls the pressure blower PB, FC3 the sampling pump P (see Figure 20), thereby adjusting the flows into and out of the system so as to maintain the desired exhaust split and dilution ratio in DT. The dilution ratio is calculated from the CO_2 concentrations and q_{mf}, using the carbon balance assumption.

Figure 13 — Partial-flow dilution system with CO_2 concentration measurement, carbon balance and total sampling



a Exhaust.

b See Figure 20.

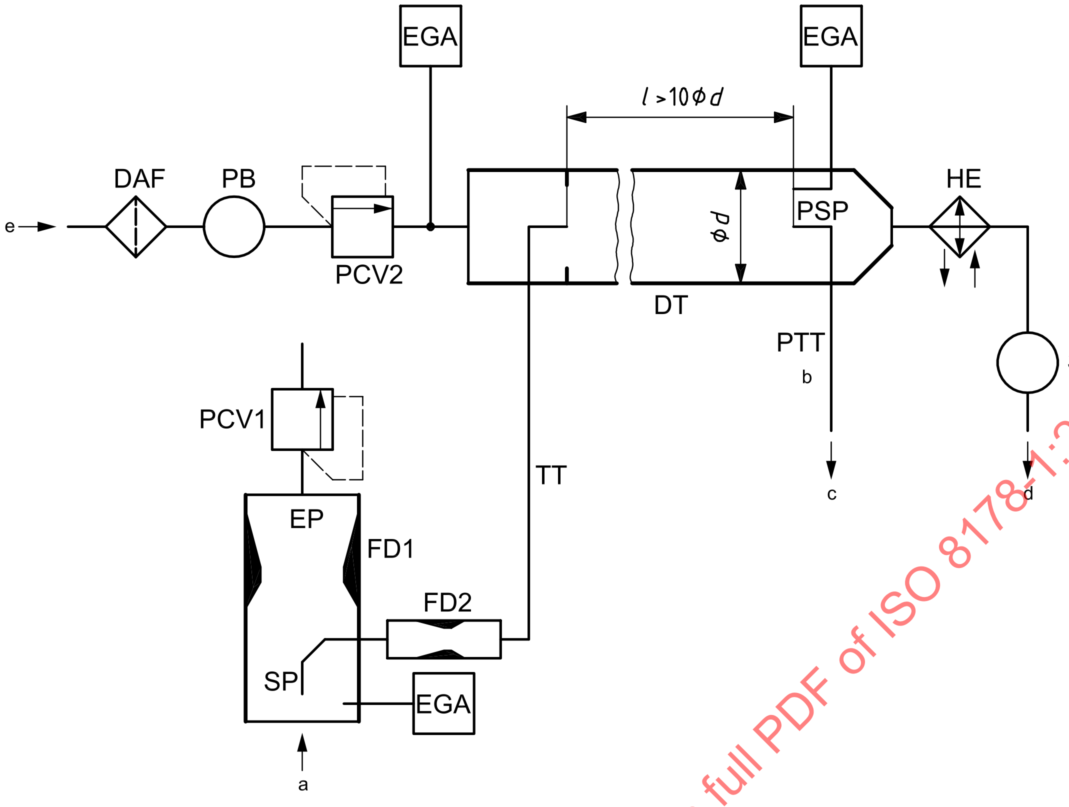
c To particulate sampling system.

d Vent.

e Dilution air.

Raw exhaust gas is transferred from the exhaust pipe EP to the dilution tunnel DT through the sampling probe SP and the transfer tube TT due to the negative pressure created by the venturi VN in DT. The gas flow rate through TT depends on the momentum exchange at the venturi zone and is therefore affected by the absolute temperature of the gas at the exit of TT. Consequently, the exhaust split for a given tunnel flow rate is not constant, and the dilution ratio at low load is slightly lower than at high load. The tracer gas concentrations (CO_2 or NO_x) are msasured in the raw exhaust gas, the diluted exhaust gas and the dilution air using the exhaust gas analyser(s) EGA, and the dilution ratio is calculated from the measured values.

Figure 14 — Partial-flow dilution system with single venturi, concentration measurement and fractional sampling



[a] Exhaust.

[b] See Figure 20.

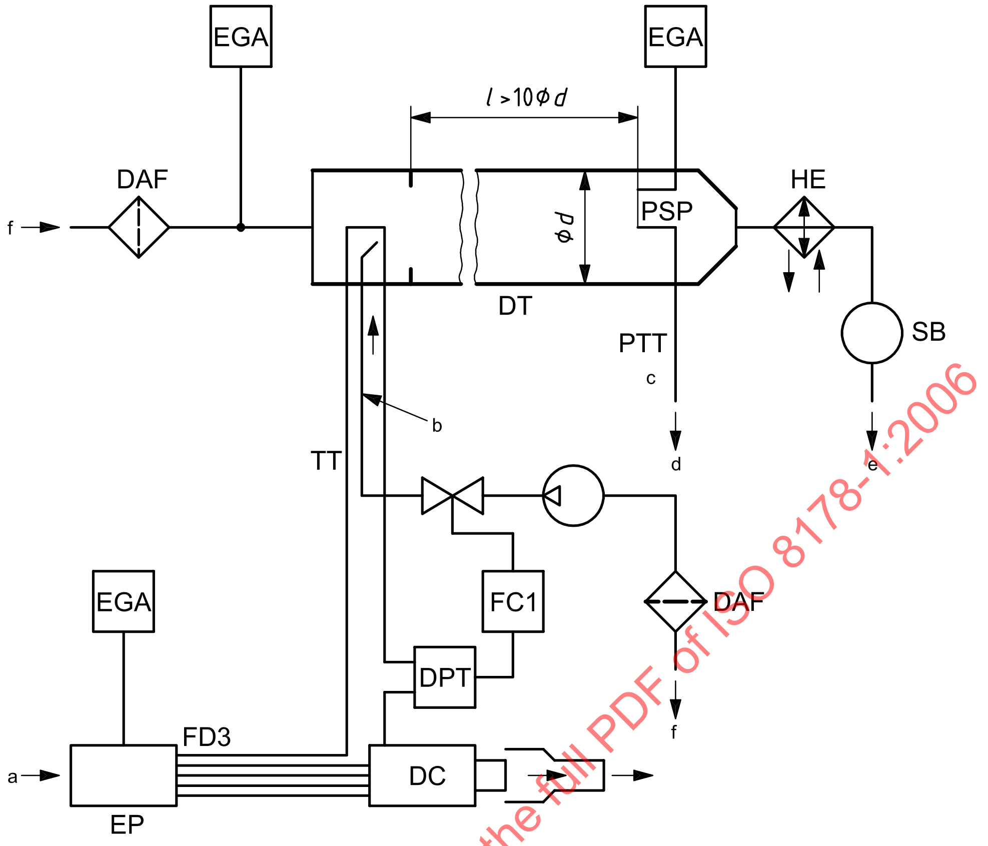
[c] To particulate sampling system.

[d] Vent.

[e] Dilution air.

Raw exhaust gas is transferred from the exhaust pipe EP to the dilution tunnel DT through the sampling probe and the transfer tube TT and a flow divider that contains a set of orifices or venturis. The first one (FD1) is located in EP, the second one (FD2) in TT. Additionally, two pressure control valves (PCV1 and PCV2) are necessary to maintain a constant exhaust split by controlling the backpressure in EP and the pressure in DT. PCV1 is located downstream of SP in EP, PCV2 between the pressure blower PB and DT. The tracer gas concentrations (CO_2 or NO_x) are measured in the raw exhaust gas, the diluted exhaust gas and the dilution air with the exhaust gas analyser(s) EGA. They are necessary for checking the exhaust split, and may be used to adjust PCV1 and PCV2 for precise split control. The dilution ratio is calculated from the tracer gas concentrations.

Figure 15 — Partial-flow dilution with twin venturi or twin orifice, concentration measurement and fractional sampling



a Exhaust.

b Fresh air injection.

c See Figure 20.

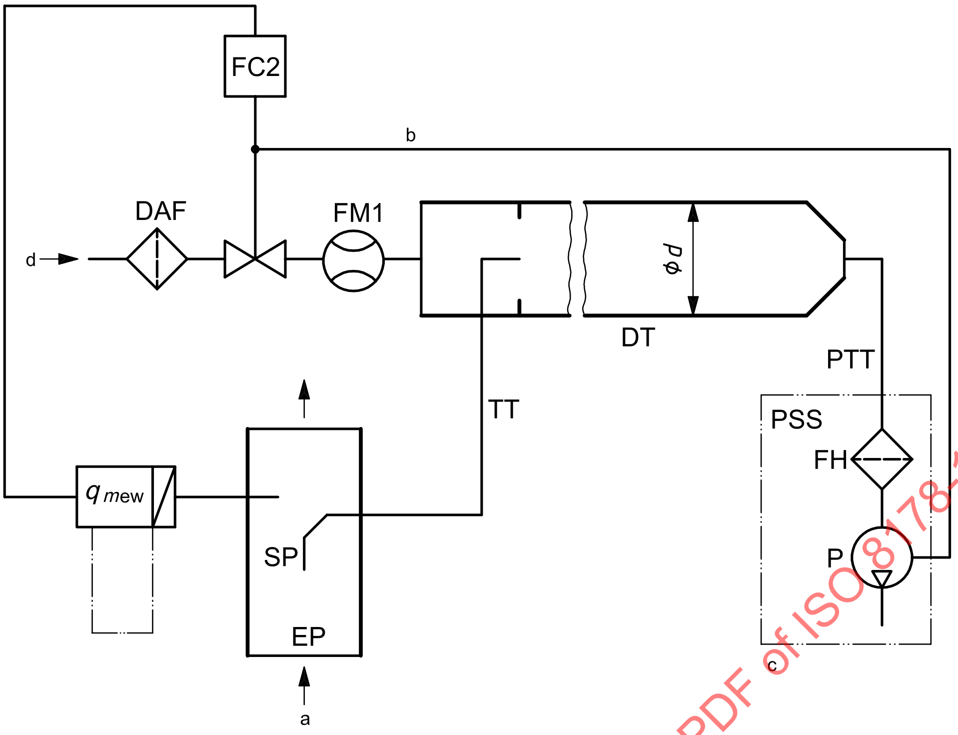
d To particulate sampling system.

e Vent.

f Dilution air.

Raw exhaust gas is transferred from the exhaust pipe EP to the dilution tunnel DT through the transfer tube TT by the flow divider FD3 that consists of a number of tubes of equal dimensions (same diameter, length and bend radius) installed in EP. The exhaust gas through one of these tubes is led to DT, and the exhaust gas through the rest of the tubes is passed through the damping chamber DC. Thus, the exhaust split is determined by the total number of tubes. A constant split control requires a differential pressure of zero between DC and the outlet of TT, which is measured with the differential pressure transducer DPT. A differential pressure of zero is achieved by injecting fresh air into DT at the outlet of TT. The tracer gas concentrations (CO_2 or NO_X) are measured in the raw exhaust gas, the diluted exhaust gas and the dilution air with the exhaust gas analyser(s) EGA. They are necessary for checking the exhaust split and may be used to control the injection air flow rate for precise split control. The dilution ratio is calculated from the tracer gas concentrations.

Figure 16 — Partial-flow dilution system with multiple-tube splitting, concentration measurement and fractional sampling



a Exhaust.

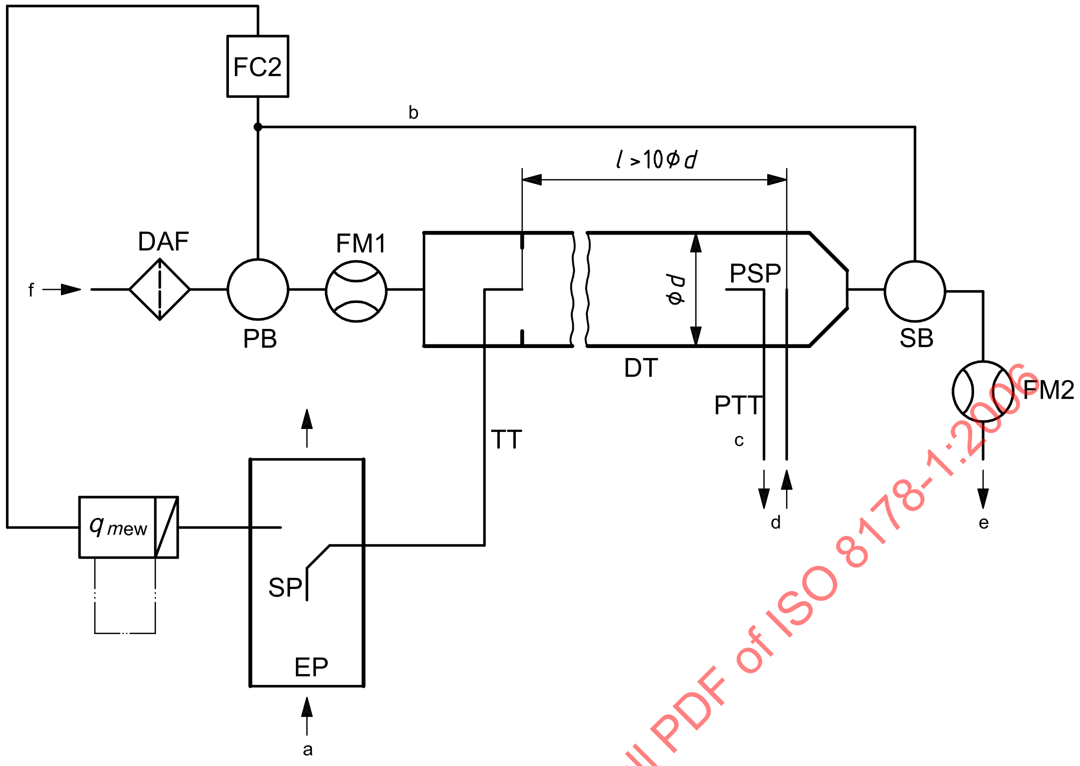
b Optional to P (PSS).

c See Figure 20.

d Dilution air.

Raw exhaust gas is transferred from the exhaust pipe EP to the dilution tunnel DT through the sampling probe SP and the transfer tube TT. The total flow through the tunnel is adjusted with the flow controller FC3 and the sampling pump P of the particulate sampling system (see Figure 20). The dilution air flow is controlled by the flow controller FC2, which may use q_{mew} or q_{maw} and q_{mf} as command signals, for the desired exhaust split. The sample flow into DT is the difference between the total flow and the dilution air flow. The dilution air flow rate is measured with the flow measurement device FM1 and the total flow rate with the flow measurement device FM3 of the particulate sampling system (see Figure 20). The dilution ratio is calculated from these two flow rates.

Figure 17 — Partial-flow dilution system with flow control and total sampling



a Exhaust.

b To PB or SB.

c See Figure 20.

d To particulate sampling system.

e Vent.

f Dilution air.

Raw exhaust gas is transferred from the exhaust pipe EP to the dilution tunnel DT through the sampling probe SP and the transfer tube TT. The exhaust split and the flow into DT is controlled by the flow controller FC2 that adjusts the flow (or speed) of the pressure blower PB and the suction blower SB, accordingly. This is possible since the sample taken with the particulate sampling system is returned into DT. q_{mew} or q_{maw} and q_{mf} may be used as command signals for FC2. The dilution air flow rate is measured with the flow measurement device FM1 and the total flow rate with the flow measurement device FM2. The dilution ratio is calculated from these two flow rates.

Figure 18 — Partial-flow dilution system with flow control and fractional sampling

Components of Figures 10 to 18

EP — exhaust pipe

The exhaust pipe may be insulated. To reduce the thermal inertia of the exhaust pipe, a thickness-to-diameter ratio of 0,015 or less is recommended. The use of flexible sections shall be limited to a length-to-diameter ratio of 12 or less. Bends shall be minimized to reduce inertial deposition. If the system includes a test bed silencer, the silencer may also be insulated.

For an isokinetic system, the exhaust pipe shall be free of elbows, bends and sudden diameter changes for at least six pipe diameters upstream and three pipe diameters downstream of the tip of the probe. The gas velocity at the sampling zone shall be higher than 10 m/s except at idle mode. Pressure oscillations of the exhaust gas shall not exceed ± 500 Pa on the average. Any steps to reduce pressure oscillations beyond using a chassis-type exhaust system (including silencer and post-treatment devices) shall not alter engine performance or cause the deposition of particulates.

For systems without isokinetic probe, it is recommended to have a straight pipe of six pipe diameters upstream and three pipe diameters downstream of the tip of the probe.

SP — sampling probe (Figures 12 to 18)

The minimum inside diameter shall be 4 mm. The minimum diameter ratio between exhaust pipe and probe shall be four. The probe shall be an open tube facing upstream on the exhaust pipe centreline, or a multiple-hole probe as described under SP1 in 16.2, Figure 3.

ISP — isokinetic sampling probe (Figures 10 and 11)

The isokinetic sampling probe shall be installed facing upstream on the exhaust pipe centreline where the flow conditions in section EP are met, and designed to provide a proportional sample of the raw exhaust gas. The minimum inside diameter shall be 12 mm.

A control system is necessary for isokinetic exhaust splitting by maintaining a differential pressure of zero between EP and ISP. Under these conditions, exhaust gas velocities in EP and ISP are identical and the mass flow through ISP is a constant fraction of the exhaust gas flow. ISP shall be connected to a differential pressure transducer DPT. The control to provide a differential pressure of zero between EP and ISP is done with the flow controller FC1.

FD1, FD2 — flow dividers (Figure 15)

A set of venturis or orifices is installed in the exhaust pipe EP and in the transfer tube TT, respectively, to provide a proportional sample of the raw exhaust gas. A control system consisting of two pressure control valves PCV1 and PCV2 is necessary for proportional splitting by controlling the pressures in EP and DT.

FD3 — flow divider (Figure 16)

A set of tubes (multiple-tube unit) is installed in the exhaust pipe EP to provide a proportional sample of the raw exhaust gas. One of the tubes feeds exhaust gas to the dilution tunnel DT, whereas the other tubes exit exhaust gas to a damping chamber DC. The tubes shall have equal dimensions (same diameter, length, bend radius) so that the exhaust split depends on the total number of tubes. A control system is necessary for proportional splitting by maintaining a differential pressure of zero between the exit of the multiple-tube unit into DC and the exit of TT. Under these conditions, exhaust gas velocities in EP and FD3 are proportional and the flow TT is a constant fraction of the exhaust gas flow. The two points shall be connected to a differential pressure transducer DPT. The control to provide a differential pressure of zero is done with the flow controller FC1.

EGA — exhaust gas analysers (Figures 12 to 16)

CO_2 or NO_x analysers may be used (with carbon balance method, CO_2 only). The analysers shall be calibrated like the analysers for the measurement of the gaseous emissions. One or several analysers may be used to determine the concentration differences.

The accuracy of the measuring systems shall be such that the accuracy of $q_{m\text{edf}i}$ is within ± 4 %.

TT — transfer tube (Figures 10 to 18)

The transfer tube shall be

- as short as possible, but not more than 5 m in length;
- equal to or greater than the probe diameter, but not more than 25 mm in diameter;
- exiting on the centreline of the tunnel and pointing downstream.

If the tube is 1 m or less in length, it shall be insulated with material with a maximum thermal conductivity of 0,05 W/(m·K) with a radial insulation thickness corresponding to the diameter of the probe. If the tube is longer than 1 m, it shall be insulated and heated to a minimum wall temperature of 523 K (250 °C).

Alternatively the transfer tube wall temperatures required may be determined through standard heat-transfer calculations as shown in Annex C.

DPT — differential pressure transducer (Figures 10, 11 and 16)

The differential pressure transducer shall have a range of ± 500 Pa or less.

FC1 — flow controller (Figures 10, 11 and 16)

For isokinetic systems (Figures 10 and 11), a flow controller is necessary to maintain a differential pressure of zero between EP and ISP. The adjustment can be done by

a) controlling the speed or flow of the suction blower SB and keeping the speed or flow of the pressure blower PB constant during each mode (Figure 10), or

b) adjusting the suction blower SB to a constant mass flow of the diluted exhaust gas and controlling the flow of the pressure blower PB, and therefore the exhaust sample flow in a region at the end of the transfer tube TT (Figure 11).

In the case of a pressure controlled system, the remaining error in the control loop shall not exceed ± 3 Pa. The pressure oscillations in the dilution tunnel shall not exceed ± 250 Pa on the average.

For a multi-tube system (Figure 16), a flow controller is necessary for proportional exhaust splitting to maintain a differential pressure of zero between the exit of the multi-tube unit and the exit of TT. The adjustment is done by controlling the injection air flow rate into DT at the exit of TT.

PCV1, PCV2 — pressure control valves (Figure 15)

Two pressure control valves are necessary for the twin-venturi/twin-orifice system for proportional flow splitting by controlling the backpressure of EP and the pressure in DT. The valves shall be located downstream of SP in EP and between PB and DT.

DC — damping chamber (Figure 16)

A damping chamber shall be installed at the exit of the multiple-tube unit to minimize the pressure oscillations in the exhaust pipe EP.

VN — venturi (Figure 14)

A venturi is installed in the dilution tunnel DT to create a negative pressure in the region of the exit of the transfer tube TT. The gas flow rate through TT is determined by the momentum exchange at the venturi zone and is basically proportional to the flow rate of the pressure blower PB leading to a constant dilution ratio. Since the momentum exchange is affected by the temperature at the exit of TT and the pressure difference between EP and DT, the actual dilution ratio is slightly lower at low load than at high load.

FC2 — flow controller (Figures 12, 13, 17 and 18; optional)

A flow controller may be used to control the flow of the pressure blower PB and/or the suction blower SB. It may be connected to the exhaust, intake air or fuel flow signals and/or to the CO_2 or NO_x differential signals.

When using a pressurized air supply (Figure 17), FC2 directly controls the air flow.

FM1 — flow measurement device (Figures 10, 11, 17 and 18)

Gas meter or other flow instrumentation to measure the dilution air flow. FM1 is optional if the pressure blower PB is calibrated to measure the flow.

FM2 — flow measurement device (Figure 18)

Gas meter or other flow instrumentation to measure the diluted exhaust gas flow. FM2 is optional if the suction blower SB is calibrated to measure the flow.

PB — pressure blower (Figures 10 to 15 and 18)

To control the dilution air flow rate. PB may be connected to the flow controllers FC1 or FC2. PB is not required when using a butterfly valve. PB may be used to measure the dilution air flow, if calibrated.

SB — suction blower (Figures 10 to 12, 15, 16 and 18)

For fractional sampling systems only. SB may be used to measure the diluted exhaust gas flow, if calibrated.

DAF — dilution air filter (Figures 10 to 18)

It is recommended that the dilution air be filtered and charcoal-scrubbed to eliminate background hydrocarbons. The dilution air shall have a temperature greater than 288 K (15 °C), and may be dehumidified. At the engine manufacturer’s request the dilution air may be sampled according to good engineering practice to determine the background particulate levels, which can then be subtracted from the values measured in the diluted exhaust (see 12.4).

DT — dilution tunnel (Figures 10 to 18)

The dilution tunnel

- shall be of a sufficient length to cause complete mixing of the exhaust and dilution air under turbulent flow conditions;
- shall be constructed of stainless steel;
- shall be at least 75 mm in diameter for the fractional-sampling type;
- should be at least 25 mm in diameter for the total-sampling type;
- may be heated to no greater than 325 K (52 °C) wall temperature by direct heating or by dilution air pre-heating, provided the air temperature does not exceed 325 K (52 °C) prior to the introduction of the exhaust in the dilution tunnel;
- may be insulated.

The engine exhaust shall be thoroughly mixed with the dilution air. For fractional-sampling systems, the mixing quality shall be checked after introduction into service by means of a CO_2 profile of the tunnel with the engine running (at least four equally spaced measuring points). If necessary, a mixing orifice may be used.

NOTE If the ambient temperature in the vicinity of the dilution tunnel (DT) is below 293 K (20 °C), precautions should be taken to avoid particle losses on to the cool walls of the dilution tunnel. Therefore, heating and/or insulating the tunnel within the limits given above is recommended.

At high engine loads, the tunnel may be cooled by a non-aggressive means such as a circulation fan, as long as the temperature of the cooling medium is not below 293 K (20 °C).

HE — heat exchanger (Figures 15 and 16)

The heat exchanger shall be of sufficient capacity to maintain the temperature at the inlet to the suction blower SB within ± 11 K of the average operating temperature observed during the test.

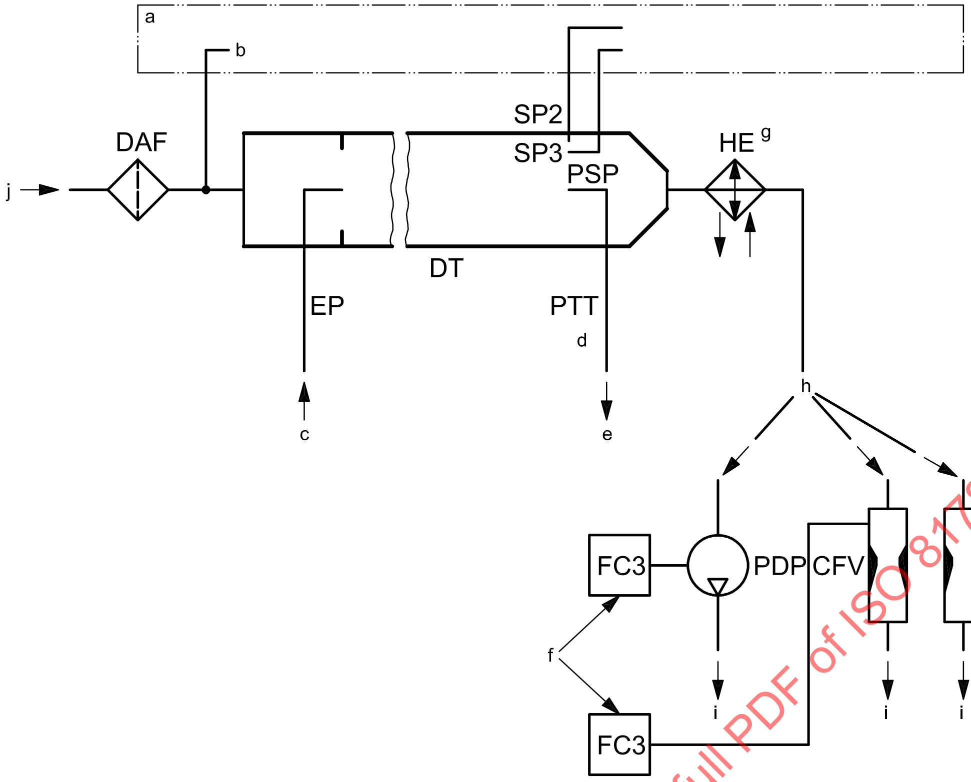
17.2.2 Full-flow dilution system

See Figure 19.

A dilution system is described based upon the dilution of the total exhaust using the CVS (constant volume sampling) concept. The total volume of the mixture of exhaust and dilution air shall be measured. Either a PDP or a CFV system may be used.

For subsequent collection of the particulates, a sample of the dilute exhaust gas is passed to the particulate sampling system (see 17.3, Figures 20 and 21). If this is done directly, it is referred to as single dilution. If the sample is diluted once more in the secondary dilution tunnel, it is referred to as double dilution. This is useful if the filter face temperature requirement cannot be met with single dilution. Although partly a dilution system, the double-dilution system is described as a modification of a particulate sampling system in 17.3, Figure 21, since it shares most of the parts with a typical particulate sampling system.

The gaseous emissions may also be determined in the dilution tunnel of a full-flow dilution system. Therefore, the sampling probes for the gaseous components are shown in Figure 19 but do not appear in the description list. The respective requirements are given in 16.2 for the main exhaust components, 16.5 for methanol, and 16.6 for formaldehyde.



a Analyser system, see Figure 4.
b Background.
c Exhaust.
d See Figure 20.
e To particulate sampling system, see Figure 20, or to DDS, see Figure 21.
f If EFC is used.
g Optional.
h Or.
i Vent.
j Dilution air.

The total amount of raw exhaust gas is mixed in the dilution tunnel DT with the dilution air. The diluted exhaust gas flow rate is measured either with a positive displacement pump PDP or with a critical-flow venturi CFV. A heat exchanger HE or electronic flow compensation EFC may be used for proportional particulate sampling and for flow determination. Since particulate mass determination is based on the total diluted exhaust gas flow, it is not necessary to calculate the dilution ratio.

Figure 19 — Full-flow dilution system

Components of Figure 19

EP — exhaust pipe

The exhaust pipe length from the exit of the engine exhaust manifold, turbocharger outlet or after-treatment device to the dilution tunnel shall be not more than 10 m. If the system exceeds 4 m in length, then all tubing in excess of 4 m shall be insulated, except for an in-line smokemeter, if used. The radial thickness of the insulation shall be at least 25 mm. The thermal conductivity of the insulating material shall have a value no greater than 0,1 W/(m·K) measured at 673 K. To reduce the thermal inertia of the exhaust pipe, a thickness-to-diameter ratio of 0,015 or less is recommended. The use of flexible sections shall be limited to a length-to-diameter ratio of 12 or less.

PDP — positive displacement pump

The PDP meters total diluted exhaust flow from the number of pump revolutions and the pump displacement. The exhaust system backpressure shall not be artificially lowered by the PDP or dilution air inlet system. Static exhaust backpressure measured with the PDP system operating shall remain within ± 1,5 kPa of the static pressure measured without connection to the PDP at identical engine speed and load. The gas mixture temperature immediately ahead of the PDP shall be within ± 6 K of the average operating temperature observed during the test, when no flow compensation is used. Flow compensation can only be used if the temperature at the inlet to the PDP does not exceed 323 K (50 °C).

CFV — critical flow venturi

CFV measures total diluted exhaust flow by maintaining the flow at choked conditions (critical flow). Static exhaust backpressure measured with the CFV system operating shall remain within ± 1,5 kPa of the static pressure measured without connection to the CFV at identical engine speed and load. The gas mixture temperature immediately ahead of the CFV shall be within ± 11 K of the average operating temperature observed during the test, when no flow compensation is used.

SSV — subsonic venturi

SSV measures total diluted exhaust flow by using the gas flow of a subsonic venturi as a function of inlet pressure and temperature and pressure drop between venturi inlet and throat. Static exhaust backpressure measured with the SSV system operating shall remain within ± 1,5 kPa of the static pressure measured without connection to the SSV at identical engine speed and load. The gas mixture temperature immediately ahead of the SSV shall be within ± 11 K of the average operating temperature observed during the test, when no flow compensation is used.

HE — heat exchanger (optional, if EFC is used)

The heat exchanger shall be of sufficient capacity to maintain the temperature within the limits required above.

EFC — electronic flow compensation (optional, if HE is used)

If the temperature at the inlet to either the PDP or CFV is not kept within the limits stated above, a flow compensation system is required for continuous measurement of the flow rate and control of the proportional sampling in the particulate system. For that purpose, the continuously measured flow rate signals are used accordingly to correct the sample flow rate through the particulate filters of the particulate sampling system (see Figures 20 and 21).

DT — dilution tunnel

The dilution tunnel

- shall be small enough in diameter to cause turbulent flow (Reynolds Number greater than 4000) and of sufficient length to cause complete mixing of the exhaust and dilution air – a mixing orifice may be used;
- shall be at least 75 mm in diameter;
- may be insulated.

The engine exhaust shall be directed downstream at the point where it is introduced into the dilution tunnel, and thoroughly mixed.

When using single dilution, a sample from the dilution tunnel is transferred to the particulate sampling system (see 17.3, Figure 20). The flow capacity of the PDP or CFV shall be sufficient to maintain the diluted exhaust at a temperature between 315 K (42 °C) and 325 K (52 °C) immediately before the particulate filter.

When using double dilution, a sample from the dilution tunnel is transferred to the secondary dilution tunnel where it is further diluted, and then passed through the sampling filters (17.3, Figure 21). The flow capacity of the PDP or CFV shall be sufficient to maintain the diluted exhaust stream in the DT at a temperature of less than or equal to 464 K (191 °C) at the sampling zone. The secondary dilution system shall provide sufficient secondary dilution air to maintain the doubly diluted exhaust stream at a temperature between 315 K (42 °C) and 325 K (52 °C) immediately before the particulate filter.

DAF — dilution air filter

It is recommended that the dilution air be filtered and charcoal-scrubbed to eliminate background hydrocarbons. The dilution air shall have a temperature of greater than 288 K (15 °C), and may be dehumidified. At the engine manufacturer's request, the dilution air may be sampled according to good engineering practice to determine the background particulate levels, which can then be subtracted from the values measured in the diluted exhaust (see 12.4).

PSP — particulate sampling probe

The probe is the leading section of PTT and

— shall be installed facing upstream at a point where the dilution air and exhaust gases are well mixed, i.e. on the dilution tunnel DT centreline of the dilution systems (see 17.2), approximately 10 tunnel diameters downstream of the point where the exhaust enters the dilution tunnel;

— shall be of 12 mm minimum inside diameter;

— may be heated to no greater than 325 K (52 °C) wall temperature by direct heating or by dilution air pre-heating, provided the air temperature does not exceed 325 K (52 °C) prior to the introduction of the exhaust in the dilution tunnel;

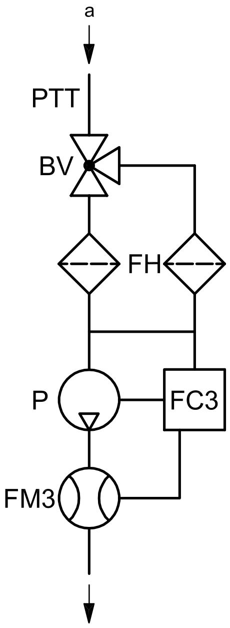
— may be insulated.

17.3 Particulate sampling system

See Figures 20 and 21.

The particulate sampling system is required for collecting the particulates on the particulate filter. In the case of total sampling partial-flow dilution, which consists of passing the entire diluted exhaust sample through the filters, the dilution (see 17.2.1, Figures 13 and 17) and sampling systems usually form an integral unit. In the case of fractional sampling partial-flow dilution or full-flow dilution, which consists of passing through the filters only a portion of the diluted exhaust, the dilution (see 17.2.1, Figures 10 to 12, 14 to 16 and 18 and 17.2.2, Figure 19) and sampling systems usually form different units. In this part of ISO 8178, the double-dilution system (Figure 21) of a full-flow dilution system is considered to be a specific modification of a typical particulate sampling system as shown in Figure 20. The double-dilution system includes all important parts of the particulate sampling system, like filter holders and sampling pump, and additionally some dilution features, like a dilution air supply and a secondary dilution tunnel.

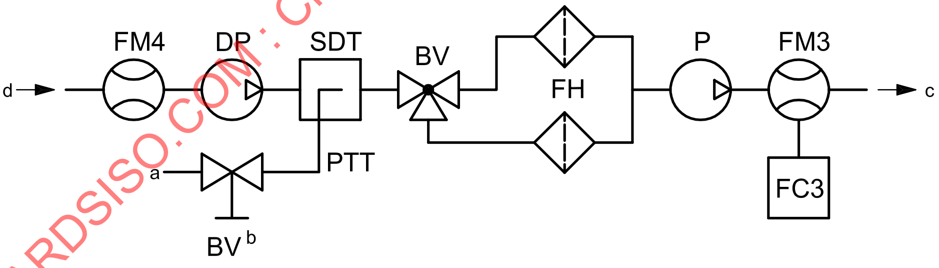
In order to avoid any impact on the control loops, it is recommended that the sample pump be running throughout the complete test procedure. For the single-filter method, a bypass system shall be used for passing the sample through the sampling filters at the desired times. Interference of the switching procedure on the control loops shall be minimized.



[a] From dilution tunnel DT (see Figures 10–16, 18 and 19).

A sample of the diluted exhaust gas is taken from the dilution tunnel DT of a partial-flow or full-flow dilution system through the particulate sampling probe PSP and the particulate transfer tube PTT by means of the sampling pump P. The sample is passed through the filter holder(s) FH that contain the particulate sampling filters. The sample flow rate is controlled by the flow controller FC3. If electronic flow compensation EFC (see Figure 19) is used, the diluted exhaust gas flow is used as command signal for FC3.

Figure 20 — Particulate sampling system



[a] From dilution tunnel DT (see Figure 19).

[b] Optional.

[c] Vent.

[d] Dilution air.

A sample of the diluted exhaust gas is transferred from the dilution tunnel DT of a full-flow dilution system through the particulate sampling probe PSP and the particulate transfer tube PTT to the secondary dilution tunnel SDT, where it is diluted once more. The sample is then passed through the filter holder(s) FH that contain the particulate sampling filters. The dilution air flow rate is usually constant whereas the sample flow rate is controlled by the flow controller FC3. If electronic flow compensation EFC (see Figure 19) is used, the total diluted exhaust gas flow is used as command signal for FC3.

Figure 21 — Secondary dilution and particulate sampling system (full-flow system only)

Components of Figures 20 and 21

PSP — particulate sampling probe

The particulate sampling probe, not shown in the figures, is the leading section of the particulate transfer tube PTT.

The probe

- shall be installed facing upstream at a point where the dilution air and exhaust gas are well mixed (see 17.2), approximately 10 tunnel diameters downstream of the point where the exhaust enters the dilution tunnel;
- shall be of 12 mm minimum inside diameter;
- may be heated to no greater than 325 K (52 °C) wall temperature by direct heating or by dilution air pre-heating, provided the air temperature does not exceed 325 K (52 °C) prior to the introduction of the exhaust into the dilution tunnel;
- may be insulated.

PTT — particulate transfer tube

The particulate transfer tube shall not exceed 1020 mm in length, and shall be minimized in length whenever possible.

The dimensions are valid for

- the partial-flow dilution fractional-sampling type and the full-flow single dilution system, from the probe tip to the filter holder;
- the partial-flow dilution total-sampling type, from the end of the dilution tunnel to the filter holder;
- the full-flow double-dilution system, from the probe tip to the secondary dilution tunnel.

The transfer tube

- may be heated to no greater than 325 K (52 °C) wall temperature by direct heating or by dilution air pre-heating, provided the air temperature does not exceed 325 K (52 °C) prior to the introduction of the exhaust into the dilution tunnel;
- may be insulated.

SDT — secondary dilution tunnel (Figure 21 only)

The secondary dilution tunnel should have a minimum diameter of 75 mm, and should be of sufficient length so as to provide a residence time of at least 0,25 s for the doubly diluted sample. The primary filter holder FH shall be located within 300 mm of the exit of the SDT.

The secondary dilution tunnel

- may be heated to no greater than 325 K (52 °C) wall temperature by direct heating or by dilution air pre-heating, provided the air temperature does not exceed 325 K (52 °C) prior to the introduction of the exhaust into the dilution tunnel;
- may be insulated.

FH — filter holder(s)

The requirements of 7.6.2.3 shall be met. The filter holder(s)

- may be heated to no greater than 325 K (52 °C) wall temperature by direct heating or by dilution air pre-heating, provided the air temperature does not exceed 325 K (52 °C) prior to the introduction of the exhaust into the dilution tunnel;
- may be insulated;

For primary and back-up filters, if used, a single filter housing or separate filter housings may be used.

P — sampling pump

The particulate sampling pump shall be located sufficiently distant from the tunnel so that the inlet gas temperature is maintained constant (± 3 K), if flow correction by FC3 is not used.

DP — dilution air pump (Figure 21 only)

The dilution air pump shall be located so that the secondary dilution air is supplied at a temperature of 298 K ± 5 K (25 °C ± 5 °C).

FC3 — flow controller

A flow controller shall be used to compensate the particulate sample flow rate for temperature and backpressure variations in the sample path, if no other means are available. The flow controller is required if electronic flow compensation EFC (see Figure 19) is used.

FM3 — flow measurement device

The gas meter or flow instrumentation for the particulate sample flow shall be located sufficiently distant from the sampling pump P so that the inlet gas temperature remains constant (± 3 K), if flow correction by FC3 is not used.

FM4 — flow measurement device (Figure 21 only)

The gas meter or flow instrumentation for the dilution air flow shall be located so that the inlet gas temperature is maintained constant (± 3 K).

BV — ball valve (optional)

The ball valve shall have an inside diameter not less than the inside diameter of the particulate transfer tube PTT, and a switching time of less than 0,5 s.

NOTE If the ambient temperature in the vicinity of PSP, PTT, SDT and FH is below 293 K (20 °C), precautions should be taken to avoid particle losses on to the cool wall of these parts. Therefore, heating and/or insulating these parts within the limits given in the respective descriptions is recommended.

At high engine loads, the above parts may be cooled by a non-agressive means such as a circulating fan, as long as the temperature of the cooling medium is not below 288 K (15 °C).

Annex A
(normative)

Calculation of the exhaust gas mass flow and/or of the combustion air mass flow

NOTE Equations in Annex A are not converted to SI symbols.

A.1 General

The equations given in Annex A are for stoichiometric calculations and for the calculation of the exhaust gas mass flow from the exhaust composition and the fuel composition.

All dimensions relating to volumes are defined for standard conditions: 0 °C, 101,32 kPa.

In Annex A the same symbols are used as in the main part.

The concentration units used are % volume for the components CO_2, O_2, H_2O and N_2 and ppm for all others.

Symbols and abbreviations (in addition to those given in Clause 4) used in Annex A are given in Table A.1.

Table A.1 — Symbols and abbreviations

Symbols	Term	Unit
q_v	Volume flow	m^3/h
$q_{v\mathrm{ew}}$	Volume flow of wet exhaust	m^3/h
$q_{v\mathrm{aw}}$	Volume flow of wet intake air	m^3/h
$q_{v\mathrm{ed}}$	Volume flow of dry exhaust	m^3/h
$q_{v\mathrm{ad}}$	Volume flow of dry intake air	m^3/h
$q_{m\mathrm{gas}}$	Emission of mass flow rate of individual gas	g/h
w_{ox}	Oxygen content of dry intake air	% mass
w_{inert}	Inert gas content of dry intake air	% mass

A.2 Stoichiometric calculations for the burning of fuel; fuel specific factors

A.2.1 Basic data for stoichiometric calculations

As far as possible, the basic data atomic mass, molar mass and molar volume are used in the formulae of this Annex. Concrete numbers for these data were mostly used only in final formulae. This has the advantage, that the derivation of the formulae can be understood more easily. Also, the fact that these data can be slightly different, depending on the data handbook used, can be best accommodated by general and not concrete formulations. The concrete numbers that were used for basic data are given in Table A.2.

Table A.2 — Atomic masses, molar masses and molar volumes

Description	Symbol	Value	Unit
Atomic mass of hydrogen	A_{rH}	1,007 94	g/atom
Atomic mass of carbon	A_{rC}	12,011	g/atom
Atomic mass of sulphur	A_{rS}	32,065	g/atom
Atomic mass of nitrogen	A_{rN}	14,006 7	g/atom
Atomic mass of oxygen	A_{rO}	15,999 4	g/atom
Molar mass of water	M_{rH2O}	18,015 34	g/mol
Molar mass of carbon dioxide	M_{rCO2}	44,01	g/mol
Molar mass of carbon monoxide	M_{rCO}	28,011	g/mol
Molar mass of oxygen	M_{rO2}	31,998 8	g/mol
Molar mass of nitrogen	M_{rN2}	28,011	g/mol
Molar mass of nitric oxide	M_{rNO}	30,008	g/mol
Molar mass of nitrogen dioxide	M_{rNO2}	46,01	g/mol
Molar mass of sulphur dioxide	M_{rSO2}	64,066	g/mol
Molar volume of water	V_{mH2O}	22,401	l/mol
Molar volume of carbon dioxide	V_{mCO2}	22,262	l/mol
Molar volume of carbon monoxide	V_{mCO}	22,408	l/mol
Molar volume of oxygen	V_{mO2}	22,392	l/mol
Molar volume of nitrogen	V_{mN2}	22,390	l/mol
Molar volume of nitric oxide	V_{mNO}	22,391	l/mol
Molar volume of nitrogen dioxide	V_{mNO2}	21,809	l/mol
Molar volume of sulphur dioxide	V_{mSO2}	21,891	l/mol

Assuming no compressibility effects, all of the gases involved in the engine intake/combustion/exhaust process can be considered to be ideal and the volumetric calculations given hereafter are based on that assumption. Hence according to Avogadro's Hypothesis, they each occupy 22,414 l/mol (see Table A.3).

NOTE 1 The molar volume of gases is a function of interactions of the molecules at collisions. The collisions of ideal gas molecules are only physical impacts, while real gas molecules interact additionally by Van-der-Waals forces at the moment of the collision. This effect reduces the molar volume of real gases. In mixtures also collisions between more ideal gases and more real gases occur; these collisions have a more ideal character. In the case of exhaust emissions the almost perfect ideal gas nitrogen has by far the highest concentration and therefore only very few collisions between real gas molecules occur.

Table A.3 — Molar volumes used in this part of ISO 8178

Description	Symbol	Value	Unit
Molar volume of water	V_{mH2O}	22,414	l/mol
Molar volume of carbon dioxide	V_{mCO2}	22,414	l/mol
Molar volume of carbon monoxide	V_{mCO}	22,414	l/mol
Molar volume of oxygen	V_{mO2}	22,414	l/mol
Molar volume of nitrogen	V_{mN2}	22,414	l/mol
Molar volume of nitric oxide	V_{mNO}	22,414	l/mol
Molar volume of nitrogen dioxide	V_{mNO2}	22,414	l/mol
Molar volume of sulphur dioxide	V_{mSO2}	22,414	l/mol

For the stoichiometry of combustion, the following composition of the dry intake air is assumed:

a) concentration of inert gases

w_{inert} = 76,8 % mass, 79,0 % volume

NOTE 2 Included in the inert gases is CO_2 with 0,061 % mass, 0,04 % volume.

b) concentration of oxygen

w_{ox} = 23,2 % mass, 21,0 % volume.

A.2.2 General formulae

A.2.2.1 Formulae related to the components

Calculation of mass concentration c_{mgas} [mg/m^3] from volumetric concentration c_{vgas} [ppm] of component:

$$c_{\mathrm{mgas}} = c_{\mathrm{vgas}} \times \rho_{\mathrm{gas}} \qquad \text{(A.1)}$$

where

ρ_{gas} is the gas density of the component [kg/m^3].

The gas density ρ_{gas} [kg/m^3] can be calculated from the basic data molecular mass M_{rgas} [g/mol] and molar volume V_{mgas} [l/mol]:

$$\rho_{\mathrm{gas}} = \frac{M_{\mathrm{rgas}}}{V_{\mathrm{mgas}}} \qquad \text{(A.2)}$$

A.2.2.2 Formulae related to the fuel

The chemical formula of the fuel can be written as $C_\beta H_\alpha S_\gamma N_\delta O_\varepsilon$.The fuel composition data α, β, γ, δ, ε are defined as the molar ratios of H, C, S, N and O related to C (chemical formula of the fuel $CH_\alpha S_\gamma N_\delta O_\varepsilon$, related to one carbon atom per molecule). The relation to one carbon atom per molecule is used because the real carbon atom number per average fuel molecule is not known with real fuels. This relationship does not work with non-carbon fuels. The fuel composition data w_{ALF}, w_{BET}, w_{GAM}, w_{DEL} and w_{EPS} are defined as the

% mass of H, C, S, N and O. The following formulae give the conversion between the two sets of data (when $\beta = 1$):

$$\alpha = \frac{\frac{w_{\mathrm{ALF}}}{A_{\mathrm{rH}}}}{\frac{w_{\mathrm{BET}}}{A_{\mathrm{rC}}}} = 11{,}9164 \times \frac{w_{\mathrm{ALF}}}{w_{\mathrm{BET}}} \tag{A.3}$$

$$\beta = \frac{\frac{w_{\mathrm{BET}}}{A_{\mathrm{rC}}}}{\frac{w_{\mathrm{BET}}}{A_{\mathrm{rC}}}} = 1 \tag{A.4}$$

$$\gamma = \frac{\frac{w_{\mathrm{GAM}}}{A_{\mathrm{rS}}}}{\frac{w_{\mathrm{BET}}}{A_{\mathrm{rC}}}} = 0{,}37464 \times \frac{w_{\mathrm{GAM}}}{w_{\mathrm{BET}}} \tag{A.5}$$

$$\delta = \frac{\frac{w_{\mathrm{DEL}}}{A_{\mathrm{rN}}}}{\frac{w_{\mathrm{BET}}}{A_{\mathrm{rC}}}} = 0{,}85752 \times \frac{w_{\mathrm{DEL}}}{w_{\mathrm{BET}}} \tag{A.6}$$

$$\varepsilon = \frac{\frac{w_{\mathrm{EPS}}}{A_{\mathrm{rO}}}}{\frac{w_{\mathrm{BET}}}{A_{\mathrm{rC}}}} = 0{,}75072 \times \frac{w_{\mathrm{EPS}}}{w_{\mathrm{BET}}} \tag{A.7}$$

$$w_{\mathrm{ALF}} = \frac{\alpha \times A_{\mathrm{rH}} \times 100}{M_{\mathrm{rf}}} \tag{A.8}$$

$$w_{\mathrm{BET}} = \frac{\beta \times A_{\mathrm{rC}} \times 100}{M_{\mathrm{rf}}} \tag{A.9}$$

$$w_{\mathrm{GAM}} = \frac{\gamma \times A_{\mathrm{rS}} \times 100}{M_{\mathrm{rf}}} \tag{A.10}$$

$$w_{\mathrm{DEL}} = \frac{\delta \times A_{\mathrm{rN}} \times 100}{M_{\mathrm{rf}}} \tag{A.11}$$

$$w_{\mathrm{EPS}} = \frac{\varepsilon \times A_{\mathrm{rO}} \times 100}{M_{\mathrm{rf}}} \tag{A.12}$$

where

M_{rf} is the molecular weight of an average fuel molecule $C_{\beta}H_{\alpha}S_{\gamma}N_{\delta}O_{\varepsilon}$:

$$M_{\mathrm{rf}} = \alpha \times A_{\mathrm{rH}} + \beta \times A_{\mathrm{rC}} + \gamma \times A_{\mathrm{rS}} + \delta \times A_{\mathrm{rN}} + \varepsilon \times A_{\mathrm{rO}} \tag{A.13}$$

A.2.2.3 Formulae related to saturation vapour pressure

Calculation of the saturation vapour pressure p_a [hPa] as a function of the temperature t [°C] according to the Federal Register:

$$\begin{aligned} p_a = {} & \exp\,(-12{,}150799 \times \ln(t) - 8499{,}22 \times t^{-2} - 7423{,}1865 \times t^{-1} + 96{,}1635147 + 0{,}024917646 \times t \\ & - 1{,}3160119 \times 10^{-5}\, t^2 - 1{,}1460454 \times 10^{-8} \times t^3 + 2{,}1701289 \times 10^{-11} \times t^4 - 3{,}610258 \times 10^{-15} \times t^5 \\ & + 3{,}8504519 \times 10^{-18} - 1{,}4317 \times 10^{-21} \times t^7\,) \end{aligned} \tag{A.14}$$

The following simpler formula leads to equivalent results:

$$\begin{aligned} p_a = {} & (\,4{,}856884 + 0{,}2660089 \times t + 0{,}01688919 \times t^2 - 7{,}477123 \times 10^{-5} \times t^3 + 8{,}10525 \times 10^{-6} \times t^4 \\ & - 3{,}115221 \times 10^{-8} \times t^5) \times \frac{1013{,}2}{760} \end{aligned} \tag{A.15}$$

A.2.2.4 Formula related to soot concentration

Calculation of the soot concentration c_{Cw} [mg/m^3 in wet exhaust] from the Bosch smoke number SN by means of the MIRA-Correlation:

$$c_{Cw} = \begin{pmatrix} 0{,}00976983 \times SN + 0{,}0234416 \times SN^2 - 0{,}00728358 \times SN^3 \\ + 0{,}00164618 \times SN^4 - 0{,}0000895464 \times SN^5 \end{pmatrix} \times 1000 \tag{A.16}$$

A.2.3 Reaction equations and formulae for the stoichiometric burning of fuel

A.2.3.1 General

A.2.3 describes the stoichiometry of the combustion of fuels containing H, C, S, N and O. The relations of masses of the reaction partners are calculated, as are the standard volumes for gaseous compounds. For each combusted element, the resulting additional volume (exhaust volume − air volume) is given. The summation of these additional volumes results in the total additional volume f_{fw}.

On this basis, formulae for further exhaust relevant data are derived (conversion factor wet/dry, stoichiometric air demand and fuel specific factor f_{fd}).

A.2.3.2 Combustion of hydrogen

$$\text{H (fuel)} + 1/4\ \text{O}_2\ \text{(air)} \rightarrow 1/2\ \text{H}_2\text{O (exhaust gas)}$$

$$1\ \text{kg H} + M_{rO2}/(4 \times A_{rH})\ [\text{kg O}_2] \rightarrow M_{rH2O}/(2 \times A_{rH})\ [\text{kg H}_2\text{O}] \qquad \text{masses}$$

$$V_{mO2}/(4 \times A_{rH})\ [\text{m}^3\ \text{O}_2] \rightarrow V_{mH2O}/(2 \times A_{rH})\ [\text{m}^3\ \text{H}_2\text{O}] \qquad \text{volumes}$$

Additional volume by combustion:

$$(2 \times V_{mH2O} - V_{mO2})/(4 \times A_{rH}) = (2 \times 22{,}414 - 22{,}414)/(4 \times 1{,}00794) = 5{,}5594\ \ [\text{m}^3/\ \text{kg H}]$$

A.2.3.3 Combustion of carbon

$$\text{C (fuel)} + \text{O}_2 \text{ (air)} \rightarrow \text{CO}_2 \text{ (exhaust gas)}$$

$$1\,\text{kg C} + M_{\text{rO2}}/A_{\text{rC}}\ [\text{kg O}_2] \rightarrow M_{\text{rCO2}}/A_{\text{rC}}\ [\text{kg CO}_2] \qquad \text{masses}$$

$$V_{\text{mO2}}/A_{\text{rC}}\ [\text{m}^3\ \text{O}_2] \rightarrow V_{\text{mCO2}}/A_{\text{rC}}\ [\text{m}^3\ \text{CO}_2] \qquad \text{volumes}$$

Additional volume by combustion:

$$\left(V_{\text{mCO2}} - V_{\text{mO2}}\right)/A_{\text{rC}} = \left(22{,}414 - 22{,}414\right)/12{,}011 = 0\ \ [\text{m}^3/\text{ kg C}]$$

A.2.3.4 Combustion of sulphur

$$\text{S} \left(\text{fuel}\right) + \text{O}_2 \left(\text{air}\right) \rightarrow \text{SO}_2 \left(\text{exhaust gas}\right)$$

$$1\,\text{kg S} + M_{\text{rO2}}/A_{\text{rS}}\ \left[\text{kg O}_2\right] \rightarrow M_{\text{rSO2}}/A_{\text{rS}}\ \left[\text{kg SO}_2\right] \qquad \text{masses}$$

Additional volume by combustion:

$$\left(V_{\text{mSO2}} - V_{\text{mO2}}\right)/A_{\text{rS}} = \left(22{,}414 - 22{,}414\right)/32{,}065 = 0\ [\text{m}^3/\text{ kg S}] \qquad \text{volumes}$$

A.2.3.5 Reaction of nitrogen

$$\text{N} \left(\text{fuel}\right) \rightarrow \text{N}_2 \left(\text{exhaust gas}\right)$$

$$1\,\text{kg N} \rightarrow 1\,\text{kg N}_2 \qquad \text{masses}$$

$$\rightarrow V_{\text{mN2}}/M_{\text{rN2}}\ \left[\text{m}^3\ \text{N}_2\right] \qquad \text{volumes}$$

Additional volume by combustion:

$$V_{\text{mN2}}/M_{\text{rN2}} = 22{,}414/28{,}01 = 0{,}80021\,\text{m}^3/\text{ kg N}$$

A.2.3.6 Consideration of the fuel oxygen

Since the combustion of the other fuel elements with the above given formulae was calculated with consumption of air oxygen, the fuel oxygen is not needed for combustion and can therefore be considered to be set free as gaseous molecular oxygen in the exhaust:

$$\text{O} \left(\text{fuel}\right) \rightarrow \text{O}_2 \left(\text{exhaust gas}\right)$$

$$1\,\text{kg O} \rightarrow 1\,\text{kg O}_2 \qquad \text{masses}$$

$$\rightarrow V_{\text{mO2}}/M_{\text{rO2}}\ \left[\text{m}^3\ \text{O}_2\right] \qquad \text{volumes}$$

Additional volume by combustion:

$$V_{\mathrm{mO2}}/M_{\mathrm{rO2}} \;=\; 22{,}414/31{,}9988 \;=\; 0{,}70046\ \mathrm{m}^3/\ \mathrm{kg}$$

A.2.3.7 Total additional volume f_{fw} [m^3/kg fuel]

The fuel-specific constants f_{fw} [m^3 volume change from combustion air to wet exhaust per kg fuel] and the corresponding value f_{fd} for the dry exhaust are further used to calculate the dry-to-wet correction factor and the exhaust densities (see A.2.4 and A.2.5). f_{fw} can be calculated by adding up the additional volumes of the combustion of the fuel elements given in A.2.3.2 to A.2.3.6:

$$f_{\mathrm{fw}} = 0{,}055594 \times w_{\mathrm{ALF}} + 0{,}0080021 \times w_{\mathrm{DEL}} + 0{,}0070046 \times w_{\mathrm{EPS}} \tag{A.17}$$

For the calculation of the exhaust volume flow V_{ew} it can be used as follows:

$$q_{v\mathrm{ew}} = q_{v\mathrm{aw}} + q_{m\mathrm{f}} \times f_{\mathrm{fw}} \tag{A.18}$$

f_{fw} is also used for calculation of wet exhaust density ρ_{ew} and dry/wet factor k_{wr}.

A.2.3.8 Calculation of the factor f_{fd} from f_{fw}

The factor f_{fd} can be used for the calculation of the dry exhaust volume flow as follows:

$$q_{v\mathrm{ed}} = q_{v\mathrm{ad}} + f_{\mathrm{fd}} \times q_{m\mathrm{f}} \tag{A.19}$$

f_{fd} values are always negative, which means that the volume of dry exhaust is always less than the volume of the intake air.

Based on (A.19), the following derivations can be made:

$$f_{\mathrm{fd}} = \frac{q_{v\mathrm{ed}} - q_{v\mathrm{ad}}}{q_{m\mathrm{f}}} \tag{A.20}$$

The volume of moisture due to combustion which must be removed from the total volume change due to combustion ($q_{m\mathrm{f}} \times f_{\mathrm{fw}}$) is given by the following:

$$\frac{w_{\mathrm{ALF}} \times q_{m\mathrm{f}} \times V_{\mathrm{mH2O}}}{100 \times 2 \times A_{\mathrm{rH}}}$$

$$f_{\mathrm{fd}} \;=\; \frac{q_{v\mathrm{ad}} + q_{m\mathrm{f}} \times f_{\mathrm{fw}} - \dfrac{w_{\mathrm{ALF}} \times q_{m\mathrm{f}} \times V_{\mathrm{mH2O}}}{100 \times 2 \times A_{\mathrm{rH}}} - q_{v\mathrm{ad}}}{q_{m\mathrm{f}}} \tag{A.21}$$

$$f_{\mathrm{fd}} \;=\; f_{\mathrm{fw}} - \frac{w_{\mathrm{ALF}} \times V_{\mathrm{mH2O}}}{200 \times A_{\mathrm{rH}}} \;=\; f_{\mathrm{fw}} - w_{\mathrm{ALF}} \times 0{,}11118 \tag{A.22}$$

$$f_{\mathrm{fd}} \;=\; -0{,}055593 \times w_{\mathrm{ALF}} + 0{,}008002 \times w_{\mathrm{DEL}} + 0{,}0070046 \times w_{\mathrm{EPS}} \tag{A.23}$$

A.2.3.9 Stoichiometric air demand A/F_{st}

With the reactions of the fuel elements given in A.2.3.2 to A.2.3.6, the stoichiometric air demand (i.e. mass of air needed for combustion of 1 kg fuel) can be given as follows:

$$A/F_{\text{st}} = \left(\frac{w_{\text{BET}}}{A_{\text{rC}}} + \frac{w_{\text{ALF}}}{4 \times A_{\text{rH}}} + \frac{w_{\text{GAM}}}{A_{\text{rS}}} - \frac{w_{\text{EPS}}}{2 \times A_{\text{rO}}}\right) \times \frac{M_{\text{rO2}}}{w_{\text{ox}}} \qquad \text{(A.24)}$$

With the term $1/w_{\text{ox}}$, the needed oxygen mass is converted to the needed air mass, and so the inert components of the air are taken into account.

In concrete numbers:

$$A/F_{\text{st}} = \left(\frac{w_{\text{BET}}}{12{,}011} + \frac{w_{\text{ALF}}}{4{,}03176} + \frac{w_{\text{GAM}}}{32{,}06} - \frac{w_{\text{EPS}}}{31{,}9988}\right) \times 1{,}382 \qquad \text{(A.25)}$$

A.2.4 Calculation of the dry-to-wet correction factor k_{wr}

A.2.4.1 Stoichiometric combustion

The dry-to-wet correction factor k_{wr} is used for converting dry measured concentrations to the wet reference condition. k_{wr} is further the quotient between dry and wet exhaust volume flow:

$$k_{\text{wr}} = \frac{c_{\text{gasw}}}{c_{\text{gasd}}} = \frac{q_{v\text{ed}}}{q_{v\text{ew}}} = 1 - \frac{q_{v\text{H2O}}}{q_{v\text{ew}}} \qquad \text{(A.26)}$$

The index "gas" indicates the individual gaseous component (e.g. CO). $q_{v\text{H20}}$ here has to be interpreted as the water content of the exhaust, which condenses in the cooling bath of the gas analysis system and which is thus removed from the exhaust before measurement. $q_{v\text{H20}}$ is calculated by adding the water from the intake air to the water formed by combustion and subtracting the rest water, which is still present after the cooling bath.

$$q_{v\text{H2O,intake air}} = \frac{q_{mad} \times H_{\text{a}} \times V_{\text{mH2O}}}{1000 \times M_{\text{rH2O}}} \quad [\text{m}^3/\text{ h}] \qquad \text{(A.27)}$$

$$q_{v\text{H2O,formed by combustion}} = \frac{w_{\text{ALF}} \times q_{mf} \times V_{\text{mH2O}}}{100 \times 2 \times A_{\text{r}}\text{H}} \quad [\text{m}^3/\text{ h}] \qquad \text{(A.28)}$$

$$q_{v\text{H2O,rest after cooler}} = \frac{q_{mad}}{1{,}293} \times \frac{p_{\text{r}}}{p_{\text{b}}} \quad [\text{m}^3/\text{ h}] \qquad \text{(A.29)}$$

where

p_{r} is the water partial pressure after the cooling bath;

$p_{\text{r}}/p_{\text{b}}$ is the mole fraction of water vapour (= volume fraction of water vapour after the cooler);

the density of dry air is 1,293 kg/m^3.

$$q_{v\text{ew}} = q_{v\text{aw}} + q_{mf} \times f_{\text{fw}} \qquad \text{(A.30)}$$

$$k_{\mathrm{wr}} = 1 - \frac{\dfrac{q_{mad} \times H_{\mathrm{a}} \times V_{\mathrm{mH2O}}}{1000 \times M_{\mathrm{rH2O}}} + \dfrac{w_{\mathrm{ALF}} \times q_{mf} \times V_{\mathrm{mH2O}}}{100 \times 2 \times A_{\mathrm{rH}}} - \dfrac{q_{mad} \times p_{\mathrm{r}}}{1{,}293 \times p_{\mathrm{b}}}}{\dfrac{q_{mad} \times H_{\mathrm{a}} \times V_{\mathrm{mH2O}}}{1000 \times M_{\mathrm{rH2O}}} + \dfrac{q_{mad}}{1{,}293} + q_{mf} \times f_{\mathrm{fw}}} \qquad \text{(A.31)}$$

Dividing the numerator and denominator by $1000/q_{mad}$ and substituting for known values of molar volumes, molecular masses and atomic masses, the following equation can be derived.

$$k_{\mathrm{wr}} = 1 - \frac{1{,}2442 \times H_{\mathrm{a}} + 111{,}187 \times w_{\mathrm{ALF}} \times \dfrac{q_{mf}}{q_{mad}} - 773{,}4 \times \dfrac{p_{\mathrm{r}}}{p_{\mathrm{b}}}}{773{,}4 + 1{,}2442 \times H_{\mathrm{a}} + \dfrac{q_{mf}}{q_{mad}} \times f_{\mathrm{fw}} \times 1000} \qquad \text{(A.32)}$$

NOTE 1 In ISO 8178-1:1996, the dry-to-wet factor k_{wr} was calculated by means of the intermediate fuel specific constant f_{fh} according to Equation A.33.

$$f_{\mathrm{fh}} = \frac{111{,}119 \times w_{\mathrm{ALF}}}{773{,}4 + \dfrac{q_{mf}}{q_{mad}} \times f_{\mathrm{fw}} \times 1000} \quad \text{and} \quad k_{\mathrm{wr}} = \left(1 - f_{\mathrm{fh}} \times \frac{q_{mf}}{q_{mad}}\right) - k_{\mathrm{w2}} + \frac{p_{\mathrm{r}}}{p_{\mathrm{b}}} \qquad \text{(A.33)}$$

NOTE 2 The f_{fh} concept was abandoned because f_{fh} is not only fuel-specific but also lambda-dependent, and because Equation A.31 or A.32 gives better precision.

A.2.4.2 Incomplete combustion

The water content of the exhaust and the dry-to-wet factor k_{wr} can be calculated from the exhaust composition in the following way.

The water concentrations (in % units) can be directly derived from the CO_2 and CO concentrations, taking into account the H/C ratio α (assuming $\beta = 1$) and the fact that one molecule of water is formed from two atoms of hydrogen. Additionally, for the hydrogen content of the exhaust a subtraction has to be made, because from that corresponding hydrogen part of the fuel no water has been formed. Furthermore, the water in the intake air and the water still present after the gas cooler have to be considered:

$$c_{\mathrm{H2O,combustion,d}} = 0{,}5 \times \alpha \times \left(c_{\mathrm{CO2d}} + \frac{c_{\mathrm{COd}}}{10^4}\right) - c_{\mathrm{H2d}} \qquad \text{(A.34)}$$

$$k_{\mathrm{wr}} = \frac{q_{v\mathrm{ed}}}{q_{v\mathrm{ew}}} = \frac{q_{v\mathrm{ed}}}{q_{v\mathrm{ed}} + q_{v\mathrm{H2O,combustion,d}} + q_{v\mathrm{H2O,a}} - q_{v\mathrm{H2O,after\ cooler}}} \qquad \text{(A.35)}$$

where the concentrations of H_2O, H_2 and CO_2 are expressed as a percentage and the concentration of CO is expressed in ppm.

$$k_{\mathrm{wr}} = \frac{1}{1 + \dfrac{q_{v\mathrm{H2O,combustion,d}}}{q_{v\mathrm{ed}}} + \dfrac{q_{v\mathrm{H2O,ad}}}{q_{v\mathrm{ed}}} - \dfrac{q_{v\mathrm{H2O,after\ cooler}}}{q_{v\mathrm{ed}}}} \qquad \text{(A.36)}$$

$$k_{\mathrm{wr}} = \frac{1}{1 + \dfrac{c_{\mathrm{H2O,combustion,d}}}{100} + \dfrac{c_{\mathrm{H2O,ad}}}{100} - \dfrac{c_{\mathrm{H2O,after\ cooler}}}{100}} \qquad \text{(A.37)}$$

$$k_{\mathrm{wr2}} = \frac{1}{1 + \alpha \times 0{,}005 \times \left[c_{\mathrm{CO2d}} + \dfrac{c_{\mathrm{COd}}}{10000}\right] - 0{,}01 \times c_{\mathrm{H2d}} + k_{\mathrm{w2}} - \dfrac{p_{\mathrm{r}}}{p_{\mathrm{b}}}} \qquad \text{(A.38)}$$

where

k_{w2} is the moisture in the intake air and is given by

$$k_{w2} = \frac{1{,}608 \times H_a}{1000 + (1{,}608 \times H_a)} \tag{A.39}$$

where H_a is the humidity of the intake air in g water per kg of dry air.

The concentration of hydrogen is derived from the water gas equilibrium according to the following equation based on SAE J 1088:

$$c_{H2d} = \frac{0{,}5 \times \alpha \times \frac{c_{COd}}{10^4} \times \left(\frac{c_{COd}}{10^4} + c_{CO2d} \right)}{\frac{c_{COd}}{10^4} + 3 \times c_{CO2d}} \tag{A.40}$$

or

$$c_{H2}[\%\text{vol.}] = \frac{0{,}5 \times \alpha \times c_{CO}[\%\text{vol.}] \times (c_{CO}[\%\text{vol.}] + c_{CO2}[\%\text{vol.}])}{c_{CO}[\%\text{vol.}] + 3 \times c_{CO2}[\%\text{vol.}]} \tag{A.41}$$

This method of k_{wr} calculation is to be preferred for rich fuel–air mixtures (high CO values) and also for emission measurements without direct air flow measurements, because the k_{wr} calculation by Equation A.32 assumes stoichiometric combustion and it needs the data for q_{mad}

A.2.5 Calculation of the dry and wet exhaust densities using f_{fw} and f_{fd}

The exhaust density is calculated by dividing the exhaust mass flow by the exhaust volume flow:

$$\rho_{ew} = \frac{q_{mew}}{q_{vew}} = \frac{q_{maw} + q_{mf}}{q_{vaw} + f_{fw} \times q_{mf}} \quad [\text{kg/m}^3] \tag{A.42}$$

$$\rho_{ew} = \frac{q_{mad} + \frac{H_a \times q_{mad}}{1000} + q_{mf}}{\frac{q_{mad}}{1{,}293} + \frac{q_{mad} \times H_a \times V_{mH2O}}{1000 \times M_{rH2O}} + f_{fw} \times q_{mf}} \tag{A.43}$$

$$\rho_{ew} = \frac{1000 + H_a + 1000 \times \frac{q_{mf}}{q_{mad}}}{773{,}4 + 1{,}2434 \times H_a + 1000 \times f_{fw} \times \frac{q_{mf}}{q_{mad}}} \tag{A.44}$$

Calculation of the density of the dry exhaust:

$$\rho_{ed} = \frac{q_{med}}{q_{ved}} = \frac{q_{mad} + q_{mf} \times \left(1 - \frac{w_{ALF}}{100} \times \frac{M_{rH2O}}{2 \times A_{rH}} \right)}{q_{vad} + f_{fd} \times q_{mf}} \quad [\text{kg/m}^3] \tag{A.45}$$

$$\rho_{ed} = \frac{q_{mad} + q_{mf} \times \left(1 - \frac{w_{ALF}}{100} \times \frac{M_{rH2O}}{2 \times A_{rH}} \right)}{\frac{q_{mad}}{1{,}293} + f_{fd} \times q_{mf}} = \frac{q_{mad} + q_{mf} \times (1 - w_{ALF} \times 0{,}08936)}{\frac{q_{mad}}{1{,}293} + f_{fd} \times q_{mf}} \tag{A.46}$$

A.3 Calculation of the exhaust mass flow from the exhaust composition (carbon and oxygen balance, for fuels with C, H, S, N and O)

A.3.1 Introduction

In this annex the carbon and oxygen balance method is used for the calculation of the exhaust mass flow, in order to enable emission calculations without measurement of air flow or exhaust flow. The calculation formulae of this edition of ISO 8178-1, Annex A are related to the concentrations in the dry exhaust, whereas in ISO 8178-1:1996 a relation to the wet exhaust was used. The conversion was made because with the dry method a better precision of the calculated exhaust mass flow was reached, especially for highly incomplete combustion situations (small gasoline engines).

The calculation of the exhaust mass flow can also be used for comparison with measured mass flows, in order to provide check methods regarding the plausibility of test results.

Low deviations between measured and calculated air flow indicate correct CO_2 or O_2 values (no leak in sampling system), correct air flow measurement (no leak in connection tubes between engine and air flow equipment) and correct fuel measurement.

Differences between measured and calculated air flows hint at the following errors.

a) Measured air flow lower than by carbon balance method:

  - leak in exhaust sampling system (highest probability) or
  - leak in air measurement equipment (moderate probability) or
  - too high fuel flow values (low probability, except for idle);

b) Measured air flow higher than by carbon balance method:

  - calibration error of exhaust analyser or
  - calibration error of air measurement equipment or
  - too low fuel flow values.

NOTE All three cases of b) are less probable than the three cases of a).

When using the carbon or oxygen balance method for calculation of emissions, a leak in the exhaust sampling system has no severe effect on the results. This is because the too low exhaust concentrations are offset by correspondingly too high calculated exhaust mass flows, so these effects cancel each other.

For the derivations within A.3.2 and A.3.3 it is assumed that the fuel consumption, the fuel composition and the concentration of the exhaust components are known. It is applicable for fuels containing H, C, S, O and N in known proportions.

A.3.2 Calculation of the exhaust mass flow on the basis of the carbon balance

A.3.2.1 General

In this section two forms of the carbon balance method are given: an iterative calculation (multi-step) procedure and a one-step calculation procedure. The one-step procedure was added to this edition of ISO 8178-1 because it is easier to use than the multi-step procedure.

A.3.2.2 Carbon balance: iterative calculation procedure

The calculation of q_{med}, as described in the following section, needs the values of ρ_{ed} and k_{wr}, which are themselves dependent on q_{mad} and thus on the result of the q_{med} calculation. Therefore, an iterative (or multi-step) calculation procedure shall be applied in the following way. With preliminary values of ρ_{ed} and k_{wr} (e.g. 1,34 kg/m^3 and 1), the q_{med} values are calculated; from these the q_{mad} values are calculated, and from these ρ_{ed} and k_{wr}. With these almost exact values of ρ_{ed} and k_{wr}, values of all data in the next iteration step using the same formulae are exact enough, so that a third iteration step will not be necessary in most cases.

A.3.2.2.1 Equations for the calculation of the exhaust mass flow

The following equations can be used for the calculation of the exhaust mass flow on the basis of the carbon balance method:

$$q_{med} = \frac{q_{mf} \times w_{BET} \times \rho_{ed} \times 10^4}{A_{rC} \times \left(\left(\frac{(c_{CO2d} - c_{CO2,a}) \times 10^4}{V_{mCO2}} + \frac{c_{COd}}{V_{mCO}} \right) \times \frac{1}{1 - \frac{p_r}{p_b}} + \left(\frac{c_{HCw}}{V_{mHC}} + \frac{c_{Cw}}{A_{rC}} \right) \times \frac{1}{k_{wr}} \right)} \quad \text{(A.47)}$$

$$q_{mad} = q_{med} - q_{mf} \times \left(1 - \frac{w_{ALF}}{100} \times \frac{M_{rH2O}}{2 \times A_{rH}} \right) = q_{med} - q_{mf} \times (1 - w_{ALF} \times 0{,}08936) \quad \text{(A.48)}$$

$$q_{mew} = q_{mad} \times \left(1 + \frac{H_a}{1000} \right) + q_{mf} \quad \text{(A.49)}$$

Inserting concrete numbers into Equation A.47 results in the following equation for incomplete combustion:

$$q_{med} = \frac{q_{mf} \times w_{BET} \times \rho_{ed} \times 832{,}57}{\left(\left((c_{CO2} - c_{CO2,a}) \times 446{,}1 + \frac{c_{COd}}{22{,}414} \right) \times \frac{1}{1 - \frac{p_r}{p_b}} + \left(\frac{c_{HCw}}{22{,}414} + \frac{c_{Cw}}{12{,}011} \right) \times \frac{1}{k_{wr}} \right)} \quad \text{(A.50)}$$

And for complete combustion:

$$q_{med} = q_{mf} \times \frac{\rho_{ed} \times 1{,}8663}{(c_{CO2d} - c_{CO2,a})} \quad \text{(A.51)}$$

Combining Equations A.50, A.48 and A.49 in one equation and using some simplifications [neglecting unburned soot and assuming a fixed cooler temperature of 4 °C, i.e. $1/(1 - p_r / p_b) = 1{,}008$], the following easier-to-use equation for the wet exhaust mass flow results:

$$q_{mew} = q_{mf} \times \left(\left(\left(\frac{w_{BET} \times \rho_{ed}}{(c_{CO2d} - c_{CO2,a}) \times 0{,}540 + \frac{c_{COd} + \frac{c_{HCw}}{k_{wr}}}{10\,000} \times 0{,}540} + w_{ALF} \times 0{,}089\,36 - 1 \right) \times \left(1 + \frac{H_a}{1\,000} \right) \right) + 1 \right) \quad \text{(A.52)}$$

For combustion of typical diesel fuel with $w_{\mathrm{BET}} = 86{,}2$ % mass and $\rho_{\mathrm{ed}} = 1{,}329$ (excess air factor of 2), the following further simplified equation can be given:

$$q_{m\mathrm{ew}} = q_{m\mathrm{f}} \times \left(\left(\left(\frac{1}{\left(c_{\mathrm{CO2d}} - c_{\mathrm{CO2,a}}\right) \times 0{,}00471 + \dfrac{c_{\mathrm{COd}} + \dfrac{c_{\mathrm{HCw}}}{k_{\mathrm{wr}}}}{10\,000} \times 0{,}00471} + w_{\mathrm{ALF}} \times 0{,}089\,36 - 1 \right) \times \left(1 + \frac{H_{\mathrm{a}}}{1\,000}\right) \right) + 1 \right) \tag{A.53}$$

A.3.2.2.2 Derivation of equations

The carbon input [g/h] into the engine from the fuel is

$$q_{m\mathrm{f}} \times w_{\mathrm{BET}} \times 10 \tag{A.54}$$

The carbon input [g/h] into the engine from the intake air is $q_{m\mathrm{CO2,a}}$ (see Equation A.57).

The carbon output from the engine in g/h is

$$q_{m\mathrm{CO2}} \times \frac{A_{\mathrm{rC}}}{M_{\mathrm{rCO2}}} + q_{m\mathrm{CO}} \times \frac{A_{\mathrm{rC}}}{M_{\mathrm{rCO}}} + q_{m\mathrm{HC}} \times \frac{A_{\mathrm{rC}}}{M_{\mathrm{rHC}}} + q_{m\mathrm{C}} \tag{A.55}$$

With the following equations the individual gas components are calculated in g/h.

$$q_{m\mathrm{CO2}} = \frac{M_{\mathrm{rCO2}} \times 10}{V_{\mathrm{mCO2}} \times \rho_{\mathrm{ed}}} \times \frac{c_{\mathrm{CO2d}}}{1 - \dfrac{p_{\mathrm{r}}}{p_{\mathrm{b}}}} \times q_{m\mathrm{ed}} \tag{A.56}$$

In Equation A.56, the $\mathrm{CO_2}$ mass emission is calculated from the volume portion by multiplication with the quotient of the gas densities ($\mathrm{CO_2}$/dry exhaust). The $\mathrm{CO_2}$ gas density is given as molecular weight per molecular volume. These principal equations are used in a comparable way for the other components:

$$q_{m\mathrm{CO2,a}} = \frac{M_{\mathrm{rCO2}} \times 10}{V_{\mathrm{mCO2}} \times \rho_{\mathrm{ed}}} \times \frac{c_{\mathrm{CO2,a}}}{1 - \dfrac{p_{\mathrm{r}}}{p_{\mathrm{b}}}} \times q_{m\mathrm{ed}} \tag{A.57}$$

$$q_{m\mathrm{CO}} = \frac{M_{\mathrm{rCO}}}{V_{\mathrm{mCO}} \times \rho_{\mathrm{ed}} \times 1000} \times \frac{c_{\mathrm{COd}}}{1 - \dfrac{p_{\mathrm{r}}}{p_{\mathrm{b}}}} \times q_{m\mathrm{ed}} \tag{A.58}$$

$$q_{m\mathrm{HC}} = \frac{M_{\mathrm{rHC}}}{V_{\mathrm{mHC}} \times \rho_{\mathrm{ed}} \times 1000} \times \frac{c_{\mathrm{HCw}}}{k_{\mathrm{wr}}} \times q_{m\mathrm{ed}} \tag{A.59}$$

$$q_{m\mathrm{C}} = \frac{1}{\rho_{\mathrm{ed}} \times 1000} \times \frac{c_{\mathrm{Cw}}}{k_{\mathrm{wr}}} \times q_{m\mathrm{ed}} \tag{A.60}$$

The balance condition (carbon input = carbon output) results in

$$q_{mf} \times w_{\mathrm{BET}} \times 10 = \frac{q_{med} \times A_{\mathrm{rC}}}{\rho_{\mathrm{ed}} \times 1000} \times \left(\frac{\left(c_{\mathrm{CO2d}} - c_{\mathrm{CO2,a}}\right) \times 10^4}{V_{\mathrm{mCO2}} \times \left(1 - \frac{p_{\mathrm{r}}}{p_{\mathrm{b}}}\right)} + \frac{c_{\mathrm{COd}}}{V_{\mathrm{mCO}} \times \left(1 - \frac{p_{\mathrm{r}}}{p_{\mathrm{b}}}\right)} + \frac{c_{\mathrm{HCw}}}{V_{\mathrm{mHC}} \times k_{\mathrm{wr}}} + \frac{c_{\mathrm{Cw}}}{A_{\mathrm{rC}} \times k_{\mathrm{wr}}} \right) \qquad \text{(A.61)}$$

A.61 can be converted to A.62, allowing the calculation of q_{med} on the basis of the carbon balance:

$$q_{med} = \frac{q_{mf} \times w_{\mathrm{BET}} \times \rho_{\mathrm{ed}} \times 10^4}{A_{\mathrm{rC}} \times \left[\frac{\frac{\left(c_{\mathrm{CO2d}} - c_{\mathrm{CO2,a}}\right) \times 10^4}{V_{\mathrm{mCO2}}} + \frac{c_{\mathrm{COd}}}{V_{\mathrm{mCO}}}}{1 - \frac{p_{\mathrm{r}}}{p_{\mathrm{b}}}} + \frac{c_{\mathrm{HCw}}}{k_{\mathrm{wr}} \times V_{\mathrm{mHC}}} + \frac{c_{\mathrm{Cw}}}{k_{\mathrm{wr}} \times A_{\mathrm{rC}}} \right]} \qquad \text{(A.62)}$$

A.3.2.3 Carbon balance: 1-step calculation procedure

Because of the not so easy to use multi-step calculation procedure, in this paragraph two iteration steps are combined in one final formula for the exhaust mass flow, thus enabling a 1-step calculation procedure. The results of the 1-step procedure are within ± 0,2 % of the multi-step procedure for all fuel compositions tested.

A.3.2.3.1 Application of formulae

The following 1-step formula can be used for the calculation of the wet exhaust mass flow:

$$q_{mew} = q_{mf} \times \left(\left(\frac{\frac{w_{\mathrm{BET}} \times w_{\mathrm{BET}} \times 1{,}4}{\left(\frac{1{,}4 \times w_{\mathrm{BET}}}{f_{\mathrm{c}}} + w_{\mathrm{ALF}} \times 0{,}08936 - 1\right) \times \frac{1}{1{,}293} + f_{\mathrm{fd}}}}{f_{\mathrm{c}} \times f_{\mathrm{c}}} + w_{\mathrm{ALF}} \times 0{,}08936 - 1 \right) \times \left(1 + \frac{H_{\mathrm{a}}}{1000}\right) + 1 \right) \qquad \text{(A.63)}$$

where

$$f_{\mathrm{c}} = \left(c_{\mathrm{CO2d}} - c_{\mathrm{CO2,a}}\right) \times 0{,}5441 + \frac{c_{\mathrm{COd}}}{18{,}522} + \frac{c_{\mathrm{HCw}}}{17355} \qquad \text{(A.64)}$$

The following even simpler formula can also be used:

$$q_{mew} = q_{mf} \times \left(\frac{w_{\mathrm{BET}} \times w_{\mathrm{BET}} \times 1{,}4}{\left(1{,}0828 \times w_{\mathrm{BET}} + f_{\mathrm{fd}} \times f_{\mathrm{c}}\right) \times f_{\mathrm{c}}} \times \left(1 + \frac{H_{\mathrm{a}}}{1000}\right) + 1 \right) \qquad \text{(A.65)}$$

NOTE Equation A.65 is given as a simpler version of Equation A.63 without significant loss of precision.