INTERNATIONAL STANDARD

# ISO 14511

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# Measurement of fluid flow in closed conduits — Thermal mass flowmeters

*Mesure de débit des fluides dans les conduites fermées — Débitmètres massiques par effet thermique*



Reference number
ISO 14511:2001(E)

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# Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this International Standard may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

International Standard ISO 14511 was prepared by Technical Committee ISO/TC 30, *Measurement of fluid flow in closed conduits*, Subcommittee SC 5, *Velocity and mass methods*.

## Introduction

This International Standard has been prepared to guide those concerned with the specification, testing, inspection, installation, operation and calibration of thermal mass gas flowmeters.

A list of standards related to ISO 14511 is given in the bibliography.

# Measurement of fluid flow in closed conduits — Thermal mass flowmeters

## 1 Scope

This International Standard gives guidelines for the specification, testing, inspection, installation, operation and calibration of thermal mass gas flowmeters for the metering of gases and gas mixtures. It is not applicable to measuring liquid mass flowrates using thermal mass flowmeters.

This International Standard is not applicable to hot wire and other hot film anemometers, also used in making point velocity measurements.

## 2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 4006, *Measurement of fluid flow in closed conduits — Vocabulary and symbols*

ISO 7066-2, *Assessment of uncertainty in the calibration and use of flow measurement devices — Part 2: Non-linear calibration relationships*

*Guide to the expression of uncertainty in measurement (GUM)*. BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, 1st edition, corrected and reprinted in 1995

IEC 61000-4, *Electromagnetic compatibility (EMC) — Part 4: Testing and measurement techniques*

## 3 Terms and definitions

For the purposes of this International Standard, the terms and definitions given in ISO 4006 and the following apply.

NOTE The term “gas” is used as a synonym for single gases, gas mixtures and vapours.

### 3.1 General terms

**3.1.1**
**flowrate**
quotient of the quantity of fluid passing through the cross-section of a conduit and the time taken for this quantity to pass through this section

NOTE In this International Standard, the term “flowrate” is used as a synonym for mass flowrate, unless otherwise stated.

**3.1.2**
**mass flowrate**
flowrate in which the quantity of fluid is expressed as a mass

NOTE The term “flowrate” is used as a synonym for mass flowrate in this International Standard, unless otherwise stated.

**3.1.3**
**accuracy of measurement**
closeness of the agreement between the result of a measurement and a true value of the measurand

NOTE Accuracy is a qualitative concept.

**3.1.4**
**uncertainty of measurement**
parameter, associated with the result of a measurement, that characterizes the dispersion of the values that can reasonably be attributed to the measurand

**3.1.5**
**repeatability**
⟨measuring instrument⟩ ability of a measuring instrument to provide closely similar indications for repeated applications of the same measurand under the same conditions of measurement

NOTE These conditions include:

— minimized variations resulting from the observer;

— the same measurement procedure;

— the same observer;

— the same measuring equipment, used under the same conditions;

— the same location;

— repeated measurements within a short period of time.

**3.1.6**
**flow profile**
graphic representation of the velocity distribution

NOTE The point flow velocity across the cross-section of a conduit is not constant. It varies as a consequence of upstream and downstream disturbances and with the Reynolds number of the flow stream. For a fully developed flow, the point flow velocity varies from 0 m/s at the pipe wall to a maximum value at the conduit centre. The flow profile describes the variation of the flow velocity across the conduit cross-section and may be expressed mathematically or graphically.

## 3.2 Specific terms

**3.2.1**
**sensor**
element of a measuring instrument or measuring chain that is directly affected by the measurand

**3.2.2**
**laminar flow element**
element inserted into the gas stream to establish a constant ratio between the main flow stream and the bypass flow through the sensor

**3.2.3**
**thermal mass flowmeter**
**TMF meter**
flow-measuring device which uses heat transfer to measure and indicate mass flowrate

NOTE The term thermal mass flowmeter also applies to the measuring portion of a thermal mass flow controller and not the control function.

**3.2.4**
**capillary thermal mass flowmeter**
**CTMF meter**
TMF meter normally consisting of a laminar flow element, bypass tube (capillary), temperature sensors (some designs include a separate heater) with supporting electronics and housing

**3.2.5**
**insertion and/or in-line thermal mass flowmeter**
**ITMF meter**
TMF meter normally consisting of one or two temperature sensing sensors (some designs have a separate heater) with supporting structure, electronics and housing, of which the sensors are exposed to the full gas stream

**3.2.5.1**
**insertion-ITMF meter**
ITMF meter with the sensors mounted on a probe, inserted through the process conduit wall, into the gas stream

**3.2.5.2**
**in-line ITMF meter**
ITMF meter with the sensors mounted in a flow body which serves as an integral part of the conduit

**3.2.6**
**thermal mass flow controller**
flow controlling device that comprises a TMF meter, a valve and controlling electronics

NOTE The output of the TMF meter is compared against an adjustable setpoint and the valve is correspondingly opened or closed to maintain the measured flowrate at the setpoint value.

**3.2.7**
**transmitter**
associated electronics providing the heater with electrical power and transforming the signals from the temperature sensors to give output(s) of the measured parameters

NOTE The transmitter can be integrally mounted to a TMF meter. However, for some applications the transmitter can be remotely installed away from the flow sensor.

**3.2.8**
**retractor mechanism**
⟨insertion-ITMF meters⟩ mechanical arrangement including an isolation valve that allows the positioning and/or extraction of the flow sensor within the conduit

**3.2.9**
**rangeability**
statement of the minimum and maximum limits of which an individual sensor can measure and indicate

EXAMPLE For a maximum flowrate = 1 000 kg/h and a minimum flowrate = 10 kg/h, the rangeability = 10 kg/h to 1 000 kg/h.

**3.2.9.1**
**turndown**
numerical ratio of the maximum to minimum limits of which an individual sensor can measure

EXAMPLE For a maximum flowrate = 1 000 kg/h and a minimum flowrate = 10 kg/h, the turndown ratio = 1 000/10 = 100:1.

NOTE In practice, the terms rangeability and turndown are used interchangeably and can be associated with an uncertainty statement.

**3.2.10**
***k*-factor**
numerical factor unique to each TMF meter which is associated with the mass flowrate derived during the calibration and when programmed into the transmitter ensures that the meter performs to its stated specification

NOTE When a surrogate gas has been used for calibration purposes, the manufacturer's gas factor list or database has been applied for conversion to the desired gas under process conditions.

**3.2.11**
**normalized volumetric flowrate** (GB)
**standardized volumetric flowrate** (US)
flowrate for which the quantity of fluid is expressed in terms of volume, with the fluid density calculated at a known and fixed pressure and temperature condition

NOTE 1 The values used to define these reference conditions (also known as "standard reference conditions") are industry and country specific and therefore shall always be specified when these units are used. Typical reference conditions are 0 °C and 101,325 kPa.

NOTE 2 Normalized volumetric units or volumetric units specified to standard reference conditions, such as "$Nm^3/h$", are commonly used with CTMF and ITMF meters, however this practice is not recommended as they are neither SI units nor symbols and their use without knowledge of the reference conditions will lead to significant errors. In this International Standard, volumetric units specified to standard reference conditions are followed by the expression "(normalized)", e.g. $m^3/h$ (normalized).

**3.2.12**
**normalized velocity** (GB)
**standardized velocity** (US)
flowrate for which the quantity of fluid is expressed in terms of the speed of flow, with the fluid density calculated at a known and fixed pressure and temperature condition

NOTE 1 The values used to define these reference conditions (also known as "standard reference conditions") are industry and country specific and therefore shall always be specified when these units are used. Typical reference conditions are 0 °C and 101,325 kPa.

NOTE 2 Normalized volumetric units or volumetric units specified to standard reference conditions, such as "Nm/s", are commonly used with CTMF and ITMF meters, however this practice is not recommended as they are neither SI units or symbols and their use without knowledge of the reference conditions will lead to significant errors. In this International Standard, volumetric units specified to standard reference conditions are followed by the expression "(normalized)", e.g. m/s (normalized).



## 4 Selection of thermal mass flowmeters

TMF meters fall into two basic design categories:

a) capillary TMF meters (CTMF meters);

b) full bore TMF meters, consisting of the following two types (ITMF meter):

   1) insertion type;

   2) in-line type.

The choice of appropriate design for a particular application is primarily dependent on:

— the required flowrate and range;

— the cleanliness of the gas;

— the conduit dimensions.

The two basic types of TMF meters have a number of overlapping characteristics for flowrate and conduit dimensions as shown in Table 1. Other factors may influence the final choice of the meter depending on the application. Table 1 is a guideline only and the manufacturer's specifications should be consulted for the absolute limits.

**Table 1 — Preliminary TMF meter selection criteria**

| **Characteristic** | **CTMF meter** | **ITMF meter** | |
|---|---|---|---|
| | | In-line | Insertion |
| Typical flow range | < 2 000 $m^3/h$ [a, b] at reference conditions of 0 °C and 101,325 kPa | 0,22 kg/h to 7 000 kg/h [a, b] | ≫ 5 kg/h [a, b, c] |
| Typical conduit size | 3 mm to 200 mm | 8 mm to 200 mm | > 80 mm |
| Gas condition | Clean and dry only | Preferably clean and dry [d] | |
| Gas temperature | < 70 °C | < 500 °C | |

a Flow range is dependent on the conduit size.

b Quoted flow range in air or nitrogen.

c This is the minimum flowrate in a 80 mm conduit. Flowrates in excess of 100 t/h can be achieved in large conduits.

d The ITMF meter can operate in the presence of dirty and/or wet gases. However, its performance is impaired.



# 5 Capillary thermal mass flowmeter (CTMF meter)

## 5.1 Principles of measurement

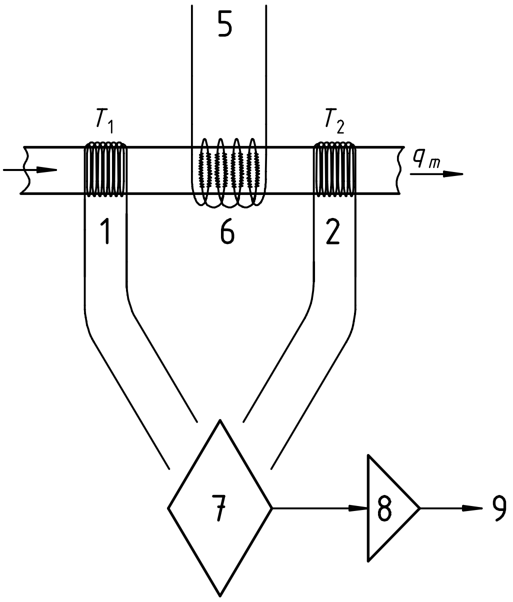
A typical CTMF meter consists of a meter body and flow sensor. The flow sensor is mounted integrally into the meter body. A defined portion of the gas flow from the meter body is diverted through the (bypass) flow sensor, through which the gas flowrate is measured.

Figure 1 shows a simplified CTMF meter with a typical flow sensor consisting of a thin tube and two temperature sensors. Depending upon the meter manufacturer, the heater can either be combined with each temperature sensor or be located separately in the middle of the flow sensor, i.e. between the temperature sensor upstream ($T_1$) and the one downstream ($T_2$) of the gas flow.

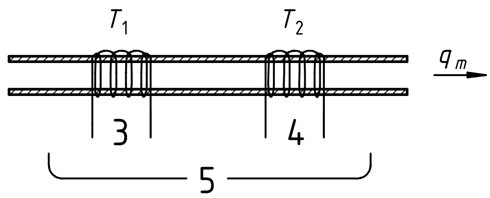
A precision power supply delivers constant heat to the flow sensor. Under stopped-flow conditions, both sensors measure the same temperature. As the flowrate increases, heat is carried away from the upstream sensor ($T_1$) towards the downstream sensor ($T_2$). A bridge circuitry interprets the temperature difference and an amplifier provides the flowrate output signal.

The measured temperature difference between the two sensors is proportional to the mass flowrate.




**a) Two temperature sensors and separate heater**




**b) Two self-heating temperature sensors**

**Key**

1 Upstream temperature sensor $T_1$
2 Downstream temperature sensor $T_2$
3 Upstream temperature sensor $T_1$ (with heater)
4 Downstream temperature sensor $T_2$ (with heater)
5 Constant power supply $P$
6 Heater
7 Bridge circuitry
8 Amplifier
9 Flow signal output (typically 0 V to 5 V d.c. for 4 mA to 20 mA)

**Figure 1 — Simplified CTMF meter**



The flow sensor measures the mass flowrate as a function of temperature difference. This can be expressed according to first law of thermodynamics (heat in = heat out, for no losses) for which the following equations apply:

$$P = \left[ q_m \times c_p \times \frac{T_2 - T_1}{f_{\text{CTMF}}} \right] + L \quad (1)$$

or after rearranging equation (1)

$$q_m = \frac{(P - L) \times f_{\text{CTMF}}}{c_p \, (T_2 - T_1)} \quad (2)$$

where

$q_m$ is the mass flowrate, expressed in kilograms per second;

$c_p$ is the specific heat, expressed in joules per kilogram per kelvin [J/(kg·K)], of the gas at constant pressure;

$T_2 - T_1$ is the temperature difference, expressed in kelvins;

$P$ is the constant input power, expressed in watts;

$L$ is the end conduction loss[1)], expressed in watts;

$f_{\text{CTMF}}$ is the constant meter factor related to the CTMF meter design.

Flow-through thermal mass flow sensors are only accurate at relatively low flowrates. Therefore, so as to measure accurately higher flowrates, it is necessary to split the total flow. This flow diversion is carried out in the meter body by means of a laminar flow element. This element produces a linear pressure drop which is proportional to the mass flowrate.

The full-scale (FS) flow range of a CTMF meter is directly influenced by the specific heat $c_p$ (at constant pressure) of the process gas.

Not all calibrations can be performed using the desired process gas. If the gas is corrosive or hazardous, it is necessary to use a reference gas for calibration, i.e. air or nitrogen. In this case, it is necessary to calculate the $c_p$ value of the process gas.

NOTE Each manufacturer of a CTMF product should be able to provide a list of gas conversion factors or to make reference to an appropriate database.

The $k$-factor is defined as:

$$k = \frac{c_{p,\text{ref}}}{c_{p,\text{proc}}} \tag{3}$$

The full-scale flowrate (FS) of the process gas is given by:

$$q_{m,\text{proc,FS}} = q_{m,\text{ref,FS}} \times k \tag{4}$$

where

$k$ is the $k$-factor;

$c_{p,\text{ref}}$ is the specific heat, at constant pressure, of the reference gas;

$c_{p,\text{proc}}$ is the specific heat, at constant pressure of the process gas;

$q_{m,\text{ref,FS}}$ is the mass flowrate, on a full-scale basis, of the reference gas;

$q_{m,\text{proc,FS}}$ is the mass flowrate, of the process gas on a full-scale basis.

Using this relationship as well as the gas tables available for specific heat, the user and the manufacturer can easily (re)calibrate the meter by using a “safe” gas.

## 5.2 Typical design

As too much heat is transferred at higher flowrates, only very low flowrates can accurately be measured using the basic CTMF meter design. Consequently, the CTMF meter type is often used in conjunction with a laminar flow

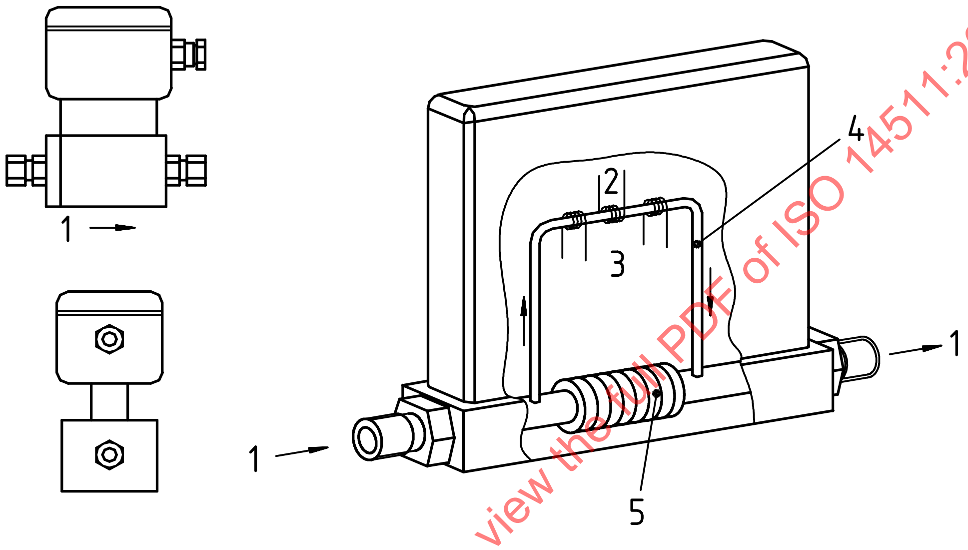
1) End conduction loss is a design-dependent quantity and is the heat lost by conduction to the flow meter body through the mounting arrangement of the transducer. It is so called since the transducer is normally mounted at one of its ends.



element, placed in the main conduit where it produces a small pressure drop. The ends of the capillary tube are connected to the inlet and outlet of the laminar flow element so as to create a small diverted flow through the capillary tube. This design ensures a fixed ratio of the total gas flowrate through the capillary for measurement. The heater and temperature sensors are usually placed on the capillary tube rather than the main conduit. However, other designs exist where the sensors are located directly on the main conduit, i.e. without the capillary and the laminar flow element.

The CTMF meter is generally supplied with screw-threaded fittings although flange fittings can be provided. This design of TMF meter is often combined with a flow controller downstream to the sensing sensor so as to obtain a mass flow controller. Typically, the electronic interface is located within the same unit as the bypass loop. Figure 2 shows a typical CTMF meter design.




**Key**

1 Direction of flow
2 Heater
3 Temperature sensors
4 Bypass loop
5 Laminar flow element

**Figure 2 — Typical CTMF meter**



## 5.3 Applications and limitations of use

### 5.3.1 Gas property effects

CTMF meters should only be used to measure dry and clean gases. Saturated vapours capable of condensing should be avoided so as to prevent clogging or contaminating the flow sensor.

From equations (1) to (4), it can be seen that the calibration of the CTMF meter is dependent on the properties of the gas. Therefore the CTMF is an *inferential* mass-flowrate meter. Although the CTMF meter responds to changes in mass flowrate, calibration is dependent on the gas being measured as well as the operating conditions. Variations in fluid properties, such as varying gas mixture composition, process pressure and/or temperature, which affect the value of specific heat, will in turn affect the performance of the CTMF meter. When this situation occurs, it may be necessary to compensate for these variations.

### 5.3.2 Application and fluid properties

In order to identify the optimum meter for a given application, it is important to establish the range of conditions to which it will be subjected. These conditions should include:

— the operating flowrates;

- the properties of the metered gas, the type of gas or the composition of the gas mixture;
- the range of pressures of the process;
- the range of temperatures of the process.

### 5.3.3 Temperature effects

Temperature changes affect the behaviour of the CTMF meter. Compensation for this effect is usually incorporated into the transmitter. Temperature variations may also induce an offset in the meter output at zero flowrate. Therefore, the meter should be zeroed at the actual temperature of the process.

Temperature effects are normally specified in percentage or degrees Celsius.

Furthermore, temperature changes may influence the specific heat value at which the CTMF meter was initially calibrated. In these cases, this effect should be determined using values from known gas data furnished by the gas manufacturer after calibration.

### 5.3.4 Pressure effects

Pressure changes may affect the specific heat of the gas and/or flow ratio between sensor and laminar flow element. It may, therefore, alter the *k*-factor of the CTMF meter. Some manufacturers make meter calibrations under pre-defined pressure conditions so as to minimize this effect. However, in other cases, reference to known gas data furnished by the gas manufacturer after calibration is required.

### 5.3.5 Pulsation effects

If the flow is pulsating, care should be taken to ensure that the transmitter responds quickly enough to follow the pulsation. Some manufacturers offer adaptive output damping when a constant output signal is required under these conditions. The manufacturer's specification for flowrate output response and/or damping should be observed.

### 5.3.6 Pressure loss

A loss in pressure occurs as the fluid flows through the CTMF meter. The magnitude of the pressure loss is a function of the pressure difference across the laminar flow element with respect to the flowrate. Most manufacturers specify this effect and typically the amount of pressure loss is smaller than 100 hPa (100 mbar) at full-scale flowrate. The value of the pressure loss should include the CTMF meter, fittings and inlet filter.

### 5.3.7 Cleanness of the gas

Solids settlement, coating, or trapped condensate can affect the meter performance. These conditions should be avoided. The preferred cleanness specification of the manufacturer shall be followed. Most manufacturers specify the allowed particle size or provide an inlet filter as standard to the CTMF meter.

### 5.3.8 Mounting orientation effects

Most manufacturers specify the effect for mounting orientations. For most instruments, this effect is negligible. The preferred mounting position for high pressure applications, however, is horizontal, because of possible zero-offset. In order to achieve the specified performance, the installation guidelines from the manufacturer shall be followed.

### 5.3.9 Installation effects for flow profile

The performance of a CTMF meter is not affected by fluid swirl and non-uniform velocity profiles induced by upstream and downstream piping configurations. No special straight-piping lengths are normally required but depend on the manufacturer. Nonetheless, good installation practices should be observed at all times.

Filters, or other protective devices should be provided upstream of the meter to remove solids or liquid droplets that can possibly cause measurement errors.

#### 5.3.10 Vibrations — hydraulic and mechanical

Vibrations in the process-line normally have no effect on the performance of the CTMF meter. However, all vibrations should remain within the limits of common practice.

#### 5.3.11 Valves

Valves upstream and downstream of a CTMF meter, installed for the purpose of isolating and zeroing the meter, can be of any type. However, they should provide tight shut-off to ensure that true zero flowrate can be achieved. Control valves in series with a CTMF meter shall be installed close together with the TMF meter so as to minimize dead volume.



## 5.4 Meter selection

### 5.4.1 Principal requirement

The principal requirement of a metering system is that it shall measure gas mass flowrate with the specified uncertainty. Consideration shall be given to the points given in 5.4.2 to 5.4.7 when choosing a suitable meter.

### 5.4.2 Performance specifications

The following performance specifications shall be taken into account:

- uncertainty:
  - compliance of the actual installation and operating conditions with the manufacturer's data;
  - calibration procedure used and traceability of calibration equipment;
- repeatability;
- rangeability;
- stability;
- temperature effect;
- pressure effect;
- mounting orientation effect.

### 5.4.3 Physical specifications

The following physical specifications shall be taken into account:

- space required (meter dimensions, upstream, downstream conduit diameters) for installation of the flowmeter, including provision for *in-situ* calibration if desired and possible;
- class and type of conduit connections;
- material compatibility including O-ring(s), (valve) seat material;
- any non-destructive testing procedures;

- hazardous area classification;
- electrical connections;
- climatic and environmental effects on the flowmeter;
- any applicable national or international requirements.

### 5.4.4 Meter ratings

The following meter ratings shall be taken into account:

- maximum allowable process pressure;
- pressure drop at the maximum flowrate;
- ambient and process gas temperature;
- outboard leak integrity rating.

### 5.4.5 Application and fluid properties

The following application and fluid properties shall be taken into account:

- operating flowrates;
- properties of the metered gas, including gas type or composition of gas mixture;
- range of operational pressures;
- range of operational temperatures;
- reference process conditions when normalized volume units of flowrate are used [i.e. $m^3/h$ (normalized), l/min (normalized)].

### 5.4.6 Corrosion

Corrosion, including galvanic corrosion, of the wetted materials can adversely affect the performance and ultimately shorten the operating life of the CTMF meter. Care should be taken when selecting the materials of construction to ensure that the process gas, including purge or cleaning fluids are compatible. All process-wetted materials shall be specified.

### 5.4.7 Transmitter specifications

The following transmitter specifications shall be taken into account:

- electrical, electronic, climatic and safety compatibility;
- required output options.

## 5.5 Installation and commissioning

### 5.5.1 General considerations

In general, consideration should be given to the following points:

— the process gas should be relatively clean and dry;

— the space required for the TMF meter installation (including provisions for the TMF meter verification by means of master-meter connections, should *in-situ* calibration be required; see 8.4 for details);

— the class and type of pipe connections, materials and the dimensions of the equipment to be used;

— any hazardous area classification;

— any climatic and environmental effects on the sensor, e.g. temperature, humidity, corrosive atmospheres, mechanical shock, vibration and electromagnetic field.

### 5.5.2 Safety

Consideration should be given to the following points on safety:

— the operation of the meter shall be limited to process conditions which remain within the meter's specifications;

— the meter shall comply with any necessary hazardous area classifications as well as all applicable national or international requirements;

— only appropriately qualified and trained personnel shall install, operate and/or maintain the meter.

### 5.5.3 Mechanical stress

Consideration should be given to the following points on mechanical stress:

— the meter should be selected to withstand temperature, pressure and conduit vibration and should be pressure-tested with a suitable fluid in accordance with the appropriate standard;

— to ensure leak-tightness in critical applications, all meters should be tested, preferably with helium gas under vacuum conditions to an appropriate standard.

### 5.5.4 Process adjustment

#### 5.5.4.1 General

If the actual operating conditions are not in compliance with the calibrated configuration of the meter, additional adjustment may be required.

#### 5.5.4.2 Zero adjustment

Once the meter installation is completed and checked for compliance with all manufacturer-specified recommendations and statutory requirements, a zero adjustment procedure at the operating process conditions may be necessary with some process gases to compensate for the effects previously described. It is essential that this procedure be carried out at the actual process temperature and pressure conditions. These conditions shall be stable and there shall be absolutely no gas flowrate. Depending on the quality of the gas and/or the nature of the application, it may be desirable to repeat this operation at regular intervals.

#### 5.5.4.3 Span adjustment

CTMF meters are normally calibrated with respect to the actual process conditions, however if the latter are different than the calibration conditions, or if the gas type or quality is different from that specified for the calibration, a span adjustment may be required. This can only be carried out if the installation provides the means of obtaining a reference flowrate value for comparison with the CTMF meter reading (see clause 8). It is essential that this procedure be carried out at the actual process temperature and pressure conditions. These conditions and the actual flowrate shall be stable during any span adjustment procedure. Depending on the quality of the gas and/or the nature of the application, it may be desirable to repeat this operation at regular intervals.

## 6 Insertion and/or in-line thermal mass flowmeter (ITMF meter)

### 6.1 Principles of measurement

#### 6.1.1 General

A typical ITMF flowmeter consists of two temperature sensors (see Figure 3).

An amount of heating power $P$ is applied to one of the sensors, causing its temperature to rise to a measured value $T_2$. The other sensor measures the gas temperature $T_1$.

The gas mass flowrate can be determined from the temperature difference between the heated sensor and the gas ($\Delta T = T_2 - T_1$) and the amount of heating power $P$ applied.

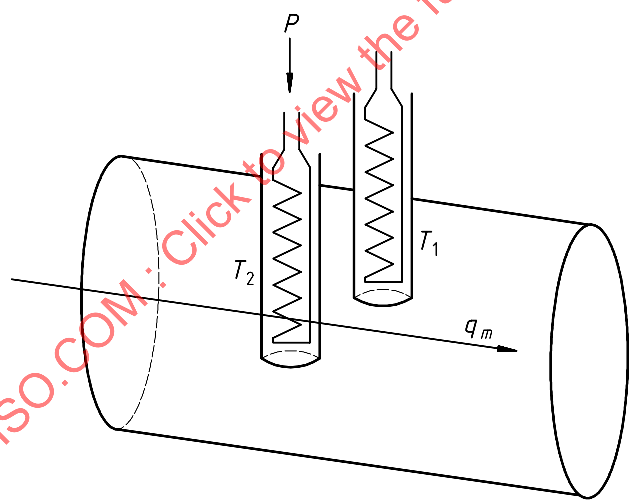



**Figure 3 — Typical ITMF meter sensor configuration**



The relationship between the heating power $P$, the difference in temperature ($\Delta T$) and the mass flowrate ($q_m$) can be expressed as follows:

$$\frac{P}{\Delta T} = K_1 + K_2 \times (q_m)^{K_3} \quad (5)$$

where

| | |
|---|---|
| $K_1$, $K_2$, and $K_3$ | are design and calibration parameters; |
| $\Delta T$ | is the temperature difference ($= T_2 - T_1$), expressed in kelvins; |
| $P$ | is the input heating power, expressed in watts; |
| $q_m$ | is the mass flowrate, expressed in kilograms per second. |

This is known as King's Law. $K_1$ and $K_2$ depend on the geometry of the sensing sensors and also on specific gas properties such as thermal conductivity, viscosity and specific heat capacity. $K_3$ is Reynolds-number-dependent.

The numerical value of these factors are meter and gas specific, therefore the ITMF meter has to be calibrated for the gas desired for flow measurement.

In practice, there are two methods of measuring the gas mass flowrate using either a constant power or constant differential temperature method.

### 6.1.2 Constant power method

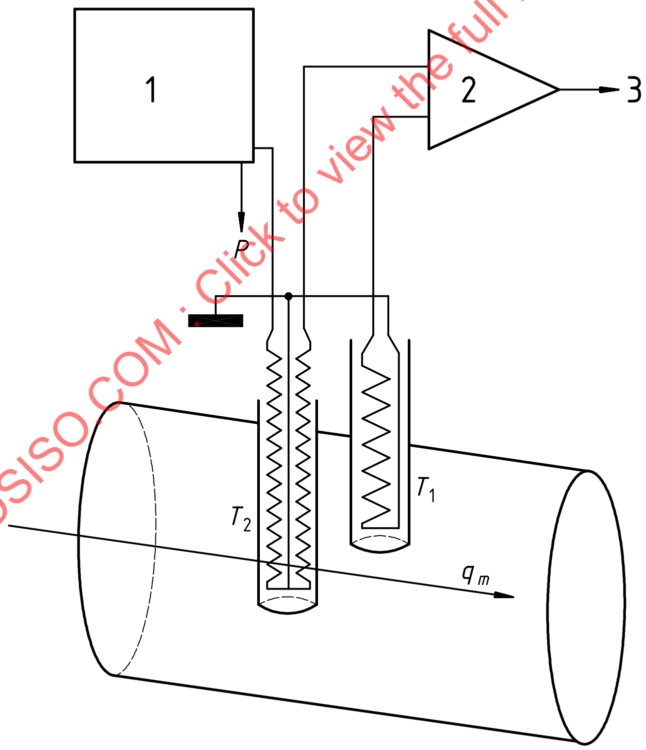
This method keeps the electrical heating power ($P$) constant while measuring the differential temperature ($\Delta T$). The simplified equation is:

$$\Delta T = K_4 + K_5 \times (q_m)^{K_6} \tag{6}$$

where

$K_4$, $K_5$ and $K_6$ are design and calibration parameters.

Typically, temperature-dependent resistors measure both the gas temperature and the heated-sensor temperature. The difference between the two temperatures is a function of the mass flowrate ($q_m$) (see Figure 4).




**Key**

1 Constant voltage supply

2 Amplifier

3 Mass flow determination

**Figure 4 — Simplified sensor circuitry for the "constant power" ITMF meter**

### 6.1.3 Constant-temperature-differential method

The temperature differential ($\Delta T$) is maintained constant while measuring the change in heating power ($P$). The simplified equation is:

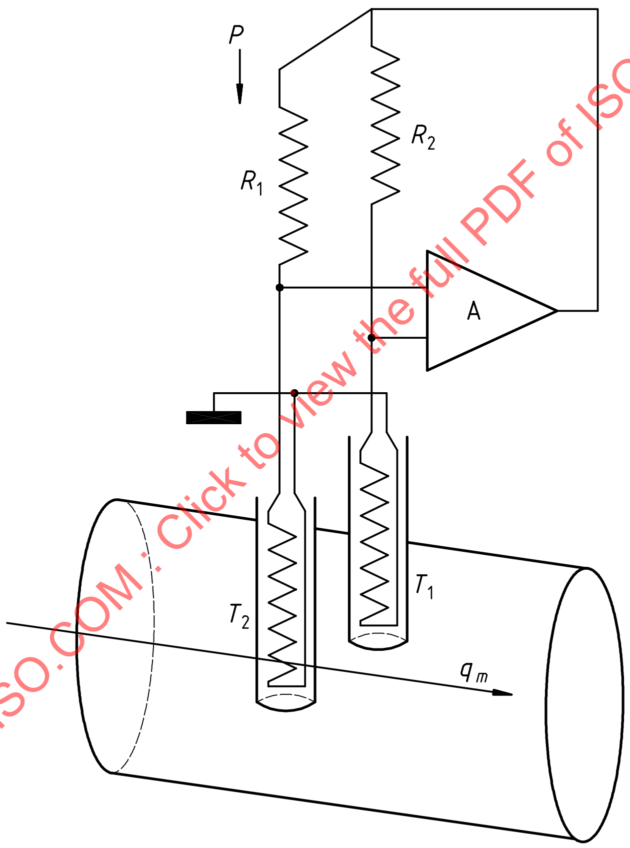
$$P = \Delta T \times \left[ K_7 + K_8 \times (q_m)^{K_9} \right] \tag{7}$$

where

$K_7$, $K_8$ and $K_9$ are design and calibration parameters.

Both the heated sensor and the gas temperature sensor are typically[2)] temperature-dependent resistors. A bridge circuit maintains the heated sensor ($T_2$) at a constant-temperature differential from the gas temperature sensor ($T_1$) (see Figure 5).






$R_1$ = Resistor 1

$R_2$ = Resistor 2

A = Amplifier

**Figure 5 — Simplified circuitry for “constant-temperature-differential” ITMF meter**

2) Other configurations exist that utilize the thermal properties of silicon diodes, thermocouples, resistance thermometer detectors (also called resistance temperature detectors) (RTD), etc.

## 6.2 Typical design

### 6.2.1 ITMF basic design

An ITMF meter is comprised of three basic functional components: the meter body or probe, sensors and electronics module. The arrangement of these components characterizes different common meter designs.

The electronics module is considered as a secondary device and may be remote from the meter body. The electronics module provides the power source for the sensors and the process electronics. The ITMF meter output can usually be specified as a rate and/or total output in a range of units. Additional outputs can usually be provided, e.g. a flow computer which can provide other performance and diagnostics information.

ITMF meters are available in different design formats generally described by their conduit fitting: flanged, threaded, wafer or insertion type (see Figures 6 and 7). The first three types are all in-line meters with a flow of gas through the meter body. The body of an insertion-ITMF meter simply contains and protects the sensors. Standard ITMF meters are available in a wide range of conduit fittings, e.g. ANSI and DIN flanges, sanitary couplings, and NPT thread.

### 6.2.2 In-line ITMF meter

An integral section of straight conduit with threaded or flanged end fittings contains the sensors. The flowing gas stream passes through the meter and over the sensors. Certain ITMF meters of this type may include straight lengths of conduit both upstream and downstream of the sensor to reduce the effects of flow disturbances. Figure 6 shows examples of typical in-line ITMF meters.



**a) Flanged type**

**b) Wafer type**

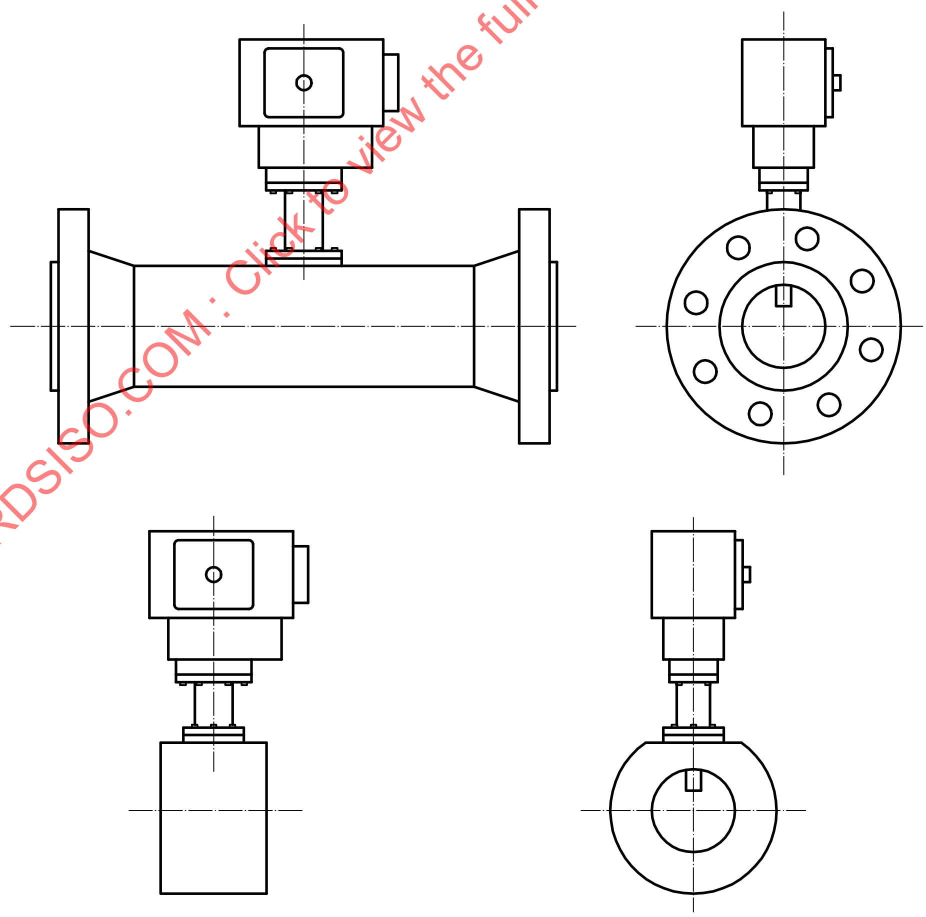


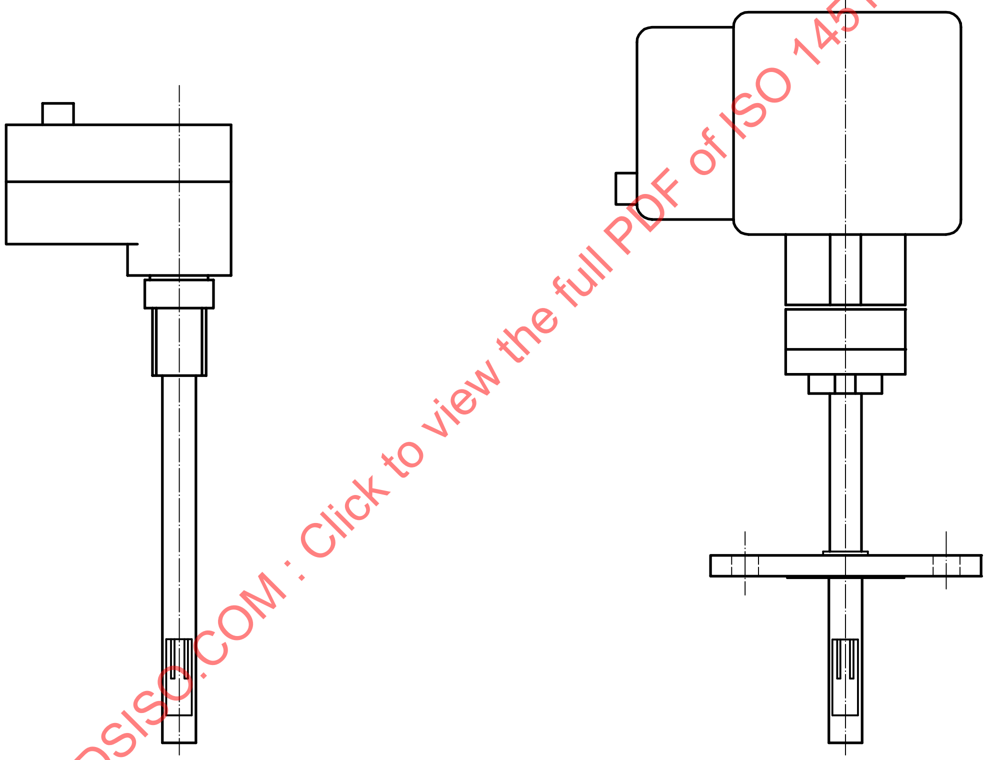
**Figure 6 — Typical flanged and wafer in-line ITMF-meter designs**

A wafer in-line ITMF meter should fit between two existing conduit flanges. The mounting length, or meter body width, is generally standardized at 65 mm.

The sensor's design depends on the manufacturer, although all incorporate at least a heat source and two temperature sensors. The location of the sensors within the cross-section of the conduit is fixed. Other components may be included for flow conditioning or physical protection.

### 6.2.3 Insertion-ITMF meter

For larger conduits, an insertion-ITMF meter is commonly used, although some designs can be used for conduits as small as 50 mm diameter. The sensors are installed at the end of a probe which is inserted into the flowing gas stream. Total mass flowrate is determined from the measured point flowrate, cross-sectional area and compensation for the flow profile. Some degree of physical protection of the sensors is usually included. Figure 7 depicts two typical insertion type ITMF meters, each with a different mounting arrangement. Other types include compression fittings, packing gland, sanitary and ultra high-purity fittings.



Flanged type

**Figure 7 — Typical insertion-ITMF meter designs**



The location of the sensors within the cross-section of the conduit is crucial for optimum performance (see 6.5). If the sensors cannot be installed in accordance with manufacturer's recommendations, then further adjustments are necessary. Certain insertion-TMF-meter designs permit sensor location adjustment within the conduit so as to easily optimize installation.

The installation of the insertion-ITMF meter into an existing conduit is made possible by means of an adapter welded to the external surface of the conduit. (The weld quality is to be in compliance with safety requirements.) The insertion-ITMF meter is to be installed in the conduit using this adapter. The fitting connection of the adapter is to match that on the insertion probe.

### 6.2.4 Multi-point insertion-ITMF meter

A special version of the insertion-ITMF meter exists that consists of multiple sets of flowrate-measuring sensors, each functioning in the same way as those of a single-point insertion sensor. Multiple sets of sensors are arranged along the length of the insertion probe, allowing the flowrate to be measured at several points across the conduit cross-section. The secondary device inputs the individual sensor measurements and calculates the average gas mass flowrate in the conduit.

This multi-point measurement technique reduces the effect of error due to non-uniform flow profiles created by upstream flow disturbances.

This type of device is generally used in conduit sizes greater than 600 mm and ducts with a cross-sectional area of 0,4 $m^2$ and larger.

## 6.3 Applications and limitations of use

### 6.3.1 General remarks

This section outlines those factors that have a direct influence on the performance of an ITMF meter.

Equations (5) to (7) show that the calibration of the ITMF meter is dependent on the properties of the gas, therefore the ITMF is an *inferential* mass-flowrate meter. Although the ITMF meter responds to changes in mass flowrate, it is necessary to calibrate it with consideration to the type of gas and the actual operating conditions. All specifications of ITMF meters are normally given with reference to dry and clean gases. Therefore, any change in the gas properties after the initial calibration will affect the measuring performance.

### 6.3.2 Normalized volume flowrate units

The normalized volume flow output [$m^3$/h (normalized)] is numerically derived by dividing the measured mass flowrate value by the density of the gas at a specified reference pressure and temperature condition.

EXAMPLE For air, the normalized density at 0 °C and 101,325 kPa equals 1,293 kg/$m^3$, a mass flowrate of 12,93 kg/h equates to a normalized volume flowrate of 10 $m^3$/h (normalized) (12,93/1,293).

If normalized volume flowrate units are used, consider the following two points to avoid measurement errors:

— the reference temperature and pressure conditions shall be the same as those used for calibration;

— changes in gas mixture composition affect the gas density at its reference pressure and temperature conditions.

### 6.3.3 Fluid property effects

Variations in fluid properties which affect the thermal conductivity, specific heat and viscosity directly influence the performance of the TMF meter.

### 6.3.4 Temperature effects

The ITMF meter can be affected by temperature effects in a variety of ways as follows.

— Dynamic: If the gas temperature changes faster than the quoted temperature response time of the ITMF meter, then measuring errors will be introduced.

— Steady state: Changes in the gas properties caused by temperature changes may, depending on the type of gas, introduce zero and calibration errors. These changes can be corrected by zeroing the ITMF meter at the actual process temperature (for which this latter can normally be compensated in transmitter settings).

— Ambient: Changes in thermal losses through the meter body caused by extreme ambient temperature changes can lead to metering errors. The ITMF meter should be installed so as to avoid exposure to extreme effects and/or precautions taken, when necessary, to maintain a reasonably stable operating environment (e.g. thermal insulation of the meter and conduit).

### 6.3.5 Pressure effects

Changes in the gas properties caused by pressure changes may, depending on the type of gas and the magnitude of the change, introduce zero and calibration errors. The former can be corrected by zeroing the ITMF meter at the zero flowrate condition and at the actual process pressure (for which this latter can normally be compensated in transmitter settings).

### 6.3.6 Fluid phase

The operating process conditions should be controlled to ensure that no phase change occurs in the vicinity of the sensors. Such changes can have a major effect on the ITMF meter performance.

### 6.3.7 Bi-directional flow

ITMF meters are generally capable of measuring flows in either direction. However, they cannot distinguish the actual direction of flow without the use of additional sensors.

### 6.3.8 Pulsation effects

Pulsating flow can cause metering errors (typically the output is biased high), the extent of which depends on the pulsation magnitude and frequency. These effects can often be compensated by adapting transmitter settings.

### 6.3.9 Pressure loss

Depending on the blockage effect of the measuring sensors across the conduit cross-sectional area, a pressure loss can occur. For most ITMF meter designs, this is equivalent to the pressure loss developed through a short length of undisturbed conduit. Such a loss is generally very small, in the order of only a few hectopascals (a few millibars), however, it can be higher depending on the conduit size, meter style and process conditions.

### 6.3.10 Sensor contamination

Settlement of solids, coating or trapped condensate may affect the meter performance.

### 6.3.11 Mounting orientation effects

For most flowrates, the performance of an ITMF meter is not affected by the orientation of the installation. Nonetheless, good installation practice and any specific manufacturer's guidelines should be followed.

At low flowrates, depending on the meter design, orientation can become important due to natural convective heat flows within the conduit. The manufacturer's guidance should be sought if accurate measurement at low and very low flows is required.

### 6.3.12 Installation effects

ITMF meters are affected by distortions to the flow profile and/or swirl in the gas stream. At all times, good installation practice shall be followed to avoid metering errors. A specified, undisturbed, constant-diameter-conduit length upstream and downstream of the flowmeter is always required. The manufacturer normally specifies this length as a number of conduit diameters ($D$). This length is dependent on the type of disturbance present upstream of the flowmeter (e.g. single or complex bend, reducer, expander, valve, etc.). Any specified recommendations should be considered as a *minimum* recommendation, especially where a combination of upstream disturbances are present and/or very light gases are concerned (e.g. hydrogen, helium).

EXAMPLE For a 150 mm diameter conduit, a typical upstream, undisturbed conduit requirement for a single 90° bend may be 20 $D$, thus equating to 3 000 mm.

Within this specified undisturbed length of the installed conduit, the following considerations should be made.

— The installed conduit should have clean, welded connections (both conduit and flange).

— A seamless conduit should be used immediately upstream of the flowmeter.

— The installed conduit should be correctly aligned with conduit flanges or process fittings.

— The installed conduit should have correctly fitted process seals and/or gaskets that do not intrude into the flow area.

— Whenever possible, the control valves should be installed *downstream* of the flowmeter.

If in doubt, consider the use of a flow-conditioning device to minimize the effects from any disturbance. Some ITMF-meter designs optionally have integrated flow conditioners.

#### 6.3.13 Conduit vibrations

Conduit vibrations normally have no effect on the performance of the ITMF meter, however the conditions of use should be within the limits of common practice. Ensure that any vibration present does not damage the instrument. The insertion-ITMF meter should be rigidly attached to the conduit wall to prevent resonance.

### 6.4 Meter selection

#### 6.4.1 General

The principal requirement of the metering system is that it shall measure the gas mass flowrate with the specified uncertainty. Consideration shall be given to the points given in 6.4.2 to 6.4.7 for choosing the most suitable meter.

#### 6.4.2 Performance specifications

The following performance specifications shall be taken into account:

— uncertainty:

  — compliance of the actual installation and operating conditions with the manufacturer's data;

  — calibration procedure used and traceability of calibration equipment;

— repeatability;

— rangeability;

— stability;

— temperature effect;

— pressure effect;

— rangeability;

— turndown ratio;

— sensor-response time;

— pressure loss at the maximum flowrate.



### 6.4.3 Physical specifications

The following physical specifications shall be taken into account:

- the space required (e.g. meter dimensions, upstream, downstream conduit diameters) for installation of the flowmeter, including provision for *in-situ* calibration-checking/calibration, retractor mechanism if desired and possible;
- the class and type of conduit connections;
- the compatibility of materials;
- any non-destructive testing procedures;
- the hazardous area classification;
- the climatic and environmental influences;
- any applicable national or international requirements.

### 6.4.4 Meter ratings

The following meter ratings shall be taken into account:

- the maximum allowable process pressure;
- the ambient and process-gas temperature.

### 6.4.5 Application and fluid properties

The following application and fluid properties shall be taken into account:

- the operating flowrates;
- the properties of the metered gas, including the gas type or composition of the gas mixture;
- the range of process pressure;
- the range of process temperature;
- the reference process conditions if normalized volume units of flowrate are to be used [$m^3/h$ (normalized), l/min (normalized)].

### 6.4.6 Corrosion

Corrosion, including galvanic corrosion of the wetted materials, can adversely affect the performance and useful operating life of the ITMF meter. Care shall be taken when selecting the materials of construction to ensure that the process gas, including purge or cleaning fluids are compatible. All process-wetted materials shall be specified.

### 6.4.7 Transmitter specifications

The following transmitter specifications shall be taken into account:

- electrical, electronic, climatic and safety compatibility;
- required signal output options;
- input power requirements.

## 6.5 Installation and commissioning

### 6.5.1 General considerations

ITMF meters are adversely affected by distortions to the flow profile and/or swirl in the gas stream. At all times, good installation practice shall be followed to avoid metering errors. The recommendations given in 6.3.12 should be followed (see Figure 8) to ensure good installation practice. For optimum performance:

— the ITMF meter should be installed where the process conditions (temperature and pressure) and ambient conditions are most stable;

— the use of a flow-conditioning device should always be considered;

— consideration should be given to providing a means of *in-situ* calibration verification.

### 6.5.2 Cleaning

For certain applications (e.g. hygienic services), provision should be made to clean the ITMF meter sensor *in situ*. Cleaning can be accomplished by:

— sterilization (steam-in-place; SIP);

— chemical or biological cleaning (clean-in-place; CIP).

During the cleaning process, the ITMF meter measurement is inoperative. Care should be taken to avoid cross-contamination after cleaning fluids have been used.

### 6.5.3 Safety

Consideration should be given to the following points on safety.

— The operation of the meter shall be limited to process conditions which remain within the meter's specifications.

— Meters shall comply with any necessary hazardous area classifications as well as all applicable national or international requirements.

— The possibility of sensor damage by impact from solids in the gas stream, with a consequential breakdown in the sensor sealing and release of gas, shall be considered. If appropriate to the application, the primary device design should provide for a secondary gas-tight seal if a sensor or seal fails.

— Only appropriately qualified and trained personnel shall install, operate and/or maintain the meter.



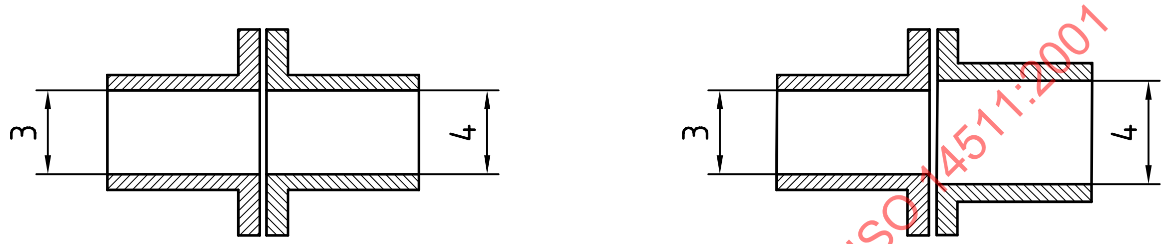
### 6.5.4 Mechanical stress

Consideration should be given to the following points on mechanical stress.

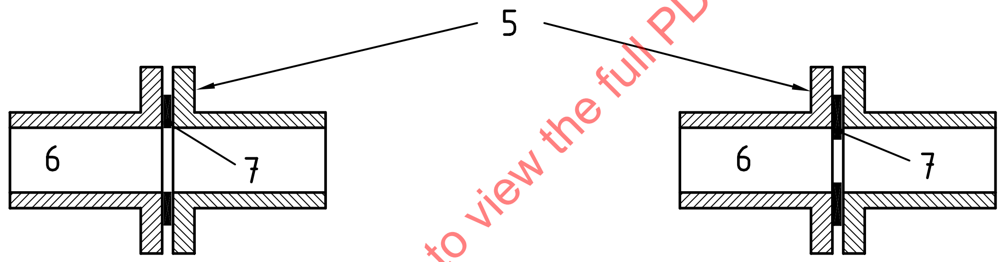
— The meter should be selected to withstand temperature, pressure and conduit vibration. Meters should be pressure-tested with a suitable fluid in accordance with the appropriate standard.

— To ensure leak-tightness in critical applications, the meter should be tested with helium gas in accordance with an appropriate standard.

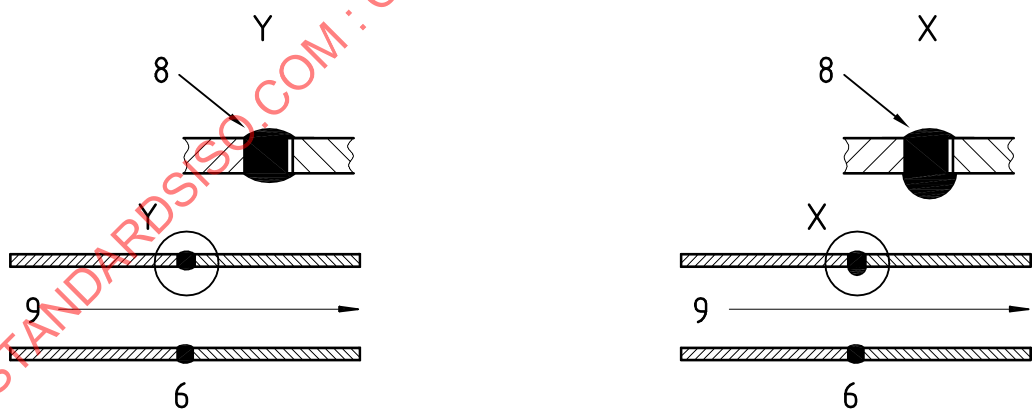

**a) Flow body and conduit alignment (view down conduit length)**




**b) Flow-body internal diameter and conduit matching**




**c) Gasket / seal alignment**




**d) Weld quality**

**Key**

1 Conduit diameter
2 In-line ITMF-body internal diameter
3 Conduit diameter 1
4 Conduit diameter 2
5 Process fitting
6 Conduit
7 Gasket and/or seal
8 Welded joint
9 Flowing gas

**Figure 8 — ITMF Installation: good and bad practices**

### 6.5.5 Process conditions

#### 6.5.5.1 General

If the operating conditions are not in compliance with the meter's calibrated configuration, additional adjustment may be required.

#### 6.5.5.2 Zero adjustment

Once the meter's installation has been completed and checked for compliance with all of the manufacturer's specified recommendations and statutory requirements, a zero adjustment procedure for the operating process conditions may be necessary with certain process gases so as to compensate for the effects described in 6.3.

It is essential that this procedure be carried out at the actual process temperature and pressure conditions. These conditions should be stable and there should be absolutely no gas flowrate.

Depending on the gas or the nature of the application, it may be desirable to repeat this operation at regular intervals.

#### 6.5.5.3 Span adjustment

ITMF meters are normally calibrated with respect to the actual process conditions. However, if the latter are different than the calibration conditions or if the gas type or quality is different from that specified for the calibration, a span adjustment may be required. This can only be carried out if the installation provides the means of obtaining a reference flowrate value for comparison with the ITMF meter reading (see clause 8). It is essential that this procedure be carried out at the actual process temperature and pressure conditions. These conditions and the actual flow should be stable during any span adjustment procedure. Depending on the gas or the nature of the application, it may be desirable to repeat this operation at regular intervals.

## 7 Instrument specification sheet and marking

### 7.1 User specification sheet

For a manufacturer to specify a TMF meter's suitability for an application, the requirements and additional minimum information given in Table 2 shall be supplied by the user.

### 7.2 Manufacturer's data sheet

The information given in Table 3 shall be provided by the manufacturer when specifying a TMF meter as well as any information for non-compliance with the user's specified requirements.