ASME MFC-13M–2006

Measurement of Fluid Flow in Closed Conduits: Tracer Methods

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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CONTENTS

Table

Nonmandatory Appendices

FOREWORD

This Standard defines the use of tracer (dilution) methods in the measurement of single-phase fluid (gas or liquid) flows in closed conduits. This method of measurement is applicable only to single-phase homogeneous fluid mixtures.

This Standard was developed to fill the need for a generalized reference based on fundamental principles to measure fluid flow using tracer methods. ISO standards issued in 1977 addressed tracer methods for gas flows; these were withdrawn in 2001, leaving a void on this subject. An Internet search on this subject will find a large number of documents, standards, references, consultants, and manufacturers. Most of the papers, standards, and products are for very specific applications and provide detailed guidance only for those needs. This Standard defines the terms and principles needed for intelligent consideration of tracer methods for any application.

ASME MFC-13M–2006 was approved by the American National Standards Institute on September 29, 2006.

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MEASUREMENT OF FLUID FLOW IN CLOSED CONDUITS: TRACER METHODS

1 SCOPE AND FIELD OF APPLICATION

For steady-state flow of fluid in a closed conduit, the only conserved parameter is the mass rate of flow, q_m. If the mass density is known, the volume rate of flow, q_v, can be deduced.

The accuracy of flow rate measurement with the tracer methods is a function of how well the injected tracer material mixes with the flowing fluid. It is also a function of the accuracy and precision of the sensing devices, and the (tracer methods) techniques used.

The following two tracer methods are used:

(a) The dilution method is based on a constant rate of tracer injection, and the concentration of tracer found in the downstream conduit is a measure of the relative flow rates.

(b) The transit time method determines the flow rate by measuring the time it takes the tracer material to travel between two detector points or between the injection point and a detector point in the conduit.

The advantages and disadvantages of these two methods are reviewed in section 4.

A wide variety of tracer materials may be used — radioactive or nonradioactive, mineral or organic materials, etc. The choice of tracer depends on the purpose of the measurement and environmental concerns (section 5). The uncertainty of the measurements depends completely on the accuracy of the methods used (section 7). Some typical tracer fluids are listed in Nonmandatory Appendix A.

2 SYMBOLS

See Table 1.

3 UNITS

Calculations for mass and volumetric flow rates in this document are expressed in terms of ratios of lengths and in other nondimensional parameters, as shown in Table 1. Hence, no dimensional units are defined for those terms.

4 METHOD OF USE

4.1 Dilution

In the dilution method, a measured quantity of tracer fluid of known composition is injected into the flowing stream at the injection point. At the detection location, the mixture is analyzed for composition. A simple calculation provides the flow of the main stream. If the mass of the tracer stream is known, then the result is in mass units.

4.1.1 Advantages of the Dilution Method

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

(b) It is not necessary that the flowing conditions of the fluid (p, T) be the same between the two measuring cross sections.

(c) It is not necessary to know the time of injection.

(d) It is inherently a mass flow measurement.

4.2 Transit Time Method

In the transit time method, a quantity of tracer fluid is injected into the flowing stream. Two detection points are commonly used, with both far enough downstream to allow adequate mixing and far enough apart to achieve adequate precision in the time measurement. The flow of the mixed fluids should be continuous from the time of injection until the mixed fluid is detected at the second detection point. The time for the detected change in fluid properties is compared at the two points to provide the average velocity of the fluid mixture. The shape of the detected rise time, the length of the pulse, and the rate of decay are all used to estimate the degree of mixing and possible error. The cross section of the flow conduit at the detection points is used with the flow time to determine the volumetric flow rate at the second detection point. The time required for tracer fluid injection is determined by the response time of the detector and the system geometry.

4.2.1 Advantages of the Transit Time Method

(a) It is necessary only to determine the modified fluid characteristic time distribution at two measuring cross sections separated by a known volume of pipe or conduit.

(b) It is not necessary to know the volume, mass, or flow rates of the injected tracer.

(c) Transit time is inherently a volumetric method.

(d) In some applications only one detection point is used, the injection point taking the place of the first detection point.

Table 1 Symbols

Symbol	Description	Dimensions	SI Units	U.S. Customary Units
q_v	Volumetric flow rate	L^3T^{-1}	m^3/s	ft^3/sec
q_m	Mass flow rate	MT^{-1}	kg/s	lbm/sec
Δc	Variation in percent concentration of tracer	. . .	%	%
f_0	Friction factor of a perfectly smooth conduit (para. 6.2.1.1)	. . .	. . .	. . .
f	Friction factor coefficient of resistance (Moody coefficient)	. . .	. . .	. . .
L/D	Ratio, conduit length to diameter, in the same units of measure	LL^{-1}	Not applicable	Not applicable
Re	Reynolds number	. . .	. . .	. . .

(e) The degree of fluid mixing is less critical in this method.

4.2.2 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 two measuring points, so that the flow parameters are approximately constant over the measuring length.

5 CHOICE OF TRACER

5.1 General

(a) Different types of tracers may be used, but for satisfactory operation the tracer injected in the flowing fluid must satisfy the following requirements:

(1) it should mix well with the fluid in the conduit

(2) the quantity used should result in negligible or known modifications of the flow rate of fluid in the flow stream

(3) the instrument used to monitor the concentration of the tracer must have sufficient measurement accuracy, and be suitable for the fluids and environment

(4) it should be chemically stable in the conditions of use

(5) if the tracer material used is also present in the flow prior to injection of the tracer, it must be at a negligible or constant concentration

(b) For the dilution method, it is important that the tracer fluid does not react with the measured fluid, or with the conduit wall material, to the extent that it affects the measurement.

(c) For transit time methods, it is recommended that

(1) the tracer concentration in the measuring cross sections can be determined at any time

(2) to achieve greatest precision, the detector signal should be proportional to the tracer concentration and the detector response time be fast enough that time accuracy is not lost

5.2 Comparison Between the Different Tracers

5.2.1 Advantages of Radioactive Tracers (See Table A-2)

(a) If a tracer emitting gamma radiation with sufficient energy is permissible, the probes may be located outside the conduit.

(b) For tracers with a short half-life and are chemically acceptable, any radioactive contamination disappears quickly.

5.2.2 Advantages of Nonradioactive Tracers

(a) Nonradioactive tracers do not require consideration of the requirements and regulations for the ownership and handling of radioactive materials.

(b) The substances generally remain stable with time. Delays between the supply and the use of the substance do not matter.

6 MEASURING LENGTH AND ADEQUATE MIXING DISTANCE

6.1 Introduction

Adequate mixing of the tracer with the flowing stream is required for accurate flow measurements. The mixing distance is defined as the shortest distance that the maximum variation, Δc, in the mixture composition, as measured over the cross section of the stream, is less than some predetermined value.

This mixing distance is not one fixed value, but will vary with the allowable concentration variations — the smaller the acceptable variation (greater precision of measurement), the greater the mixing distance. The length of the available conduit may limit reduction of percent variation in concentration, Δc, below a certain value. This also varies with the fluid flow properties (i.e., greater turbulence and flow disturbances aid mixing).

A multipoint sampling or detection arrangement should be used where possible, particularly when a systematic variation in concentration 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 as stringent as for the dilution methods.

Several techniques are available to improve the mixing that can reduce the required mixing distance. See paras. 6.2 through 6.4.

6.2 Mixing Distance

6.2.1 Theoretical Derivation of Mixing Distance. The mixing length determined by experiment may differ considerably from the length predicted theoretically (para. 6.2.2). Paragraph 6.2.1.1 should be used only as a preliminary guide.

6.2.1.1 Central Injection. Equations (1) through (3) relate mixing distance, L/D, to the varying concentration of tracer across the conduit. These were developed based on Reynolds number, Re, and pipe friction. Equation (1) is based on an assumed constant radial diffusion coefficient and uniform flow velocity. Equation (2) is based on 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.

$$\frac{L}{D} = 1.18\sqrt{\frac{8}{f}}\left(2.94 - \frac{\ln(\Delta c)}{2.30}\right) \tag{1}$$

$$\frac{L}{D} = \left(2.95 - \frac{\ln(\Delta c)}{2.40}\right)\sqrt{\frac{8}{f}} \tag{2}$$

$$\frac{L}{D} = \left[20.50 - 2.85 \cdot \ln(\Delta c)\right] Re^{0.10}\left(\frac{f_0}{f}\right) \tag{3}$$

where the symbols are defined in Table 1.

Equations (1) through (3) are shown graphically in Nonmandatory Appendix B, Fig. B-1, which shows the increase in the required mixing distance for a decrease in Δc for a Reynolds number of $Re = 10^5$ and a smooth conduit. Note that Fig. B-1 is qualitative in nature and the plot is for guidance only.

The slight dependence of mixing distance on Reynolds number is shown for eq. (3) in Fig. B-2 as an example. For a change in Re from 10^5 to 10^6, at $\Delta c = 1\%$ the mixing distance increases by about 25%.

6.2.1.2 Ring Injection. The mixing distances are reduced to about one-third of the values derived for a central injection point for uniform injection using a ring with a radius of 0.63 of the conduit radius.

6.2.2 Experimental Test of Mixing Distance. Mixing distance experimentally determined for central injection in an unobstructed, straight, circular conduit is reported to be 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. Caution shall therefore be used in the treatment of theoretical results.

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

6.2.3 Multiorifice 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. Reduction in distance may also be achieved by increasing the maximum acceptable variation in percent concentration, Δc (Figs. B-2 and B-3).

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 Fig. B-3.

6.2.4 High Velocity Jets. If the tracer is injected against the flow with a velocity greater than the mean velocity of the fluid 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 these parameters is not available, but reductions in mixing distance to approximately 30% of that for a single central injector can be obtained by using an array of jets to better distribute the tracer fluid across the conduit.

6.2.5 Vortex Generators. A turbulent wake that will stimulate mixing and reduce the mixing distance can be achieved with flow deflection plates that generate vortices in the flow.

The mixing distance can be considerably reduced with the use of passive mixers.

6.2.6 Fans and Pumps. A considerable reduction in mixing distance may be achieved by injecting the tracer upstream of a fan, compressor (gas), or pump (liquid). Information on mixed flow in pumps indicates that this considerably reduces the mixing distance.

6.2.7 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 promoters is not available, but measuring sections that include these devices are preferred. In the transit time method, however, the length of conduit between detectors should be straight and free of obstruction for the best accuracy.

6.3 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 that is less than the mixing distance can be reduced, if samples are recovered simultaneously from a number of positions across the conduit and the data analyzed.

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

6.4 Measuring Length

6.4.1 Dilution Method. For the method of constant rate injection, the measuring length is defined as the length of conduit between the injection point and the sampling point. This length should be determined after consideration has been given to paras. 6.2 through 6.4 concerning mixing of the tracer.

The addition of tracer 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 points where tracer enters or leaves the system, 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 rate measured is the flow in the conduit immediately upstream of the loss zone.

6.4.2 Transit Time Method. The measuring length for the transit time method consists of two parts

(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, when two are used

Paragraph 6.4.2(a) should be determined after consideration has been given to paras. 6.2 through 6.4 about the mixing of the tracer. The mixing requirement for this method may not be as stringent as for the dilution method, depending on the tracer and method of detection used.

Paragraph 6.4.2(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.

Due to turbulent mixing and diffusion of the injected tracer during the time of travel to the downstream detector, the front of the tracer detected by the downstream detector is generally not well defined. To ascertain a corrected transit time or arrival of the injected tracer at the downstream detector, statistical data reduction technique on the distribution of concentration of the tracer at the downstream detector is often employed. Use of statistical techniques to ascertain the transit time can reduce the uncertainty in determining the transit time of tracers.

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

Losses of fluid from the conduit before the first detection position does 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 fluid in the length of conduit between the detection points will result in error in the flow rate measurement. It is essential that the conduit between the two detector positions has no open branch connections or leakage.

For the highest accuracy, the length of conduit between detector positions should be straight and free from obstruction (e.g., nonfull port valves, partially closed valves, etc.).

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

7 ERRORS

7.1 General

As with any measurement of physical quantities, the determination of a flow rate in a conduit by tracer methods is subject to uncertainties that relate to either of the following:

(a) systematic errors due to errors in the measuring apparatus or in the measuring process used

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

7.2 Systematic Errors

7.2.1 Instrument Error

7.2.1.1 Dilution Method. Any uncertainties in the composition of the tracer fluid, the injection flow rate, and/or the analysis of the mixed fluids will contribute directly to uncertainties in the inferred fluid flow rate. Incomplete mixing of the tracer and the main flow will lead to nonrepresentative fluid samples and flow uncertainty.

7.2.1.2 Transit Time Method. The response time of the detector will affect the uncertainty of the flow rate measurement.

7.2.2 Reaction Error. 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 that may be caused by these reactions generally lead to an overestimation of the flow rate (disappearance of or unaccounted for tracers) when using dilution methods.

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

7.2.3 System Unknowns. Unseen and unknown flow path situations can affect the readings, such as flow leaking into or out of the system, side openings, and dead end piping, which can delay a part of the flow. Hot spots causing side reactions, cold spots that cause condensation (in vapors), and liquid traps that trap and then release fluid components also can cause unexplainable differences in readings.

7.3 Random Errors

7.3.1 General. 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 possible by an analysis of a large number of measurements.

(b) in the particular case of a measurement that was repeated only a few times, the 95% confidence limits may be estimated using the Student's *t* variable sampling and analysis procedure.

7.3.2 Dilution. Uncertainties in the knowledge of the composition of the tracer fluid are directly reflected in the uncertainty in the measurement. The tracer fluid may be diluted for a number of reasons, such as for safer or easier handling, to provide a greater volume of injected fluid to improve mixing, or simply because it is available in that form. Any uncertainty in the knowledge of the rate of injection into the main stream also will directly impact the measurement error. These uncertainties can be estimated and the conventional statistical methods may be used to estimate uncertainties due to these causes.

The discussion of mixing and mixing distances in sections 1 through 7 and Figs. B-1 through B-3 suggest the extent of uncertainty caused by imperfect mixing; therefore, caution is recommended.

It is possible to develop an estimate of the quality of mixing by comparing the total quantity of tracer accounted for at the detector versus the quantity injected. Every application will differ and every test result should be analyzed to develop an estimate of the resulting uncertainties.

7.3.3 Transit Time. The primary source of uncertainty in the transit method is related to time measurements. These include the response time of the detectors and the time difference between the two detectors. Good mixing provides a faster rise time as the flow passes the detectors, thus improving the precision of the time difference. Any uncertainty in the internal shape of the conduit will directly affect the reported flow rate.

7.3.4 Error Reduction. There may be advantages in using all of the collected data for analysis of both time and concentration to improve the understanding of the flow conditions and reduce the uncertainties involved. An uncertainty analysis of the specific situation should suggest the best ways to reduce errors. It should be clear that the use of multiple injection points across the cross section of the conduit, along with multiple detection points in the larger-size conduits, will improve accuracy and reduce the required mixing distances.

8 EXTENSIONS OF THE METHODS

The basic physical principles discussed in section 6 can be applied to flow measurement beyond the scope of this Standard. Some examples include: application to open channel flows and the determination of leakage into or out of a system.

9 PRACTICAL APPLICATION NOTES

Tracer methods are most commonly used to calibrate installed meters or as investigative tools. Flow measurements in some large conduits and channels have used an array of multiple injection nozzles set in the flow with a matching array of detectors located downstream. Accuracy was improved with the use of pressure-actuated valves in each nozzle to assure that all flows begin at the same time. Even where the transit times differ, it is possible to consider all the data and sum the flows.

Flows in small conduits have been measured where the flow can be switched between sections of conduit operating at different temperatures. The detected variable would be temperature. Flows beneath the surface of the earth have been determined using stable tracer materials. Dye injected into a cooling water stream made the outflow of the fluid visible with the use of aerial photography for detection. Human blood flow is measured with radioactive tracers and multiple x-ray photographs of the heart. Some flowmeter manufacturers can provide recommendations, and even the materials and equipment, for in-situ calibration.

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NONMANDATORY APPENDIX A
TYPICAL TRACER FLUIDS

Table A-1 Typical Nonradioactive Tracers, Gas

Tracer	Formula
Helium	He
Sulfur hexafluoride	SF_6
Methane	CH_4
Nitrous oxide	N_2O

Table A-2 Typical Radioactive Tracers, Gas

Tracer	Formula (if Any)	Half-Life
Argon 41	. . .	110 min
Arsenic 76	$^{76}AsH_3$	26.5 hr
Bromine 82	$C_2H_5{}^{82}Br$ or $CH_3{}^{82}Br$	36 hr
Krypton 85	. . .	10.6 yr
Sulfur 35	$^{35}SF_6$	87 days
Xenon 133	. . .	5.27 days

Table A-3 Typical Nonradioactive Tracers, Liquid

Tracer	Effect of Concentration
Sodium dichromate ($Na_2Cr_2O_72H_2O$)	2×10^{-1} mg/l with direct analysis, 2×10^{-3} mg/l after reconcentration
Sodium chloride (NaCl): 1–10 mg/l, depending on original conductivity	. . .
Rhodamine B ($C_{28}H_{31}Cl_1N_2O_3$)	2×10^{-4} mg/l — rhodamine weight
Lithium chloride (LiCl)	. . .
Fluorescein ($C_{20}H_{10}O_5Na_2$) [Note (1)]	5×10^{-3} mg/l

GENERAL NOTE: Other tracers have been used, particularly sodium nitrite ($NaNO_2$), manganese sulfate monohydrate ($MnSO_4$ $4H_2O$), and sulforhodamine G.

NOTE:

(1) This is only one of the various fluorescein dyes in use, and the chemical formulas will vary.

Table A-4 Typical Radioactive Tracers, Liquid

Tracer	Half-Life	Energy
Bromine 82	36 hr	Gamma energies of 0.55–1.48 MeV
Sodium 24	15 hr	Gamma energies of 1.37–2.75 MeV
Other Isotopes		
Gold 198	2.7 days	Gamma energies of 0.41–1.09 MeV
Iodine 131	8.04 days	Gamma energies of 0.251–0.81 MeV
Chromium 51	27.8 days	Gamma energy of 0.32 MeV
Tritium	12.26 yr	Beta energy of 0.018 MeV may also be used
137 cesium–137 m-barium	2.6 min	Gamma energy of 0.66 MeV
113 tin–113 m-indium	104 min	Gamma energy of 0.39 MeV

GENERAL NOTE: An MeV is one million electron volts.

NONMANDATORY APPENDIX B MIXING DISTANCES

Fig. B-1 Theoretical Results

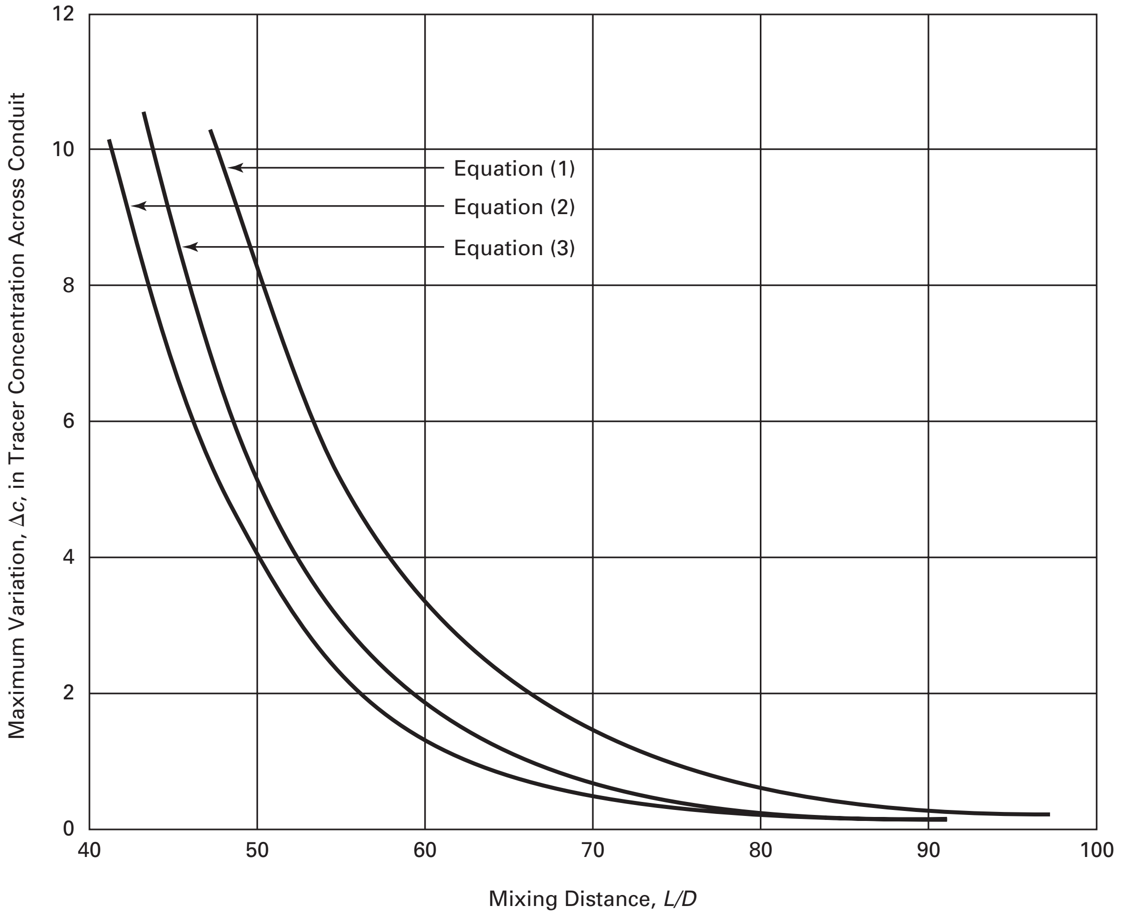


Fig. B-2 Reynolds Number Effect on Mixing Distance

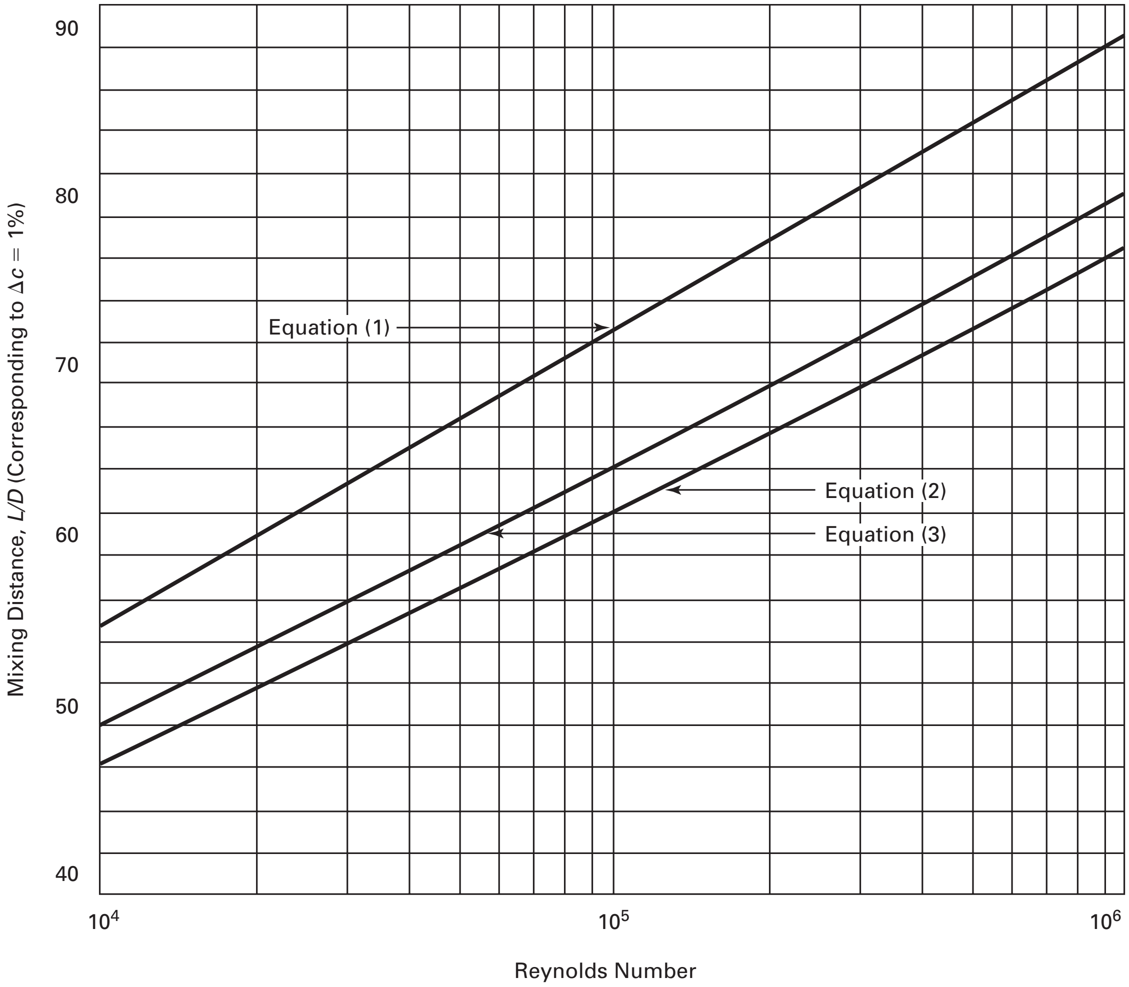
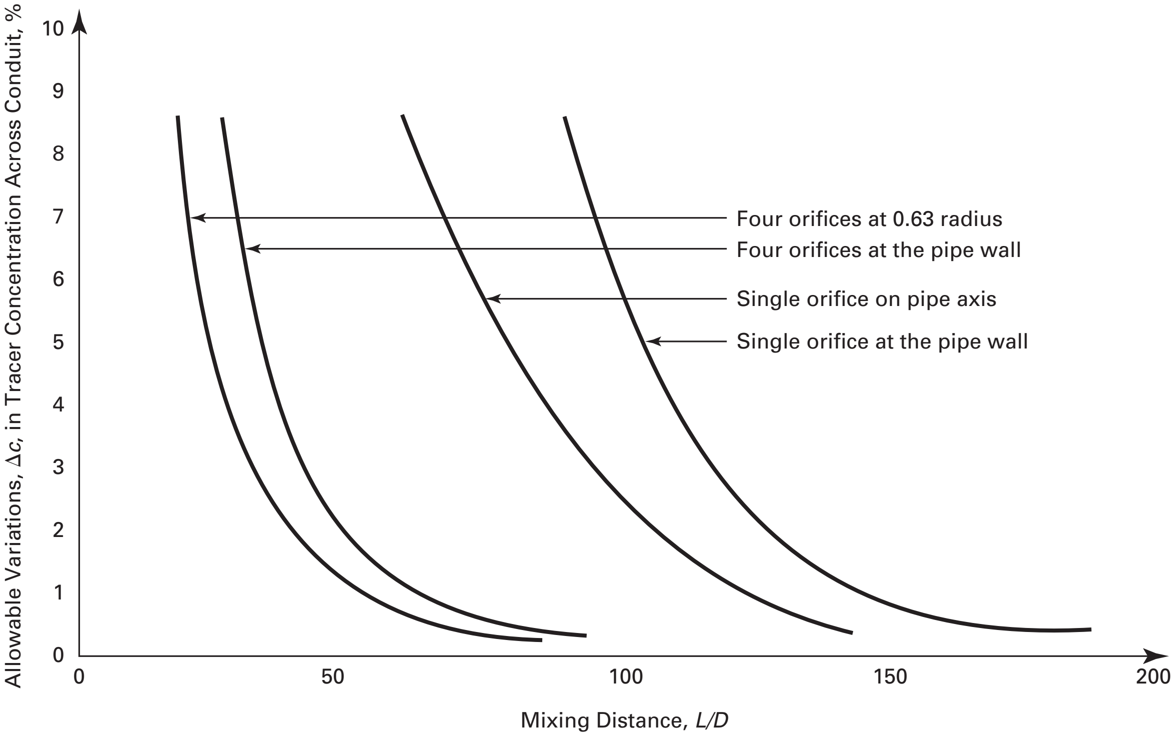


Fig. B-3 Experimental Results



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