INTERNATIONAL STANDARD ISO 4053/I

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION • МЕЖДУНАРОДНАЯ ОРГАНИЗАЦИЯ ПО СТАНДАРТИЗАЦИИ • ORGANISATION INTERNATIONALE DE NORMALISATION

Measurement of gas flow in conduits — Tracer methods — Part I : General

Mesurage de débits de gaz dans les conduites — Méthodes par traceurs — Partie I : Généralités

First edition — 1977-09-15

UDC 532.574.87

Ref. No. ISO 4053/I-1977 (E)

Descriptors : flow measurement, pipe flow, gas flow, tracer methods, statistical tests, error analysis.

Price based on 10 pages

FOREWORD

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Draft International Standards adopted by the technical committees are circulated to the member bodies for approval before their acceptance as International Standards by the ISO Council.

International Standard ISO 4053/I was developed by Technical Committee ISO/TC 30, *Measurement of fluid flow in closed conduits*, and was circulated to the member bodies in September 1976.

It has been approved by the member bodies of the following countries :

Australia	Italy	Turkey
Belgium	Korea, Rep. of	United Kingdom
France	Mexico	U.S.A.
Germany	Netherlands	Yugoslavia
India	Romania	

The member body of the following country expressed disapproval of the document on technical grounds :

Japan

Printed in Switzerland

Measurement of gas flow in conduits — Tracer methods — Part I : General

0 INTRODUCTION

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

The complete series of standards will be 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 deals with the measurement of gas flow in conduits by using tracer methods.

In a steady flow of compressible fluid, the only conservative parameter is the mass rate of flow q_m. Therefore the whole of this International Standard will refer to mass rate of flow q_m.

However, for those fluids for which the composition (and therefore, the mass density) may not be known accurately, the volume rate of flow q_v could be measured, it being understood that this volume rate of flow is only valid for the conditions of temperature and pressure at which it has been measured.

This International Standard applies to flow measurement in conduits into which a tracer can be injected in such a way that effective mixing in single phase with the gas flowing in the pipe can be achieved.

The fluid in the conduit can be a mixture of several gases provided the thermodynamic state and conditions of flow of this mixture are well defined.

Two fundamental test procedures are used :

— The first, known as the constant rate injection method, is based on the dilution principle : a tracer solution is injected into the conduit and the dilution (ratio) of this tracer in the gas flowing in the conduit is determined, this dilution being proportional to the rate of flow.

— The second is a method of measurement of the transit time (formerly called Allen velocity method) : the tracer is injected into the conduit and the time taken by the tracer to travel a specified length between two cross-sections in each of which it is detected, is measured.

The advantages and disadvantages of these two methods are considered in clause 4. The distance between injection and measuring sections shall be sufficient to achieve mixing of the tracer with the gas flowing in the conduit according to the methods; the adequate mixing distance is considered in clause 6.

A large number of different tracers may be used, such as radioactive or non-radioactive, mineral or organic materials. The choice of tracer depends on the circumstances of the measurement (see clause 5). The uncertainty of the measurements may be less than 1 % under good conditions (see clause 7).

2 VOCABULARY AND SYMBOLS

The vocabulary and symbols used in this International Standard are defined in ISO 4006, *Measurement of fluid flow-rate in closed conduits — Vocabulary and symbols.*

3 UNITS

The basic units in this International Standard are SI units.

4 CHOICE OF METHOD

4.1 Comparison between dilution method and method based on transit time measurement.

4.1.1 *Advantages of the dilution method*

It is not necessary to know the geometrical characteristics of the conduit.

It is not necessary that the conditions of the gas flow rate (p, T) be constant along the measuring length.

4.1.2 *Advantages of method based on transit time measurement*

It is necessary only to determine the concentration-time distribution at two measuring cross-sections separated by a known volume of pipe.

It is not necessary to know volumes, masses or rates of flow of the injected tracer.

4.1.3 *Special recommendation for the method based on transit time measurement*

For this method, it is preferable to have a conduit length of constant cross-section between the two measuring points so that the flow parameters be approximately constant in the measuring length.

5 CHOICE OF TRACER

5.1 General

A large number of different tracers may be used, such as mineral or organic, radioactive or non-radioactive, but it is necessary for any tracer to comply with the following requirements :

a) it should mix easily with the gas in the conduit;

b) it should cause only negligible or known modifications of the rate of flow;

c) it should be measurable with sufficient accuracy at a concentration lower than the highest permissible concentration while taking account of toxicity, corrosion, etc.;

d) it should be chemically stable in the conditions of use;

e) it should only be present in the gas originally flowing in the conduit at a negligible or constant concentration;

f) it should be cheap.

In addition, for dilution method, it is important that the tracer :

g) should not react with the gas flowing in the conduit or with any other substance with which it may come into contact (in particular, the conduit walls) in such a way as to affect the measurement.

Furthermore, for transit time methods, it is recommended that :

h) the tracer concentration in the measuring cross-section can be determined, if necessary, at any moment;

i) to obtain the greatest precision, the detector signal be proportional to the tracer concentration (of which it is not necessary to know the exact value) and that its response time be negligible.

The following substances are given as examples :

5.1.1 *Non-radioactive tracers*

- Helium He
- Sulphur hexafluoride SF_6
- Methane CH_4
- Nitrous oxide N_2O

5.1.2 *Radioactive tracers*

Tracer	Formula (if any)	Half-life
Argon 41		110 min
Arsenic 76	$^{76}AsH_3$	26,5 h
Bromine 82	$C_2H_5{}^{82}Br$ or $CH_3{}^{82}Br$	36 h
Krypton 85		10,6 years
Sulphur 35	$^{35}SF_6$	87 days
Xenon 133		5,27 days

5.2 Comparison between the different tracers

5.2.1 *Advantages of radioactive tracers*

With tracers emitting γ radiation with sufficient energy, it is possible to carry out the measurement by means of probes located outside the conduit.

With short half-life tracers, the basic substance of which is chemically inoffensive, any radioactive contamination danger disappears quickly and there is no permanent pollution.

5.2.2 *Advantages of non-radioactive tracers*

It is not necessary for the operators to be specially trained and classified.

Administrative authorizations are not necessary for each measurement and radioprotective means are not required.

The substances generally remain stable with time; delays between the supply and the use of the substance do not matter.

6 CHOICE OF MEASURING LENGTH AND ADEQUATE MIXING DISTANCE

6.1 Introduction

When a tracer is used to measure the flow of gas in a conduit, there should be sufficient distance between the region in which the tracer is injected and the region in which concentration or transit time measurements are made.

The distance which is required in order to allow the tracer to mix with the gas in the conduit is known as the mixing

distance. This distance is defined as the shortest distance at which the maximum variation (x), over the cross-section, of $\int_0^\infty C_2 dt$ for the integration method or the concentration of tracer for the constant rate injection method is less than some predetermined value (for example, 0,5 %) where C_2 is the concentration of the tracer in the conduit. Thus, the mixing distance is not a fixed value, but varies according to the allowed concentration variations : the smaller the acceptable variation the greater the mixing distance.

For highest accuracy in flow measurement it is necessary to ensure the smallest possible values of (x) at the measuring cross-section. However, in practice higher values of (x) may have to be tolerated when sufficiently long lengths of conduit are not available.

A multipoint sampling or detection arrangement should be used where possible, particularly when a systematic variation in concentration or in $\int_0^\infty C_2 dt$ may exist at the sampling cross-section.

Depending on the tracer and the method of detection used, the mixing requirements for the transit time method may not be so stringent as for dilution methods.

Several techniques have been developed to reduce the mixing distance and these should be used whenever it is possible (see 6.3).

6.2 Mixing distance

6.2.1 *Theoretical derivation of mixing distance*

Attention is drawn to the fact that the mixing length found in practice can vary considerably from the length predicted theoretically (see 6.2.2). Sub-clause 6.2.1.1 should not be used as more than a preliminary guide.

6.2.1.1 CENTRAL INJECTION

The following equations relating mixing distance (L/D) in terms of the varying concentration of tracer across the conduit, Reynolds number (Re) and pipe friction have been developed. Equation (1) is derived on the basis of a constant radial diffusion coefficient and uniform flow velocity; equation (2) is derived on the basis of a parabolic distribution of radial diffusion coefficient and uniform flow velocity; equation (3) assumes a parabolic distribution of radial diffusion coefficient and a logarithmic velocity profile.

$$\frac{L}{D} = 1{,}18 \sqrt{\frac{8}{\lambda}} \left(2{,}94 - \frac{\ln x}{2{,}30}\right) \quad \ldots (1)$$

$$\frac{L}{D} = \left(2{,}95 - \frac{\ln x}{2{,}4}\right) \sqrt{\frac{8}{\lambda}} \quad \ldots (2)$$

$$\frac{L}{D} = (20{,}5 - 2{,}85 \ln x)\, Re^{1/10} \left[\frac{\lambda_0}{\lambda}\right]^{1/2} \quad \ldots (3)$$

where

x is the maximum variation, in %, across the pipe of concentration C_2 for the constant rate injection method, or of $\int_0^\infty C_2 dt$ for the integration method, at a distance L from the point of injection;

D is the diameter of the conduit;

λ is the coefficient of resistance of the conduit;

λ_0 is the coefficient of resistance of a perfectly smooth conduit.

The above equations presented graphically in figure 1 show the increase in mixing distance with decrease of x for a Reynolds number of $Re = 10^5$ and a smooth conduit.

The slight dependence of mixing distance on Reynolds number (see equation (3) for example) is shown in figure 2. For a change in Re from 10^5 to 10^6, at $x = 1$ % the mixing distance increases by only 25 %, approximately.

6.2.1.2 RING INJECTION

For uniform injection over a ring with a radius of 0,63 of the conduit radius, the mixing distances are reduced to about one-third of the values derived for a central injection.

6.2.2 *Experimental derivation of mixing distance*

Values of mixing distance obtained experimentally for a central injection in an unobstructed, straight, circular conduit are about twice the values predicted theoretically. The difference is attributed to several causes but particularly to the difference between the actual flow conditions and those assumed in the theoretical analysis. Care shall therefore be exercised in the treatment of theoretical results.

Details concerning experimental determination of good mixing are given in the parts of the relevant standard.

The measured change in mixing distance with (x) for a central injection and for three other methods of injection is shown as an example in figure 3. It should be noted that the flow turbulence level influences these results.

6.3 Examples of methods of reducing mixing distance

6.3.1 *Multi-orifice injectors*

When the tracer is injected equally through a number of orifices spaced across the conduit (at least four), a reduction in mixing distance can be achieved compared with the mixing distance associated with a central injector.

An example of the reduction in mixing distance that can be achieved by using four injectors, equally spaced around the wall of a conduit and a radius of 0,63 for the conduit radius, is shown in figure 3.

6.3.2 *High velocity jets*

If the tracer is injected against the flow with a velocity which far exceeds the mean velocity of the gas in the conduit, impact mixing occurs at the termination of the jet. The reduction in mixing distance depends on the number and the momentum of the jets and their inclination to the direction of flow.

Accurate quantitative information on the effect of the above parameters is not yet available but reductions in mixing distance to approximately 30 % of that for a single central injector can be obtained by using a simple configuration of jets.

6.3.3 *Vortex generators*

A turbulent wake which stimulates mixing and reduces the mixing distance can be obtained by flow deflection plates built into the conduit close to the injection region.

For example, the mixing distance has been reduced to one-third of that with a single central injector by injecting the tracer through three triangular plates set at an angle of 40° to the direction of flow.

6.3.4 *Fans*

A considerable reduction in mixing distance may be effected by injecting the tracer upstream of a fan. Information on mixed-flow pumps indicates that this type of pump reduces the mixing distance by about 100 diameters.

6.3.5 *Bends, valves and other obstructions*

Obstructions in the conduit introduce additional turbulence and thus tend to reduce the mixing distance. Quantitative information on these types of mixing promotors is not available but measuring sections that include these devices are to be preferred. In the transit time method, however, the length of conduit between detectors should be straight and free of obstruction if the highest accuracy is required.

6.4 Case of a measuring length less than the mixing distance

The error due to the use of a distance between the injection cross-section and the sampling cross-section less than the mixing distance can be reduced if samples are recovered simultaneously from a number of positions across the conduit and are then mixed prior to measurement.

For example, at $Re = 10^5$ six sampling points having the same discharge equally spaced across the conduit at 50 diameters downstream from the point of injection were found to be equivalent to a single sampling point at the wall at about 100 diameters from the point of injection.

6.5 Choice of measuring length

6.5.1 *Dilution method*

For constant rate injection method, the measuring length is defined as the length of conduit between the injection position and the sampling point. This length should be determined after consideration has been given to 6.2, 6.3 and 6.4 about the mixing of the tracer.

The addition of gas of the same nature as that in the measuring length does not affect the result, provided that the mixture remains homogeneous at all points of the measuring cross-section. The flow measured is the total flow through the measuring cross-section.

If the measuring length includes losses or sampling points, the result obtained is valid only if it is possible to estimate or to verify that the mixture is homogeneous upstream of the loss zone. In this case, the flow measured is the flow in the conduit immediately upstream of the loss zone.

6.5.2 *Transit time method*

The measuring length for the transit time method may be considered to consist of two parts, i.e. :

a) the length of conduit between the point of injection of the tracer and the first detector position;

b) the length of conduit between the two detector positions.

Part a) should be determined after consideration has been given to 6.2, 6.3 and 6.4 about the mixing of tracer. The mixing requirement for this method may not be so stringent as for the dilution method, depending on the tracer and method of detection used.

Part b) should be determined from consideration of the degree of longitudinal dispersion of the tracer, the mean velocity expected and the accuracy of measurement of transit time.

Additions of gas before the first detector position of the same nature as the gas in the measuring length upstream of the detector do not affect the result, provided that the mixture remains homogeneous at all points of the cross-section in which the first detector is positioned.

Losses of gas from the conduit before the first detection position do not affect the result but if the tracer is not completely mixed at the position of the loss, the amplitude of the concentration-time distribution at the detection positions may be affected and its value changed by a constant factor for each measurement.

Losses or additions of gas in the length of conduit between detection positions would cause serious errors in the measurement of flow. Consequently it is essential that the conduit between the two detector positions contains no branch connections and that there is no leakage from it.

For the highest accuracy, the length of conduit between detector positions should be straight and free from obstruction (for example valves).

In all cases it is necessary to know the volume of conduit between the detector positions.

7 ERRORS

7.1 General

As with any measurement of a physical quantity, the determination of a flow rate in a conduit by tracer methods is subject to uncertainties related :

— either to systematic errors due to errors in the measuring apparatus or in the measuring process used;

— or to a random error obtained by random variations in the flow system (especially for gaseous fluids with a compressibility which may affect flow parameters) or in the measuring equipment.

7.2 Systematic errors

7.2.1 As with any measuring instruments, those used for flow measurement may possess a number of imperfections, linked to their design or to selected method of use, which affect the measurements in a known manner. These effects may be eliminated totally or partly, either by using appropriate methods or by applying corrections to the results based on a knowledge of some environmental parameters of the measuring process.

7.2.2 Another type of systematic error can exist in the measurement of flow by means of tracers, of which the direction may be defined but the magnitude cannot be estimated; such errors result from phenomena connected with the disappearance of certain quantities of tracer by chemical reaction with the conduit walls. The systematic errors which may be caused by these reactions generally lead to an overestimation of the flow rate (disappearance of tracer) when using dilution methods.

This error can be reduced to insignificance by the selection of a suitable tracer, and the use of appropriate injection, detection sampling and analysis procedures.

7.3 Random errors

In this International Standard, error values correspond to 95 % confidence limits.

7.3.1 The possible error on a flow rate measurement cannot be determined exactly *a priori*, but it is possible :

a) to achieve statistical estimation of the tolerance (for 95 % confidence limits), under general conditions of use of a particular method, by an evaluation of the tolerances on individual measurements in the calculation of rate of flow (this estimation is made possible by an analysis of a large number of measurements);

b) in the particular case of a measurement repeated only a small number of times, to determine 95 % confidence limits applicable to the estimate of the result that would have been obtained if the measurements had been repeated for a large number of times as obtained from the mean of the measuring sample alone (use of the Student variable).

In the case of gaseous fluids it will be necessary to check the reproducibility of flow, and in particular to decide *a priori* on intervals of variation of flow parameters so that the above mentioned statistical laws may be applicable.

7.3.2 *Tolerance under general conditions of use*

The tolerance may be assumed to be twice the standard deviation of the measurement of flow rate in the case of Gaussian distribution of errors. If the individual errors in the various measurements are small and independent, the tolerance on flow measurement is then equal to :

$$2\frac{\sigma_{q_v}}{q_v} = 2\sqrt{\left(\frac{\partial q_v}{\partial x_1}\times\frac{\sigma_{x1}}{q_v}\right)^2 + \left(\frac{\partial q_v}{\partial x_2}\times\frac{\sigma_{x2}}{q_v}\right)^2 + \ldots}$$

where

$\frac{\partial q_v}{\partial x_1}, \frac{\partial q_v}{\partial x_2}, \ldots$ are partial derivatives, the value of which depends on the manner in which q_v is a function of x_1, x_2, ...;

$x_1, x_2, x_3, \ldots$ are the independent quantities measured;

σ_{x1}, σ_{x2}, σ_{x3}, ... are the standard deviations of the measurements of $x_1, x_2, x_3, \ldots$

If an independent quantity y has been obtained by N repeated measurements, which would be the case where, for example, a dilution ratio has been obtained from a large number of samples, and if the results of these measurements are denoted by $y_1, y_2, \ldots, y_n$, the standard deviation of the mean y_0 of these N measurements is defined as :

$$\sigma_{y_0} = \sqrt{\frac{\sum_{i=1}^{i=N}(y_1 - y_0)^2}{N(N-1)}}$$

If the value of an independent quantity results from a small number of measurements N, it is possible within a given confidence limit to define an interval in which the standard deviation of a large number of measurements can be found :

$$\frac{s\sqrt{N}}{\chi_{(n+100)/2}} < \text{standard deviation} < \frac{s\sqrt{N}}{\chi_{(100-n)/2}}$$

where

s is the estimate of the standard deviation calculated from a small number of measurements;

n is the confidence limit (in %) chosen;

$\chi_{(n+100)/2}$ and $\chi_{(100-n)/2}$ are the numerical values derived from a distribution table of χ^2 (see table in annex).

The value of n is generally taken to be 95.

Example : the 95 % confidence interval of the standard deviation of a quantity, the estimation of which from 19 measurements is s, is :

$$\frac{s\sqrt{19}}{\sqrt{8,23}} \quad \frac{s\sqrt{19}}{\sqrt{31,5}} \quad \text{i.e. } 1,5\,s \text{ and } 0,78\,s$$

where 8,23 and 31,5 are respectively the values read in the distribution table of χ^2 :

$$\left.\begin{array}{l} \text{column } P = 0,975 = \dfrac{95 + 100}{2 \times 100} \\ \text{column } P = 0,025 = \dfrac{100 - 95}{2 \times 100} \end{array}\right\} \text{line } \nu = 18 = 19 - 1$$

7.3.3 *Estimation of the tolerance on a particular measurement repeated a small number of times*

The 95 % confidence interval of the mean value is :

$$\overline{q_v} \pm t^* \frac{s}{\sqrt{N-1}}$$

where

$\overline{q_v}$ and s are the estimates of the mean and of the standard deviation respectively as obtained from the measurements;

t^* is the numerical value of the Student variable derived from a distribution table;

ν is the degree of freedom.

An extract from this table is given below.

ν	t^*
1	12,706
2	4,303
3	3,182
4	2,776
5	2,571
6	2,447
8	2,306
10	2,228
15	2,131
20	2,086
25	2,060
30	2,042
40	2,021
80	2,000
120	1,980
∞	1,960

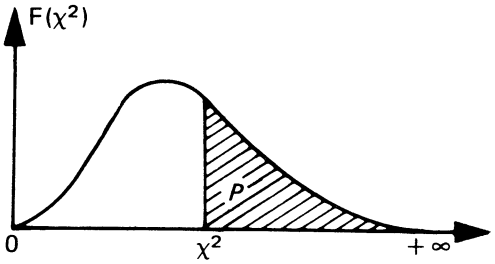
7.3.4 The error of the measurement is obtained from the equation given in 7.3.3 and should be compared with the error estimated from the equation in 7.3.2 in order to check that the method has been correctly applied. If a considerable difference in values is obtained, the results should be re-examined in order to determine the source of the discrepancy.

ANNEX

DISTRIBUTION TABLE OF χ^2
(Pearsons' Law)

Values of χ^2 having the probability P to be exceeded with ν degrees of freedom

$$P = \frac{n + 100}{2 \times 100} \text{ or } \frac{100 - n}{2 \times 100}$$



When $\nu \leqslant 30$

ν \ P	0,990	0,975	0,950	0,900	0,100	0,050	0,025	0,010	0,001
1	0,0002	0,0010	0,0039	0,0158	2,71	3,84	5,02	6,63	10,83
2	0,02	0,05	0,10	0,21	4,61	5,99	7,38	9,21	13,82
3	0,12	0,22	0,35	0,58	6,25	7,81	9,35	11,34	16,27
4	0,30	0,48	0,71	1,06	7,78	9,49	11,14	13,28	18,47
5	0,55	0,83	1,15	1,61	9,24	11,07	12,83	15,09	20,52
6	0,87	1,24	1,64	2,20	10,64	12,59	14,45	16,81	32,46
7	1,24	1,69	2,17	2,83	12,02	14,07	16,01	18,47	24,32
8	1,65	2,18	2,73	3,49	13,36	15,51	17,53	20,09	26,13
9	2,09	2,70	3,33	4,17	14,68	16,92	19,02	21,67	27,88
10	2,56	3,25	3,94	4,87	15,99	18,31	20,48	23,21	29,59
11	3,05	3,82	4,57	5,58	17,27	19,67	21,92	24,72	31,26
12	3,57	4,40	5,23	6,30	18,55	21,03	23,34	26,22	32,91
13	4,11	5,01	5,89	7,04	19,81	22,36	24,74	27,69	34,53
14	4,66	5,63	6,57	7,79	21,06	23,68	26,12	29,14	36,12
15	5,23	6,20	7,26	8,55	22,31	25,00	27,49	30,58	37,70
16	5,81	6,91	7,96	9,31	23,54	26,30	28,84	32,00	39,25
17	6,41	7,56	8,67	10,08	24,77	27,59	30,19	33,41	40,79
18	7,01	8,23	9,39	10,86	25,99	28,87	31,53	34,80	42,31
19	7,63	8,91	10,12	11,65	27,20	30,14	32,85	36,19	43,82
20	8,26	9,59	10,85	12,44	28,41	31,41	34,17	37,57	45,32
21	8,90	10,28	11,59	13,24	29,61	32,67	35,48	38,93	46,80
22	9,54	10,98	12,34	14,04	30,81	33,92	36,78	40,29	48,27
23	10,20	11,69	13,09	14,85	32,01	35,17	38,08	41,64	49,73
24	10,86	12,40	13,85	15,66	33,20	36,41	39,37	42,98	51,18
25	11,52	13,12	14,61	16,47	34,38	37,65	40,65	44,31	52,62
26	12,20	13,84	15,38	17,29	35,56	38,88	41,92	45,64	54,05
27	12,88	14,57	16,15	18,11	36,74	40,11	43,19	46,96	55,48
28	13,57	15,31	16,93	18,94	37,92	41,34	44,46	48,28	56,89
29	14,26	16,05	17,71	19,77	39,09	42,56	45,72	49,59	58,30
30	14,95	16,79	18,49	20,60	40,26	43,77	46,98	50,89	59,70