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Measurement of gas flow in conduits — Tracer methods — Part IV : Transit time method using radioactive tracers

Mesurage de débits de gaz dans les conduites — Méthodes par traceurs — Partie IV : Méthode fondée sur le mesurage du temps de transit, utilisant des traceurs radioactifs

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FOREWORD

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Measurement of gas flow in conduits — Tracer methods — Part IV : Transit time method using radioactive tracers

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0 INTRODUCTION

This International Standard is the fourth of a series of standards covering tracer methods of gas flow measurement in conduits.

The complete series of standards is as follows :

— *Part I : General.*

— *Part II : Constant rate injection method using non-radioactive tracers.*

— *Part III : Constant rate injection method using radioactive tracers.*

— *Part IV : Transit time method using radioactive tracers.*

1 SCOPE AND FIELD OF APPLICATION

This International Standard specifies the transit time method using radioactive tracers for the measurement of gas flow in conduits.

2 REFERENCE

ISO 4053/I, *Measurement of gas flow in conduits — Tracer methods — Part I : General.*

3 PRINCIPLE

Flow-rate measurement by the transit time method (formerly called the "Allen velocity method") is based on measuring the transit time of "labelled" particles between two cross-sections of the conduit a known distance apart. Labelling of the fluid particles is achieved by injecting a tracer into the flow upstream of the two measurement cross-sections (i.e. detector positions) and the transit time is determined from the difference of the mean arrival times of the tracer at each of the detector positions.

Under certain conditions (see clause 4), the volume flow-rate q_v (see nomenclature in ISO 4053/I) in the measurement section is given by :

$$q_v = \frac{V}{\bar{t}}$$

where

V is the volume of the conduit between the detector positions;

$\bar{t}$ is the transit time of the labelled fluid particles.

In general, the theoretical condition for the validity of the formula is that the measuring section be "closed to diffusion", i.e. that the ratio of the local velocity to the longitudinal dispersion coefficient be equal at both ends of the measuring section.

In practice, this condition is fulfilled when the conduit has a constant cross-section.

The value of $\bar{t}$ is obtained by measuring the difference in abscissae of characteristic points (in theory, the centre of gravity, but in practice other characteristic points may be found, see 6.7) of recorded distributions, corresponding to concentration/time distributions or their integrals, obtained at each detector position. The signal from the detectors shall be proportional to the tracer concentration. The exact value of the proportionality constant and hence the concentration need not, however, be known.

The mass flow-rate is calculated by determining simultaneously the volume flow-rate and the gas density.

4 REQUIRED CONDITIONS

4.1 Tracer

The tracer shall meet the general requirements defined in clause 5 of ISO 4053/I. A list of tracers generally used, with their advantages and disadvantages, is also given in the same clause.

4.2 Mixing of tracer

The tracer shall be sufficiently mixed with the flow at the first detector position for the recorded concentration/time distributions at both detectors to be adequately representative of the mean flow (see 5.1). The selection of the positions for the injection and the detectors is controlled by the fluid velocity, tracer dispersion, and the conduit layout. The conditions for this selection are dealt with in clause 5. At low Reynolds number, $Re \leqslant 5\,000$, the mixing of tracer is not sufficient and no reliable measurement can be made.

4.3 Test procedure

The procedure for the preparation and the injection of the tracer gas (which in practice should be injected as rapidly as possible to minimize the longitudinal dispersion of the tracer) is covered in 6.3 and 6.4. The internal volume of the measuring section shall be determined with sufficient accuracy (see 5.7). Other requirements relating to the tests and the calculation of the transit time from the data are given in clause 6.

5 CHOICE OF MEASURING LENGTH

In the transit time method, the measuring length consists of two parts :

- the length of conduit between the injection point and the position of the first detector;
- the length of conduit between detectors.

5.1 Length of conduit between injection and first detector

In theory, when the tracer concentration, C_2, in the conduit is measured at only a single point in each measurement cross-section, the length of conduit between the injection and first detector shall be equal to or greater than the mixing distance.

The mixing distance is defined as the shortest distance at which the maximum variation of $\int_0^\infty C_2 \, dt$ over the cross-section is less than some predetermined value (for example 0,5 %). (See clause 5 of ISO 4053/I.)

There are, however, insufficient experimental results available to relate variations in $\int_0^\infty C_2 \, dt$ at the first detector position, to the overall accuracy of transit time as determined from concentration measurements at single points in the measurement cross-sections.

If the measurement of concentration at each detector position represents the mean concentration in the cross-section (for example by simultaneous measurements at many points or by a detector sensitive to tracer across the cross-section), the degree of mixing required at the first detector position is not as great as that corresponding to the mixing distance. In these circumstances the necessary distance between the injection position and the first detector position can be considerably less than the mixing distance. For example, when using a γ-emitting tracer centrally injected into a conduit and detecting by three scintillation detectors positioned at each measurement cross-section, and when the distance between injection and the first detector is only 12 conduit diameters, no additional error in flow-rate measurement has been observed in practice.

The length of conduit between the injection position and the first detector should preferably contain no pipe fittings or sections likely to increase significantly the longitudinal dispersion of tracer at the detector positions. Examples of such fittings and sections are valves, flow regulators and flow distribution headers.

5.2 Length of conduit between detector positions

The length of conduit necessary between the detector positions depends on the axial velocity of the fluid, the spatial dispersion of the tracer at the detector positions and the required accuracy of the measurement of transit time.

The length of straight conduit, L, between detector positions, the various ratios, p, of the transit time to the mean duration for the tracer "pulse" to pass each detector position (i.e. corresponding to the passage of 99,7 % of the tracer) and the various lengths of conduit, N, between the injection and first detector positions, are related to each other by the formula :

$$L = 4{,}25\, p\, (p + \sqrt{N})$$

where L and N are expressed in conduit diameters.

This relationship is shown graphically in figure 1.

If the concentration/time distributions are recorded on a single-channel recorder, it is necessary for the length of conduit between detectors to be greater than the mean spatial dispersion of the tracer at the detector positions so that the recorded distributions do not overlap. This is achieved when $p > 1$.

If a multi-channel recorder is used, this distance can be reduced, but it is necessary that for accurate measurement of transit time the length of conduit between detectors is not less than a half of the mean spatial dispersion of the tracer. For guidance, it is recommended to use in practice $p \geqslant 0{,}5$.

5.3 Measuring section

For the highest accuracy of flow measurement, the length of conduit between detector positions shall consist of a straight pipe of uniform cross-section and shall contain no pipe fittings or sections where dead zones are likely to affect the concentration/time distribution measured at the second detector. Examples of such fittings and sections are valves, flow regulators, abrupt changes of cross-sectional area, closed-ended branch pipes or sharp bends.

The overall accuracy of the flow measurement depends on the accuracy with which the internal volume of the measuring section has been determined.

5.4 Losses and additions

Additions of fluid upstream of the first detector position, of the same nature as the fluid in the conduit, do not affect the result provided that this fluid is mixed with the main flow at the first detector position.

Losses of fluid from the conduit before the first detector position do not affect the result but, if the tracer is not completely mixed at the point of loss, the amplitude of the concentration/time distribution at the detector positions may be affected and its value changed by a constant factor.

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Losses or additions of fluid in the length of conduit between the detector positions would cause serious errors in the measurement of flow-rate. Consequently, it is essential that the conduit between the two detector positions contain no branch connections and is free from leaks.

6 PROCEDURE

6.1 Handling of radioisotopes

The use of radioisotopes (storing, transportation, handling) shall comply with any existing statutory regulations.

6.2 Location of injection points

The number and position of injection points located at the injection cross-section depends mainly on the length of conduit between the injection position and the first detector position and the method of measuring the tracer concentration at the detector positions (i.e. "averaging" method or single-point sample).

When the available length of conduit between the injection point and the first detector is less than the theoretical mixing distance, it is recommended to proceed as mentioned in clause 6 of ISO 4053/I. It is advisable to choose procedures which enable the injection of all the tracer to be nearly instantaneous. In particular, a suitable procedure consists in using a single central injection against the flow or any other device which respects the symmetry of the conduit; injection may also be made upstream of a fan or a turbulence-generating device. If multi-orifice injections are used, the device shall be designed so as to allow a simultaneous injection in every point.

6.3 Preparation of the injected gas

The concentration of tracer in the injected gas shall be uniform. Homogeneity is generally achieved by molecular diffusion.

The required concentration will depend on the volume of gas to be injected for each measurement, the volume flow-rate to be measured, the degree of longitudinal dispersion of the tracer at the detector positions and the sensitivity of the detectors. In the case of a rapid symmetrical injection of tracer, the estimation of its maximum concentration, C_m, in curies per cubic metre, in an unobstructed straight pipe of diameter D, at N conduit diameters downstream of the injection point can be obtained from the following expression :

$$C_m \approx \frac{3A}{4D^3\sqrt{N}}$$

where A is the amount of tracer injected, in curies.

It is of interest to note that the maximum concentration does not depend on the flow-rate in the conduit.

When a turbulence-generating device is positioned in the measuring length between the injection position and the first detector, the maximum concentration may be greater than that derived from the above equation.

This expression may also be used to estimate the amount of tracer to be injected for each flow measurement from a knowledge of the sensitivity of the measurement detectors. The amount of injected tracer shall be such that the tracer concentration at the detector position be within the linear range of the detector.

6.4 Injection of tracer gas

In order to minimize dispersion of the measured concentration/time distributions, the tracer shall be injected as rapidly as possible, with no "tailing" of the injected gas from the injection tubes within the conduit. This can be achieved by any of the following means :

a) by means of injection valves at the extremity of each injection point (for example spring-loaded pop-valves); these valves shall open simultaneously, close rapidly and be leak-free;

b) by ensuring that the injected tracer is flushed into the conduit by a flow of tracer-free gas;

NOTE – The tracer may be injected in the conduit by means of an additional pressure of gas according to methods consistent with either of the above requirements.

c) by breaking with a suitable device an ampoule containing the gas to be injected in the conduit.

6.5 Detection of tracer

The tracer concentrations can be determined with detectors situated within the conduit or preferably outside or with detector flow-cells for sampling the flow-rate in the measuring cross-sections.

The difference in the time responses of the detector arrangements at the two cross-sections shall be negligible compared to the transit time. It is always desirable to adopt identical detectors in both measuring cross-sections.

If the mixture quality or the detectors are suspect, the procedure shall be as follows : several detectors shall be positioned around the conduit at each measuring cross-section, and the transit times measured by detectors situated in the same geometrical configurations shall be compared.

A rapid response time of the detection arrangement can be obtained, for example, by the use of an integrating count ratemeter to measure the integral of the concentration/time distribution at each measurement cross-section.

6.6 Number of injections

The number of successive injections required for each measurement of flow-rate depends on steadiness of the flow being measured, the random error in determining the transit time and the required overall limit of uncertainty on the measurement of flow-rate.

Because in practice an absolutely constant flow-rate is rarely achieved, it is recommended that at least five successive injections of tracer and associated measurements of

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transit time be made at each flow-rate to enable an objective analysis of the random uncertainties of measurement to be made (see clause 8).

6.7 Calculation of transit time

The transit time of the tracer between detector positions may be determined by suitable graphical constructions or direct computation on concentration/time distributions, or their integrals, recorded simultaneously with accurate timing signals from a suitable device. The transit time may be determined from the difference in times corresponding to the following positions on the recorded distribution from the detectors (see figure 2) :

6.7.1 *Centres of gravity* [see figure 2 a)]

The centre of gravity is the correct theoretical characteristic point in all cases.

6.7.2 *Mid-area positions* (i.e. half-areas) [see figure 2 b)]

In the case of a straight conduit, the mid-area position is also a correct characteristic point.

6.7.3 *Part-height positions* [see figure 2 c)]

The characteristic points under this sub-clause are defined by drawing a line parallel to the time axis at a level between 1/3 and 2/3 the maximum concentration. The mid-point where this line cuts the rise and fall of the pulse from the detector is then the characteristic point of that pulse. The half height and 0,6 × the maximum concentration are two commonly used levels.

6.7.4 *Other points*

The choice of other points, such as the maximum concentration [see figure 2 d)], shall only be used when a rapid approximate determination is required.

Alternatively, the transit time may be determined from suitable "triggering" of an automatic timing system by the passage of tracer at each detector. The accuracy of this method depends on the method of operating the timing system and the accuracy of applied corrections for differences in the concentration/time distributions at each detector position.

Where the transit time is determined from concentration/time distributions measured by detector flow-cells, corrections should be made for differences between the transfer times from the measuring cross-section to the flow-cells.

6.8 Determination of measuring section volume

The internal volume of the measuring section shall be determined either from direct measurements of the capacity of the section or from measurements of the mean conduit diameter and length of conduit between the detectors.

The construction drawings shall not be used for the determination of volume. It is necessary to choose the pipe section to be used as the measuring section before its erection and to determine its effective volume. It is important that this effective volume does not change owing to erection.

It should be noted that the relative uncertainty on the determination of volume has equal importance as the relative uncertainty on the determination of transit time for the assessment of the overall uncertainty on the volume flow-rate.

6.9 Measurement of gas density

If the composition of the gas and its deviation from ideal gas laws are known, the gas density may be determined from measurements of gas pressure and gas temperature in the measuring section.

Alternatively, the gas density may be measured using a suitable density cell inserted either directly into the gas flow or into a flow of sample gas at the same pressure and temperature as the gas in the measuring section. Corrections should be made for small differences in the gas conditions between the measuring cross-section and the gas density cell.

It should be noted that the relative uncertainty in the determination of gas density has equal importance as the relative uncertainties in the determination of measuring section volume and transit time in the assessment of the overall uncertainty on the mass flow-rate of gas.

7 SELECTION OF TRACER

7.1 Characteristics

The general principles for the selection of tracers are given in clause 5 of ISO 4053/I. In the present case, the following should also be taken into consideration.

7.1.1 *Type and energy of emitted radiations.*

γ-emitting tracers are preferred to β-emitting tracers because the measurement of this type of radiation can be made through pipe walls and the self-absorption of radiation by the fluid is decreased. It should however be noted that β-emitting isotopes are more easily handled.

7.1.2 *Maximum useful specific activity available.*

7.1.3 *Cost.*

7.1.4 *Maximum permissible concentration in air.*

This is an important factor in the tracer selection. Preference shall be given to the tracer with the highest ratio of the maximum permissible concentration to the concentration consistent with the desired accuracy.

7.1.5 *Half-life.*

The transit time method makes it possible to use tracers with much shorter half-lives than those required for dilution methods.

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A tracer shall be chosen with the shortest possible half-life consistent with the above-mentioned conditions and with the conditions of supply, storage and measurement of the isotope, in order to minimize any effect of contamination and radiological problems associated with the handling of the isotope.

7.2 Example of radioactive tracers used

A list of tracers which can be used is given in 5.1.2 of ISO 4053/I. Among the mostly used tracers those listed in the table can be mentioned.

8 ESTIMATION OF THE UNCERTAINTIES IN FLOW-RATE MEASUREMENT

Reference shall be made for the error determination to clause 7 of ISO 4053/I.

Generally the list of error sources is closely dependent on the various steps of the procedure described in clause 6.

8.1 The determination of the effective volume is carried out with an uncertainty due to the irregularity of the conduit between the measuring cross-sections, and to the accuracy and the pitch of the geometrical measurements. The choice of a value results in a systematic error in any flow-rate values calculated from this value, which can be associated with an additional random error if uncontrolled parameters, such as temperature and pressure, cause the measured volume to vary. The number of measurements of the conduit diameter shall be commensurate with the overall required accuracy of the flow measurement.

8.2 Incomplete mixing of the tracer at the measuring cross-sections may introduce a systematic uncertainty the value of which cannot yet be calculated. This error is considerably less than that obtained by the use of the constant rate injection method for the same degree of mixing, particularly when the concentration is measured at several points of the cross-section or when the radiation detectors are sensitive to flow in a large proportion of the conduit cross-section.

8.3 The detector defines at any time in the measuring cross-sections an approximate value of the mean tracer concentration. The value of the transit time calculated from the concentration/time curves at the positions of both measuring cross-sections is consequently affected by a systematic error which can be minimized by improvement of the detector (number and position of detector points in the section).

8.4 It is possible for the threshold sentitivity of the detection equipment to affect the accuracy of the transit time measurement, particularly when the sensitivities of both detectors are not equal, insufficient tracer is injected into the conduits and when dead spaces exist in the

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TABLE — **Most commonly used isotopes**

Isotope	Type of radiation emitted				Maximum permissible concentration[1] Ci/m³*
	Beta		Gamma		
	Energy MeV	Abundance %	Energy MeV	Abundance %	
Argon 41 (Half-life 110 min)	1,20 2,48	99,1 0,9	1,29	99,1	2×10^{-7}
Bromine 82 (Half-life 36,0 h) e.g. $C_2H_5\ ^{82}Br$ or $CH_3\ ^{82}Br$	0,44	100	0,55 0,62 0,70 0,78 0,83 1,04 1,32 1,48	75 42 28 83 25 29 28 17	1×10^{-7}
Krypton 85 (Half-life 10,6 years)	0,15 0,67	0,4 99,6	0,51	0,4	1×10^{-6}
Sulphur 35 (Half-life 87 days) e.g. $^{35}S\ F_6$	0,167	100	–	–	3×10^{-8}
Xenon 133 (Half-life 5,27 days)	0,34	100	0,081	35	1×10^{-6}

1) Values of maximum permissible concentration in air are given as a guide only, and reference should be made to national regulations.

* 1 Ci/m³ = $3,7 \times 10^{10}$ Bq/m³ (becquerel per cubic metre)

measuring section (i.e. when the ratio of the maximum signal from the detector to its threshold level is inadequate). This error can be made negligible with a suitably designed detection system, the use of sufficient tracer and the absence of dead spaces in the measuring length.

8.5 The accuracy of the transit time value is directly related to the accuracy of the pulse-emitting timing device used for the establishment of the recording time scale. The systematic uncertainty in the measurement of time caused by an inaccurate timing device can be reduced as much as possible by a suitable choice of device, whilst the random uncertainty due to readability of the time scale can be reduced by increasing the transit time (i.e. increasing the distance between detectors).

8.6 The use of different methods of determining characteristic points of the pulses as described in 6.7 introduces an additional uncertainty in the determination of the mean transit time. The systematic uncertainty of this error can be decreased when the same method of analysis is used at both sections and when dispersion of tracer is short relative to the transit time. The random uncertainty of this source depends on the method of analysis and the variation in transit time caused by the unsteadiness of flow-rate.

8.7 Uncertainties in the measurement of gas density affect the overall uncertainty in the measurement of mass flow (see example in clause 9).

8.8 Because the measurement of flow-rate by the transit time method is not instantaneous and does not apply to an average steady flow, the fluctuations of the flow-rate about the mean value introduce a random error.

8.9 The use of the transit time method involves various uncertainties which are difficult to evaluate before the measurement. No accuracy estimation can therefore be given before the measurement. However, it can be stated that under favourable conditions an accuracy of 1 % or better can be achieved.

8.10 In all cases the random uncertainty in transit time, which includes errors concerning the degree of mixing and the detection system, may be evaluated, *a posteriori*, by repeating measurements of a flow-rate with the same equipment and comparing the uncertainty with the estimation of random uncertainty, by analysing the components of the uncertainty which can be expected under normal conditions of application (see 7.3.3 of ISO 4053/I).

9 EXAMPLE OF FLOW-RATE CALCULATION

Bromine 82 ($C_2H_5{}^{82}Br$) is used to measure the flow of nitrogen in a pipe of 20 cm diameter. A single radiation detector is placed 10 m from the injection position and a second detector is placed 10 m downstream of the first. Injection of tracer is through a probe located centrally in the pipe.

9.1 Degree of mixing at the first measuring cross-section

The first measuring cross-section is 10/0,2 = 50 pipe diameters downstream of the injection position. With reference to 6.2 and figure 3 of ISO 4053/I, the variation in $\int_0^\infty C_2\,dt$ at this position is approximately 12 %. This degree of mixing is adequate for achieving an uncertainty of flow-rate measurement of better than 1 % when a γ-emitting tracer is used.

9.2 Estimation of separation and dispersion of recorded traces

The ratio, p, of transit time to the mean time for the tracer pulse to pass each detector position is such that

$$\frac{10}{0,2} = 4,25\,p\left(p + \sqrt{\frac{10}{0,2}}\right)$$

Therefore $p = 1,39$.

Because p is greater than 1, the tracer will have left the first measuring cross-section before it reaches the second measuring cross-section (with collimated radiation detectors), so that a single-channel recorder may be used to record the passage of tracer.

If 100 µCi of bromine 82 is used for each injection, the maximum concentration at the second measuring cross-section is given by the formula

$$C_m \approx \frac{3 \times 100}{4 \times 0,2^3\sqrt{20/0,2}} \approx 940\ \mu Ci/m^3$$

This calculated value may be used to check whether the sensitivity of the measurement equipment is adequate for the required accuracy of flow-rate measurement.

9.3 Volume of measuring section

The mean internal diameter of the measuring section determined from 20 separate measurements is 0,202 ± 0,000 5 m (95 % confidence level) and the measured distance between the measuring cross-sections is 10,01 ± 0,001 m.

The internal volume V is therefore :

$$V = \frac{\pi \times 0,202^2 \times 10,01}{4} = 0,320\ 8\ m^3$$

with an estimated uncertainty of

$$\pm 100\sqrt{\left(2 \times \frac{0,000\ 5}{0,202}\right)^2 + \left(\frac{0,001}{10,01}\right)^2}$$

$$\approx \pm 0,5\ \%$$

9.4 Transit time

Another important source of uncertainty in the measurement of transit time lies in the determination of the characteristic points. The value of this uncertainty is included in the uncertainty derived from the variation in measured transit times for a given flow-rate (see 9.6).

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The transit time (t_i) corresponding to a given flow-rate is obtained by comparing the distance between the mid-areas of the concentration/time curves [see figure 2 b)] with a graphically recorded time scale derived from a crystal-controlled oscillator with an uncertainty of ± 0,01 %.

9.5 Gas density

The gas density (ρ) is measured with a density meter calibrated to an accuracy of ± 0,2 % (95 % confidence level). The mean density of the nitrogen is 19,3 kg/m^3 ± 0,2 %.

9.6 Mass flow-rate in the pipe

The mass flow-rate (m_i) of nitrogen in the pipe at each injection is given, in kilograms per second, by the formula

$$m_i = \frac{V\rho}{t_i} = \frac{0{,}320\,8 \times 19{,}3}{t_i}$$

The mean mass flow-rate ($\bar{m}$) over the total measurement period of n injections is

$$\bar{m} = \frac{1}{n}\sum_{i=0}^{i=n} m_i = \frac{V\rho}{n}\sum_{i=0}^{i=n}\frac{1}{t_i}$$

and the random uncertainty due to the flow variations, determination of characteristic points of the recorded traces and random uncertainties in the time scale is given by the formula

$$t^*\sqrt{\frac{\Sigma\,(m_i-\bar{m})^2}{n\,(n-1)}}$$

where

n is the number of injections;

t^* is the Student's t statistic for $n-1$ degrees of freedom.

In this example the mean mass flow-rate is 24,3 kg/s with a random uncertainty due to flow fluctuations etc. of ± 0,4 % (95 % confidence level). The overall uncertainty in mean mass flow-rate can be estimated by combining the component uncertainties detailed above; viz :

$$\sqrt{0{,}5^2 + 0{,}01^2 + 0{,}2^2 + 0{,}4^2}$$

$$\approx 0{,}67\ \%$$

This example describes the measurement of flow in favourable measurement conditions but the uncertainty of flow measurement can be considerably greater than this value if other error sources, as listed in clause 8, are present. An objective estimation of the magnitude of these uncertainties could be made by comparison against primary standards of flow measurement, either directly or indirectly, and taking account of variations in the measuring conditions (i.e. measuring section, detector positions etc.).

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