ASME MFC-11–2006
(Revision of ASME MFC-11M–2003)

# Measurement of Fluid Flow by Means of Coriolis Mass Flowmeters



AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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Three Park Avenue • New York, NY 10016

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ASME issues written replies to inquiries concerning interpretations of technical aspects of this Standard. Interpretations are published on the ASME Web site under the Committee Pages at http://cstools.asme.org as they are issued.





The American Society of Mechanical Engineers
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# FOREWORD

Coriolis flowmeters cover a family of devices with varying designs that depend on the Coriolis force generated by the fluid (liquid or gas) flowing through oscillating tube(s). The primary purpose of Coriolis flowmeters is to measure mass flow. However, some of these flowmeters also measure liquid density and temperature of the oscillating tube wall. From the measurements, the mass flow of liquid or gas, liquid density, liquid volume flow, and other related quantities can be determined. This Standard was approved by the American National Standards Institute (ANSI) on July 13, 2006.

# ASME MFC COMMITTEE
# Measurement of Fluid Flow in Closed Conduits

(The following is the roster of the Committee at the time of approval of this Standard.)

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New York, NY 10016-5990

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| | |
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# MEASUREMENT OF FLUID FLOW BY MEANS OF CORIOLIS MASS FLOWMETERS

## 1 SCOPE

ASME MFC-11 establishes common terminology and gives guidelines for the selection, installation, calibration, and operation of Coriolis flowmeters for the determination of mass flow, density, volume flow, and other parameters. The content of this Standard is applied to the flow measurement of liquids, gases, mixtures of gases, multiphase flows, and miscible and immiscible mixtures of liquids.

## 2 TERMINOLOGY, SYMBOLS, REFERENCES, AND BIBLIOGRAPHY

Paragraph 2.1 lists definitions from ASME MFC-1M used in ASME MFC-11.

Paragraph 2.2 lists definitions specific to this Standard.

Paragraph 2.3 lists symbols (see Table 2.3) used in this Standard (see notes and superscripts).

Paragraph 2.4 lists abbreviations (see Table 2.4) used in this Standard.

Paragraph 2.5 lists references used in this Standard and a bibliography.

### 2.1 Definitions Copied From ASME MFC-1M

*accuracy:* the degree of freedom from error, the degree of conformity of the indicated value to the true value of the measured quantity.

*calibration:*

*(a)* the process of comparing the indicated flow to a traceable reference standard

*(b)* the process of adjusting the output of a device to bring it to a desired value, within a specified tolerance for a particular value of the input.

*cavitation:* the implosion of vapor bubbles formed after flashing when the local pressure rises above the vapor pressure of the liquid. See also *flashing*.

*Coriolis flowmeter:* a device consisting of a flow sensor and a transmitter which measures the mass flow by means of the Coriolis force generated by flowing fluid through oscillating tube(s); it may also provide measurements of density and temperature.

*cross-talk:* if two or more Coriolis flowmeters are to be mounted close together, interference through mechanical coupling may occur. This is often referred to as cross-talk. The manufacturer should be consulted for methods of avoiding cross-talk.

*density calibration factor(s):* calibration factor(s) associated with density measurement.

*drive system:* means for inducing the oscillation of the tube(s).

*flashing:* the formation of vapor bubbles in a liquid when the local pressure falls to or below the vapor pressure of the liquid, often due to local lowering of pressure because of an increase in the liquid velocity. See also *cavitation*.

*flow calibration factor(s):* calibration factor(s) associated with mass flow measurement.

*flow sensor:* a mechanical assembly consisting of an oscillating tube(s), coil drive system, oscillating tube deflection measurement-sensor(s), flanges/fittings, and housing.

*housing:* environmental protection of the flow sensor.

*oscillating tube(s):* tubes(s) through which the fluid to be measured flows.

*rangeability:* Coriolis flowmeter rangeability is the ratio of the maximum to minimum flowrates or Reynolds number in the range over which the flowmeter meets a specified uncertainty and/or accuracy.

*repeatability of measurement (qualitative):* the closeness of agreement among a series of results obtained with the same method on identical test material, under the same conditions (same operator, same apparatus, same laboratory, and short intervals of time).

*repeatability of measurement (quantitative):* the value below which the absolute difference between any two single test results obtained under the same conditions, [see *repeatability of measurement (qualitative)*], may be expected to lie with a specified probability. In the absence of other indications, the probability is 95%.

*reproducibility (quantitative):* the closeness of agreement between results obtained when the conditions of measurement differ; for example, with respect to different test apparatus, operators, facilities, time intervals, etc.

NOTE: The following three paragraphs are included to help with understanding the definitions of repeatability and reproducibility.

*(a)* Repeatability is a quantified measure of the short term stability of a flowmeter. Repeatability can be determined from successive tests of the meter, over short periods of time, without changing the test conditions. Repeatability can be quantified in terms of the standard deviation or the max./min. differences in these results.

*(b)* Reproducibility is a quantified measure of the longer-term stability of a flowmeter. Reproducibility can be determined from

tests of the meter, over longer (specified) periods of time, or when test conditions may change (changes to be specified); such as the typical meter-usage patterns as turning the meter off and then turning it back on, or testing it on successive days. Reproducibility can be quantified in terms of the standard deviation or the max./min. differences in these results.

(c) Resultant differences for reproducibility may be larger than their repeatabilities because of the test conditions.

*secondary containment:* housing designed to provide protection to the environment if the oscillating tube(s) fail.

*transmitter:* electronic system providing the drive and transforming the signals from the flow sensor to give output(s) of measured and inferred parameters; it also provides corrections derived from parameters such as temperature.

*uncertainty (of measurement):* the range within which the true value of the measured quantity can be expected to lie with a specified probability and confidence level.

*zero stability:* maximum expected magnitude of the Coriolis flowmeter output at zero flow after the zero adjustment procedure has been completed, expressed by the manufacturer as an absolute value in mass per unit time.

### 2.2 Definitions Specific for This Document

*base conditions:* specified conditions to which the measured mass of a fluid is converted to the volume of the fluid.

*error:* the difference between a measured value and the "true" value of a measurand.

NOTE: The "true" value cannot usually be determined. In practice, a conventional recognized "standard" or "reference" value is typically used instead.

*installation effect:* any difference in performance of a component or the measuring system arising between the calibration under ideal conditions and actual conditions of use. This difference may be caused by different flow conditions due to velocity profile, perturbations, or by different working regimes (pulsation, intermittent flow, alternating flow, vibrations, etc.).

*linearity:* the consistency of the change in the scaled output of a Coriolis flowmeter for a related scaled change in the input of the flowmeter.

*master flowmeter:* a flowmeter calibrated with a primary flow reference and used as a secondary or transfer reference to calibrate other flowmeters.

*pig:* a mechanical device, pressured through piping to clean the walls and/or remove construction debris. There is a type of smart pig that can identify, record, and transmit the condition of the internal surface of the pipe and locations of the defect.

*pressure loss:* the difference between the inlet pressure and the outlet pressure of the Coriolis flowmeter.

*reference:* a verifiable artifact or test facility that is traceable to a recognized national or international measurement standard.

*specific gravity (SG):* the ratio of a liquid density to a reference density (generally the reference density is water at triple point or air at standard conditions; 14.696 psia and 600°F).

*turndown:* a numerical indication of the rangeability of a measuring device is the ratio of the manufacturer's specification maximum to minimum flow rates; calculated as $q_{max}/q_{min}$.

*volumetric prover:* the use of a calibrated volume tank, liquid density, and most generally a diverter valve to calibrate a flowmeter.

### 2.3 Symbols Used in This Standard

See Table 2.3.

### 2.4 Abbreviations Used in This Standard

See Table 2.4.

### 2.5 References and Bibliography

ASME B31.3, Process Piping

ASME MFC-1M, Glossary of Terms Used in the Measurement of Fluid Flow in Pipes

ASME MFC-2M, Measurement Uncertainty for Fluid Flow in Closed Conduits

ASME MFC-7M, Measurement of Gas Flow in Pipes Using Critical Flow Venturi Nozzles

ASME MFC-9M, Measurement of Liquid Flow in Closed Conduits by Weighing Method

Publisher: The American Society of Mechanical Engineers (ASME), Three Park Avenue, New York, NY 10016; Order Department: 22 Law Drive, P.O. Box 2300, Fairfield, NJ 07007

Handbook of Chemistry and Physics (CRC), CRC Press, ISO, 57th ed., 1976–1977

Publisher: CRC Press, 200 NW Corporate Boulevard, Boca Raton, FL 33431

International Vocabulary of Basic and General Terms in Metrology (VIM), ISO, 2nd ed., 1993

ISO 10790, Measurement of fluid flow in closed conduits — Guidance to the selection, installation and use of Coriolis meters (mass flow, density and volume flow measurements)

ISO 10970, Amendment 1, Guidelines for gas measurements

Publisher: International Organization for Standardization (ISO), 1 rue de Varembé, Case Postale 56, CH-1211, Genève 20, Switzerland/Suisse

## Table 2.3 Symbols

| Symbol | Description (*first use*) | Dimensions [Note (1)] | SI Units | U.S. Customary Units |
|---|---|---|---|---|
| $A$ | oscillating tube cross sectional area (Fig. 3.1.1) | $L^2$ | m$^2$ | in.$^2$ |
| $A_B$ | base accuracy (para. 3.2) | Dimensionless | | |
| $A_T$ | total accuracy (para. 3.2) | Dimensionless | | |
| $a_i$ | manufacturer's specification [eq. (9-5)] | Dimensionless | | |
| $a_r$ | radial acceleration [Note (2)] (Fig. 3.1.1) | $LT^{-2}$ | m/s$^2$ | ft/s$^2$ |
| $a_t$ | transverse acceleration [Note (2)] (Fig. 3.1.1) | $LT^{-2}$ | m/s$^2$ | ft/s$^2$ |
| | | | | |
| $C$ | mechanical stiffness — spring constant [Note (2)] [eq. (6-1)] | $MT^{-2}$ | kg/s$^2$ | lb/s$^2$ |
| | | | | |
| $F_c$ | Coriolis force [Note (2)] [eq. (3-3)] | $MLT^{-2}$ | m(kg/s$^2$) | ft-lb/s$^2$ |
| $f_R$ | resonant frequency [Note (2)] (para. 3.1.2) | $T^{-1}$ | 1/s | 1/s |
| | | | | |
| $g_c$ | dimensional conversion constant [Note (2)] [eq. (4-1)] | Dimensionless | | |
| | | | | |
| $K_1$, $K_2$ | calibration coefficients for density [eq. (6-5)] | Dimensionless | | |
| $K_P$ | pressure loss coefficient [eq. (4-1)] | Dimensionless | | |
| $K_{lm}$ | linear mass calibration constant [eq. (9-2)] | Dimensionless | | |
| $k$ | coverage factor, for expanded uncertainty (para. 9.4) | Dimensionless | | |
| | | | | |
| $m$ | mass [Note (2)] [eq. (3-3)] | $M$ | kg | lb |
| $m_{\text{liq-tb}}$ | mass of liquid in the tubes, [eq. (6-2)] | $M$ | kg | lb |
| $m_{\text{tb}}$ | mass of oscillating tube(s), [eq. (6-2)] | $M$ | kg | lb |
| | | | | |
| $N_c$ | number of cycles [Note (2)] [eq. (6-6)] | Dimensionless | | |
| | | | | |
| $P_b$ | pressure of gas base conditions (Table C-1) | $ML^{-1}T^{-2}$ | Pa, bar | psi |
| | | | | |
| $q$ | flow rate [volume or mass] (para. 3.2) | $L^3T^{-1}$, $MT^{-1}$ | m$^3$/s, kg/s | lb/s |
| $q_m$ | mass flow rate [Note (2)] [eq. (3-4)] | $MT^{-1}$ | kg/s, kg/min | lb/s, lb/min |
| $q_{\max}$ | maximum flow rate for an acceptable $\Delta p_c$ (para. 4.1.2) | $L^3$ | kg | lb |
| $q_{\min}$ | minimum flow rate for a maximum acceptable measurement error (para. 4.1.1) | $L^3$ | kg | lb |
| $q_{m,t}$ | total mass flow rate of the mixture [eq. (8-5)] | $MT^{-1}$ | kg/s | lb/s |
| $q_{v,t}$ | net total volume flow rate [eq. (8-7)] | $L^3T^{-1}$ | m$^3$/s | gal/s |

## Table 2.3 Symbols (Cont'd)

| Symbol | Description (*first use*) | Dimensions [Note (1)] | SI Units | U.S. Customary Units |
|---|---|---|---|---|
| $q_{m,A}$, $q_{m,B}$ | net mass flow rate of components A and B [eq. (8-5)] | $MT^{-1}$ | kg/s | lb/s |
| $q_v$ | volume flow rate [Note (2)] | $L^3T^{-1}$ | m$^3$/s | gal/s |
| $q_{v\text{-}liq}$ | liquid volume flow rate as measured [eq. (7-2)] | $L^3T^{-1}$ | m$^3$/s | gal/s |
| $q_{v\text{-}g\text{-}b}$ | gas volume flow rate as measured [eq. (7-3)] | $L^3T^{-1}$ | m$^3$/s | ft$^3$/s |
| $q_{v,A}$ | net volume flow rate of component A [eq. (8-7)] | $L^3T^{-1}$ | m$^3$/s | gal/s |
| $q_{v,B}$ | net volume flow rate of component B [eq. (8-8)] | $L^3T^{-1}$ | m$^3$/s | gal/s |
| | | | | |
| $R_{fm}$ | flowmeter reading [eq. (9-2)] | Dimensionless | | |
| $r$ | radius of rotation for mass $\Delta m$, (Fig. 3.1.1) | $L$ | m | in. |
| | | | | |
| $Sx_i$ | sensitivity coefficient [eq. (9-4)] | Dimensionless | | |
| $S_{Klm}$ | sensitivity coefficient for $K_{lm}$, linear mass calibration constant [eq. (9-4)] | Dimensionless | | |
| $S_{Rfm}$ | sensitivity coefficient $R_{fm}$, flowmeter reading [eq. (9-4)] | Dimensionless | | |
| $S_{\rho f}$ | sensitivity coefficient $\rho f$ fluid density [eq. (9-4)] | Dimensionless | | |
| | | | | |
| $T$ | temperature (Figs. 4.1.3-1 through 4.1.3-4) | °K | °C | °F |
| $T_b$ | gas base condition temperature (Table C-1) | °K | °C | °F |
| $T_f$ | period of the tube oscillation [Note (2)] [eq. (6-6)] | $T$ | s | s |
| $t_w$ | time window (gate) [Note (2)] [eq. (6-6)] | $T$ | s | s |
| | | | | |
| $x$ | horizontal coordinate — abscissa | Dimensionless | | |
| | | | | |
| $y$ | vertical coordinate — ordinate | Dimensionless | | |
| | | | | |
| $u_x$ | calculated standard uncertainty in $x$ (para. 9.5.1) | Dimensionless | | |
| $u_y$ | calculated standard uncertainty in $y$ (para. 9.5.1) | Dimensionless | | |
| $u_{qm}$ | combined standard uncertainty in mass flow rate (para. 9.5.1) | Dimensionless | | |
| $u_{qv}$ | combined standard uncertainty in volume flow rate (para. 9.5.2) | Dimensionless | | |
| $u(x_i)$ | standard uncertainty in $x_i$ [eq. (9-6)] | Dimensionless | | |
| $u(y)$ | standard uncertainty in $y$ [eq. (9-6)] | Dimensionless | | |
| | | | | |
| $V$ | volume | $L^3$ | m$^3$ | ft$^3$ |
| $V_{g\text{-}b}$ | gas volume at base conditions [eq. (7-4)] | $L^3$ | m$^3$ | ft$^3$ |
| $V_{\text{liq}}$ | liquid volume [eq. (7-4)] | $L^3$ | m$^3$ | gal |
| $V_{\text{liq-tb}}$ | volume of liquid in the oscillating tube [eq. (6.2)] | $L^3$ | m$^3$ | gal |
| $v$ | fluid velocity [Note (2)] (Fig. 3.1.1) | $LT^{-1}$ | m/s | ft/s |

## Table 2.3 Symbols (Cont'd)

| Symbol | Description (*first use*) | Dimensions [Note (1)] | SI Units | U.S. Customary Units |
|---|---|---|---|---|
| $W$ | mass fraction | $ML^{-3}$ | kg/m$^3$ | lb/ft$^3$ |
| $W_A$, $W_B$ | respective mass fractions of component *A* and component *B* [eqs. (8-1) and (8-2)] | $ML^{-3}$ | kg/m$^3$ | lb/ft$^3$ |
| $WC$ | inches of water in a water column (Table C-1) | $ML^{-1}T^{-2}$ | Pa | in. |
| | | | | |
| $ZS$ | zero stability (para. 3.2) | $MT^{-1}$ | kg/s | lb/s |
| | | | | |
| $\varepsilon_m$ | accuracy of the mass measurement expressed as a percentage [eq. (7-3)] | Dimensionless | | |
| $\varepsilon_{v\text{-liq}}$ | accuracy of liquid volume measurement expressed as a percentage [eq. (7-3)] | Dimensionless | | |
| $\varepsilon_{v\text{-}g\text{-}b}$ | accuracy of the standard gas volume measurement expressed as a percentage [eq. (7-5)] | Dimensionless | | |
| $\varepsilon_{\rho\text{-liq}}$ | accuracy of the liquid density measurement expressed as a percentage [eq. (7-3)] | Dimensionless | | |
| $\varepsilon_{\rho\text{-}g\text{-}b}$ | accuracy of reference density with respect to the base conditions expressed as a percentage [eq. (7-6)] | Dimensionless | | |
| $\pi$ | universal constant [Note (2)] | Dimensionless | | |
| | | | | |
| $\rho f$ | density of the fluid [eq. (3-4)] | $ML^{-3}$ | kg/m$^3$ | lb/ft$^3$ |
| $\rho_{g\text{-}b}$ | gas density at base conditions [eq. (7-4)] | $ML^{-3}$ | kg/m$^3$ | lb/ft$^3$ |
| $\rho_{\text{w,ref}}$ | density of water under reference conditions [eq. (6-7)] | $ML^{-3}$ | kg/m$^3$ | lb/ft$^3$ |
| $\rho_{\text{liq}}$ | density of the liquid [eq. (6-3)] | $ML^{-3}$ | kg/m$^3$ | lb/ft$^3$ |
| $\rho_{\text{meas}}$ | measured density of the mixture [eq. (8-1)] | $ML^{-3}$ | kg/m$^3$ | lb/ft$^3$ |
| $\rho_A$, $\rho_B$ | respective densities of component *A* and component *B* [eq. (8-1)] | $ML^{-3}$ | kg/m$^3$ | lb/ft$^3$ |
| | | | | |
| $\varphi$ | volume fraction (para. 8.2.3) | Dimensionless | | |
| $\varphi_A$, $\varphi_B$ | respective volume fractions (expressed as a percentage) of component A and component B in relation to the mixture (para. 8.2.3) | Dimensionless | | |
| | | | | |
| $\omega$ | angular velocity [eq. (3-1)] | $T^{-1}$ | s$^{-1}$ | s$^{-1}$ |
| | | | | |
| $\Delta m$ | mass [eq. (3-3)] | $M$ | kg | lb |
| $\Delta p_c$ | pressure drop – Coriolis [eq. (4-1)] | $ML^{-2}$ | kg/m$^2$ | psi |
| $\Delta x$ | length [eq. (3-5)] | $L$ | m | in. |
| | | | | |
| * | multiply (para. 3.2) | Dimensionless | | |

NOTES:
(1) Dimensions: $M$ = mass, $L$ = length, $T$ = time, °$K$ = thermodynamic temperature.
(2) Symbols identical to ASME MFC-1M.

**Table 2.4 Abbreviations**

| Abbreviations | Descriptions (*first use*) |
|---|---|
| $c_p$ | Centipoise, viscosity unit [centistokes (cSt), viscosity used in petroleum industry, is centipoise divided by SG.] (Table C-2) |
| DN | European piping size (diameter normal, millimeters) (Fig. 4.1.3-1) |
| lbm | Pounds of mass (Table C-2) |
| $NM^3H$ | Normal cubic meters/hour (Fig. 4.1.3-1) |
| psi | Unit of pressure, pounds per square inch (para. 9.5.3) |
| psia | Unit of pressure, pounds per square inch of pressure referenced to zero pressure (Table C-1) |
| psig | Unit of pressure, pounds per square inch of pressure referenced to the ambient (Table C-1) |
| bar | Unit pressure |
| point P | Point of rotation, pivot, point (P) (Fig. 3.1.1) |
| $R_t$ | Rotating tube, (Fig. 3.1.1) |
| scfh | Volume rate of flow, standard cubic feet per hour (Table C-1) |
| *SG* | Specific gravity [eq. (6.7)] |
| $SG_L$ | Specific gravity of liquids (Table C-1) |
| $SG_G$ | Specific gravity of gases (Fig. 4.1.3-1) |
| °C | Temperature (Fig. 4.1.3-1) |
| °F | Temperature (Table C-1) |

## 3 MASS FLOW MEASUREMENT

Coriolis flowmeters determine mass flow rate of fluids and some can determine the flowing density of process liquids. Sections 3 and 6 describe the underlying principles for mass flow rate and density determinations. The determination of other parameters such as volumetric flow and concentration are described in sections 7 and 8.

### 3.1 Apparatus

**3.1.1 Principle of Operation.** Coriolis flowmeters operate on the principle that inertial forces are generated whenever a particle in a rotating body moves relative to the body in a direction toward or away from the center of rotation. This principle is shown in Fig. 3.1.1.

A particle of length $\Delta x$ having mass $\Delta m$ slides with constant velocity $v$ in a rotating tube $R_t$ that is rotating with angular velocity ω about a fixed point *P*. The particle undergoes an acceleration, which can be divided into two components.

(*a*) a radial acceleration, $a_r$ equal to $\omega^2 r$ and directed towards *P*:

$$a_r = \omega^2 r \tag{3-1}$$

where
$a_r$ = radial acceleration
$r$ = radius of rotation for mass $\Delta m$
$\omega$ = angular velocity

(*b*) a transverse (Coriolis) acceleration $a_t$ equal to $2\omega v$, at right angles to $a_r$ and in the direction shown in Fig. 3.1.1:

$$a_t = 2\omega v \tag{3-2}$$

where
$a_t$ = transverse acceleration
$v$ = velocity of the particle of mass

To impart the Coriolis acceleration to the particle, a force of magnitude $2v\omega\Delta m$ is required in the direction of $a_t$. This force comes from the rotating tube. The reaction of this force back on the rotating tube is commonly referred to as the Coriolis force.

$$\Delta F_c = 2\omega v \Delta m \tag{3-3}$$

where
$F_c$ = the Coriolis force
$\Delta m$ = mass

From the illustration, it can be seen that when a fluid of density $\rho_f$ flows at constant velocity $v$ along a tube rotating as in Fig. 3.1.1, any length $\Delta x$ of the rotating tube experiences a transverse Coriolis force of magnitude $\Delta F_c = 2\omega v \rho_f A \Delta x$ where $A$ is the cross sectional area of the rotating tube interior. The mass flow rate, $q_m$, can be expressed as:

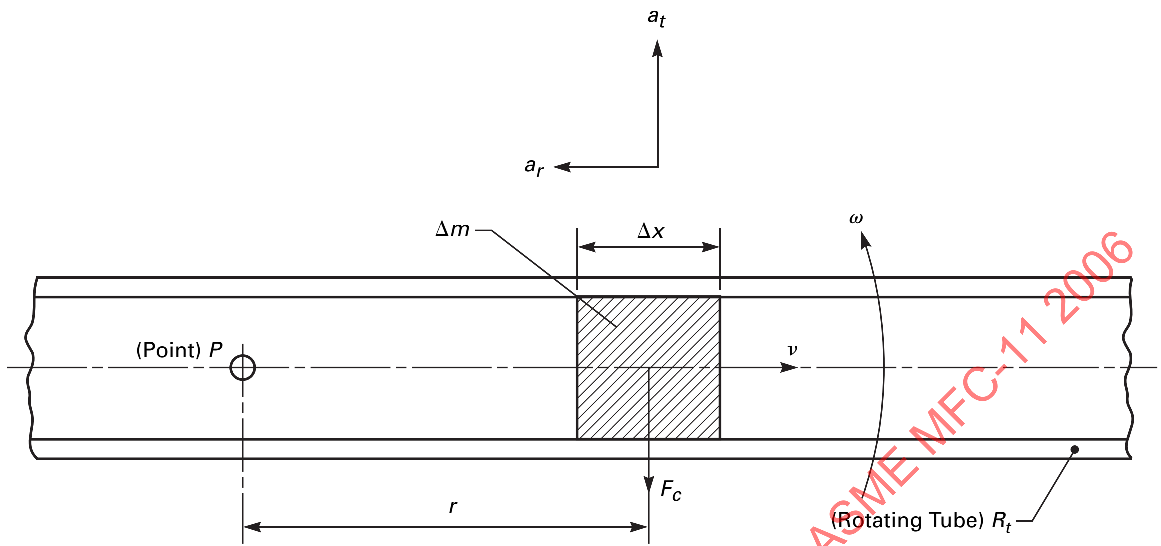
$$q_m = \rho_f v A \tag{3-4}$$

and

$$\Delta F_c = 2\omega q_m \Delta x \tag{3-5}$$

where
$A$ = rotating (oscillating) tube cross sectional area
$q_m$ = mass flow rate
$\Delta x$ = length
$\rho_f$ = density of the fluid

**Fig. 3.1.1 Principle of Operation of a Coriolis Flowmeter**






Hence, we see that (direct or indirect) measurement of the Coriolis force on an oscillating tube can provide a determination of the mass flow rate. This is the basic principle of operation of the Coriolis flowmeter.

**3.1.2 Coriolis Flow Sensor.** In commercial designs of Coriolis flowmeters, the generation of inertial forces through continuous rotary motion is not practical and instead the necessary forces are generated by oscillating the tube.

In one class of Coriolis flowmeters, the oscillating tube is anchored at two points and oscillated at a position between the two anchors, thus giving rise to opposite oscillatory rotations of the two halves of the tube. In another version, a section of tube is oscillated and a transverse Coriolis force is generated. Coriolis flowmeters have one or more oscillating tube(s) that are straight or curved.

The smallest driving force required to keep the tube in constant oscillation occurs when the frequency of oscillation is at, or close to, the resonant frequency of the filled oscillating tube.

The movement of the oscillating tube(s) is measured at various points. When flow is present, Coriolis forces act on the oscillating tube(s), causing a small displacement, deflection, or twist that may be observed as a phase difference between the sensing points.

Coriolis forces (and hence distortion of the oscillating tube) only exist when both axial flow and forced oscillation are present. When there is forced oscillation but no flow, or flow with no oscillation, no deflection will occur and the Coriolis flowmeter will show no output.

The flow sensor is characterized by flow calibration factors that are determined during manufacture and calibration. These values are unique for each sensor and should be recorded on a data plate secured to the sensor.

**3.1.3 Coriolis Transmitter.** A Coriolis meter requires a transmitter to provide the drive energy to oscillate the measuring tubes and process the measurement signals to produce a mass flow rate measurement. The mass flow rate can be integrated and retained in memory and/or displayed by the transmitter.

Additional parameters exist within the transmitter software that should be configured for the specific application. Other coefficients must also be entered if density or volume outputs are required.

## 3.2 Accuracy

For Coriolis flowmeters, the accuracy specification usually includes the combined effects of linearity, repeatability, hysteresis, and zero stability.

Zero stability may also be given as a separate parameter in mass per unit time. In order to determine the Coriolis accuracy, it is generally necessary to calculate zero stability as a percentage of the reading at a specified flow rate, and add this value to the combined effects of linearity, repeatability, and hysteresis stated in units of percent of reading. A typical equation for flowmeter accuracy is as follows:

$$A_T = \pm A_B\% \pm (100*ZS/q)\ \%\ \text{of reading}$$

where

$A_T$ = total accuracy, base accuracy plus zero stability effect
$A_B$ = base accuracy, includes linearity, repeatability, and hysteresis
$q$ = flow rate
$ZS$ = zero stability specification
$*$ = multiply

Repeatability, expressed as a percentage of the reading, may also be a separate parameter.

Accuracy and repeatability statements are usually made at reference conditions that are specified by the manufacturer. These reference conditions should include temperature, humidity, pressure, fluid density, and flow range.

## 3.3 Factors Affecting Mass Flow Measurement

**3.3.1 Density and Viscosity.** A broad range of densities and viscosities have a negligible effect on the Coriolis flowmeter performance capability, consequently, compensation is usually not necessary. (See para. 4.4.8 for other viscosity effects.)

Density and viscosity variations can induce an offset in the Coriolis flowmeter output at zero flow. Thus, it may be necessary to check the flowmeter zero at the process conditions. (See para. 3.4.)

**3.3.2 Multiphase Flow.** Multiphase applications involving nonhomogeneous mixtures can cause measurement errors and in some cases stop the Coriolis flowmeter operation. (See para. 4.4.3.) Increased nonhomogeneity of the liquid mixture can lead to deterioration in performance and may result in loss of signal attributed to the absorption of the oscillation energy required to vibrate the flow sensor. (See Section 8.) In liquid service, care should be taken to ensure that gas bubbles and/or solids are not allowed to accumulate in the sensor. In gas service, means should be provided to prevent liquid condensate or oil carryover from a compressor from settling in the sensor. Flow velocity should be sufficient to carry gas bubbles, pooled liquids, or settled solids out of the sensor.

The overall measurement performance results will be least affected when the multiphase period occurs at the beginning and/or end of the measurement process and the duration of this period is very short compared to the entire measurement period.

While the Coriolis flowmeter will not be damaged when beginning and ending the measurement with an empty flow sensor, the results of the measurement may be outside the expected performance accuracy. A Coriolis flowmeter system solution may be designed, capable of starting and finishing the measurement process from an empty or partially full pipe and/or sensor condition. The system may include, but is not limited to, an air/vapor eliminator for liquid service or a liquid trap for gas service, a reverse flow check valve, and a flow computer, or transmitter software algorithms used to manage expected measurement errors. Contact the Coriolis flowmeter manufacturer for additional information regarding this type of application.

**3.3.3 Temperature.** Temperature changes affect the mechanical structure of the flow sensor and compensation is necessary. This compensation, based on an integral temperature sensor, is performed by the transmitter. However, large differences in temperature between the oscillating tube(s) and the ambient temperature can cause errors in the temperature compensation. The use of insulation materials can reduce these effects.

NOTE: The temperature measured in the Coriolis flowmeter is that of the oscillating tube walls and may not be the same as the process fluid temperature.

**3.3.4 Pressure.** Coriolis flow sensor designs vary significantly between manufacturers and even within the designs of a single manufacturer. Some designs or flow sensor sizes may be more susceptible to pressure effects than other designs. Thus, it is not possible to herein describe specific installation recommendations. Check with the manufacturer for recommendations and procedures to adjust the calibration factors or enable active compensation for pressure effects.

Pressure changes can also induce an offset in the Coriolis flowmeter output at zero flow. This effect may be eliminated by performing a zero adjustment (see para. 3.4) at the process pressure.

**3.3.5 Installation.** Stresses exerted on the flow sensor from the surrounding pipe work can introduce an offset in the Coriolis flowmeter output at zero flow. This offset should be checked after the initial installation or after any subsequent change in the installation. A zero adjustment (see para. 3.4) should be performed if the offset is unacceptable.

## 3.4 Zero Adjustment

After the Coriolis flowmeter installation is complete, a zero adjustment may be needed. It is recommended that zero be checked and adjusted if the offset is unacceptable. Zero adjustments should be made according to the manufacturer's instruction. In general, to check or adjust the zero flow, the flowmeter should be full of the process fluid and all flow stopped. Zero adjustment should be made, if possible, under process conditions of temperature, pressure, and density. It is essential that the fluid remain stable and there are no bubbles or heavy sediment and no fluid movement. Therefore, it is recommended that both upstream and downstream valves are closed during the zero adjustment process.

## 3.5 Calibration of Mass Flow

### 3.5.1 Definition

*calibration:*

*(a)* the process of comparing the indicated flow to a traceable reference standard

*(b)* the process of adjusting the output of a device to bring it to a desired value, within a specified tolerance for a particular value of the input

**3.5.2 Calibration Guidelines.** The uncertainty of the calibration can be no less than the uncertainty of the reference standard and any errors that are introduced during the calibration.

Most manufacturers calibrate their Coriolis flowmeters using water and gravimetric weigh scales or transfer standards directly traceable to scales. Water and gravimetric scales or transfer standards are generally used to calibrate flowmeters that are to be used in either liquid or gas applications because they are available with lower uncertainties than those of gas labs. The calibration factors determined by this procedure should be noted on the flow sensor data plate and calibration certificates for the Coriolis flowmeter should be available.

Test data in the public domain substantiates that a Coriolis flowmeter factor is independent of fluid used during calibration within the uncertainty of the calibration references.

As the Coriolis flowmeter is a mass flow device, it is preferable to perform the calibration against a mass-traceable reference. Calibration against a volume-traceable reference combined with a density-traceable reference may be used where applicable. Master flowmeters, like turbine flowmeters, sonic nozzles, or Coriolis flowmeters, may be used to calibrate Coriolis flowmeters. Calibration of the master flowmeters must be traceable to recognized standards.

Detailed calibration information including calibration intervals, suggested procedures, calibration levels, and an example of a calibration certificate are included in Nonmandatory Appendix A.

## 4 CORIOLIS FLOWMETER SELECTION AND APPLICATION GUIDELINES

### 4.1 Coriolis Flowmeter Selection Considerations

*(a)* The major consideration when selecting and sizing a Coriolis flowmeter is the tradeoff between pressure loss and flowmeter performance (accuracy). The following information is used to select and size a Coriolis flowmeter:

*(1)* flow rate range
*(2)* pressure range
*(3)* temperature range
*(4)* available pressure drop
*(5)* liquid density
*(6)* liquid viscosity
*(7)* gas composition or flowing density at minimum operating pressure and maximum operating temperature
*(8)* required flowmeter performance (accuracy)

*(b)* Properly selecting a Coriolis flowmeter consists of choosing a flowmeter size that optimizes the tradeoff between measurement error at $q_{min}$ (see para. 4.1.1) and pressure loss at $q_{max}$ (see para. 4.1.2), at acceptable velocities through the flowmeter oscillating tube(s). At a given flow rate

*(1)* pressure drop and velocity are higher through a smaller diameter Coriolis flowmeter but potential measurement error at the lowest flow rates is generally reduced and useable turndown ratio is typically increased.

*(2)* pressure drop and velocity are lower when a larger diameter Coriolis flowmeter is chosen but measurement error at low flow rates will increase and turndown ratio will decrease.

**4.1.1 Minimum Flow Rate ($q_{min}$).** The minimum flow rate, $q_{min}$, (mass or volume) of a Coriolis flowmeter is determined by the maximum permissible measurement error.

NOTE: The measurement error of a Coriolis flowmeter is determined from the flowmeter's zero stability ($ZS$) and the manufacturer's published accuracy equation. Once $q_{min}$ is determined in base units (mass or volume) for a particular gas or liquid mixture, it will remain constant over the range of temperature, pressure, and flow velocity. Only a change in gas composition or base conditions will cause the value of $q_{min}$ to change.

**4.1.2 Maximum Flow Rate ($q_{max}$).** The maximum flow rate, $q_{max}$, (mass or volume) of a Coriolis flowmeter is determined by the maximum acceptable pressure drop ($\Delta p_c$) across the flowmeter.

**4.1.3 Coriolis Flowmeter Pressure Loss ($\Delta p_c$).** Correct sizing of the Coriolis flowmeter will optimize the flowmeter performance over the flow rate range with a pressure drop that is acceptable for the application. If maintaining a low pressure drop is a priority, flowmeter selection will be made to provide the lowest possible pressure drop at maximum flow while maintaining an acceptable measurement performance at minimum flow rates.

*(a)* Figures 4.1.3-1 and 4.1.3-2 show examples of the relationship between pressure drop and Coriolis flowmeter performance in gas applications at 70 bar (1,000 psig) and 35 bar (500 psig) for several typical sizes of Coriolis flowmeters.

*(b)* Figure 4.1.3-3 shows examples of the relationship between pressure drop and Coriolis flowmeter performance in liquid application over a wide turndown for several typical sizes of Coriolis flowmeters.

*(c)* Figure 4.1.3-4 shows examples of Coriolis flowmeter performance in a liquid application at $q_{min}$ for several typical sizes of Coriolis flowmeters.

NOTE: Check with the manufacturer for similar data on Coriolis flowmeters being considered for your applications.

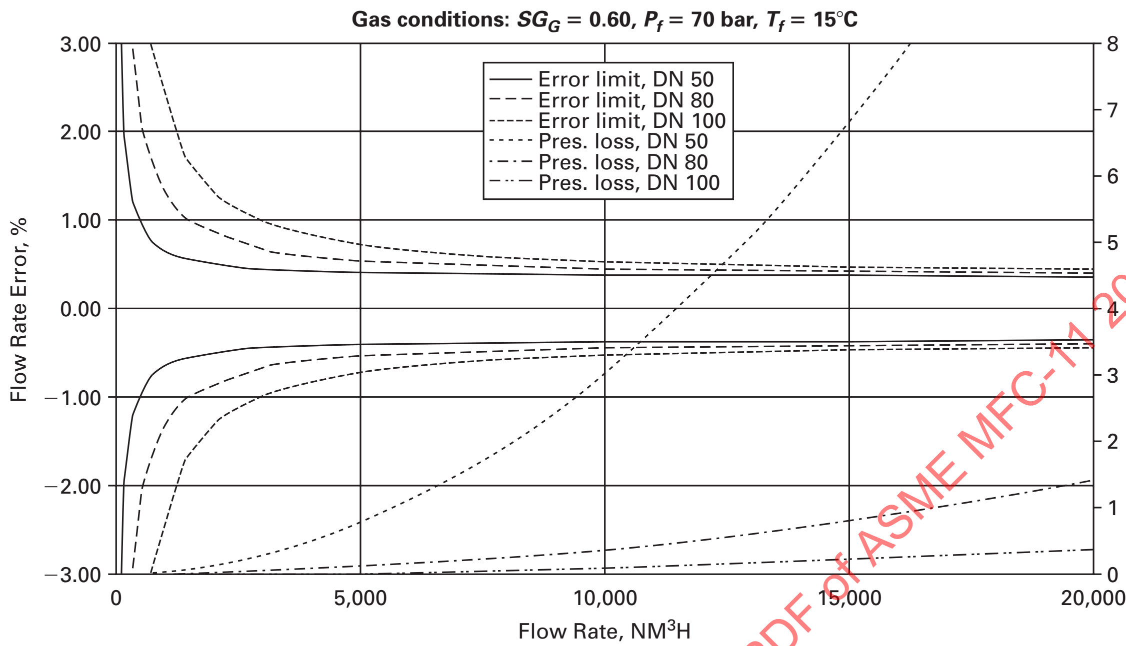
Pressure drop is determined by a constant called the pressure loss coefficient, $K_p$, and is defined as

$$K_p = 2g_c \Delta p_c / \rho_f v^2 \qquad (4\text{-}1)$$

Rewriting this equation to solve for pressure drop ($\Delta p_c$) the equation becomes

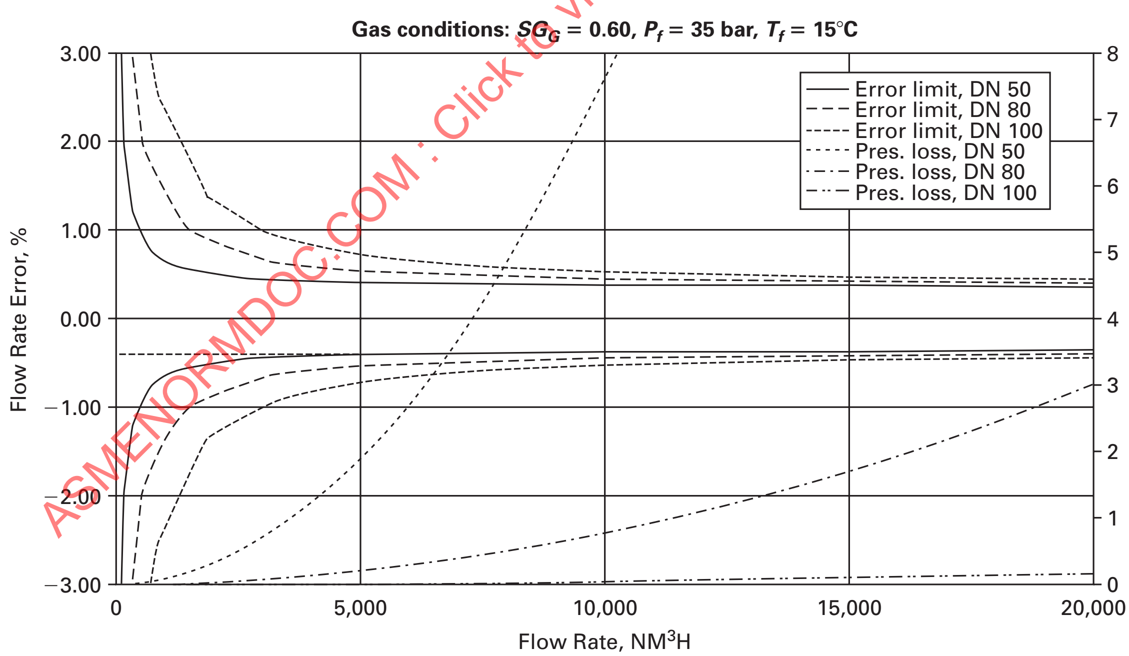
$$\Delta p_c = K_p \rho_f v^2 / 2g_c \qquad (4\text{-}2)$$

**Fig. 4.1.3-1 Examples of Coriolis Flowmeter Performance and Pressure Loss vs. Flow Rate**



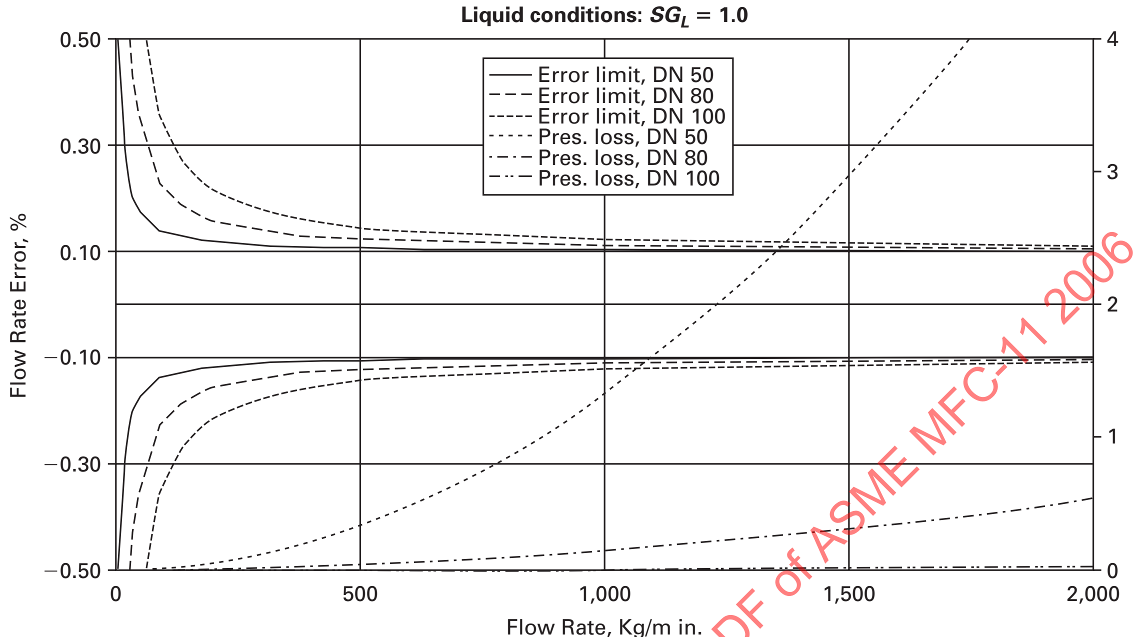

GENERAL NOTE: Coriolis flowmeter performance and pressure drop vs. flow rate at 70 bar (1,000 psig) for some DN 50, 80 and 100 (2, 3, and 4 in.) bent tube (approximately "U" shape) flowmeters.

**Fig. 4.1.3-2 Examples of Coriolis Flowmeter Performance and Pressure Loss vs. Flow Rate**



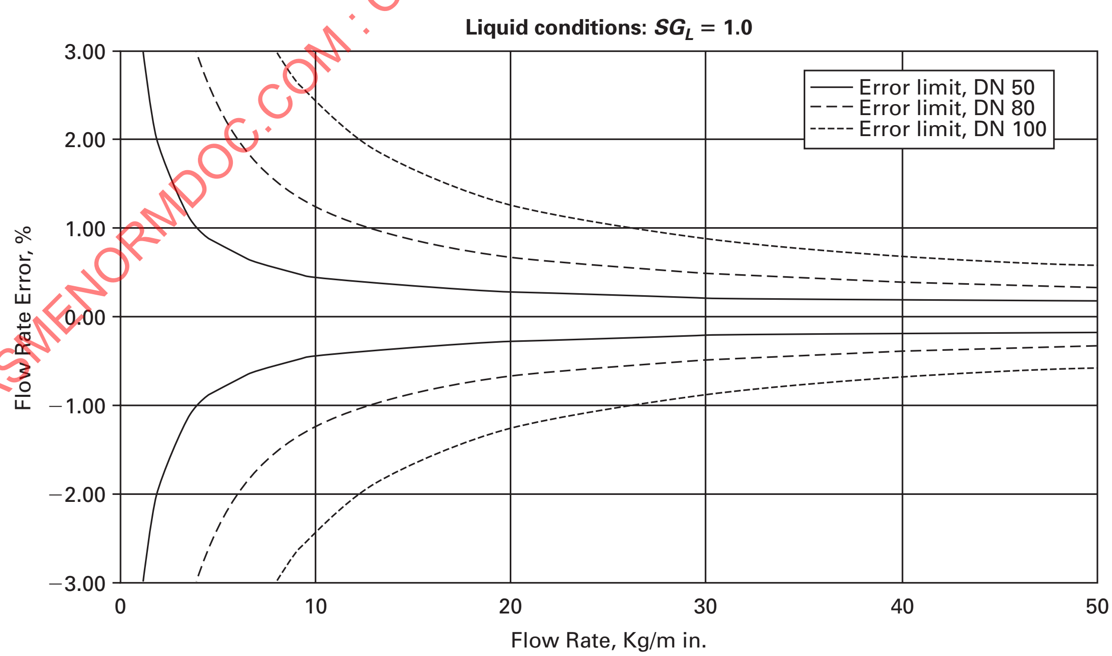

GENERAL NOTE: Coriolis flowmeter performance and pressure loss vs. flow rate at 35 bar (500 psig) for some DN 50, 80 and 100 (2, 3, and 4 in.) bent tube (approximately "U" shape) flowmeters.

**Fig. 4.1.3-3 Examples of Coriolis Flowmeter Performance and Pressure Loss vs. Flow Rate**




GENERAL NOTE: Coriolis flowmeter performance and pressure loss vs. flow rate with liquids for some DN 50, 80 and 100 (2, 3, and 4 in.) bent tube (approximately "U" shape) flowmeters.

**Fig. 4.1.3-4 Examples of Coriolis Flowmeter Performance vs. Flow Rate**




GENERAL NOTE: Coriolis flowmeter performance vs. flow rate with liquids for some DN 50, 80 and 100 (2, 3, and 4 in.) bent tube (approximately "U" shape) flowmeters.

The equations show that with constant density of flowing fluid, $\rho_f$, the pressure loss, $\Delta p_c$, is directly proportional to the square of the flowing velocity, $v$. As the pressure drop is proportional to the square of the velocity, choosing a larger line size flowmeter will lower the pressure drop. However, the measurement error over the operating flow rate range for the larger-size flowmeter will typically be greater. For a given flow rate and flowing condition, every meter design and size of Coriolis flowmeter will have a specific pressure drop. Consult the Coriolis flowmeter manufacturer for specific pressure drop information.

**4.1.4 Coriolis Flowmeter Selection.** Coriolis flowmeter rangeability is the ratio of the maximum to minimum flow rates in the flow measurement range for which the flowmeter meets a manufacturer's specified accuracy. The turndown ratio is a result of the user-selected maximum flow rate and the accepted measurement error at the minimum flow rate.

Nonmandatory Appendix C includes examples of Coriolis flowmeter sizing for both gas and liquid applications.

**4.1.5 Design Pressure and Temperature.** The selected Coriolis flowmeter's pressure and temperature ranges must meet the requirements of the application. Most manufacturers offer flowmeter options that allow a wide range of pressure and temperature conditions.

## 4.2 Performance

The flowmeter performance varies depending on the parameter to which it applies. For specifics on the accuracy of mass flow, density, and volume flow measurement see paras. 3.2, 6.4, and 7.3.3. For other parameters, see section 8.

NOTE: Manufacturer's performance statements should be given for specified reference conditions. If the conditions of use are significantly different from those of the original calibration, the flowmeter performance may be affected.

## 4.3 Physical Installation

The installation of the Coriolis flowmeter should take into account physical constraints, process fluid, flow conditions, and application considerations. The following are major considerations that are recommended for review for each installation.

**4.3.1 General.** The manufacturer should describe the preferred installation arrangement and state any restrictions of use. Coriolis flowmeters are generally placed in the mainstream of the flow but may also be placed in a bypass arrangement for density measurements or other circumstances.

**4.3.2 Installation Criteria.** Consideration should be given to the following points:

*(a)* the space required for the Coriolis flowmeter installation, including provision for external volumetric prover or master flowmeter connections, should in-situ calibration be required

*(b)* the class and type of pipe connections and materials, as well as the dimensions of the equipment to be used

*(c)* the hazardous area classification

*(d)* the environmental effects on the flow sensor, for instance temperature, humidity, corrosive atmospheres, mechanical shock, vibration, and electromagnetic field

*(e)* the mounting and support requirements

**4.3.3 Piping Requirement.** For liquid applications the Coriolis flowmeter performance may be impaired if the oscillating tube(s) are not completely filled with the flowing liquid. Consult the manufacturer for information on the flowmeter performance effects and possible methods to drain or purge.

For gas applications the Coriolis flowmeter performance is impaired if the oscillating tube(s) contain liquid. Consideration should be given to the gas water vapor content, content of other vapors, or a potential for condensing components from the gas.

Installation location and orientation may have a beneficial effect on the performance of a Coriolis flowmeter in applications where the system is susceptible to drainage or solids settling in liquid service and pooling or condensing in gas service. (See paras. 4.3.4 and 4.3.5.)

**4.3.4 Process Fluid Quality.** For liquid applications, the use of strainers, filters, air and/or vapor eliminators or other protective devices may be required for the removal of solids or vapors that could cause damage or induce errors in measurement. In general, these devices should be placed upstream from the Coriolis flowmeter.

For gas applications, the use of filters, traps, or other protective devices may be required for the removal of solids or liquids that could cause damage or induce errors in measurement. In general, these devices should be placed upstream from the Coriolis flowmeter.

**4.3.5 Orientation.** For proper operation, the flow sensor should be mounted such that the oscillating tube(s) remain completely filled with the process fluid while the fluid is being metered.

*(a)* For liquid flow measurement applications, tube coatings, trapping of gas, or settling of solids can affect the Coriolis flowmeter's performance. The orientation of the Coriolis flowmeter will depend on the application as well as the geometry of the oscillating tube(s).

*(b)* For gas flow measurement applications, the condensing of liquids, or settling of liquids can affect the Coriolis flowmeter performance. The orientation of the Coriolis flowmeter will depend on the application as well as the geometry of the oscillating tube(s).

**4.3.6 Flow Conditions and Straight Length Requirements.** Coriolis flow sensor designs vary significantly between manufacturers and even within the designs of a single manufacturer. Some designs may be more susceptible to velocity profile or fluid swirl than other designs. Thus, it is not possible to herein describe specific installation recommendations. The manufacturer should be consulted for flow conditions and straight length recommendations.

**4.3.7 Valves.** Valves upstream and downstream of a Coriolis flowmeter, installed for the purpose of isolation and zero adjustment, may be of any type, but should provide no flow shutoff for the operating conditions.

Some applications may use control valves in series with a Coriolis flowmeter. The control valve may be installed downstream from the flowmeter. This allows the control valve to be used to help maintain higher pressure in the flowmeter, thus reducing the potential for cavitation and flashing. (See para. 4.3.10.)

**4.3.8 Cleaning.** For certain applications the Coriolis flowmeter may require in-situ cleaning, which, depending on design, may be accomplished by[1,2]

*(a)* mechanical means (using a pig or ultrasonically)
*(b)* self-draining (liquid)
*(c)* hydrodynamic means
*(d)* sterilization (steaming-in-place)
*(e)* chemical or biological (cleaning-in-place)

**4.3.9 Hydraulic and Mechanical Vibrations.** The Coriolis flowmeter operating frequency should be available to the user. The user should review the process and external mechanically imposed vibration frequencies, which could affect the performance of the flowmeter. Consult with the manufacturer if vibration problems are anticipated or if they occur.

In environments with high mechanical vibrations or flow pulsation, consider the use of isolation or pulsation-damping devices. (See para. 4.4.7.) Consultation with the manufacturer may be appropriate if vibration problems are anticipated or if they occur.

**4.3.10 Flashing and/or Cavitation.** For some liquid applications with relatively high fluid velocities, which may occur in Coriolis flowmeters, local dynamic pressure drops inside the flowmeter may result in flashing and/or cavitation. Both flashing and cavitation in Coriolis flowmeters (and immediately upstream and/or downstream of them) should be avoided. Flashing may cause measurement errors. Cavitation may damage the flow sensor.

**4.3.11 Pipe Stress and Torsion.** The flow sensor may be subjected to axial, bending, and torsional forces during operation. Changes in these forces, resulting from variations in process temperature and/or pressure, can affect the performance of the Coriolis flowmeter, particularly at flow rates low in the flowmeter's range. Care should be taken to minimize the stresses on the Coriolis flowmeter caused by the installation. Under no circumstances should the Coriolis flowmeter be used to align and/or support the pipe work.

**4.3.12 Cross-Talk Between Flow Sensors.** Coriolis flow sensor designs vary significantly between manufacturers and even within the designs of a single manufacturer. Some designs may be more susceptible to cross-talk interference than other designs. Thus, it is not possible to herein describe specific installation recommendations. The manufacturer should be consulted for methods of avoiding cross-talk.

### 4.4 Process Conditions and Fluid Properties

**4.4.1 General.** Variations in fluid properties and process conditions may influence the Coriolis flowmeter's performance. (See paras. 3.3 and 6.5.)

**4.4.2 Application Considerations.** In order to select a Coriolis flowmeter for a given application, it is important to establish the range of process conditions for the application. These application process conditions should include

*(a)* the operating flow rates and the following flow characteristics: unidirectional or bidirectional, continuous, intermittent, or fluctuating
*(b)* the range of operating densities
*(c)* the range of operating temperatures (minimum and maximum)
*(d)* the range of operating pressures
*(e)* the permissible pressure loss
*(f)* the range of operating viscosities
*(g)* the maximums and minimums of the preceding properties during startup, shutdowns, or process upsets
*(h)* the properties of the metered fluids, including vapor pressure at operating conditions
*(i)* the effects of corrosive additives or contaminants on the Coriolis flowmeter and the quantity and size of foreign matter, including abrasive particles that may be carried in the fluid stream

**4.4.3 Nonhomogeneous and Homogeneous Mixtures (See Para. 6.4.4 and Para. 7.2.2.3).** Liquid mixtures, homogeneous mixtures of solids in liquids, immiscible liquids, homogeneous mixtures of liquids with low volumetric ratios of gas, or homogeneous mixtures of gases can be measured satisfactorily.

Increased nonhomogeneity of the liquid mixture can lead to deterioration in performance and may result in loss of signal attributed to the absorption of the oscillation energy required to vibrate the flow sensor. Multiphase applications involving nonhomogeneous mixtures can cause additional measurement errors and can interrupt Coriolis flowmeter operation for some flowmeter designs.

[1] Care should be taken to avoid cross-contamination after cleaning fluids have been used.

[2] Chemical compatibility should be established between the flow-sensor-wetted materials, process fluid, and cleaning fluid.

Care should be taken to ensure that gas bubbles and/or solids are not allowed to accumulate in the Coriolis flowmeter. The accumulation of gas bubbles or solids in the flowmeter may adversely affect the flowmeter's accuracy.

While the Coriolis flowmeter will not be damaged when beginning and ending the measurement with an empty flow sensor, the results of the measurement may be outside the expected performance accuracy. A Coriolis flowmeter system solution may be designed, capable of starting and finishing the measurement process from an empty or partially full pipe and or sensor condition. The system may include, but is not limited to, an air/vapor eliminator, a reverse flow check valve, and a flow computer or transmitter software algorithms used to manage expected measurement errors. Contact the Coriolis flowmeter manufacturer for additional information.

**4.4.4 Influence of Process Fluid.** Erosion, corrosion, and deposition of material on the inside of the oscillating tube(s) (sometimes referred to as coating) can initially cause measurement errors in flow and density, and in the long-term, flow sensor failure. Proper selection of the Coriolis flowmeter material can reduce the instance of failure. Periodic inspection and maintenance should be done on the flowmeter for applications that may cause these types of problems.

**4.4.5 Temperature Effects.** A change in temperature may affect the properties of flow sensor materials, and thus will influence the response of the sensor. A means of compensation for this effect is usually incorporated in the design by the manufacturer.

**4.4.6 Pressure Effects.** Static pressure changes may affect the Coriolis flowmeter performance, the extent of which should be specified by the manufacturer. These changes are generally insignificant.

**4.4.7 Pulsating Flow Effects.** Coriolis flowmeters generally are able to perform under pulsating flow conditions. However, there may be circumstances where pulsations can affect the performance of the flowmeter. (See para. 4.3.9.) The manufacturer's recommendations should be observed regarding the application and the possible use of pulsation damping devices.

**4.4.8 Viscosity Effects.** Fluids with high viscosity will draw energy from the flow sensor drive system particularly at the start of flow. Depending on the Coriolis flowmeter design, this phenomenon may cause the oscillating tube(s) to momentarily stall until the flow is properly established. Some manufacturer's meters are designed to minimize or overcome viscous effects.

### 4.5 Pressure Loss

A loss in pressure will occur as the fluid flows through the flow sensor. The magnitude of this loss will be a function of the size and geometry of the oscillating tube(s), the fluid flow rate, and the dynamic viscosity of the process fluid. Manufacturers should specify the loss in pressure that occurs under reference conditions and the information necessary to calculate the loss in pressure, which occurs under operating conditions. The overall pressure of the system should be checked to ensure that it is sufficiently high to accommodate the loss in pressure across the Coriolis flowmeter.

### 4.6 Safety

**4.6.1 General.** The Coriolis flowmeter should not be used under conditions that are outside the flowmeter's specification. Flowmeters also should conform to any necessary hazardous area classifications. The following additional safety considerations should be made.

**4.6.2 Hydrostatic Pressure Test.** The wetted parts of the fully assembled flow sensor must be hydrostatically tested in accordance with the appropriate standards.

**4.6.3 Mechanical Stress.** The Coriolis flowmeter should be designed to withstand all loads originating from the oscillating tube(s) system, temperature, pressure, and pipe vibration. The user should respect the limitations of the flow sensor.

**4.6.4 Erosion.** Liquid cavitation or fluids containing solid particles can cause erosion of the oscillating tube(s) during flow. The effect of erosion is dependent on Coriolis flowmeter size, geometry, fluid velocity, particle material, and size. Erosion should be assessed for each type of use of the flowmeter.

Erosion can occur in high gas velocity in some Coriolis flowmeter applications even though contaminants are reduced to a minimum.

**4.6.5 Corrosion.** Corrosion of the process conduit material can adversely affect the operating life of the flow sensor. The construction material of the sensor should be selected to be compatible with process fluids and cleaning fluids. Special attention should be given to corrosion and galvanic effects in no-flow or empty-pipe conditions.

NOTE: Consult the manufacturer regarding specific process compatibilities.

**4.6.6 Housing Design.** The housing should be designed primarily to protect the flow sensor from the effects of the surrounding environment (dirt, condensation, and mechanical interference), which could interfere with operation. If the oscillating tube(s) of the Coriolis flowmeter were to fail, the housing containing the tube(s) would be exposed to the process fluid and conditions, which could possibly cause housing failure. It is important to take into consideration the following possibilities:

*(a)* The pressure within the housing may exceed the design limits.

*(b)* The fluid may be toxic or volatile and thereby create a safe-handling issue or be corrosive and leak from the housing.

In order to avoid such problems, certain housing designs provide

*(1)* secondary pressure containment

*(2)* burst discs or pressure-relief valves, drains, or vents, etc.

For guidelines on specifying secondary pressure containment, see Nonmandatory Appendix B.

**4.6.7 Cleaning.** For general guidelines see para. 4.3.8. Care should be taken to ensure that cleaning conditions (liquids, temperatures, flow rates, etc.) have been selected to be compatible with the materials of the Coriolis flowmeter.

### 4.7 Transmitter

Coriolis flowmeters are multivariable instruments providing a wide range of measurement data from a single connection to the process. The transmitter is typically located in an enclosure. The enclosure may be mounted locally as part of the Coriolis flowmeter or remotely. When selecting the most appropriate transmitter arrangement and options, consideration should be given to the following:

*(a)* the electrical, electronic, climatic, and safety compatibility

*(b)* the hazardous area classification of the flow sensor, and transmitter, and the availability of special enclosure options

*(c)* the transmitter enclosure mounting, i.e., integral or remote

*(d)* the number and type of outputs, including digital communications

*(e)* the ease and security of programming

*(f)* the Coriolis flowmeter diagnostic capability, and whether there is output(s) to allow remote indication of system errors

*(g)* the available input options, for instance remote zero adjustment, totalizer resetting, and alarm acknowledgement

*(h)* the capability of a local display for programming and operation

## 5 INSPECTION AND COMPLIANCE

*(a)* As Coriolis flowmeters are an integral part of the piping (in-line instrumentation), it is essential that the instrument be subjected to testing procedures similar to those applied to other in-line equipment. This could include

*(1)* dimensional check

*(2)* hydrostatic test

*(3)* radiographic and/or ultrasonic examinations of the Coriolis flowmeter to detect internal defects (i.e., inclusions) and verify weld integrity

Results of the preceding tests should be available as a certified report, when requested.

*(b)* The following certificates, when requested, should be available:

*(1)* material certificates, for all pressure-containing parts

*(2)* certificate of conformance (electrical area classifications)

*(3)* certificate of suitability for legal trade or custody transfer

*(4)* calibration certificate and performance results

*(5)* certificate of suitability for sanitary applications

## 6 DENSITY MEASUREMENT OF LIQUID

Most Coriolis flowmeters can provide density measurement for liquids.

**CAUTION: As of this writing the gas density measurement capability of Coriolis flowmeters is limited and the gas density measurement should not be used to convert mass flow of gas to actual volumetric flow rate of gas.**

Section 6 through para. 7.2.3.2 applies to the density measurement of liquids.

### 6.1 Principle of Operation

Coriolis flowmeters are typically operated at their resonant frequency. For a resonant system there is a relationship between this frequency and the oscillating mass. The resonant frequency, $f_R$, of a Coriolis flowmeter and related equations is written as

$$f_R = \left(\frac{1}{2\pi}\right)(C/m)^{1/2} \tag{6-1}$$

$$m = m_{tb} + m_{liq\text{-}tb} \tag{6-2}$$

$$m_{liq\text{-}tb} = (\rho_{liq})(V_{liq\text{-}tb}) \tag{6-3}$$

where

$C$ = mechanical stiffness or spring constant of the oscillating tube arrangement
$f_R$ = resonant (natural) frequency
$m$ = mass
$m_{liq\text{-}tb}$ = mass of liquid within the oscillating tube(s)
$m_{tb}$ = mass of oscillating tube(s)
$V_{liq\text{-}tb}$ = volume of liquid within the oscillating tube(s)
$\rho_{liq}$ = density of liquid

The mechanical stiffness or spring constant of the oscillating tube arrangement depends on the design of the Coriolis flowmeter and the Young's modulus of elasticity of the tube material.

Equations (6-1), (6-2), and (6-3) may be used to solve for the liquid density, which is given by

$$\rho_{liq} = [C/(V_{liq\text{-}tb}\,(2\pi\ f_R)^2] - (m_{tb})/V_{liq\text{-}tb} \tag{6-4}$$

rewritten as

$$\rho_{liq} = K_1 + K_2/f_R^2 \tag{6-5}$$

where

$K_1$ and $K_2$ = density calibration factors (coefficients) for the density measurement that are determined during the calibration process
= influenced by temperature and are commonly compensated for by means of integral temperature measurement

The frequency, $f_R$, in eqs. (6-4) and (6-5) is determined by measuring the period of the oscillating tube, $T_f$, or by counting the number of cycles, $N_c$, during a time window (gate), $t_w$.

$$f_R = 1/T_f \text{ or } f_R = N_c/t_w \tag{6-6}$$

where

$N_c$ = number of cycles
$T_f$ = period of the oscillating tube
$t_w$ = time window (gate)

## 6.2 Specific Gravity

Dividing the liquid density under process conditions by the density of pure water under reference conditions, results in the specific gravity, $SG$.

$$SG = \rho_{\text{liq}}/\rho_{\text{w,ref}} \tag{6-7}$$

where

$\rho_{\text{liq}}$ = the density of liquid under metering conditions
$\rho_{\text{w,ref}}$ = the density of water under reference conditions (typically the reference temperature is 4°C but reference conditions may vary by industry standards)

## 6.3 Accuracy

The density accuracy specification usually includes the combined effects of linearity, repeatability, and hysteresis. Density accuracy is expressed as an absolute value in mass per unit volume (i.e., g/cm$^3$, kg/m$^3$, or lbm/ft$^3$).

Accuracy and repeatability statements are usually given for reference conditions, which are specified by the manufacturer.

## 6.4 Factors Affecting Liquid Density Measurement

**6.4.1 General.** The measurement of density can be influenced by changes in process conditions. In certain applications, these influences may be significant and manufacturers should be able to quantify the effect or give guidance on the likely impact on the performance of the Coriolis flowmeter.

If users require more measurement reference and traceability than their Coriolis flowmeter supplier's calibration, Coriolis flowmeters can be field calibrated. Field calibration can be used to verify possible installation effects or process temperature effects.

**6.4.2 Temperature.** Temperature changes can affect the density calibration factor of the Coriolis flowmeter. Compensation for these changes is necessary and is frequently performed by the transmitter. However, due to the nonlinearity of the density equation, the effect may not be entirely eliminated. In order to minimize this effect in precision applications, it may be necessary to adjust the density calibration of the flowmeter at the operating temperature. Large differences in temperature between the oscillating tube(s) and the ambient temperature can cause errors in temperature compensation. The use of insulation materials may minimize these effects.

NOTE: In certain applications, e.g., cryogenic liquids, there may be a transient temperature influence resulting from a step change in process temperature (thermal shock) that will momentarily influence the density measurement.

**6.4.3 Pressure.** Coriolis flow sensor designs vary significantly between manufacturers and even within the designs and flow sensor sizes of a single manufacturers. Some designs or flow sensor sizes may be more susceptible to pressure effects than other designs. Thus, it is not possible to herein describe specific installation recommendations. Check with the manufacturer for recommendations and procedures to adjust the density calibration factor due to pressure effects.

**6.4.4 Multiple Phases.** The density of liquid mixtures, homogeneous mixtures of solids in liquids, or homogeneous mixtures of liquids with a low volumetric ratio of gas can be measured satisfactorily with Coriolis flowmeters. Consult the manufacturer for design limits. In some circumstances, multiphase applications, particularly gas bubbles in liquids, can cause additional measurement errors and even stop operation. The degree to which bubbles or suspended solids can be tolerated without influencing the density measurement will depend on their distribution in, and coupling with, the carrier liquid. For example, large pockets of gas in liquid are more troublesome for measurement than homogeneously distributed bubbles in a highly viscous liquid.

Coriolis flowmeters can usually be configured to provide a volumetric output using the Coriolis mass-flow and density measurement capabilities. If a stand-alone densitometer and the Coriolis mass-flow signals are used to compute volumetric flow, varying process density and frequency of calculations may affect the system's performance.

**6.4.5 Flow Effect.** Density calibration is usually carried out under static conditions, i.e., without any liquid flowing.

Operation on a flowing liquid may influence the density measurement. Liquid velocities that give rise to such an effect will vary depending on the sensor size and design. For increased precision, it may be advisable to perform the density calibration under flowing conditions. Some manufacturers offer automatic compensation for flow effects on density measurement.

**6.4.6 Corrosion, Erosion, and Coating.** Corrosion, erosion, and coating may affect the mass and stiffness of the oscillating tube. These effects will induce errors in the density measurement. In applications where these effects are likely, care should be taken in specifying suitable materials, selecting the most appropriate Coriolis flowmeter size (limiting velocity), and where necessary, applying regular cleaning.

**6.4.7 Installation.** In general, installation stresses do not influence the density measurement. However, for certain flow sensor designs, there may be a minor orientation effect. In precise density measurement applications, it may be necessary to calibrate the Coriolis flowmeter in its intended final orientation or alternatively perform a field adjustment. (See para. 6.5.3.)

### 6.5 Liquid Density Calibration and Adjustment

**6.5.1 General.** Coriolis flowmeters may be calibrated during manufacture and/or by field adjustment. Only single-phase, clean liquids should be used for calibration or adjustment. The oscillating tube(s) should be clean and free of coating or deposits and should be flushed immediately prior to calibration. Deviation from these requirements can result in significant measurement errors.

**6.5.2 Manufacturer's Density Calibration.** Coriolis flowmeters are frequently calibrated by the manufacturer for density measurement using air and water as reference fluids. The density calibration factors determined by this procedure may be provided by the manufacturer. If a more precise density measurement is required, a special calibration may be necessary.

**6.5.3 Field Density Adjustment.** The advantage of field adjustment is that it can be performed by the user with the process liquids in the oscillating tube(s).

The transmitter may be equipped with facilities to support a field adjustment with the Coriolis flowmeter filled with one or more liquids.

## 7 VOLUME FLOW MEASUREMENT UNDER METERING CONDITIONS

### 7.1 General

Coriolis flowmeters directly measure mass flow rate and liquid density under metering conditions. Therefore, they are generally used where measurements of either or both of these parameters are of importance. However, there are applications where the advantages of a Coriolis flowmeter would be very beneficial, but the desired measurement is volume under metering conditions. Coriolis flowmeters may be effectively used for liquid volume flow measurement. (See para. 6.1 for Coriolis gas density capability.)

### 7.2 Volume Calculation for Liquids

Density is defined as mass per unit volume. Therefore, liquid volume may be calculated from mass and density as follows:

$$V_{\text{liq}} = m/\rho_{\text{liq}} \tag{7-1}$$

where

$V_{\text{liq}}$ = liquid volume under metering conditions
$m$ = mass
$\rho_{\text{liq}}$ = density under metering conditions

Equation (7-1) may be incorporated directly into the transmitter software provided the Coriolis flowmeter can measure both mass and density (see sections 3 and 6). Since the mass is measured as a function of time (mass flow rate), the volume calculated is also a function of time.

$$q_{v\text{-liq}} = q_m/\rho_{\text{liq}} \tag{7-2}$$

where

$q_{v\text{-liq}}$ = the liquid volume flow rate under metering conditions
$q_m$ = the mass flow rate

The Coriolis flowmeter may then provide the liquid volume flow rate calculated from eq. (7-2) as an output signal. The calculated liquid volume flow rate may also be integrated with respect to time to obtain the total volume.

NOTE: The calculated liquid volume flow is based on dynamic mass flow and dynamic density measurements made under process conditions. Liquid volume flow in this form will, therefore, also be a dynamic measurement under process conditions rather than reference conditions.

**7.2.1 Volume Accuracy for Liquids.** Coriolis flowmeter manufacturers generally publish their specified accuracy for liquid volume measurement. The expected accuracy for liquid volume flow measurement may be calculated as follows:

$$\varepsilon_{v\text{-liq}} = [(\varepsilon_m)^2 + (\varepsilon_{\rho\text{-liq}})^2]^{1/2} \tag{7-3}$$

where

$\varepsilon_{v\text{-liq}}$ = accuracy of the liquid volume measurement
$\varepsilon_m$ = accuracy of the mass measurement (see para. 3.2)
$\varepsilon_{\rho\text{-liq}}$ = accuracy of the liquid density measurement (see para. 6.4)

The terms in eq. (7-3) must be expressed as a ± percentage of reading.

**7.2.2 Special Influences for Liquids**

**7.2.2.1 Combined Measurement Effects.** Coriolis flowmeters can only give a computed value of the volume, and as such, the reliability can be only as good as the measured data entered into the volume equation. On this basis, any variation in the liquid or in process parameters that influence the reliability of mass flow and density measurements will have a combined effect on the reliability of the calculated volume measurement. For specific effects of variations in process conditions on mass flow and density measurements, see Sections 3 and 6.

**7.2.2.2 Empty Pipe Effect.** A Coriolis flowmeter, measuring liquid volumetric flow, will be dramatically affected when the oscillating tubes become empty as the liquid is displaced by vapor. If this occurs while there is still flow present, the calculation of the liquid volume according to eq. (7-1) will generate a relatively large measurement error. This problem can be avoided by incorporating a suitable low-density cut-off setting, designed to inhibit any flow measurement unless the flowmeter is properly filled with liquid. Consultation with manufacturers may provide alternative methods for eliminating this problem.

**7.2.2.3 Multiple Fluids (Mixtures of Liquids and Gases).** Liquid volumes cannot be measured reliably if there is more than one phase present.

### 7.2.3 Factory Calibration

**7.2.3.1 Mass Flow and Density Calibration.** Coriolis flowmeters are mass flow and density measuring devices. These two parameters should be calibrated in accordance with the recommendations given in paras. 3.5 and 6.6, before the flowmeter is used for volumetric measurements. Once the flowmeter has been calibrated for mass flow and density, a theoretical prediction of the liquid volume accuracy can be determined using eq. (7-3) described in para. 7.2.1.

**7.2.3.2 Liquid Volume Check.** The expected value of accuracy for liquid volume measurement may be checked by performing a volumetric or gravimetric test against known standards. In addition to the standard calibration certificate, on request, manufacturers may be able to provide test data showing liquid volume flow rates and corresponding volumetric errors. These errors can be determined using the mass flow calibration data and the precise calibration liquid density. The liquid volume determination can also be checked by means of a field test, which should be performed using the Coriolis flowmeter in its operational installation using the process liquid.

## 7.3 Gas Volume Calculation

**7.3.1 General.** Coriolis flowmeters directly measure mass flow rate and at the time this document was written the Coriolis flowmeter gas density measurement capability was limited. Therefore, precise direct volume measurements of gas flows with Coriolis flowmeter is not possible with the presently available technology. When a volume measurement of gas is desired, it is calculated in terms of known reference conditions, generally referred to as base conditions, yielding a measurement in standard cubic units. This is only possible when the gas composition is known and base conditions are defined.

NOTE: The conversion from mass to standard volumes for gas may be done in either the Coriolis transmitter or a flow computer depending on equipment capabilities and user's practices.

**7.3.2 Volume Calculation for Gas.** Density is defined as mass per unit volume. Therefore, standard gas volume can be calculated from mass and density as follows:

$$V_{g\text{-}b} = m/\rho_{g\text{-}b} \tag{7-4}$$

where

$V_{g\text{-}b}$ = the standard gas volume at base conditions
$m$ = the mass
$\rho_{g\text{-}b}$ = the gas density at base conditions

Equation (7-4) may be incorporated into the Coriolis transmitter software or into a flow computer.

Since the mass is measured as a function of time (mass flow rate), the calculated standard volume is also a function of time.

$$q_{v\text{-}g\text{-}b} = q_m/\rho_{g\text{-}b} \tag{7-5}$$

where

$q_{v\text{-}g\text{-}b}$ = the gas volume flow rate under metering conditions
$q_m$ = the mass flow rate

NOTE: The calculated standard gas volume flow is based on a dynamic mass flow measurement and a reference density measurement. Standard gas volume flow in this form will, therefore, also be a dynamic measurement under process conditions relying on a correct characterization of the gas under base conditions.

**7.3.3 Volume Accuracy for Gas.** Some Coriolis flowmeter manufacturers publish their expected accuracy for standard volume measurement. The expected accuracy for standard volume flow measurement may be calculated as follows:

$$\varepsilon_{v\text{-}g\text{-}b} = [(\varepsilon_m)^2 + (\varepsilon_{\rho\text{-}g\text{-}b})^2]^{1/2} \tag{7-6}$$

where

$\varepsilon_{v\text{-}g\text{-}b}$ = the accuracy of the standard gas volume measurement
$\varepsilon_m$ = the accuracy of the mass measurement (see para. 3.2)
$\varepsilon_{\rho\text{-}g\text{-}b}$ = the accuracy of the reference density with respect to the base conditions

The terms in eq. (7-6) must be expressed as a ± percentage of reading.

#### 7.3.4 Special Influences for Gas

**7.3.4.1 General.** Coriolis flowmeters can output a computed value of the standard volume and, as such, the reliability can be only as good as the measured data used for the volume calculation equation. On this basis, any variation in the fluid or in process parameters that influence the reliability of mass flow measurement will have a combined effect on the reliability of the calculated standard volume. For specific effects of variations in process conditions on mass flow see para. 3.3.

**7.3.4.2 Piping Effect.** A Coriolis flowmeter measuring gas mass flow will be impaired if the oscillating tube(s) contain a liquid. If the mass flow measurement is impaired, the standard volume calculations provided will be in error. See para. 4.3.

#### 7.3.5 Factory Calibration

**7.3.5.1 Mass Flow.** Coriolis flow measurement of gas is a mass flow measurement. The Coriolis flowmeter should be calibrated as described in para. 3.5. When the flowmeter has been calibrated for mass flow, a theoretical prediction of the gas volume accuracy can be determined using eq. (7-6) described in para. 7.3.3.

## 8 ADDITIONAL MEASUREMENTS

### 8.1 General Considerations for Multicomponent Systems

The density measurement made by a Coriolis flowmeter is a function of the composite density of the process fluid in the oscillating tube(s). If the fluid contains two components and the density of each component is known, the mass or volume fraction of each component can be determined.

**8.1.1 Two-Component Liquid Systems with Known Densities.** By combining the (independent) mass flow rate and density (or concentration) measurements, the net mass flow of each component of a two-component mixture can also be calculated. Net flow measurements are limited to two-component systems where the carrier and target densities are known. For example, flow rates of each component of two-component systems such as water-and-oil mixtures, liquid-and-solid slurries, sugar measurements, and other two-component systems can be determined using a Coriolis flowmeter. (See para. 6.5.)

**8.1.2 Multicomponent Systems.** In principle, a Coriolis flowmeter will measure the composite density of two-component fluids, including two-phase systems. This is generally true in the case of slurries (solids carried by a liquid). However, measurements of a gas phase in a liquid stream, or conversely, a liquid in a gas stream, can be difficult to make due to structural influences within the sensing element. Consult the manufacturer if two-phase flow is to be measured.

**8.1.3 Multifluid Systems.** Coriolis mass flowmeters will measure the mass flow of multiple fluids where the mixture is comprised of more than two fluids. However, the net flow measurements are limited to only allowing one variable quantity in a liquid mixture, the target, where the fixed quantity of the mixed liquid carrier is well known. Individual gas quantities in gas mixtures cannot be determined. (See para. 6.1.)

### 8.2 Immiscible Mixtures

**8.2.1 General.** An immiscible liquid is a liquid containing two or more components which do not mix. The total volume is the sum of the individual volumes under metering conditions.

When measuring a two-component process flow, whether they are two immiscible liquids or a liquid and a solid, the relationship between density and concentration can be defined by eqs. (8-1) and (8-2) given in para. 8.2.2. Examples of these types of mixtures are starch and water, sand and water, and oil and water.

**8.2.2 Mass Fraction.** Equations (8-1) and (8-2) describe the relationship between component $A$ and component $B$ respectively, as a mass fraction $w$ expressed as a percentage.

$$W_A = \{\rho_A(\rho_{\text{meas}} - \rho_B)/[\rho_{\text{meas}}(\rho_A - \rho_B)]\} * 100\% \qquad (8\text{-}1)$$

$$W_B = \{\rho_B(\rho_A - \rho_{\text{meas}})/[\rho_{\text{meas}}(\rho_A - \rho_B)]\} * 100\% \qquad (8\text{-}2)$$

where

$W_A$ and $W_B$ = respective mass fractions of component $A$ and component $B$ in relation to the mixture

$\rho_A$ and $\rho_B$ = respective densities of component $A$ and component $B$

$\rho_{\text{meas}}$ = the measured density of the mixture

**8.2.3 Volume.** Equations (8-1) and (8-2) describe the relationship between component $A$ and component $B$, as a volume fraction $\varphi$ expressed as a percentage.

$$\varphi_A = [(\rho_{\text{meas}} - \rho_B)/(\rho_A - \rho_B)] * 100\% \qquad (8\text{-}3)$$

$$\varphi_B = [(\rho_A - \rho_{\text{meas}})/(\rho_A - \rho_B)] * 100\% \qquad (8\text{-}4)$$

where

$\varphi_A$ and $\varphi_B$ = respective volume fractions (expressed as a percentage) of component $A$ and component $B$ in relation to the mixture

$\rho_A$, $\rho_B$, and $\rho_{\text{meas}}$ are defined in eqs. (8-1) and (8-2).

The volume fraction is a rearrangement of eqs. (8-1) and (8-2).

**8.2.4 Net Mass Flow Rate.** By combining the total mass flow rate and the mass fraction measurements, the net mass flow rate of each of two components can be calculated as follows:

$$q_{m,A} = (q_{m,t})(W_A) * 100\% \quad (8\text{-}5)$$

$$q_{m,B} = (q_{m,t})(W_B) * 100\% \quad (8\text{-}6)$$

where

$q_{m,t}$ = total mass flow rate of the mixture

$q_{m,A}$ and $q_{m,B}$ = net mass flow rate of components $A$ and $B$, respectively

$W_A$ and $W_B$ are defined in eqs. (8-1) and (8-2).

**8.2.5 Net Volume Flow Rate.** By combining the total volume flow rate and volume fraction measurements, the net volume flow rate of each of two components can be calculated as follows:

$$q_{v,A} = (q_{v,\,t})[(\varphi_A)/(100\%)] \quad (8\text{-}7)$$

$$q_{v,B} = (q_{v,\,t})[(\varphi_B)/(100\%)] \quad (8\text{-}8)$$

where

$q_{vt}$ = net total volume flow rate

$q_{v,A}, q_{v,B}$ = net volume flow rate of components $A$ and $B$, respectively

$\varphi_A$ and $\varphi_B$ are defined in eqs. (8-3) and (8-4).

### 8.3 Miscible Liquids Containing Chemically Noninteracting Components

A miscible liquid consists of two or more components, which mix completely or dissolve together. The total volume of the liquid may be different from the sum of the individual volumes at metering conditions.

When two liquids are completely miscible, such as alcohol and water, the mass fraction (of either liquid component) versus density is usually read from table values. It is not possible to obtain a general equation that is valid for all miscible liquids due to the nonlinear relationship between mass fraction and density. It is, therefore, necessary to derive an equation for each mixture.

## 9 CORIOLIS FLOW MEASUREMENT UNCERTAINTY ANALYSIS PROCEDURE

The uncertainty procedure consists of the four steps listed below.

### 9.1 Step 1: Data Reduction Equation

Write a data reduction equation defining the output as a function of one or more inputs.

The data reduction equation defines the output as a function of one or more inputs. In general, an output $y$ is a function of $n$ input variables.

$$y = f(x_1, x_2, ..., x_n) \quad (9\text{-}1)$$

For a linear mass flowmeter:

$$q_m = K_{lm}R_{fm} \quad (9\text{-}2)$$

$$q_v = K_{lm}R_{fm}/\rho_f \quad (9\text{-}3)$$

where

$q_m$ = mass flow rate

$q_v$ = volume flow rate

$K_{lm}$ = linear mass calibration constant, (K-factor) generally adjusted for flowmeter scale

$R_{fm}$ = flowmeter reading (voltage, current, frequency, etc.)

$\rho_f$ = fluid density (from the Coriolis flowmeter or a separate densitometer)

### 9.2 Step 2: Sensitivity Coefficients

Determine the sensitivity coefficients for each component in Step 1.

A sensitivity coefficient must be determined for each of the variables that contribute uncertainty to eq. (9-1).

The sensitivity coefficients are required when the components of uncertainty are combined at the end of the analysis procedure. For eqs. (9-2) and (9-3), the sensitivity of $y$ to $x_i$ is given by eq. (9-4).

$$Sx_i = (\delta_y/\delta x_i)[y(x_i)] \quad (9\text{-}4)$$

where

$Sx_i$ = sensitivity coefficient

From a practical standpoint, the sensitivity coefficients are interpreted as the percent change in $y$ that results from a 1% shift in $x_i$.

For a linear mass flowmeter

$$S_{Klm} = S_{Rfm} = S_{\rho f} = 1.0$$

where

$S_{Klm}$ = sensitivity coefficient for $K_{lm}$, the calibration constant

$S_{\rho f}$ = sensitivity coefficient for $\rho_f$, fluid density

$S_{Rfm}$ = sensitivity coefficient for $R_{fm}$, flowmeter reading

### 9.3 Step 3: Numerical Values

Uncertainty evaluations are defined as Type A or Type B based on how the numerical values are determined as follows:

*(a)* Type A evaluations of uncertainty are those using statistical methods.

*(b)* Type B evaluations of uncertainty are those carried out by means other than the statistical analysis of a series of observations.

For a Type A evaluation, the standard uncertainty, $u(x_i)$, is equal to the standard deviation of the probability distribution, usually assumed to be a normal distribution.

Typically, with Type B evaluations, the manufacturers' specification limits are assumed to represent a rectangular probability distribution, where the standard uncertainty of a measured value, $x_i$, is calculated from

$$u(x_i) = a_i(3)^{-1/2} = (0.58)(a_i) \tag{9-5}$$

where
$a_i(3)^{-1/2}$ = standard deviation of the rectangular probability distribution (see ISO 5168)
$a_i$ = manufacturer's specification generally listed as $\pm a_i$

### 9.4 Step 4: Combine Numerical Values

Combine the numerical values obtained in Step 3 to give a numerical value for the uncertainty.

From eq. (9-1):

$$y = f(x_1, x_2, ..., x_n)$$

The standard uncertainty in $y$ is given by:

$$u(y)^2 = \Sigma[S_n^2\, u(x_i)^2] \quad (i = 1, 2, ..., n) \tag{9-6}$$

where
$u(y)$ = standard uncertainty in $y$
$u(x_i)$ = standard uncertainty in $x_i$
$k$ = coverage factor for an expanded uncertainty

The expanded uncertainty is given by $k[u(x_i)]$ where $k$ is the coverage factor. Different values of $k$ correspond to different confidence interval values. In measurement, it is customary to set $k = 2$, which corresponds approximately to a 95% confidence interval. The 95% confidence interval is interpreted as 95% of all values will lie within $\pm k[u(x_i)]$ of the mean.

The uncertainties in the individual components must be defined in a uniform manner (i.e., uniform units) before they are combined.

### 9.5 Numerical Examples

The following numerical examples are intended to illustrate the process of uncertainty analysis. The examples are designed to increase in complexity to help the user gain an understanding of the analysis process.

**9.5.1 Example 1: Mass Flow.** The mass flow rate is calculated based on eq. (9-2), ($q_m = K_{lm}R_{fm}$).

The accuracy of the Coriolis flowmeter K-factor is obtained from the manufacturer's specification.

From eq. (9-5), $u(x_i) = (0.58)(a_i)$

where
$a_i$ = accuracy of the Coriolis flowmeter

Given $a_i = 0.10\%$ of flow rate

$$u_x = (0.58)(0.10)\% = 0.058\% = 0.00058$$

The combined standard uncertainty, see eq. (9-6), in mass flow rate ($u_{qm}$) is calculated:

$$u_{qm}^2 = (0.00058)^2$$
$$u_{qm} = (0.00058)$$
$$u_{qm} = 0.058\%$$

This means that 95% ($k=2$) of all measurements will fall within ±(2)(0.058%) = ±0.116% of the true value.

This example represents the very simple case where the uncertainty is determined entirely from the manufacturer's specification.

$u_x$ = calculated uncertainty in $x$
$u_y$ = calculated uncertainty in $y$
$u_{qm}$ = combined uncertainty in mass flow rate
$u_{qv}$ = combined uncertainty in volume flow rate

**9.5.2 Example 2: Volume Flow.** The objective of this example is to illustrate the process of combining the uncertainties of several inputs. The example assumes a Coriolis flowmeter is used to measure a liquid giving the measurement result as a volume. This application has at least two possible configurations.

(a) using the Coriolis density function
(b) using a separate densitometer

The uncertainties in mass and density measurement are taken from manufacturers' specifications.

Using eq. (9-3), ($q_v = K_{lm}R_{fm}/\rho$) and eq. (9-5), [$u(x_i) = (0.58)(a_i)$]

$$u_1 = (0.58)(0.10)\% = 0.058\% = 0.00058$$

Density, $\rho$ = 0.0005g/cc = 0.05% for water, $u_2 = (0.58)(0.05)\% = 0.029\% = 0.00029$.

The combined standard uncertainty, see eq. (9-6), in volume flow-rate ($u_{qv}$) is calculated

$$u_{qv}^2 = u_1^2 + u_2^2$$

$$u_{qv}^2 = (0.00058)^2 + (0.00029)^2$$

$$u_{qv} = (0.000648)$$

$$u_{qv} = 0.065\%$$

This means that 95% of all measurements will fall within ±(2)(0.065)% = ±0.13% of the true value.

**9.5.3 Example 3: User Measurement Uncertainty Based on the Calibration of Their Flowmeters in Their Laboratory.** This example builds on Example 1. The objective is to illustrate some of the details that can be considered in a more complex example. A user has decided to base the uncertainty of their measurement on a laboratory calibration rather than a manufacturer's specification.

The uncertainty in the laboratory's flow standard is stated to be ±0.08%. The calculated standard uncertainty is $u_1 = (0.58)(0.08)\% = 0.046\%$.

$$u_1 = 0.046\%$$

Analysis of the calibration results identify random effects associated with the calibration, the calculated standard deviation is 0.03%. The standard uncertainty is $u_2 = 0.03\%$.

$$u_2 = 0.03\%$$

The Coriolis flowmeter output is an analog 4-20 ma signal. The data acquisition system has an uncertainty specification of ±0.02%. The calculated standard uncertainty is $u_3 = (0.58)(0.02)\% = 0.0116\%$. This component of uncertainty is not a part of the Coriolis flowmeter but in the present example it represents uncertainty in the indicated value of mass flow rate.

This Coriolis flowmeter will be operated at elevated pressure. The manufacturer provides a correction for the pressure effect. The uncertainty in the correction is stated by the manufacturer to be ±0.02% per 10 psi. The calculated standard uncertainty is $u_4 = (0.58)(0.02)\% = 0.0116\%$. But pressure correction is in relation to calibration pressure, so for the example assume that the flowmeter is being operated at a 5 psi difference from calibration pressure. Then the sensitivity would be (5 psi)/(10 psi) = 0.5. Therefore total uncertainty for pressure correction $u_4 = (0.0116)(0.5)\% = 0.0058\%$.

$$u_4 = 0.0058\%$$

The uncertainty in the indicated value of mass flow rate, $u_{qm}$, is

$$u_{qm}{}^2 = u_1{}^2 + u_2{}^2 + u_3{}^2 + u_4{}^2$$

$$u_{qm} = (u_1{}^2 + u_2{}^2 + u_3{}^2 + u_4{}^2)^{1/2}$$

$$u_{qm} = [(0.00046)^2 + (0.00030)^2 + (0.000116)^2 + (0.000058)^2]^{1/2}$$

$$u_{qm} = (0.00000032)^{1/2} = 0.000564 = 0.0564\%$$

This means that 95% of all measurements fall within ±(2)(0.0564)% = ±0.113% of the true value.

# NONMANDATORY APPENDIX A
# FLOW CALIBRATION TECHNIQUES

## A-1 INTRODUCTION

### A-1.1 Definition

*calibration:*

*(a)* the process of comparing the indicated flow to a traceable reference standard

*(b)* the process of adjusting the output of a device to bring it to a desired value, within a specified tolerance for a particular value of the input.

### A-1.2 Types of Calibration

There are two types of calibration, described in detail in section A-2, as follows:

*(a)* Type 1 standard calibration: the details of which are specified by the manufacturer

*(b)* Type 2 special calibrations: the details of which are specified by the user

Coriolis flowmeters may be calibrated using gravimetric, master flowmeter, and volumetric techniques.

## A-2 CALIBRATION METHODS

### A-2.1 General Considerations

When calibrating Coriolis flowmeters, collect data from the transmitter output(s), which is (are) independent of any damping settings. A sufficient amount of data should be collected during the test to establish the calibration uncertainty.

There are three methods for calibrating Coriolis flowmeters: gravimetric, volumetric, and by use of a master flowmeter. In each case, two operational techniques may be used.

*(a) Steady State Flow.* Data collection starts and stops while the fluid is maintained at a stable flow rate.

*(b) Batching.* Data collection starts at zero flow conditions and stops at zero flow conditions. The run time or batch time should be sufficiently long so that errors induced by flow rate variations at the start and end of the run are small compared to the total calibration uncertainty.

### A-2.2 Gravimetric Methods

See ASME MFC-9M.

### A-2.3 Volumetric

(At the time of this writing, ASME MFC-17M was in development.)

The Coriolis flowmeter may be calibrated using an established volumetric method; for example collecting the test fluid in a certified vessel or using a volume prover. However, the collected quantity (volume) must be converted into mass by multiplying by the fluid density (liquid density). The liquid density can be measured dynamically using a densitometer or, if the liquid density is constant, by sampling methods. If the properties of the fluid are well known, the density can also be determined by measuring the fluid temperature and pressure within the vessel.

### A-2.4 Master Flowmeter (Reference Flowmeter)

The master flowmeter calibration technique may be used to calibrate a Coriolis flowmeter. Master flowmeters may be turbine flowmeters, sonic nozzles, or Coriolis flowmeters. Calibration of the master flowmeters must be traceable to recognized standards. The stability and accuracy of the master flowmeter must be fully documented.

If the master flowmeter is a volumetric device, its measurement must be converted to mass using the liquid density. The density may be measured dynamically using an on-line densitometer or, if the liquid density is constant, using sampling methods. If the equation of state of the fluid is well known, the density may be determined by measuring the fluid temperature and pressure during the test.

NOTE: Calibration of a Coriolis flowmeter by using a master flowmeter of the same operating principle, such as a Coriolis flowmeter, must be performed with caution. For example, if a Coriolis flowmeter's performance is affected by any changes in the operating conditions, both the unit being calibrated and the master flowmeter may be affected in the similar manner (bias), and may not be indicated in the flowmeter calibration result.

### A-2.5 Calibration Frequency

A Coriolis flowmeter properly installed and used with clean, noncorrosive, and nonabrasive fluids is stable. The frequency of calibration of the flowmeter is governed by the criticality of the measurement and the nature of the operating conditions. For fiscal or custody transfer applications, this frequency may be prescribed by regulation, or agreement between the relevant parties.

If the Coriolis flowmeter installation conditions change, for instance as a result of pipe work modification in the vicinity of the flowmeter, it is possible that the Coriolis flowmeter zero will be affected. This may be corrected by performing a zero adjustment. A zero