A STANDARD

FOR USERS AND MANUFACTURERS OF

THREMAL DISPERSION MASS FLOW METERS ©

BY

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FOREWORD

Thermal dispersion mass flowmeters comprise a family of instruments for the measurement of the total mass flow rate of a fluid, primarily gases, flowing through closed conduits.

The operation of thermal dispersion mass flowmeters is attributed to L.V. King who, in 1914 (Ref. 1), published his famous King's Law revealing how a heated wire immersed in a fluid flow measures the mass velocity at a point in the flow. King called his instrument a "hot-wire anemometer". However, it was not until the 1960's and 1970's that industrial-grade thermal dispersion mass flowmeters finally emerged.

This standard covers the thermal dispersion type of thermal mass flowmeter. The second type is the capillary tube type of thermal mass flowmeter, typically provided in its mass flow controller configuration. Both types measure fluid mass flow rate by means of the heat convected from a heated surface to the flowing fluid. In the case of the thermal dispersion, or immersible, type of flowmeter, the heat is transferred to the boundary layer of the fluid flowing over the heated surface. In the case of the capillary tube type of flowmeter, the heat is transferred to the bulk of the fluid flowing through a small heated capillary tube. The principles of operation of the two types are both thermal in nature, but are so substantially different that two separate standards are required. Additionally, their applications are much different. Thermal dispersion flowmeters are commonly used for general industrial gas flow applications in pipes and ducts, whereas capillary tube flowmeters are primarily used for smaller flows of clean gases in tubes.

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A STANDARD
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1 Scope

This standard establishes common terminology and gives guidelines for the quality, description, principle of operation, selection, installation, and flow calibration of thermal dispersion flowmeters for the measurement of the mass flow rate, and to a lesser extent, the volumetric flow rate, of the flow of a fluid in a closed conduit. Multivariable versions additionally measure fluid temperature. Thermal dispersion mass flowmeters are applicable to the flow of single-phase pure gases and gas mixtures of known composition and, less commonly, to single-phase liquids of known composition.

2 Terminology and Symbols

2.1 Definitions

Definitions taken from ASME MFC–1M–2003, Glossary of Terms Used in the Measurement of Fluid Flow In Pipes (Ref. 2), and from ASME MFC–11M–2005, Measurement of Fluid Flow by Means of Coriolis Mass Flowmeters (Ref. 3), are referenced as such. Definitions specific to this standard have no reference notation.

Accuracy: the degree of freedom from error; the degree of conformity of the indicated value to the true value of the measured quantity (Ref. 2).
Base Conditions: specified conditions of base temperature and base pressure with which the volume of a fluid is converted to the mass of the fluid. Base conditions typically are used to convert the volumetric flow rate of a gas to mass flow rate and to convert the velocity of a gas to mass velocity. See also *Base Temperature* and *Base Pressure.*
Base Pressure: the pressure base condition of a fluid. Typically, the “normal” and “standard” base conditions are both 101,325 Pascals (1 atmosphere). See also *Base Conditions.*
Base Temperature: the temperature base condition of a fluid. Typically, the “normal” base temperature is 0 °C, and the “standard” base temperature is 21.1 °C (70 °F). See also *Base Conditions.*
Batching Flow Calibration Standard: a flow calibration standard that provides an output signal only when a discrete quantity, or batch, of fluid fills the flow calibration standard. See also *Flow Calibration Standard.*
Cavitation: the implosion of vapor bubbles formed after flashing when the local pressure rises above the vapor pressure of a liquid (Ref. 2). See also *Flashing.*

Conduit Factor: a correction factor for the velocity distribution in a flow conduit that is the ratio of the average velocity over the cross-sectional area of the conduit to its centerline velocity. See also *Fully Developed Velocity Distribution.*

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 (Ref. 2). See also *Cavitation.*

Flow Calibration: the process of comparing the indicated mass flow rate to a traceable flow calibration standard, and the process of adjusting the output of the flowmeter under test to bring it to a desired value, within a specified tolerance for a particular value of the input.

Flow Calibration Facility: an open or closed loop piping system used for the flow calibration of the flowmeter under test. At a minimum, the flow calibration facility has the following components: flow generator, flow calibration standard, and the flowmeter under test. See also *Flow Calibration.*

Flow Calibration Standard: an in-line or batching flowmeter used in a flow calibration facility as a secondary, or transfer, standard for the flow calibration of the flowmeter under test. The flow calibration standard must be traceable to a recognized national or international measurement standard. See also *Flow Calibration*, *In-line Flow Calibration Standard*, and *Batching Flow Calibration Standard.*

Flow Conditioner: a device installed in a pipe line upstream and downstream of a flowmeter (or built into an in-line flowmeter) for the purpose of uniformizing or regulating the flow profile and reducing swirling flow.

Flow Profile: a graphic three-dimensional representation of the velocity distribution in a flow conduit (Ref. 2). See also *Fully Developed Velocity Distribution* and *Swirling Flow.*

Flow Sensor: a fluid mass flow rate sensing subassembly in a thermal dispersion mass flowmeter consisting of a fluid temperature sensor and an electronically heated velocity sensor, both immersed in, or exposed to, the flowing fluid.

Fully Developed Velocity Distribution: a velocity distribution, in a straight length of pipe, that has zero radial and azimuthal fluid velocity components and an azisymmetric axial velocity profile that is independent of the axial position along the pipe (Ref. 2). See also *Flow Profile* and *Swirling Flow.*

In-Line Flow Calibration Standard: a flow calibration standard that provides a continuous output signal. See also *Flow Calibration Standard.*

In-Line Flowmeter: a flowmeter that is installed directly in the pipe line and has the full fluid flow in the pipe flowing through it.

Insertion Flowmeter: a flowmeter that is inserted into the pipe line and measures flow velocity at a point (or small volume) in the cross-sectional area of the pipe.

Installation Effect: any difference in performance of the flowmeter arising between the flow calibration under ideal conditions and the actual conditions of use. This difference may be caused by different flow conditions due to changes in flow profile, perturbations, or by different working regimes (pulsations, intermittent flow, alternating flow, vibrations, etc.) (Ref. 3).

Linearity: the consistency of the change in the scaled output of the flowmeter for a related scaled change in the input of the flowmeter (Ref. 3).

Permanent Pressure Loss: the difference between the inlet pressure and the outlet pressure of the flowmeter.

Rangeability: the ratio of the maximum to minimum mass flow rates in the range over which the flowmeter meets a specified uncertainty or accuracy (Ref. 2).

Repeatablity (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) (Ref. 2). See also *Repeatability (Quantitative).*

Repeatability (Quantitative): the value below which the absolute difference between any two single test results obtained under same condition may be expected to lie with a specified probability. In the absence of other indications, the probability is 95% (Ref. 2). See also *Repeatability (Quantitative).*

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. (Ref. 2). The following two paragraphs are included to help with understanding the definitions of repeatability and reproducibility.

- 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 (Ref. 3).
- Reproducibility is a quantified measure of the longer term stability of a flowmeter. Reproducibility can be determined from tests of the flowmeter, over longer (specified) periods of time, or when test conditions may change (changes to be specified), such as the typical flowmeter-usage patterns as turning the flowmeter 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. Resultant differences for reproducibility may be larger than their repeatabilities because of the test conditions (Ref. 3).

Resistance Temperature Detector: a sensor that measures temperature by means of the increase in its electrical resistance as temperature increases.

Sensitivity: the slope of the raw non-linear flow calibration curve of the output signal vs. mass flow rate of a thermal dispersion mass flowmeter.

Skin Resistance: the thermal resistance of the intervening layers of material, or skin, in the heated section of the velocity sensor of a thermal dispersion mass flowmeter that exist between the embedded heated resistance temperature detector and the external surface. See also *Resistance Temperature Detector.*

Stem Conduction: the heat lost from the heated section of the velocity sensor of a thermal dispersion mass flowmeter that is conducted through the stem of the velocity sensor to the ambient environment external to the flowmeter.

Swirling Flow: flow that has axial and circumferential velocity components (Ref. 2). See also *Flow Profile* and *Fully Developed Velocity Distribution.*

Temperature Compensation: means in the transmitter for correcting the output signal of thermal dispersion mass flowmeters for changes in fluid temperature. See also *Transmitter.*

Transmitter: the 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 (Ref. 2). See also *Flow Sensor.*

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 (Ref. 2).

Volumetric Prover: The use of a calibrated volume tank, gas density, and most generally a diverter valve to calibrate a flowmeter. Bell provers and piston provers are typical volumetric provers. See also *Batching Flow Calibration Standards.*

2.2 Symbols

Table 2.2 Symbols

Symbol	**Description (First Use)**	**Dimen-sions$^{(1)}$**	**SI Units$^{(2)}$**	**USC Units$^{(2)}$**
Abs( )	absolute value of the quantity in parentheses (Equation C1)	dim-less		
A_e	external surface area of the heated section of the velocity sensor (Equation 4.2)	L^2	m^2	ft^2, in^2
A_{fs}	accuracy of flowmeter, percent of full scale (Equation 5.2)	dim-less	% FS	% FS
A_{pipe}	cross-sectional area of the flow conduit or flowbody (Equation 4.6)	L^2	m^2	ft^2, in^2
A_r	accuracy of flowmeter , percent of reading (Equation 5.1)	dim-less	% Rd	% Rd
A_t	overall accuracy of flowmeter, in percent of reading (Equation 5.1)	dim-less	% Rd	% Rd
b_i	gas factors, i = 1, 2,…,5 (Equation 4.10)	dim-less		
C_P	pressure influence coefficient (Section 5.6.1)	$M^{-1}LT^2$	%Rd/bar	%Rd/psi
c_p	coefficient of specific heat of the fluid at constant pressure (Equation 4.9)	$L^2T^{-2°}K^{-1}$	J/kg·°K	Btu/lb·F
C_T	temperature influence coefficient (Section 5.6.1)	$°K^{-1}$	%Rd/°K	%Rd/°F
D	outside diameter of the velocity sensor (Equation 4.2)	L	m	Ft, in
F_c	conduit factor (Equation 4.8)	dim-less		
f ( )	function of terms in parentheses (Equation 4.9)	dim-less		
h	film coefficient for convective heat transfer from the heated section of the velocity sensor (Equation 4.3)	$MT^{-3}°K^{-1}$	$w/m^2 \cdot °K$	$Btu/h \cdot ft^2 \cdot °F$
h_e	equivalent film coefficient for convective heat transfer from the heated section of the velocity sensor (Equation 4.2)	$MT^{-3}\,°K^{-1}$	$w/m^2 \cdot °K$	$Btu/h \cdot ft^2 \cdot °F$
I	electrical current input to T_1 RTD in the heated section of the velocity sensor (Section 3.5.2)	amperes	amperes	amperes
k_f	thermal conductivity of the fluid (Equation 4.9)	$MLT^{-3}°K^{-1}$	w/m·°K	Btu/h·ft· °F
L	length of the heated section of the velocity sensor (Equation 4.2)	L	m	ft, in
M	molecular weight of the gas (Equation 4.21)	---	kg/kgmole	lb/lbmole
N	number at equal areas in the cross-sectional area A_{pipe} of a flow conduit (Equation 4.20)	dim-less		
n	number of input variables (Equation C2)	dim-less		
Nu	Nusselt number (Equation 4.9)	dim-less		

Table 2.2 Symbols, Cont'd.

Symbol	Description (First Use)	Dimensions(1)	SI Units(2)	USC Units(2)
P	static pressure of the flowing fluid (Equation 4.21)	$ML^{-1}T^{-2}$	Pa, bar	psi
P_b	base static pressure of the flowing fluid (Section 4.7.3) • "normal" base conditions: $P_b = P_n$ = 101,325 Pa(1 atm.) • "standard" base conditions: $P_b = P_s$ = 101,325 Pa(1 atm.)	$ML^{-1}T^{-2}$	Pa, bar	psi
P_L	The upper or lower limit of the pressure flow calibration reference condition range (Equation C1)	$ML^{-1}T^{-2}$	Pa, bar	psi
Pr	Prandtl number (Equation 4.9)	dim-less		
Q	heat convected away from the heated section of the velocity sensor by the fluid (Equation 4.1)	ML^2T^{-3}	w	Btu/h
Q_L	stem conduction heat loss (Equation 4.1)	ML^2T^{-3}	w	Btu/h
q_m	mass flow rate of the fluid (Section 3.2)	MT^{-1}	kg/s	lb/s,lb/min
$q_{m,fs}$	full scale mass flow rate of the flowmeter (Equation 5.2)	MT^{-1}	kg/s	lb/s,lb/min
$q_{m,i}$	mass flow rate of the fluid measured by flow sensor i (Equation 4.20)	MT^{-1}	kg/s	lb/s,lb/min
q_v	volumetric flow rate of the fluid (Equation 4.16)	L^3T^{-1}	m^3/s	ft^3/min
$q_{v,b}$	volumetric flow rate of the fluid referenced to base ("b") conditions (Equation 4.17	L^3T^{-1}	bm^3/s	bft^3/min
R	universal gas constant (Equation 4.21)		m^3·bar/(kgmole·°K)	ft·lbf/(lbmole·°R)
Re	Reynolds number of the velocity sensor (Equation 4.9)	dim-less		
Re_{pipe}	Reynolds number of the flow conduit, pipe, or flow body (Equation 4.8)	dim-less		
R_s	skin thermal resistance (Equation 4.5)	$M^{-1}L^{-2}T^3$°K	°K/w	°F/(Btu/h)
R_1	electrical resistance of the T_1 RTD (Equation 4.1)	ohms	ohms	ohms
S_i	sensitivity coefficient of q_m to input variable x_i (Equation C3)	varies		
t	the factor in uncertainty from the students "t" distribution (Equation C3)	dim-less		
t_{68}	the factor in uncertainty yielding a 68.3 percent confidence level (Equation C3)	dim-less		
t_{95}	the factor in uncertainty yielding a 95.5 percent confidence level (Equation C3)	dim-less		
T_b	Base temperature of the flowing fluid (Section 4.7.3) • "normal" base conditions: $T_b = T_n$ = 0 °C • "standard" base conditions: $T_b = T_s$ = 21.1 °C (or 70 °F)	°K	°K, °C	°F
T_e	average external surface temperature over the length of the heated section of the velocity sensor (Equation 4.5)	°K	°K, °C	°F
T_f	temperature of the flowing fluid measured by the T_f RTD in the fluid temperature sensor (Section 3.2)	°K	°K, °C	°F
T_L	the upper or lower limit of the temperature flow calibration reference condition range (Equation C1)	°K	°K, °C	°F
T_1	average temperature of the T_1 RTD over the length L of the heated section of the velocity sensor (Section 3.2)	°K	°K, °C	°F
$u\ (q_m)$	uncertainty in mass flow rate q_m (Equation C3)	MT^{-1}	kg/s	lb/s,lb/min
$u\ (x_i)$	uncertainty in input variable x_i (Equation C3)	varies		
V	point velocity of the fluid (Equation 4.7)	LT^{-1}	m/s	ft/min
V_{ave}	average velocity of the fluid over area A_{pipe} (Equation 4.6)	LT^{-1}	m/s	ft/min
$V_{ave,\ b}$	average velocity of the fluid over area A_{pipe} referenced to base ("b") conditions (Equation 4.6)	LT^{-1}	nm/s	sft/min

Table 2.2 Symbols, Cont'd.

Symbol	Description (First Use)	Dimen-sions$^{(1)}$	SI Units$^{(2)}$	USC Units$^{(2)}$
V_b	point velocity of the fluid referenced to base conditions (Equation 4.7)	LT^{-1}	nm/s	sft/min
Vol	displaced volume (Section A3.3.2)	L^3	m^3	ft^3
W	electrical input to the T_1 RTD in the heated section of the velocity sensor (Section 3.5.1)	ML^2T^{-3}	w	Btu/h
x_i	input variable, $i = 1, 2, \ldots, n$ (Equation C2)	varies		
Z	mobility of the gas (Equation 4.21)	dim-less		
Greek Symbols				
δ	partial differential (Equation C3)	dim-less		
ΔT	differential temperature $T_1 - T_f$ (Section 3.5.1)	°K	°K, °C	°F
Δt	transit time (Section A 3.3.2)	T	s	s
μ	absolute viscosity of the fluid (Equation 4.9)	$ML^{-1}T^{-1}$	kg/s·m	lb/ft·h
ρ	mass density of the fluid (Equation 4.6)	ML^{-3}	kg/m^3	lb/ft^3
ρ_b	mass density of the fluid that is referenced to base ("b") conditions and is a constant (Equation 4.6)	ML^{-3}	kg/m^3	lb/ft^3
ρV	mass velocity (Section 4.6.1)	$ML^{-2}T^{-1}$	kg/s·m^2	lb/min·ft^2
$\Sigma(\;)$	sum of terms in parentheses (Equation C3)	dim-less		
Subscripts				
b	referenced to base conditions of T_b and P_b	dim-less		
f	fluid	dim-less		
fs	full scale value	dim-less		
m	mass flow rate	dim-less		
n	normal base conditions of $T_b = 0$ °C and $P_b = 1$ atmosphere	dim-less		
s	standard base conditions of $T_b = 21.1$ °C (or 70 °F) and $P_b = 1$ atmosphere	dim-less		
v	volumetric flow rate	dim-less		
1	Refers to the T_1 RTD	dim-less		

Notes:

1 M = mass; L = Length; T = time; °K = thermodynamic temperature (degrees Kelvin); dim-less = dimensionless; varies = dimensions depend on the quantity to which the symbol refers.

2 FS = full scale; Rd = reading; Pa = Pascal; b = referenced to base conditions; lb = lbm = pound mass; °R = degrees Rankine.

2.3 Abbreviations

Table 2.3 Abbreviations

Abbreviation	Description
b	refers to base conditions
bara	bars, absolute
barg	bars, gage
bm/s	meters per second referenced to base "b" conditions
bm$^{3/}$s	cubic meters per second referenced to base "b" conditions
DN	European piping size (diameter normal, millimeters)

Table 2.3 Abbreviations, Cont'd.

Abbreviation	Description
nm/s	meters per second referenced to"normal" base conditions
nm^3/s	cubic meters per second referenced to "normal" base conditions
PN	European pressure standard (pressure normal, bars)
PRTD	platinum resistance temperature detector
psi	pounds force per square inch
psia	pounds force per square inch, absolute
psig	pounds force per square inch, gage
RTD	resistance temperature detector
scfm	standard cubic feet per minute referenced to "standard" base conditions
sfpm	standard feet per minute referenced to "standard" base conditions
T_f RTD	RTD in fluid temperature sensor
T_1 RTD	RTD in heated section of velocity sensor

3 General Description

Thermal dispersion mass flowmeters measure the mass flow rate of a fluid or a mixture of fluids of known composition flowing through a closed conduit. Multivariable versions also measure the volumetric flow rate and fluid temperature. This section describes the configurations and major components of thermal dispersion mass flowmeters.

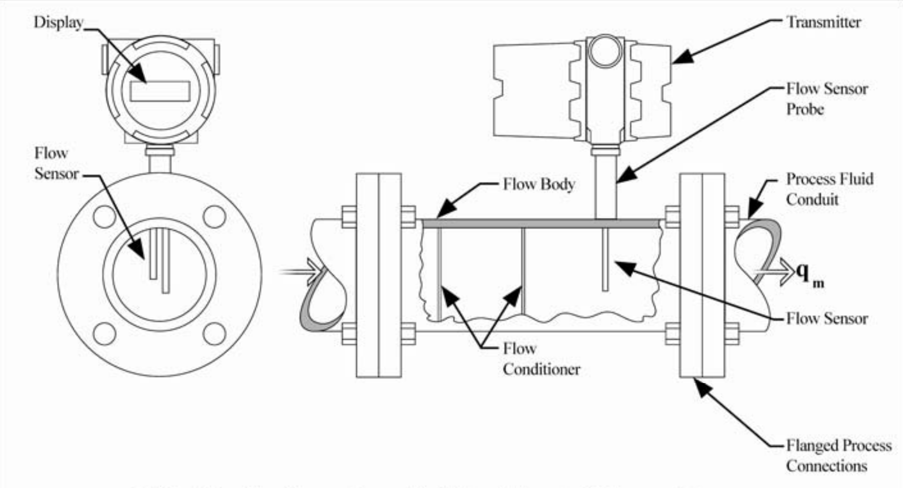
3.1 Configurations

Thermal dispersion mass flowmeters have two primary configurations: in-line and insertion. Figure 1 shows the two configurations and their major components.

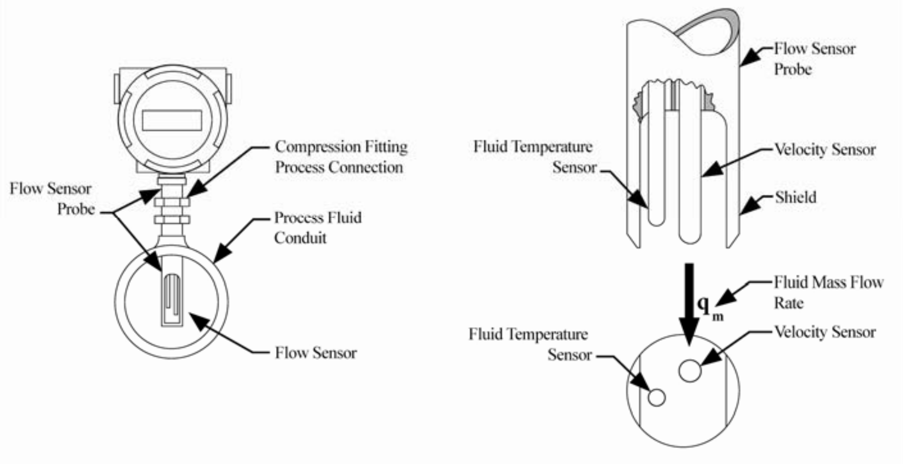
3.l.1 In-Line Flowmeter Configuration

In-line thermal dispersion mass flowmeters typically are applied to pipes and conduits with diameters (or equivalent diameters) less than about 200 mm (8 inches). As shown in Figure 1, in-line flowmeters consist of the following major components: flow body, process connections, flow sensor, flow sensor probe, flow conditioner, transmitter enclosure, and transmitter. In-line flowmeters measure the total mass flow rate flowing through the pipe.

The process connections are either flanges, pipe threads, or compression fittings.A separate or built-in flow conditioner upstream of the flow sensor reduces the straight length of pipe upstream of the flow body required to achieve a flow profile independent of upstream flow disturbances and non-uniformities.



(a) In-Line Configuration with Meter-Mounted Transmitter



(b) Insertion Configuration, Installed **(c) Detail of Flow Sensor**

Figure 1 The Two Configurations and Major Components of Thermal Dispersion Mass Flowmeters

3.1.2 Insertion Flowmeter Configuration

Insertion flowmeters (Ref. 4) typically are applied to pipes and conduits with diameters (or equivalent diameters) greater than about 200 mm (8 inches). Because they are more economical than in-line flowmeters, they also have found applications in smaller pipes or conduits and wide use as flow switches.

Insertion flowmeters have the same major components as in-line flowmeters, but do not have a flow body. Their process connection is a compression fitting or flange that is welded onto, or threaded into, an existing process fluid conduit. Insertion flowmeters measure the mass velocity at a point in the conduit’s cross-sectional area, but usually are flow calibrated to measure the total mass flow rate flowing through the conduit.

Multi-point insertion flowmeters measure the mass velocity at several points in the cross-sectional area of large pipes, ducts, and stacks. The total mass flow rate through the conduit is the average mass velocity multiplied by the cross-sectional area (Ref. 5).

3.2 Flow Sensor

As shown in Figures 1 and 2, the flow sensor of both in-line and insertion configurations has an electrically heated velocity sensor and a fluid temperature sensor immersed in the flowing fluid. This is why thermal dispersion mass flowmeters are also called "immersible" thermal mass flowmeters. Reference 6 describes the several types of flow sensors used in immerible thermal mass flowmeters.

The heated section of the velocity sensor consists of a self-heated temperature sensor that both heats the sensor and measures its own average temperature $\boldsymbol{T_1}$**.** The fluid temperature sensor is not self-heated and measures the temperature $\boldsymbol{T_f}$ of the flowing fluid. For higher accuracy applications, the sensor elements in the velocity sensor and the fluid temperature sensor should be wire-wound or thin-film platinum resistive temperature detectors (RTDs). The electrical resistance of RTD's increases as temperature increases. The platinum RTD sensor element in the velocity sensor is called the " T_l RTD". The platiunum RTD sensor element in the fluid temperature sensor is called the "T_f RTD". Other types of sensor elements such as thermistors, thermocouples, and micro-electronic machined devices are used by some manufacturers.

In traditional velocity sensors, the T_1 RTD sensor is potted into the tip of the tubular sheath. The potting compound, or filler material, typically is ceramic cement or epoxy. Another category of flow sensors avoids the use of potting compounds by tightly fitting a wire-wound platinum RTD into the tip of the sheath.

The flow sensors of most industrial-grade thermal dispersion mass flowmeters have cylindrical single-ended velocity and fluid temperature sensors mounted side-by-side as shown in Figures 1 and 2. Both sensors are sheathed in corrosion-resistant tubular metallic sheaths. The principle of operation described in Section 4 is based on this most common type of flow sensor construction.

Light-duty flowmeters have unsheathed single-ended, side-by-side sensors immersed in the flow or a piggy-back construction that has co-axial velocity and fluid temperature sensors with the velocity sensor mounted on the end.

In yet another flow sensor construction for in-line meters, the flow sensor is embedded in the wall of the flow body and is not immersed in the flowing fluid (Ref. 7). Here the flow sensor consists of a heater element with adjacent upstream and downstream temperature sensor elements. This construction has been used for liquid flow applications.

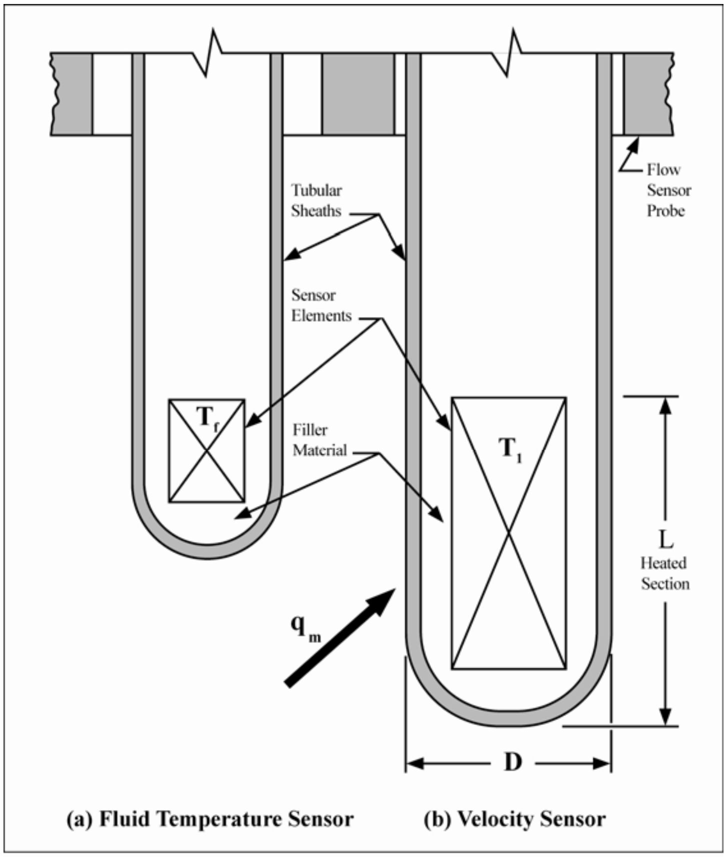


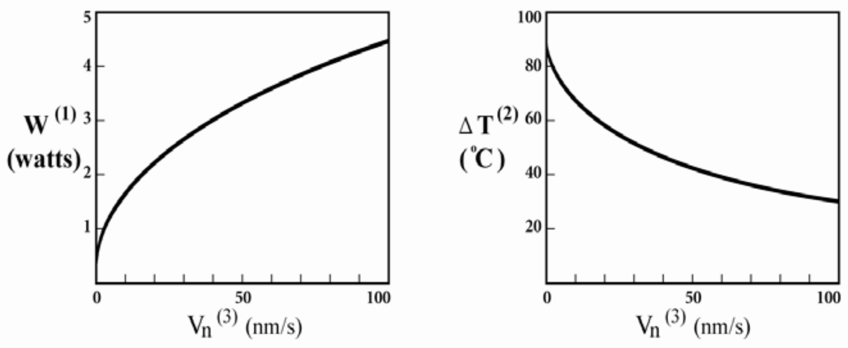
Figure 2 Flow Sensor

In operation, the fluid temperature sensor measures the fluid temperature T_f. The sensor drive in the transmitter delivers electrical current to the velocity sensor such that it is self-heated to an average temperature T_1 that is elevated above the fluid temperature. The heat convected from the velocity sensor to the flowing fluid provides the desired direct measurement of fluid mass flow rate q_m.

3.3 Transmitter

The transmitter is the electronic system providing the flow sensor drive. The transmitter transforms, or linearizes, the signals from the sensors into engineering outputs of the variables. The transmitter is housed in an enclosure that conforms to relevant codes, such as hazardous location codes.

Digital transmitter electronic systems with digital communication and a digital display facilitate flowmeter diagnostics, validation, calibration adjustment, and reconfiguration. Microcomputer-based digital systems provide correction for changes in fluid temperature and optionally for other influence parameters.



(a) Constant Temperature Differential **(b) Constant Current**

Notes:
(1) $\Delta T = 50\ ^{o}C$, constant.
(2) ΔT at zero flow is $50\ ^{o}C$.
(3) V_n is the point velocity referenced to "normal" conditions of $T_n = 0\ ^{o}C$ and $P_n = 101,325$ Pa (1 atmosphere).
(4) For air at $T_f = 20\ ^{o}C$. Curves are approximate.

Figure 3 Two Modes of Flow Sensor Operation (4)

3.4 Temperature Compensation

In the great majority of applications for thermal dispersion mass flowmeters, the process fluid is a gas. Some of the properties of gases influencing convective heat transfer depend on gas temperature. The properties of liquids may also depend on the fluid temperature. For this reason, general-purpose thermal dispersion mass flowmeters should have means for compensating for changes in fluid temperature.

The front end of the flow sensor drive is often an analog Wheatstone bridge circuit. The velocity sensor and the fluid temperature sensor are located on opposite legs of the bridge. This provides analog compensation for changes in fluid temperature. The bridge voltage is a high level output signal in the order of several volts, thereby greatly enhancing the signal-to-noise ratio. The Wheatstone bridge and temperature compensation are thoroughly described in the open literature (Refs. 6, 8, 9, and 10).

3.5 Modes of Operation

The flow sensor drive has two modes of operation: the constant temperature differential mode and the constant current mode (Refs. 6 and 8). Figure 3 shows typical raw non-linear output signals without signal conditioning for both modes. Sections A1 and A2 in Appendix A discuss these curves and the need for flow calibration.

3.5.1 Constant Temperature Differential Mode

In this mode of operation, the flow sensor drive maintains at a constant value the difference $\Delta T = T_1 - T_f$ between the temperature of the heated velocity sensor T_1 and the fluid temperature T_f. The output signal is the electrical power W supplied to the heated velocity sensor required to keep ΔT constant.

3.5.2 Constant Current Mode

In this mode of operation, the flow sensor drive maintains at a constant value the electrical current I supplied to the heated velocity sensor. The output signal is ΔT.

4 Principle of Operation

This section describes the principle of operation of thermal dispersion mass flowmeters (Refs. 6, 8, 9, and 10). The flow sensor construction used in this discussion is that most commonly deployed - - single-ended tubular velocity and fluid temperature sensors mounted in parallel and adjacent to each other. The velocity sensor element and the fluid sensor element are the platinum RTD elements T_1 RTD and T_f RTD, respectively. This is the flow sensor construction of Figures 1-4.

Although this section applies to both gas and liquid flows, it has primary application to gas flows because they constitute the vast majority of installations.

The purpose of this description is to give the reader a general understanding of the principle of operation. It describes the major factors of influence, but avoids complexities, such as the solution of differential equations. In practice, all thermal dispersion flowmeters should be flow calibrated, following the procedures in Appendix A.

4.l Fluids

4.1.1 Gases

Thermal dispersion flowmeters are ideally suited for the measurement of the mass flow rate of gases. Their sensitivity is highest at lower flows and at gas pressures that are in the low to medium range.

4.1.2 Liquids

Thermal dispersion technology is not well suited for liquid flow applications because at zero flow rate a majority of the heat budget is carried away by the liquid due to its high thermal conductivity relative to that of gases. This reduces measurement sensitivity. To avoid cavitation problems ΔT must be set to a relatively low value. This also reduces sensitivity and increases dependence on small changes in liquid temperature. Application to liquid flows should be limited to cases, such as ultra-low flow applications, where thermal dispersion technology offers advantages over other flowmeter technologies.

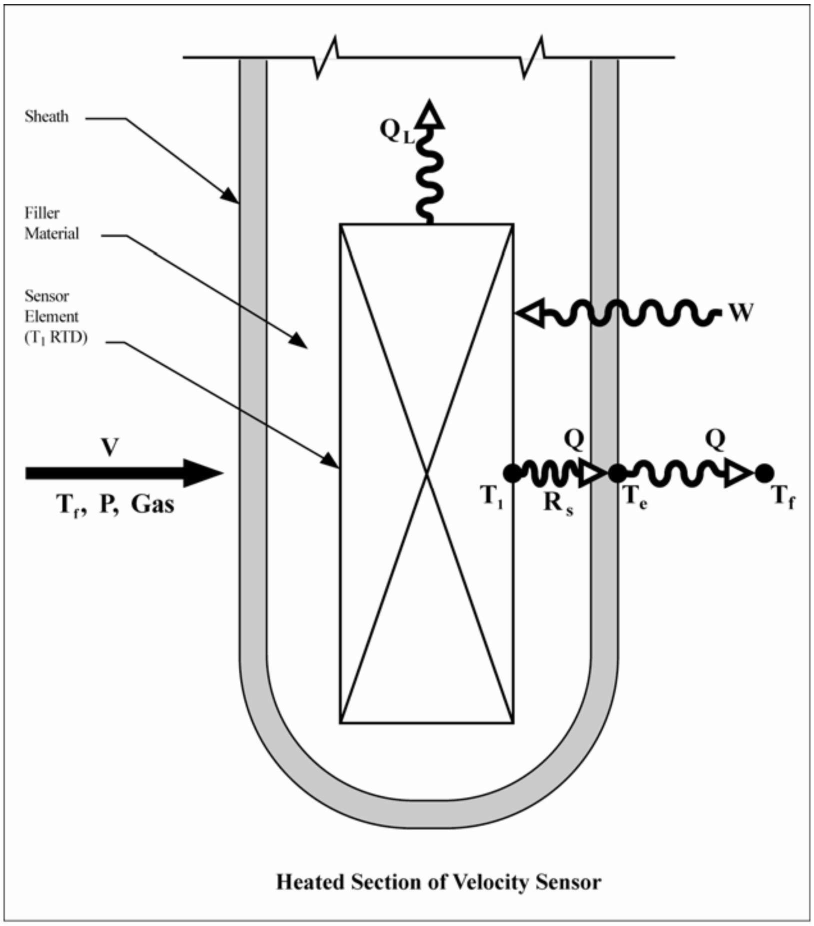


Figure 4 Principle of Operation

4.1 Measurement of Mass Flow Rate

Thermal dispersion mass flowmeters measure the heat convectively transferred from the heated velocity sensor to the gas molecules passing through the viscous boundary layer surrounding the sensor’s heated cylindrical surface. Since the molecules bear the mass of the gas, thermal dispersion flowmeters directly measure *mass* flow rate.

4.2 First Law of Thermodynamics

Figure 4 shows the first law of thermodynamics applied to the heated section of the velocity sensor.

4.2.1 First Law

With reference to Figure 4, the first law of thermodynamics applied to the entire heated section of the velocity sensor at steady state conditions is: heat (or power) into the heated section equals the heat (or power) out, or

$$W = Q + Q_L \qquad \textbf{4.1}$$

Where:

$W = I^2R_1 =$ Electrical power supplied to the T_1 RTD.

$R_1 =$ Electrical resistance of the T_1 RTD.

$Q =$ Heat convected away from the heated section by the fluid.

$Q_L =$ Stem conduction = Heat lost from the heated section via conduction down the stem of the velocity sensor to the ambient environment external to the flow body (See Section 4.3.3).

$I =$ Current supplied to the T_1 RTD.

All terms in Equation 4.1 are in units of watts. Radiative heat transfer is ignored because it is relatively small, except in extremely high temperature gas-flow applications. The term Q is

$$Q = h_e A_e \,(T_1 - T_f) \qquad \textbf{4.2}$$

Where:

$A_e = \pi DL =$ External surface area of the heated section.

$D =$ Outside diameter of the velocity sensor.

$L =$ Length of the heated section.

$T_1 =$ Average temperature of the T_1 RTD over the length L of the heated section, the quantity directly measured by the T_1 RTD.

$T_f =$ The temperature of the flowing fluid measured by the T_f RTD.

The term h_e in Equation 4.2 is the "equivalent" film coefficient for convective heat transfer, defined as

$$h_e = h/(1 + h\,A_e\,R_s) \qquad \textbf{4.3}$$

Where:

$h =$ Film coefficient for convective heat transfer from the velocity sensor. h is the quantity we seek.

$R_s =$ "Skin resistance", defined in the following Section 4.3.2.

The final expression for the first law of thermodynamics applied to the entire heated section of the velocity sensor now becomes

$$W = h_e A_e \,\Delta T + Q_L \qquad \textbf{4.4}$$

Where:

$\Delta T = T_1 - T_f =$ Temperature differential.

As discussed in Section 3.5, in the constant temperature differential mode of operation, W is the output quantity, and ΔT is held constant. In the constant current mode of operation, ΔT is the output quantity, and the current I is held constant

4.2.2 Skin Resistance

The average external surface temperature T_e over length L shown in Figure 4 is less than the temperature T_1 of the T_1 RTD because a temperature drop is required to pass the heat Q through the intervening layers of the velocity sensor between the T_l RTD and the external surface. These intervening layers - - the filler material and the tubular sheath - - are called the “skin”. Their thermal resistance R_s is called the “skin resistance.” R_s is defined by

$$Q = (T_1 - T_e) / R_s \qquad 4.5$$

At higher flow rates, the skin resistance R_s causes the droop, or reduction in sensitivity, of the flowmeter’s output signals, as evidenced by Figure 3. Skin resistance is an unwanted quantity and should be minimized by manufacturers.

4.2.3 Stem Conduction

Conduction of heat through the stem of the velocity sensor couples the heated section to the ambient environment external to the flowmeter. The value of Q_L in Equations 4.1 and 4.4 therefore changes with changes in ambient temperature. Stem conduction is a second unwanted quantity (along with skin resistance) and should be minimized or accounted for by manufacturers.

4.3 Law of Conservation of Mass

The law of conservation of mass (the continuity equation) for the flow conduit or flow body is

$$q_m = \rho V_{ave} A_{pipe} = \rho_b V_{ave,b} A_{pipe} \qquad 4.6$$

Where:
ρ = Mass density of the fluid.
V_{ave} = Average fluid velocity over A_{pipe}.
A_{pipe} = Cross-sectional area of the flow conduit or flow body.
$(\ )_b$ = Term is referenced to base conditions (e.g., “standard” or “normal” conditions) of base temperature T_b and base pressure P_b.
q_m = Total mass flow rate in the flow conduit or, in the case of in-line flowmeters, the flow body.

From Equation 4.6 it is obvious that $\rho V_{ave} = \rho_b V_{ave,b}$. Likewise, continuity considerations require the same relationship for the point velocity V; i.e.,

$$\rho V = \rho_b V_b \qquad 4.7$$

The flow sensor measures the point velocity at a point (or small volume) within the conduit's cross-sectional area A_{pipe}. The ratio F_c of the average velocity V_{ave} to the point velocity V is defined as

$$F_c = V_{ave}/V = \text{Conduit factor} \qquad \textbf{4.8}$$

In-line thermal dispersion mass flowmeters with a built-in flow conditioner have a conduit factor F_c close to unity, as do insertion meters in undisturbed flow down-stream of nozzles or smooth contractions. Most insertion flowmeters have the center of the active area of the velocity sensor located at the conduit's center line. For this case and with a fully developed velocity distribution in the conduit, Reference 11 (pp. 5.4 to 5.8) presents an empirical equation for F_c as a function of the Reynolds number Re_{pipe} of the conduit and wall roughness. Typical values of F_c for this function are

$F_c = 0.5$ for pure laminar flow ($Re_{pipe} \leq 2{,}000$).

$F_c = 0.83 \pm 0.03$ for turbulent flow ($Re_{pipe} \geq 40{,}000$).

4.4 Correlations for Convective Heat Transfer

4.4.1 General Empirical Correlation

The film coefficient h is found using empirical correlations. In most applications the fluid is a gas; compressibility effects are negligible; and the gas pressure is not excessively high. In this case, the correlation for h is expressed as a function of the following non-dimensional parameters.

$$Nu = f(Re, Pr) \qquad \textbf{4.9}$$

Where:

$Nu = hD/k_f$ = Nusselt number, the non-dimensional heat-transfer parameter.

$Re = \rho VD/\mu$ = Reynolds number of the velocity sensor, the non-dimensional ratio of dynamic to viscous forces, based on D.

$Pr = \mu c_p/k_f$ = Prandtl number, the ratio of the diffusivity of momentum to the diffusivity of heat (a fluid properties parameter).

k_f = Thermal conductivity of the fluid.

μ = Absolute viscosity of the fluid.

c_p = Coefficient of specific heat of the fluid at constant pressure.

4.4.2 Example Correlations

Following are two example correlations.

$$Nu = b_1 + b_2\, Pr^{\,b3}\, Re^{b4} \qquad \textbf{4.10}$$

$$Nu = Pr^{b1} (b_2 Re^{b3} + b_4 Re^{b5}) \qquad 4.11$$

Where:
b_i = Gas factors.

The gas factors in the above equations are constants found via flow calibration by the manufacturer following the procedures in Appendix A.

4.5 Solution for Reynolds Number Re

4.5.1 General Solution

The primary desired output variable is the total mass flow rate q_m flowing through the conduit or flow body. q_m depends on the product ρV, the fluid's mass density times the point velocity, embodied in the Reynolds number $Re = \rho VD/\mu$. ρV is often called the "mass velocity" and is the total mass flow rate per unit area (kg/s·m^2). The solutions for the output variables presented in Section 4.7 are proportional to the Reynolds number Re. In this section we find Re as a function of the Nusselt number.

Nu is found by combining Equations 4.3 and 4.4.

$$Nu = hD/k_f = [D/(k_f A_e)][W - Q_L]/ [\Delta T - (W - Q_L)R_s] \qquad 4.12$$

The terms D, A_e, and R_s in Equation 4.12 are either directly or indirectly determined by the manufacturer via flow calibration for each flowmeter following the procedures in Appendix A.

The solution for Nu is inserted into the empirical correlation Equation 4.9 (e.g., Equations 4.10 and 4.11) that is then solved for Re.

4.5.2 Example Solution

For example, if the correlation in Equation 4.10 is used, Re can be found explicitly as

$$Re = [(Nu - b_1) / (b_2 Pr^{b3})]^{(1/b4)} \qquad 4.13$$

Insertion of the expression for Nu given by Equation 4.12 into the above equation yields the desired solution for Re for this example

$$\mathrm{Re} = [[[D/(k_f A_e)][W - Q_L]/[\Delta T - (W - Q_L)R_s] - b_1]/(b_2 Pr^{b3})]^{(1/b4)} \qquad 4.14$$

4.6 Solutions for Output Variables

4.6.1 Purpose

This section presents final closed-form expressions for all output variables of thermal dispersion mass flowmeters based on the results of previous Sections 4.3 to 4.6.

In-line flowmeters are flow calibrated (See Appendix A) to directly measure the total flow rate in the pipe line and thereby measure the flow rate quantities q_m, q_v, and $q_{v,b}$ in following Equations 4.15, 4.16, and, 4.17, respectively.

Insertion flowmeters are often flow calibrated (See Appendix A) to directly measure the total flow rate in a flow conduit and thereby measure the flow rate quantities q_m, q_v, and $q_{v,b}$ in following Equations 4.15, 4.16, and 4.17, respectively. Alternatively, insertion flowmeters are flow calibrated to measure the velocity at a point in the conduit's cross-sectional area and thereby directly measure the quantities V and V_b in following Equations 4.18 and 4.19, respectively, and indirectly measure the flow rate quantities q_m, q_v, and $q_{v,b}$ by applying the appropriate conduit factor F_c in following Equations 4.15, 4.16, and 4.17, respectively.

4.6.2 Other Approaches

It shall be understood that the following closed-form expressions and their derivations are presented solely to describe the principle of operation of thermal dispersion mass flowmeters. They are primarily relevant to digital flowmeters. Some manufacturers may use other approaches, particularly those with analog or hybrid analog/digital products.

4.6.3 Definitions of Terms Used In Solutions for Output Variables

A_{pipe} = Cross-sectional area of flow conduit or flow body.
D = Outside diameter of the velocity sensor.
F_c = Conduit factor, the flow profile correction factor (See Equation 4.8).
$Re = \rho VD/\mu$ = Reynolds number of the velocity sensor, based on D.
μ = Absolute viscosity of the fluid.
ρ = Mass density of the fluid.
$(\ )_b$ = Subscript signifying term is referenced to base conditions of fluid temperature T_b and fluid pressure P_b, for example:

- For "standard" ("s") base conditions:
  $T_b =$ 21.1 °C (or 70 °F)
  $P_b =$ 101,325 pascals (1 atmosphere)
- For "normal" ("n") base conditions:
  $T_b =$ 0 °C
  $P_b =$ 101,325 pascals (1 atmosphere)

4.6.4 Mass Flow Rate In A Flow Conduit q_m (kg / s)

$$q_m = (F_c A_{pipe}) (\mu/D) Re \qquad 4.15$$

4.6.5 Volumetric Flow Rate In A Flow Conduit q_v (m^3/s)

$$q_v = (F_c A_{pipe}/\rho) (\mu/D) Re \qquad 4.16$$

4.6.6 Volumetric Flow Rate In A Flow Conduit Referenced to Base Conditions, $q_{v,b}$ (bm ^{3}/s)

$$q_{v,b} = (F_c A_{pipe} / \rho_b) (\mu/D) Re \qquad 4.17$$

- For “standard” base conditions “b” = “s”.
- For “normal” base conditions “b” = “n”.

4.6.7 Point Velocity V (m/s)

$$V = (1/\rho) (\mu/D) Re \qquad 4.18$$

4.6.8 Point Velocity Referenced To Base Conditions V_b (bm/s)

$$V_b = (1/\rho_b) (\mu/D) Re \qquad 4.19$$

- For “standard” base conditions “b” = “s”.
- For “normal” base conditions “b” = “n”.

4.6.9 Mass Flow Rate In A Flow Conduit Measured Via A Multi-Point Insertion Flow Meter q_m (kg/s)

In flow conduits with large cross-sectional areas, the total mass flow rate $\mathbf{q_m}$ is often measured with a multi-point insertion thermal dispersion mass flowmeter, especially if the measurement plane is downstream of an elbow or other upstream flow disturbances (See Ref. 5). Multi-point insertion flow meters are designed and installed such that a separate flow sensor is located at the centroid of N equal areas in the cross-sectional area A_{pipe} of the conduit. q_m is found as follows.

$$q_m = q_{m,1} + q_{m,2} + \cdots + q_{m.N} \qquad 4.20$$

Where:
$q_{m,i} = (A_{pipe}/N) (\mu/D) Re_i$ = Mass flow rate measured by flow sensor i
$(i = 1,2, \cdots, N)$.

4.6.10 Gas Mass Density ρ (kg/m^3)

The mass density for gases obeying a modified perfect-gas-law equation of state is calculated as follows.

$$\rho = PM / (Z R T_f) \qquad 4.21$$

Where:
P = Absolute static pressure of the gas.
M = Molecular weight of the gas.
Z = Mobility of the gas.
R = The universal gas constant.
T_f = Absolute static temperature of the gas.

The gas temperature T_f in Equation 4.21 either is directly measured by flowmeters with the multivariable feature or is inputted from a nearby temperature transducer in the pipe line. The gas pressure P is inputted from a nearby pressure transducer in the pipe line.

5 Guidelines for Flowmeter Selection

Improper flowmeter selection is a common factor that can impair flowmeter performance in the field.

This section is primarily applicable to gas flow applications. Following Section 6.2.2 describes liquid flow applications. The guidelines presented in this section are valid for the most common, or typical, thermal dispersion mass flowmeters. It is understood that departures from the statements and numerical values herein may exist for some manufacturers.

The following information is used to select and size both in-line and insertion flowmeters: gas composition; mass flow rate range; pressure range; temperature range; permanent pressure loss; and performance (accuracy, repeatability, time response, and reproducibility). Most manufacturers use sophisticated software accounting for these variables to properly select and size the flow rate for the user's application. It is recommended that the user rely on the veracity of the flowmeter selected via this process.

Table B1 in Appendix B presents a typical table used for sizing in-line flowmeters for air flow applications.

The specifications in the following may vary from manufacturer to manufacturer. Users should not deploy thermal dispersion mass flowmeters in applications not falling within the manufacturer's specifications. Non-conforming applications may require that the manufacturer provide a special flowmeter design or flow calibration.

5.1 Mass Flow Rate Range

Mass flow rate ranges are expressed here as the point mass velocity V_b referred to base conditions of T_b and P_b . V_b is explicitly applicable to insertion flowmeters. The total mass flow rate q_m for in-line flowmeters is found via Equations 4.6 and by multiplying V_b by $F_c \rho_b A_{pipe}$.

5.1.1 Minimum Mass Flow

The flowmeter's accuracy specification should be taken into account in determining the minimum mass flow rate. Thermal dispersion mass flowmeters are in the category of flowmeters that do measure zero flow. Detectable minimum point mass velocities as low as approximately 20 sfpm (approx. 0.1 nm/s) are specified by some manufacturers.

5.1.2 Maximum Mass Flow Rate

The following limitations should be considered in determining the maximum mass flow rate.

- The Mach number (the ratio of the actual velocity to the speed of sound of the gas) should not exceed approximately 0.3 to avoid unwanted compressibility effects.
- Measurement sensitivity should be sufficiently high. Figure 3 shows the decrease in measurement sensitivity at higher mass flow rates.
- The permanent pressure loss should not be excessive. Typically permanent pressure loss is sufficiently low that it is not a consideration (See Section 5.4 and Appendix B).

For both in-line and insertion flowmeters the typical maximum point mass velocity for air referenced to base conditions is approximately 20,000 sfpm (approx. 100 nm/s). With special flow calibration, the maximum point mass velocity can be extended to approximately 35,000 sfpm (approx. 175 nm/s). Appendix B shows typical maximum air mass flow rates through in-line flowmeters of various sizes.

5.1.3 Rangeability

Rangeability is the ratio of the maximum mass flow rate to the minimum flow rate. Thermal dispersion mass flowmeters are in a class of flowmeters that have high rangeability. Typical flow calibration yields rangeabilities from 10:1 to 100:1.

Manufacturers extend the mass flow rate range of thermal dispersion mass flowmeters by dividing the total range into separate segments that are then individually flow calibrated. In this case, manufacturers should use multiple flow calibration standards if required to insure specified accuracy. Multi- range flow calibration can yield rangeabilities exceeding 100:1.

5.2 Pressure Range

The process pressure range of both in-line and insertion meters depends on the pressure rating of the process connection. For in-line flowmeters with Class 150 lb flanges (PN 16), the typical process pressure range specified by manufacturers is 0 to 230 psig (0 to 16 barg) at ambient temperature. The typical maximum pressure typically specified for in-line flowmeters is 300 psig (approx. 20 barg) at ambient temperature (requires threaded or Class 300 lb, PN 40, flanges). For insertion flowmeters with a compression fitting process connection, the maximum pressure rating typically specified is 500 psig (approx. 35 barg) at ambient temperature. A typically specified minimum pressure is -7 psig (approx. -0.5 barg) for both in-line and insertion flowmeters.

Because the strength of materials degrades with increasing temperature, for safety purposes users are cautioned to follow the manufacturer’s specifications for maximum process pressure versus process temperature.

5.3 Temperature Range

Process temperature ranges specified by manufacturers typically range from approximately 15 to 250 °F (approx. -10 to 120 °C) to -40 to 350 °F (approx. -40 to 175 °C). Some manufacturers offer optional temperature upper limits ranging from 750 to 930 °F (approx. 400 to 500 °C).

5.4 Permanent Pressure Loss

Thermal dispersion mass flowmeters are in the category of flowmeters with relatively low permanent pressure loss. In-line flowmeters without a flow conditioner and insertion flowmeters having flow conduits with internal diameters equal to, or larger than, approximately 3 inches (approx. 0.1 m) have negligible permanent pressure loss. Appendix B shows the permanent pressure loss of typical in-line flowmeters.

5.5 Gas Composition

Thermal dispersion mass flowmeters should be used for pure gases or gas mixtures of known composition. Typical pure gases include nitrogen, oxygen, carbon dioxide, methane, propane, hydrogen, argon, and helium. Typical gas mixtures include air, natural gas, combustion gases, stack gases, flare gases, and digester gases.

Consideration should be given to water vapor content and the potential for condensation of gas components. The gas should be compatible with, and not corrode, the wetted materials of the flowmeter.

5.6 Performance

5.6.1 Mass Flow Rate Measurement Accuracy and Repeatability

Manufacturers of thermal dispersion mass flowmeters should include the combined effects of linearity, repeatability, hysteresis, and zero stability in their mass flow rate accuracy specification.

Manufacturers typically present the overall accuracy A_t (in units of percent of reading) in the following ways.

- Based on percent of reading A_r

$$A_t = \pm A_r \tag{5.1}$$

- Based on percent of full scale A_{fs}

$$A_t = \pm A_{fs}\, q_{m,fs} / q_m \tag{5.2}$$

- Combination of the above

$$A_t = \pm (A_r + A_{fs}\, q_{m,fs}/q_m) \tag{5.3}$$

Where:
q_m = Actual mass flow rate.
$q_{m,fs}$ = Full scale (upper range limit) mass flow rate of flowmeter.

Manufacturers should express the overall accuracy A_t in terms of the specific ranges of the reference conditions of mass flow rate, process temperature, and process pressure for which it applies. The manufacturer should provide additional accuracy terms covering the case where the actual process temperature T_f and pressure P fall outside of their reference condition ranges.

Typically, these terms are presented as a temperature influence coefficient C_T and a pressure influence coefficient C_P. C_T is in units of percent of reading accuracy per degree centigrade, or equivalent. C_P is in units of percent of reading accuracy per bar, or equivalent. These influence coefficients are multiplied respectively by the absolute value of the difference between the actual temperature or pressure and the upper or lower limits of the temperature or pressure reference condition ranges, and are then added to the relevant overall accuracy statement in Equations 5.1, 5.2, or 5.3. This is best understood by referring to the example accuracy calculation in Appendix C.

Repeatability, expressed by the manufacturer as a percentage of reading or of full scale, may also be important in flowmeter selection. Typical manufacturer’s repeatability specifications fall in the range of 0.1 to 0.5 percent of reading.

5.6.2 Multivariable Measurement Accuracy

Manufacturers of thermal dispersion mass flowmeters with optional temperature measurement typically express temperature measurement accuracy as an error in °C. Manufacturers should express the overall accuracy in terms of the specific range of temperature to which it applies and provide a temperature influence coefficient, or the equivalent, covering departures from this range.

5.6.3 Time Response

Manufacturers’ specified time response to a change in mass flow rate ranges from approximately 1 to 7 seconds to within ± 63 % of the final value (i.e., one time constant) for flowmeters operated in the constant temperature differential mode and ranges from approximately 7 to 15 seconds to within ± 63% of the final value for flowmeters operated in the constant current mode (See Section 3.5). Constant current operation is slower than constant temperature differential operation because the temperature of the entire mass of the velocity sensor must change if velocity changes. Time response becomes faster as the mass flow rate increases. Most manufacturers specify time response at the maximum mass flow rate of their flow-meter. Users should select flowmeters that use the constant temperature differential mode of operation for applications requiring faster time response.

5.6.4 Reproducibility

The reproducibility, or stability over time, of the flow sensor depends on its exposure to severe operating conditions, such as temperature cycling, temperature over ranging, and pipe line vibrations. Velocity sensors constructed with filler materials such as ceramic cements or epoxies that are exposed to such severe operating conditions may be susceptible to long-term drift (See Section 3.2). Velocity sensors that avoid the use of these materials minimize the effect of long-term drift when subjected to severe operating conditions. Preferably, susceptible flowmeters should not be installed at locations in the pipe line that have severe operating conditions. If this is not possible, devices that reduce the severity of the operating conditions should be installed upstream of the flowmeter.

6 Guidelines for Installation and Applications

Sub-optimal performance of thermal dispersion mass flowmeters is often caused by installation effects and misapplications.

Flowmeter installation should take into account physical constraints, flow conditions, application considerations, and safety (Refs. 11 and 12). The manufacturer should specify installation dimensions, preferred installation configurations, and any installation constraints or restrictions of use.

6.1 Installation

6.1.1 General Installation Criteria

- With the exception of hot-tap applications (See Section 8.7), during installation the process flow and electrical power should be turned off, the line should not be pressurized, and the line’s temperature should not be excessive.
- The flowmeter should be installed so that the direction of flow in the pipe coincides with flow direction arrow or indicator on the flowmeter.
- The process pressure and temperature should not exceed the manufacturer’s specified ratings.
- The class and type of pipe, process connections, pipe materials, and erosion, corrosion, and deposition of material in the pipe line should be considered.
- The flowmeter’s process connections should be: (1) seated squarely on the mating fluid connection seals such that no part of the gasket is in the flow and (2) secured following the manufacturer’s guidelines such that leak-rate specifications are satisfied.
- Any applicable hazardous area classification should be considered. The cable entry into the transmitter enclosure should meet the hazardous area standard.

- Proper wiring and electrical power should be verified and follow applicable codes. The voltage, its frequency, and its polarity should meet specifications.
- The environmental effects on the flowmeter, such as ambient temperature, ambient pressure, humidity, corrosive atmospheres, mechanical shock, mechanical pipe line vibrations, and external electromagnetic fields should be considered. High ambient and process temperatures may require the installation of remote electronics (See Section 6.1.5).
- Shut-off valves upstream and downstream of the flowmeter, installed for the purpose of isolating, removing, zeroing, or flow calibrating the flowmeter, should not disturb the main process flow when not in use.
- Thermal dispersion mass flowmeters do operate in pulsating flows, but performance may be degraded in intense pulsating flows, such as locations immediately downstream of pumps. In this case, isolation or pulsation damping devices should be considered. The manufacturer's recommendations should be observed regarding the use of such devices.

6.1.2 Spacial and Orientation Requirements

- Sufficient spacial clearance should be provided for flowmeter installation. Special considerations should take into account the need for safe and convenient human access, as well as space for in situ flow calibration, if required.
- Sufficient clearance should be provided for insertion flowmeters to facilitate their unobstructed removal.
- Insertion flowmeters with hot-tap hardware should have extra clearance, and the proper insertion depth should be verified.
- The flowmeter should not be installed at a location in the piping system that is susceptible to liquid collection or condensation.
- The flowmeter should be oriented in the flow conduit, or pipe, in the orientation for which it was flow calibrated. This is important because the zero flow reading depends on natural convection which in turn depends on the orientation of the flow sensor relative to the gravitational force vector.
- The most common deployment is in horizontal pipes. In this case, the de facto flowmeter orientation is with the flowmeter mounted on top of the pipe.
- For deployment in vertical pipes, the flow direction either upward or downward should be specified by the user.

6.1.3 Process Fluid Quality

For gas applications, the use of filters, traps, or other protective devices may be required for removing solids, liquids, and liquid drops that could cause damage to the flow sensor or induce errors in measurement. In general, these devices should be placed upstream of the flowmeter. Occasional liquid drops striking the heated velocity sensor usually do not cause damage, but will cause a spike in output until they burn off.

For liquid applications (See Section 6.2.2), the use of strainers, filters, air and vapor eliminators or other protective devices may be required to remove solids, vapors and gas bubbles that could cause damage to the flow sensor or induce errors in measurement. In general, these devices should be placed upstream of the flowmeter.

6.1.4 Flow Conditions and Straight Pipe Length Requirements

The performance of thermal dispersion mass flowmeters can be degraded if the flowmeter is installed where flow conditions are different from those for which the flowmeter was calibrated. Components in the pipe system upstream, and to a lesser extent downstream, of the flowmeter can create flow profile non-uniformities, swirling flow, and turbulence that may degrade flowmeter performance. Such flow-disturbing components include a single elbow, multiple elbows, expansions, contractions, tees, heaters, coolers, and valves. The flowmeter's location should be chosen to minimize the effect of such flow disturbances. If possible, control valves should be located downstream of the flowmeter.

Viscous forces in a length of straight pipe before and after the flowmeter tend to uniformize the flow and, with sufficiently long length, drive it towards a fully developed velocity distribution. To insure specified performance and avoid installation effects, the manufacturer's requirements for straight pipe lengths upstream and downstream of the flowmeter should be followed. The straight pipe requirements for typical in-line and insertion flowmeters are shown in Tables 6.1 and 6.2, respectively.

Flow conditioners installed as separate units upstream of in-line and insertion flowmeters may be used to uniformize the flow and reduce the effect of up-stream flow-disturbing components. Alternatively, an in-line flowmeter with a built-in flow conditioner may be used.

6.1.5 Remote Electronics Installation

If the ambient temperature added exceeds the manufacturer's specified limits, the electronics transmitter enclosure should be mounted remotely. A typical upper-limit value is approximately 140 °F (approx. 60 °C). In excessively hot conditions, consideration should be given to installing the flowmeter horizonally so that natural convection carries less heat upwardly from the hot pipe line to the transmitter enclosure.

For remote installation, the cable connecting the transmitter enclosure to the flow sensor should be that provided by the manufacturer and typically should not be lengthened or shortened by the user because the electrical resistance of the cable is part of the flow sensor's circuit. Some manufacturers provide compensation for cable length.

Straight Pipe Length Requirements at 1 Bara Pressure(6)

Flow Disturbing Component	Thermal Dispersion Mass Flowmeter (1)		Orifice Plate (4) (Upstream Length)
	Upstream (2)	Downstream (3)	
Single 90° Elbow	1 D	0 D	28 D
Reduction (4:1)	3 D	0 D	14 D
Expansion (4:1)	3 D	0 D	30 D
After Control Valve (5) or Pressure Regulator	3 D	0 D	32 D
Two 90° Elbows In Same Plane	3 D	0 D	36 D
Two 90° Elbows In Different Planes	5 D	0 D	62 D

Notes:

1 = For an in-line flowmeter with a flow conditioner consisting of two separated perforated plates located in the flow body upstream of the flow sensor.

2 = Number of diameters D of straight pipe required between the exit of the upstream flow disturbing component and the entrance of the flowmeter.

3 = Number of diameters D of straight pipe required between the exit of the flowmeter and the entrance of the downstream flow disturbing component.

4 = For comparison purposes only. The table shows the number of diameters D of upstream straight pipe required between the exit of the upstream flow disturbing component and an ISO Standard 5167 orifice plate with a beta ratio of 0.7.

5 = If the valve is always wide open, base the length requirement on the valve's inlet or outlet fitting.

6 = Consult manufacturer for pressure effects.

Table 6.1 Straight Pipe Length Requirements for an In-Line Flowmeter with a Built-In Flow Conditioner

Straight Pipe Length Requirements at 1 Bara Pressure (5)

Flow Disturbing Component	Upsteam (1)	Downstream (2)
Single 90° Elbow	15 D	5 D
Reduction	15 D	5 D
Expansion	30 D	10 D
After Control Valve(3) or Pressure Regulator	40 D	5 D
Two 90° Elbows in Same Plane	20 D	5 D
Two 90° Elbows in Different Planes (4)	40 D	10 D

Notes:

1 = Number of diameters D of straight pipe required between the exit of the upstream flow disturbing component and the insertion flowmeter.

2 = Number of diameters D of straight pipe required between the insertion flowmeter and the entrance of the downstream flow disturbing component.

3 = If the valve is always wide open, the length requirement should be based on the valve's inlet or outlet fitting.

4 = For three 90° elbows, the required length should be doubled.

5 = Consult manufacturer for pressure effects.

Table 6.2 Straight Pipe Length Requirements for Insertion Flowmeters with No Flow Conditioning

6.1.6 Influence Parameters

Process temperature, process pressure, and ambient temperature have a secondary influence on mass flow rate measurement accuracy. To achieve best measurement accuracy, users should have a good knowledge of the actual process temperature, process pressure, and ambient temperature of their application and specify these conditions upon purchase of the flowmeter. For best measurement accuracy, the manufacturer should match these conditions during flow calibration.

6.1.6.1 Process Temperature

As described in Section 3.4, accurate measurement requires that the flowmeter have means for compensating for changes in process temperature, either via analog, digital, or combined analog and digital temperature compensation. The temperature influence coefficient C_T described in Section 5.6.1 accounts for the effect of process temperature on the overall accuracy of mass flow rate measurement. Better temperature compensation leads to lower values of C_T.

6.1.6.2 Process Pressure

Thermal dispersion mass flowmeters intrinsically correct for the majority of changes in process pressure because they directly measure the Reynolds number. The Reynolds number depends on the gas mass density which, in turn, depends on the pressure. Nevertheless, this correction does not account for the relatively weak effect of process pressure on natural convection that primarily influences the zero and lower flow ranges. The pressure influence coefficient C_P described in Section 5.6.1 accounts for the effect of process pressure on the overall accuracy of mass flow rate measurement. In the event that the actual process pressure in the field is different from that at flow calibration, some flowmeters with digital electronics provide pressure compensation by facilitating the user inputting the actual line pressure measured by a separate pressure transducer located nearby in the process line.

6.1.6.3 Ambient Temperature

The stem conduction phenomenon described in Section 4.3.3 couples the flow sensor with the ambient temperature external to the flowmeter. If the actual ambient temperature in the field is different from that at flow calibration, stem conduction can degrade accuracy. This unwanted influence is worse in lower flow ranges and in flowmeters with high stem conductance, i.e., those with relatively short velocity and temperature sensors. Some flowmeters with digital electronics provide compensation for changes in ambient temperature.

6.2 Applications

6.2.1 Gas Flow Applications

The vast majority of applications are gas flow applications because they benefit from a high sensitivity of measurement (See Section 4.1.1). All previous subsections in this Section 6 are primarily devoted to gas flow applications.

6.2.2 Liquid Flow Applications

Liquid flow applications are a minor fraction of the applications for thermal dispersion mass flowmeters. The diminished sensitivity of liquid flow applications is discussed in Section 4.1.2.

The following should be considered in liquid flow applications. In all cases manufacturers' specifications should be followed.

- The difference ΔT between the temperature of the heated velocity sensor and the temperature of the liquid should not exceed an upper critical limit. For water flows, this critical limit is approximately 10 to 20 °C. If the critical limit is exceeded, higher liquid flows may reduce the pressure behind the heated velocity sensor to the extent that flashing to the vapor phase and subsequent cavitation may occur. These are unwanted phenomenon that can cause erratic and erroneous measurements as well as damage to the flow sensor. Flow sensors operated in the constant temperature differential mode are preferred for liquid flow applications because ΔT is instantaneously maintained at its constant value preselected for the liquid-flow application (See Section 3.5.1). Flow sensors operated in the constant current mode have a variable temperature difference that is difficult to set up for liquid flow (See Section 3.5.2).
- The process liquid should meet the fluid quality standards set forth in Section 6.1.3. Industrial liquid flows with poor fluid quality can cause contamination and fouling of the flow sensor.

6.3 Zero and Span Adjustment

After flowmeter installation is complete, a zero adjustment following the manufacturer's instructions may be needed if the zero offset is unacceptable. To properly check or adjust the zero, the flow must be stopped. It is recommended that both upstream and downstream valves are closed during the process of zero adjustment. If possible, zero adjustment should be made under actual temperature and pressure process conditions.

After installation, a span adjustment can be made if needed, following the manufacturer's instructions. Electrical span and multiple-point flow calibration verification and adjustment can be accomplished by using an accurate external digital voltmeter. Nevertheless, only a flow calibration using a flow calibration standard in series with the flowmeter can be used with absolute certainty to span and flow calibrate the flowmeter. This is done either in situ or by removing and sending the flowmeter to the factory for flow recalibration. The flow calibration entity should follow the guidelines set forth in Appendix A.

Before making field adjustments, the user should verify that the flowmeter is not actively monitoring or reporting to any master control system. Adjustments to the electronics may cause direct changes to flow settings.

6 Inspection and Compliance

If applicable, and upon request, the manufacturer should provide the following certifications to the user.

- Material certificates for pressure-containing parts.
- Certificate of conformance with applicable hazardous area classifications.
- Flow calibration certificate and performance results.
- Certificate of suitability for sanitory applications, if applicable.

Since the flowmeter is an integral part of the piping system, it may be subjected to special inspection test procedures similar to those applicable to other pipe line equipment or instrumentation. This could include a dimensional check, hydrostatic test, and radiographic and/or ultrasonic tests to verify weld integrity. Upon request, manufacturers performing these special tests should make the results available to the user as a certified report.

7 Safety

Thermal dispersion mass flowmeters may be used in high pressure and high temperature applications. They also may be used for flammable and toxic gas applications and may be installed in locations with external flammable atmospheres. Therefore, care should be taken to insure that the integrity of the flowmeter and general safety is maintained under actual process conditions.

8.1 Manufacturers' Specifications

Flowmeters should not be used in conditions that fall outside the manufacturer's specifications, whether they are the manufacturer's normal published specifications or those resulting from a special request. The following issues should be given consideration in providing for the safety and protection of users and their property.

8.2 Process Pressure and Temperature

8.2.1 Design and Construction

For obvious reasons, a burst or major leak in the flowmeter should be avoided. Manufacturers should design and construct their flowmeters taking this into consideration. During operation, users should avoid over-pressurizing and over-heating the flowmeter.

The degradation in the strength of materials with increasing process temperature should be taken into account. Manufacturers should express the pressure ratings of their flowmeters in terms of the intended temperature range of operation and should properly convey the information that the upper-limit pressure rating decreases as process temperature increases.

8.2.2 Pressure Testing

Manufacturers should hydrostatically test the fully assembled wetted parts of their flowmeters . Upon request, manufacturers should provide evidence confirming that the fully assembled flowmeter was tested. This evidence should be available in terms of either a certificate or a test procedure.

8.3 Hazardous Area Locations

If the flowmeter is located in a hazardous area, it should comply with applicable codes and standards. Explosion-proof transmitter enclosures should comply with applicable standards. Upon request, the manufacturer should provide the user with a certificate indicating that the flowmeter is in conformance with the applicable standards. The user should install and operate the flowmeter in accordance with the applicable standards.

8.4 Electrical Safety

During installation of the flowmeter, the user should perform the electrical wiring with the power off. Special caution should be exercised to avoid shocks when wiring the flowmeter to AC power. Manufacturers' instructions and applicable electrical safety and fire prevention codes should be followed.

If applicable, the flowmeter should have the appropriate certification insuring that electromagnetic fields generated by the flowmeter do not interfere with proximal electrical devices, and vice versa.

8.5 Leaks

Thermal dispersion mass flowmeters may be used with unhealthful or irritating gases. Manufacturers should publish the leak rates of the flow bodies of their flowmeters and, upon request, provide the user with a leak test certificate or a test procedure. It is recommended that the user make certain that the flowmeter is properly installed and seated squarely on its seals to minimize process gas leaks. Seals should be inspected to insure their integrity prior to installation.

8.6 Fluid Quality

8.6.1 Erosion

The effect of possible erosion of the flow body depends on the gas velocity and the concentration, size, and composition of solid, and to a lessor extent, liquid particles suspended in the flow. Although typically of minor concern in gas flow applications, erosion should be assessed for each type of use of the flowmeter.

In liquid flows, cavitation and suspended solid particles that may cause erosion should be assessed.

8.6.2 Corrosion

The flowmeter selected should be constructed of materials that are compatible with the fluid. Special attention should be given to corrosive gases or liquids. When in its liquid or droplet form, liquids can react with gases to form acids or other corrosive agents. Such foreign components should be eliminated from the pipe line via upstream traps or other filtering devices.

8.6.3 Unsafe Flow Calibration Gases

As shown in Appendix A, the flow-calibrating entity should provide proper venting of unsafe flow calibration gases, such as toxic or corrosive gases. Additionally, it is recommended that the flow calibration system be thoroughly purged with an inert gas.

8.7 Hot Tapping

In some applications, insertion flowmeters are installed in the pipe line with hot tap hardware. The hot tap assembly provides an isolation valve facilitating withdrawal and removal of the insertion flowmeter from an active pipe line without interruption of the flow or leakage of fluid. The pressure rating of the hot tap hardware should meet, or exceed, that of the pipe line. For safety purposes, hot tapping should be performed by a trained professional, and the installation should be done with caution. Governmental regulations often require a hot tap permit. The user is responsible for providing proof of such a permit.

9 References

9.1 General References

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Appendix A

Flow Calibration

(Mandatory Appendix)

A1 Introduction

Because the critical dimensions of the flow sensor of thermal dispersion mass flowmeters are so small, manufacturing technology is currently incapable of maintaining sufficiently small tolerances to insure reproducibility from flow sensor to flow sensor. Additionally, analog electronic components have variations and digital electronics have a fundamental digital resolution. For these reasons, every general purpose thermal dispersion mass flowmeter should be flow calibrated by the manufacturer, just like most other kinds of flowmeters. Exceptions may include thermal dispersion flow switches and low accuracy flowmeters.

The term “flow calibration” as used herein has the following definition.

- The process of comparing the flowmeter’s indicated mass flow rate to a traceable flow calibration standard.
- The process of adjusting the flowmeter’s output to bring it to a desired value, within a specified tolerance, for a particular value of the mass flow rate input.

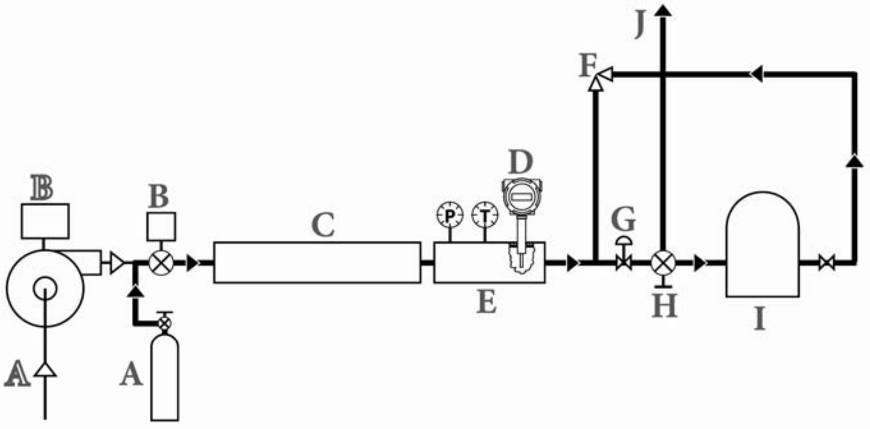
Flow calibration falls into two categories.

- Standard flow calibration - - the details of which are specified by the manufacturer.
- Special flow calibration - - the details of which are specified by the user.

The majority of this Appendix A applies to gas flow calibration. Section A7 covers liquid flow calibration. The distinction between flow calibrating in-line versus insertion flowmeters is described in Section 4.7.1. The guidelines set forth in this appendix should be followed by all flow calibrating entities - - the manufacturer, the user, and third parties. It is recommended that the flow calibration laboratory have an ISO 9001 certification. It is advantageous that the flow calibration laboratory can demonstrate compliance with standards ANSI/IEC/ISO 17025: 2000 and Z540-1.

A2 Flow Calibration Curves

Figure 3 shows the flow calibration curves of typical thermal dispersion mass flowmeters. The curves are non-linear and of a logarithmic nature. The non-linearity is advantageous because it provides wide rangeability for a single flowmeter. It is



Notes:

A = Flow source (air blower or pump; or pressurized gas tank).
B = Flow controller (variable speed motor drive; or flow control valve).
C = Flow conditioning section (See Section A3.2).
D = Flowmeter under test (insertion meter shown).
E = Test section (part of flow conditioning section; for insertion flowmeters only; see Section A3.2).
F = Pressure relief valve (for pressurized facilities only).
G = Pressure regulator (for pressurized facilities only).
H = Diverter valve (for batching calibration standards only).
I = Flow calibration standard (either batching or in-line).
J = Vent (leads to outside environment or to scrubber or other gas purifying device).

Figure A1 Typical Open Loop Gas Calibration Facility

disadvantageous because it requires several flow calibration points to properly define the calibration curve. It is recommended that the flow calibrating entity use a procedure that fits a smooth curve through the data. References 8 and 13 provide insight into curve fitting.

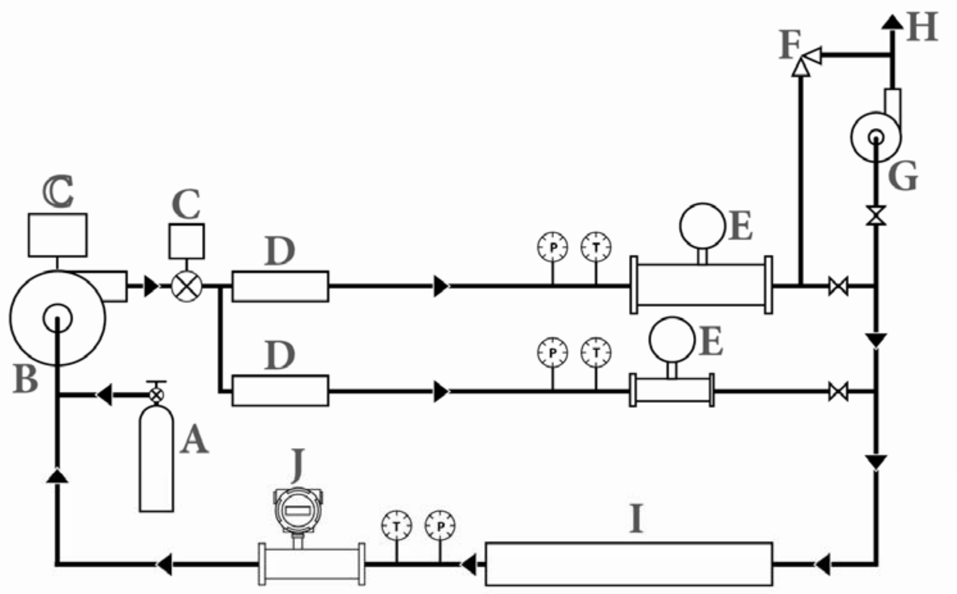
A3 Flow Calibration Methods

A3.1 Flow Calibration Facilities

Gas flow calibration facilities are of two types - - open loop and closed loop. Figure A1 shows as typical open loop facility. Figure A2 shows a typical closed loop facility. Each figure lists the typical components of the facility. Two of their critical components - - the flow conditioning section and the flow calibration standard - - are given special attention in the following sections.

Flow calibration facilities should be capable of

- Generating a stable, steady-state, reproducible gas mass flow rate.
- Accommodating with required accuracy the entire mass flow range specified. If extrapolation has been used to extend the range, this information should be made available to the user upon request.
- Reproducing the gas composition, temperature, and pressure to be encountered in the actual application. Closed loop facilities, such as that shown in Figure A2, are designed to accomplish this objective. Alternately, a surrogate, or



Notes:

A = Gas source (for pressurized facilities -- compressed air or pressurized gas tank; for air wind tunnels -- no "gas source" is used).

B = Flow source (for pressurized facilities -- high pressure axial or centrifugal pump; for air wind tunnel -- fan or blower).

C = Flow controller (variable speed motor drive; or flow control valve).

D = Flow conditioning section (for flow calibration standard(s)).

E = Flow calibration standard(s) (in-line only; multiple sized standards may be used to extend rangeability; see Section A3.3.1).

F = Pressure relief valve.

G = Vacuum pump (evacuates gas in system prior to gas filling).

H = Vent (leads to outside environment or to scrubber or other gas purifying device).

I = Flow conditioning section (See Section A3.2).

J = Flowmeter under test (for insertion or in-line flowmeters; in-line flowmeter shown).

Figure A2 Typical Closed Loop Gas Calibration Facility

reference, gas may be used at reference temperature and pressure conditions.

It should be noted by the flow calibrating entity that the simplest flow calibration facility - - an open loop air flow facility with a fan as the flow generator - - actually is a closed loop facility with the loop closing within the laboratory. For air velocities less than about 5 m/s, such ambient pressure flow calibration facilities can experience shifts due to the opening and closing of doors to the room and other causations of pressure and temperature changes in the room. Operators of such facilities should minimize and account for the effect of such variations on the accuracy of flowmeters calibrated in this manner.

A3.2 Flow Conditioning Section

The flow conditioning section is an essential, but often overlooked, component of the flow calibration facilities shown in Figures A1 and A2. Its purpose is to condition the flow prior to its entering the flowmeter under test. The flow conditioning section should have the following attributes.

- It should be capable of reproducing the flow conditions of the actual application.
- For in-line flowmeters, the flow conditioning section should be straight pipe with lengths upstream and downstream of the flowmeter under test that meet the minimum specifications requirements specified by the manufacturer. A flow straightening and swirling flow eliminating device may be required upstream of the upstream pipe.
- For insertion flowmeters installed in pipes with fully developed velocity profiles, the flow conditioning section should be a length of straight pipe upstream of the flowmeter under test that is sufficiently long to create a fully developed velocity distribution.
- For insertion flowmeters used in large flow conduits and in general applications, it is recommended that the flow conditioning section is capable of generating a flat, quiet, non-swirling velocity profile. In this case, the preferred flow conditioning section has the following components:
  (1) a flow quieting section, such as a plenum with a flow straightener and screens or other means that reduce flow non-uniformities;
  (2) a nozzle to further flatten the velocity profile;
  (3) a test section consisting of either a straight walled section or a free jet into which the flow sensor of the insertion flowmeter under test is inserted. The test section should have a velocity profile that is uniform in its central portion within approximately 0.5 to 1%; a turbulence intensity less than about 0.5%; and a cross-sectional area large enough so that the flow blockage ratio is less than approximately 5 to 10 %.

A3.3 Flow Calibration Standards

It is recommended that the flow calibration standard component of the flow calibration facility have an accuracy at least 3 times better (i.e., an uncertainty of 1/3, or less) than that specified for the flowmeter under test. Flow calibration of the flow calibration standard should be traceable to a recognized national or international measurement standard, and its most recent traceable accuracy should be documented. This information should be made available by the manufacturer, upon the user's request.

Flow calibration standards that measure volumetric flow rate or displaced volume should have temperature and pressure transducers located close to the entrance of the flow calibration standard, but with no flow obstruction. These measurements are used to compute the mass density ρ of the gas (i.e., in units of kg/m^3), as in Section 4.7.10. ρ is then used to compute the mass flow rate q_m, as shown in subsequent sections.

Flow calibration standards are of two types.

- In-line flow calibration standards - - used in both open loop and closed loop flow calibration facilities.

- Batching flow calibration standards - - used in open loop flow calibration facilities.

A3.3.1 In-Line Flow Calibration Standards

Typical in-line flow calibration standards that measure the volumetric flow rate q_v (e.g., in units of m^3/s) include: rotating and reciprocating positive displacement flowmeters; turbine flowmeters; multipath ultrasonic flowmeters; venturi flowmeters; flow nozzles; and sonic nozzles. The desired mass flow rate is computed as $q_m = \rho\, q_v$ (kg/s).

Typical in-line flow calibration standards that directly measure the mass flow rate q_m include: coriolis mass flow meters, specially calibrated thermal dispersion mass flowmeters, and specially calibrated capillary tube thermal mass flowmeters. Flow calibration of a thermal dispersion mass flow meter with another specially calibrated thermal dispersion mass flowmeter should be performed with caution because influence parameters may affect each flowmeter in a similar manner (bias) that may not be indicated in the flow calibration result.

A3.3.2 Batching Flow Calibration Standards

Typical batching flow calibration standards measure the volume of the flow calibration gas passing through the flowmeter under test (Ref. 14). Typical flow calibration standards of this kind are positive displacement flow calibrators, or volumetric provers, such as bell provers and piston provers. In these flow calibrators, the displaced volume Vol (e.g., in units of m^3) and the time of transit Δt (e.g., in units of seconds) of the bell or piston are measured and used to compute the desired mass flow rate as $q_m = \rho\, Vol / \Delta t$ (kg/s).

Vol and Δt should be measured only during the steady-state rise of the bell or piston, i.e., after their initial acceleration and before their final deceleration. The transit time Δt should be sufficiently long so that both the resolution of the Δt measurement and small flow rate variations have a negligible effect. Because the size of batching flow calibration standards is limited, their use should be relegated to gas mass flow rates in the lower ranges. In-line standards should be used for higher ranges.

A4 Flow Calibration Procedures

All flow calibrating entities should adopt the following procedures.

- The flowmeter under test is installed in accordance with the manufacturer’s recommendations (See Section 6.1).
- The flow calibration is preceded by an appropriate warm-up period for each flow rate calibration data point.
- All transmitter configuration data is recorded prior to the start of the test.
- The test flow rates are selected to ensure that the flowmeter’s performance meets its specification over the operating flow range.

- The calibration of the flow calibration standard is current and traceable.
- The uncertainty of the flow calibration standard is recommended to be 1/3, or less, of the specification for the flowmeter under test.
- The flow rate is maintained constant while a data point is being taken. This is especially important if a batching flow calibration standard is used.
- The zero value is measured and only when there is absolutely no flow in the facility.
- Variations in gas temperature and pressure are minimized during the flow calibration process. The gas temperature should be held within approximately ± 3 °C (± 5.4 °F) during flow calibration. The gas pressure should be held within approximately ± 0.2 bar (± 3 psi).

A5 Calibration Certificate

The flow calibrating entity should provide the user, for every flowmeter, a certificate that includes the following data.

- A unique certificate number, repeated on each page along with the page number and the total number of pages.
- The calibration date.
- The certificate's date of issue.
- The identity of the party commissioning the calibration.
- The name and location of the flow calibration laboratory.
- The test gas data and the test temperature, pressure, etc.
- The calibration laboratory's basic methodology of flow calibration (See Section A3).
- The unique identification of the flowmeter under test.
- The traceability of the flow calibration facility.
- A reference identifying the flow calibration laboratory's documentation and how it can be reviewed.
- The uncertainty statement for the flow calibration laboratory.
- The relevant ambient conditions.
- The name of the calibration operator.
- The configuration data within the transmitter when the calibration was performed.
- A table showing all mass flow rate data including the temperature, pressure, and other measurements taken concurrently.

A6 Frequency of Recalibration

Thermal dispersion mass flowmeters generally require infrequent flow recalibration. The manufacturer should inform the user of the typical recalibration frequency for their application. The frequency of recalibration is governed by the criticality of the measurement, the nature of the operating conditions, the level of confidence required by the user, and the stability of the flow sensor. For fiscal and custody transfer applications, a higher recalibration frequency is recommended. If the installation conditions change, such as the result of pipe work modifications in the vicinity of the flowmeter, recalibration may be required.

A7 Liquid Flow Calibration

Liquid flow calibration systems fall into three categories: gravimetric, volumetric, or in-line flow calibration. Many of the gas flow calibration procedures in the proceeding sections are applicable to liquid flow calibration. Liquid flow calibration is thoroughly described in the open literature (e.g., Refs. 3, 14, and 15).

Appendix B

In-Line Flowmeter Sizing and Permanent Pressure Loss

(Non-Mandatory Appendix)

B1 In-Line Flowmeter Sizing

Table B1 shows the mass flow rates for typical in-line thermal dispersion mass flowmeters in sizes ranging from 0.25 to 8 inches (DN 6 to DN 200 mm) and with a built-in flow conditioner. Manufacturers should be consulted for applications requiring higher ranges.

Air and Nitrogen Mass Flow Rate Ranges				
Pipe Size (inches)	Minimum Range		Maximum Range	
	scfm(1)	nm^3/h(2)	scfm(1)	nm^3/h(2)
0.25	0 – 0.5	0 – 0.7	0 - 9	0 - 14
0.5	0 - 2	0 – 3.0	0 - 40	0 - 60
0.75	0 - 4	0 – 5.9	0 - 75	0 - 120
1.0	0 - 6	0 – 8.9	0 - 120	0 - 180
1.5	0 - 15	0 - 22	0 - 280	0 - 440
2.0	0 - 23	0 - 33	0 - 470	0 - 680
3.0	0 - 50	0 - 74	0 - 1000	0 - 1500
4.0	0 - 90	0 - 130	0 - 1800	0 - 2700
6.0	0 - 200	0 - 300	0 - 4000	0 - 5900
8.0	0 - 350	0 - 520	0 - 7000	0 - 10000

Notes:

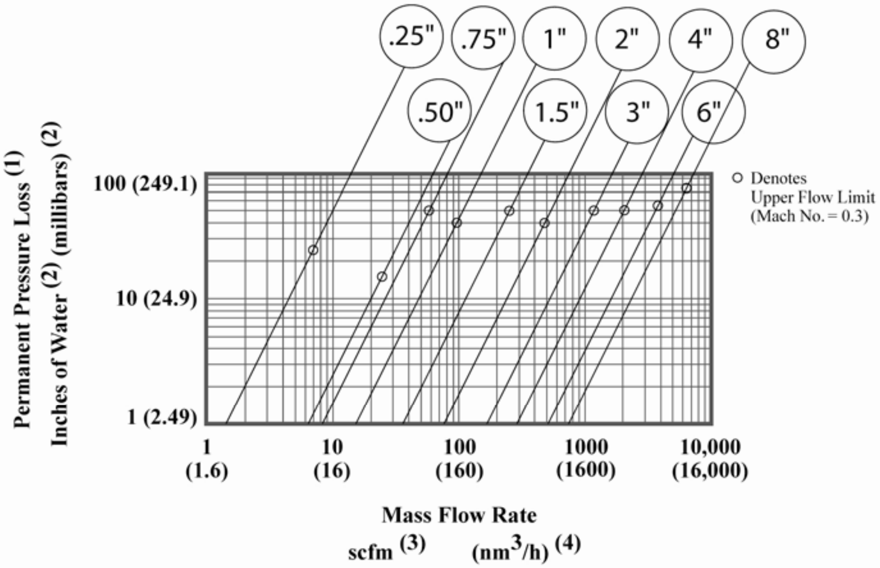
1 = At base conditions of 21.1 ºC temperature and 1 atmosphere pressure.

2 = At base conditions of 0 ºC temperature and 1 atmosphere pressure.

Table B1 Sizes and Mass Flow Rates for Typical In-Line Flowmeters

B2 Permanent Pressure Loss

Section 5.4 discusses the permanent pressure loss of in-line and insertion flowmeters. Figure B1 shows the permanent pressure loss for typical in-line flowmeters in sizes ranging from 0.25 to 8 inches (DN 6 to DN 200 mm) and with a built-in flow conditioner. Manufacturers should be consulted for applications requiring lower permanent pressure losses.



Notes:

(1) For air and nitrogen at 20 ^{o}C temperature and 1 atmosphere pressure.

(2) 1 inch of water at 60 ^{o}F= 0.0361 psi.
1 millibar = 0.001 bar = 100 pascal = 0.0145 psi.

(3) At base conditions of 21.1 ^{o}C temperature and 1 atmosphere pressure.

(4) At base conditions of 0 ^{o}C temperature and 1 atmosphere pressure.

(5) Built-in flow conditioner consists of two separate perforated plates in series.

Figure B1 Permanent Pressure Loss for Typical In-Line Flowmeters with a Built -In Flow Conditioner (5)

Appendix C

Accuracy and Uncertainty

(Non-Mandatory Appendix)

C1 Introduction

Section 5.6.1 of the main text provides a general discussion of the accuracy of mass flow rate measurement. This appendix presents an example calculation of overall accuracy and a simplified discussion of uncertainty.

C2 Example Accuracy Calculation

This section gives a typical numerical calculation of the overall accuracy A_t including the use of the temperature influence coefficient C_T and the pressure influence coefficient C_P. It is based on Equation 5.3 in the main text.

If both T and P fall outside their reference condition range, the overall accuracy (in units of percent of reading) based on Equation 5.3 is as follows.

$$A_t = \pm [A_r + A_{fs}\, q_{m,fs} / q_m + C_T\, Abs\, (T_f - T_L) + C_P\, Abs\, (P - P_L)] \qquad \textbf{C-1}$$

Where:
T_L = The upper or lower limit of the temperature reference condition range.
P_L = The upper and lower limit of the pressure reference condition range.
$Abs\,(\;\;)$ = Absolute value of the difference in parentheses.

For example, let us assume that a thermal dispersion mass flowmeter has been flow calibrated at 20 °C and 5 bara, but the actual process temperature is T_f is 40 °C and the actual process pressure P is 7 bara. Let us further assume that: A_r = 1.0 percent of reading over 10 to 100 percent of full scale range; A_{fs} = 0.5 percent of full scale over 10 to 100 percent of full scale range; the actual mass flow rate q_m is 80% of the full scale value $q_{m,fs}$; the reference temperature range is ± 10 °C of the flow calibration temperature; the reference pressure range is ± 1 bar of the flow calibration pressure; the temperature influence coefficient C_T is 0.04 percent of reading per degree centigrade for actual temperatures in the range of ± (10 to 25 °C) of the flow calibration temperature; and the pressure influence coefficient C_P is 0.3 percent of reading per bar for actual pressure in the range of ± (1 to 16 bar) of the flow calibration pressure. In this case, the overall accuracy is calculated as follows.

$$A_t = \pm\ [1.0 + 0.5 / 0.8 + 0.04 \text{ x } (40 - 30) + 0.3 \text{ x } (7 - 6)]$$

$A_t = \pm$ **2.325** percent of reading

C3 Discussion of Uncertainty

The uncertainty of flowmeters is thoroughly covered in the open literature (See Refs. 3, 13, 16, and 17). For the present purposes, the following short discussion of uncertainty is adequate.

In general, the mass flow rate q_m is a function of n input variables x_i , as follows.

$$q_m = f(x_1, x_2, \ldots, x_n) \qquad \textbf{C2}$$

The uncertainty in q_m is expressed as $u(q_m)$. If the errors are random and are not systematic (i.e., there is no bias), then the uncertainty in the mass flow rate of thermal dispersion mass flowmeters is expressed as follows.

$$u(q_m) = t\,[\Sigma(S_i^2\, u(x_i)^2)]^{1/2} \quad \text{for } i=1,2,\ldots,n \qquad \textbf{C3}$$

Where:

$S_i = \delta q_m / \delta x_i$ = The sensitivity coefficient of q_m to input variable x_i .

$u(x_i)$ = The uncertainty of input variable x_i .

$t = t_{68}$ or t_{95} = The factor from the students “t” distribution required to yield an uncertainty in q_m with a confidence level of 68.3 percent or 95.5 percent, respectively. For more than 10 degrees of freedom, the following values of the t’s are used: $t_{68} = 1$ and $t_{95} = 2$. t_{68} yields the one-sigma uncertainty value, and t_{95} yields the two-sigma uncertainty value.