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Measurement of fluid flow rate in closed conduits — Radioactive tracer methods

Mesure du débit des fluides dans des conduites fermées — Méthodes par traceur radioactif

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Foreword

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This document was prepared by Technical Committee ISO/TC 30, *Measurement of fluid flow in closed conduits*, Subcommittee SC 5, *Velocity and mass methods*.

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Introduction

The accurate knowledge of fluid flow rates (liquid and gas) in industrial systems is an essential requirement of processing industries. The fluid flow rate measurement is usually needed for various reasons i.e. calibration of installed flow meters, fluid balance, measurement of efficacy of pumps or turbines, distribution of flow in a network of pipes, etc. Generally, the industrial systems where the flow rates are needed to be measured are classified into two categories, namely open channels and closed conduits. Closed conduits are conveyance systems where the flow of fluid is confined on all boundaries (i.e. pipe systems) while open channels are systems where the stream has a free surface open to the atmosphere such as canals, rivers, streams, sewer lines, effluent channels, partly filled conduits.

This document deals with single phase fluid flow rate measurement in closed conduits only, by using the radioactive tracer method. Flow in closed conduits is caused by an axial pressure difference. Various types of flow meters, such as ultrasonic, electromagnetic, acoustic, Venturi, Pitot tube, and gamma transmission, are routinely used for flow rate measurements in closed conduits in industry. The selection of a suitable method for a particular application depends on the type and nature of the system, physical properties of the flowing fluid, flow patterns of the fluid, limitations imposed by the design and operating condition of the plant, cost and installation of the equipment. One advantage of the radioactive tracer methods is that measurement can be carried out online in harsh industrial environment, from outside of the conduits while the process is in operation, with no disruption, and with a high accuracy. This document treats radioactive tracer methods only.

The use of radioactive tracer methods for the measurement of fluid flow rates in closed conduits is one of the most common and well-established application of the radioactive tracer technology in industry. The major methods that have been found to be particularly applicable for online flow rate measurement and flowmeter calibration are the pulse velocity or transit time method, as well as dilution methods, known as constant rate injection method and integration method.

This document is developed to fill the need for a generalized reference based on fundamental principles to measure fluid flow using radioactive tracer methods.

For single phase steady-state flow of fluid in a closed conduit, the volumetric flow rate can be measured using this method. If the mass density is known, the mass flow rate can be deduced from the volume flow rate.

The accuracy of flow rate measurement with the radioactive tracer methods depends on how well the injected tracer material mixes with the flowing fluid before the measuring section. It depends on the amount of tracer injected and the accuracy of the measurement devices.

Measurement of fluid flow rate in closed conduits — Radioactive tracer methods

1 Scope

This document defines the measurement of single phase fluid flow rate in closed conduits using radioactive tracer methods.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
closed conduit
conveyance system where the flow of fluid is confined on all boundaries (i.e. pipe systems)

3.2
mixing length
l_m
shortest distance at which the variation in concentration of the tracer over the cross-section is less than some pre-determined value (for example 0,5 %)

4 Principles of radioactive tracer methods

4.1 General

Three radioactive tracer methods for flow rate measurement have been used:

— transit time method;

— constant rate injection method;

— integration method.

Both the constant rate injection method and the integration method are part of the dilution methods. Radiation dose considerations are given in Annex B.

4.2 Transit time method

4.2.1 Principle

In the transit time method, a quantity of a radioactive tracer is injected instantaneously into a flowing stream. Two detection cross-sections downstream the injection cross-section are commonly used for registration of the gamma radiation emitted from the radioactive tracer in the flow. Both cross-sections are sufficiently far from the injection cross-section to allow adequate (homogeneous) mixing of the tracer with the fluid flow. Each detector registers a response curve when the tracer cloud crosses the detection cross-section. The two response curves are compared to provide the transit time of the tracer or fluid between the two detection cross-sections. Under these conditions, the volumetric flow rate Q is given by Formula (1):

$$Q = \frac{V}{\bar{t}} \tag{1}$$

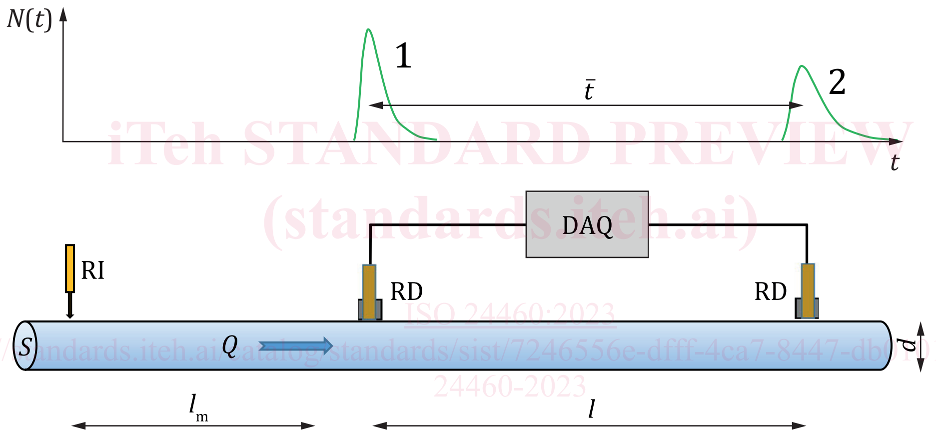
where

Q is the volumetric flow rate;

V is the volume of the conduit between the detection cross-sections;

$\bar{t}$ is the transit time of the tracer between the two detection cross-sections.

The value of $\bar{t}$ is obtained by measuring the difference in the centre of gravity, i.e. the first moment of the two response curves as shown in Figure 1.



Key

1 response curve of 1st detector
2 response curve of 2nd detector
t time
$\bar{t}$ transit time of the tracer between the two detection cross-sections
Q volumetric flow rate
DAQ data acquisition system
S area of across-section
RI radioactive tracer injector
RD radiation detector
l_m mixing length
l distance between the two detection cross-sections
d inner diameter of conduit
$N(t)$ measured radiation count rate

Figure 1 — Principle of transit time method

The volume of the measuring section, V, and the volume flow rate, Q, are given respectively by Formulae (2) and (3):

$$V = S \cdot l \tag{2}$$

$$Q = \frac{V}{\bar{t}} = \frac{S \cdot l}{\bar{t}} \tag{3}$$

where

V is the volume of the conduit between the detection cross-sections;

S is the cross-section of the fluid in the closed conduit;

l is the distance between the two detection cross-sections;

$\bar{t}$ is the transit time of the tracer between the two detection cross-sections.

The transit time, $\bar{t}$, is calculated by the difference in the mean residence times (first moments) between the two response curves, as given by Formula (4):

$$\bar{t} = \tau_2 - \tau_1 = \frac{\sum t_{2i} n_{2i}}{\sum n_{2i}} - \frac{\sum t_{1i} n_{1i}}{\sum n_{1i}} \tag{4}$$

where

$\bar{t}$ is the transit time of the tracer between the two detection cross-sections;

τ is the mean residence time, and the indexes 1 and 2 refer to the 1st and 2nd detector, respectively;

n is the corrected count per count time, and the indexes 1 and 2 refer to the 1st and 2nd detector, respectively.

4.2.2 Special recommendation for the transit time method

For this method, a conduit length of constant cross-section between the two detection cross-sections should be ensured, so that the flow parameters are constant over the measuring length. The internal volume of the measuring section shall be determined with sufficient accuracy.

4.2.3 Advantages of transit time method

The radioactive tracer transit time method seems to provide the most effective field calibration method for flow rate measurement in closed conduits. It is suitable for both liquid and gas flows and covers a large range of flow rates with a small uncertainty (see Annex A).

The main advantages of this method are as follows:

— it is only necessary to determine the response curve at two detection cross-sections;

— it is not necessary to know activity, volume or flow rates of the injected radioactive tracer;

— it is not necessary to collect any samples;

— the activity of the radioactive tracer used by this method is considerably smaller than needed for other methods.

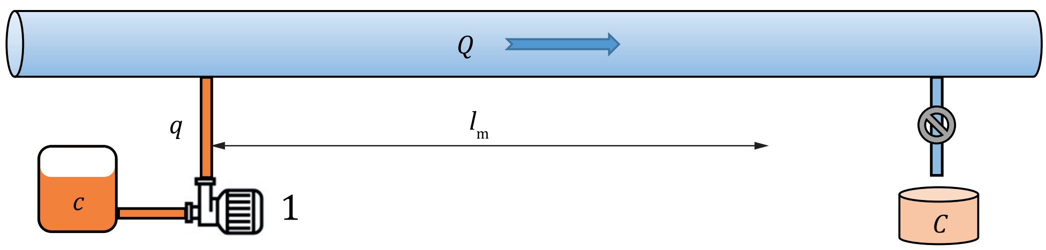
4.3 Constant rate injection method

4.3.1 Principle

The constant rate injection method is based on the principle of conservation of tracer activity. A tracer of activity concentration c is injected with constant volume flow rate q to the main flow with volume flow rate Q. As there is no gain or loss of tracer in the measuring section, the injected tracer shall eventually appear with the same total activity (but with a different activity concentration, C, because of dilution in the main flow) at any downstream detection point, as given by Formula (5):

$$q \times c = Q \times C \tag{5}$$

Figure 2 shows the principle of constant rate injection method.



Key

1 constant rate injection pump

Q volumetric flow rate in closed conduit

q volumetric flow rate of tracer solution

l_m mixing length

c activity concentration of tracer solution

C activity concentration of collected sample

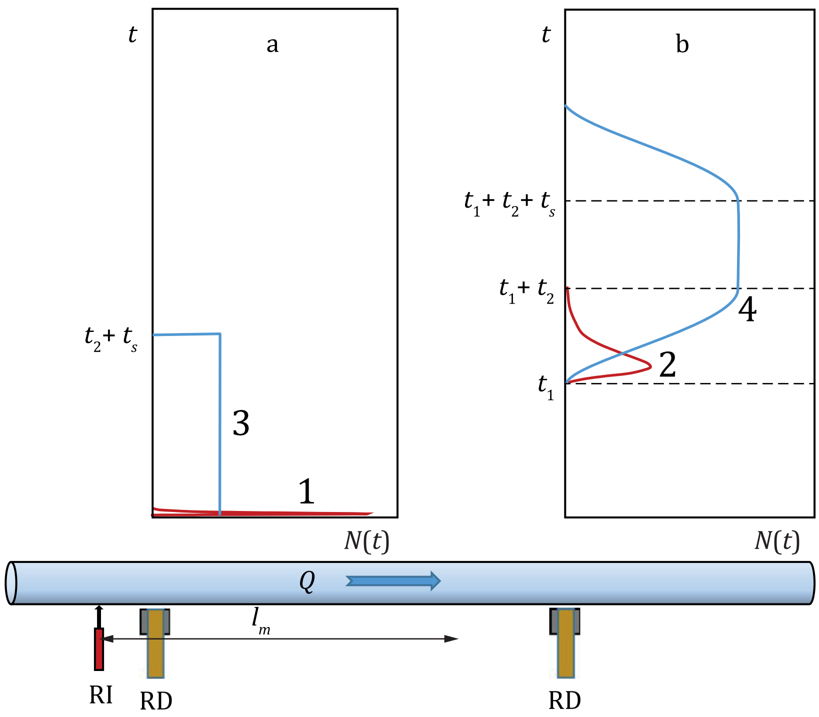
Figure 2 — Principle of constant rate injection method

The volumetric flow rate of the mainstream can be calculated by Formula (6):

$$Q = q \frac{c}{C} \tag{6}$$

4.3.2 Duration of injection

The duration of injection shall be such that stable concentration conditions are established at all points of the sampling cross-section over a sufficient period of time. A suitable duration of injection may be determined by a preliminary investigation involving a pulse injection of a radioactive tracer. The response curve (curve 2 of Figure 3) of the pulse injection is obtained at the sampling cross-section. The curve starts at time t_1 after the injection and the duration of the curve is t_2.



Key

1	pulse injection curve
2	response curve of the pulse injection
3	imaginary constant rate injection curve
4	response curve of the imaginary constant rate injection
Q	volumetric flow rate
t	time
t_s	time for sampling
$N(t)$	measured radiation count rate
RI	radioactive tracer injector
RD	radiation detector
l_m	mixing length
[a]	Tracer injection curves at injection point.
[b]	Tracer response curves at measuring point.

Figure 3 — Determination of the duration of injection

In constant rate injection method, if it is required to achieve steady conditions for a period of time t_s in a selected sampling cross-section, it is necessary to keep the constant rate injection for a period of time $t_2 + t_s$. Then, the measurement (detection or sampling) can be performed from the time $t_1 + t_2$ to time $t_1 + t_2 + t_s$, after the start of the constant rate injection.

4.3.3 Advantage of the constant rate injection method

The main advantage of this method is:

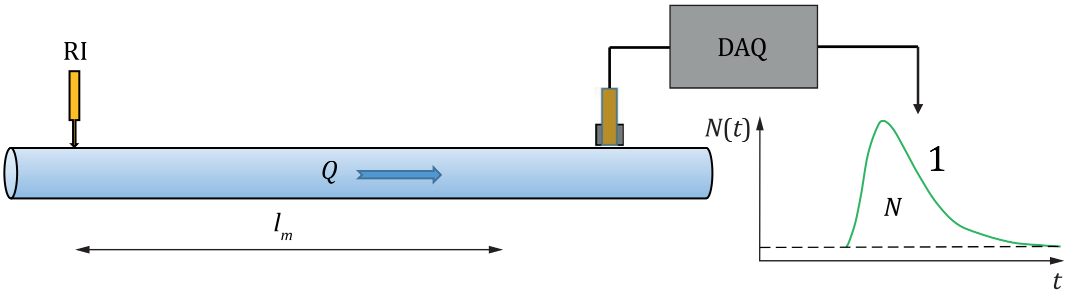
— that it is not necessary to know the geometrical characteristics of the conduit.

4.4 Integration method

4.4.1 Principle

In integration (or total-count) method, it is assumed that if an activity *A* of tracer is injected, then this amount — as there is no gain or loss of tracer in the measuring section — shall eventually pass any downstream detection cross-section.

Pulse injection of tracer into closed conduit is applied. The flow rate is determined from the cumulative response of a detector located externally on the closed conduit. Figure 4 shows the principle of the integration method.



Key

1 response curve of injected radioactive tracer

RI radioactive tracer injector

Q volumetric flowrate

l_m mixing length

DAQ data acquisition system

$N(t)$ measured radiation count rate

N integrated net radiation count

t time

Figure 4 — Principle of integration method

The integrated net radiation count, *N*, (corrected for background and decay) is registered, then the flow rate *Q* is given by Formula (7)

$$Q = F\frac{A}{N} \tag{7}$$

where

A is the total injected activity [Bq];

F is the calibration factor relating *A* to *N* [counts per unit time per Bq/l];

N is the integrated net radiation count.

The calibration factor, *F*, [counts per unit time per unit activity concentration] shall be determined beforehand. For the calibration of detector placed external to a closed conduit a section of identical conduit shall be set up. This section shall be longer than the field of view of the collimated detector. Then, the net radiation count rate of an identically located detector to a known activity concentration within the conduit shall be measured.

4.4.2 Advantages of the integration method

The main advantages of the integration method compared to the constant rate injection method are:

— a smaller amount of radioactive tracer can be used;

— less field operation time is needed.

5 Choice of radioactive tracer

5.1 General

5.1.1 Requirements

The radioactive tracer shall comply with the following requirements:

— have identical flow behaviour as the fluid being traced;

— mix easily and homogeneously with the fluid in the conduit;

— be measurable with sufficient sensitivity;

— have a suitable half-life for the examination;

— be sufficiently chemically stable under the conditions of use;

— be affordable.

5.1.2 Radioactive tracers

Tables 1 and 2 present the commonly used radioactive tracers for measurement of fluid flow rate. Only gamma ray emitting tracers are considered here.

Table 1 — Tracers labelled with radionuclides produced in nuclear reactors or particle accelerators

Radionuclide	Half-life	Gamma energy in keV (Probability in %)	Chemical form of tracer/ form of carrier compound	Traced phase
Sodium-24 (^{24}Na)	15 h	1 368,6 (100) 2 754,0 (100)	$^{24}Na^+$/Sodium carbonate, Na_2CO_3 or Sodium bicarbonate, $NaHCO_3$	Aqueous
Bromine-82 (^{82}Br)	36 h	554,5 (71,7) 619,1 (43,7) 698,4 (28,4) 776,5 (83,6) 1 044,0 (25,6) 1 317,5 (26,9)	$^{82}Br^-$/Ammonium bromide, NH_4Br	Aqueous
			Radiolabelled p-dibromobenzene, $C_6H_4{}^{82}Br_2$/ $C_6H_4Br_2$	Organic
			$CH_3{}^{82}Br$/Methyl bromide, CH_3Br	Gases
Iodine-123 (^{123}I)	13,2 h	159,0 (83,3)	$^{123}I^-$/Potassium iodide, KI or sodium iodide, NaI	Aqueous
			Radiolabelled iodobenzene, $C_6H_5{}^{123}I/C_6H_5I$	Organic
Iodine-131 (^{131}I)	8,03 d	364,5 (81,5)	$^{131}I^-$/Potassium iodide, KI or sodium iodide, NaI	Aqueous
			Radiolabelled iodobenzene, $C_6H_5{}^{131}I/C_6H_5I$	Organic

