D1.1

SoA of measuring devices installed in NG transmission and distribution networks

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Clean Hydrogen Partnership

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TECHNICAL REFERENCES

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1	04/08/2023	Review	UNIBO, Enagás, GRTGAZ, GS, INRETE, SNAM, FBK
2	08/08/2023	Correction of figures' caption	UNIBO

TABLE OF CONTENT

TERMINOLOGY

Class 1 meter: Meter which has an error of indication between [-2%, +2%] for flow rates between the minimum flowrate (Q_{min}) and the transitional flowrate (Q_t) and between [-1%, +1%] for flow rates between the Q_t and the maximum flowrate (Q_{max}). When the errors between Q_t and Q_{max} have the same sign, they do all not exceed 0,5 %.

DN: The nominal diameter (symbol DN) is a conventional value with which hydraulic components such as pipes, flanges, valves are identified.

Error of indication (E): Expressed as percentage, it results from the measured volume of the meter (V_I) minus the reference value of the measurand (V_C) divided by the latter value. The error of indication is calculated as reported in Eq. (a1):

$$\mathrm{E} = \frac{\mathrm{V}_I - V_C}{V_C} \quad \text{(a1}$$

G: It indicates the size of the gas meters. It indicates the nominal gas flow rate through the meter in SCMH (standard cubic meters per hour). Discrete values for G exists and differ for the minimum, the maximum and transitional volumetric flow rate.

Linearity: it is the ability of the meter to respond to changes in a measured variable in the same way across the full range.

Maximum flowrate (Q_{max}): The maximum flowrate is the highest flowrate at which the gas meter provides indications that satisfy the requirements regarding the maximum permissible error (MPE).

Minimum flowrate (Q_{min}): The minimum flowrate is the smallest flowrate at which the gas meter provides indications that satisfy the requirements regarding the MPE.

PN: It represents the nominal pressure of the component, i.e., the maximum pressure (expressed in bar) to which the component withstands without a failure.

Rangeability: The ratio between the minimum flowrate (Q_{min}) and the maximum flowrate (Q_{max}), for which the meter performs within the maximum permissible errors.

Repeatability: The property that the application of the same measurand under the same conditions of measurement shall result in the close agreement of successive measurements.

Resolution: The smallest difference between indications of a meter that can be meaningfully distinguished

Transitional flowrate (Q_t): The transitional flowrate is the flowrate occurring between the maximum and minimum flowrates at which the flowrate range is divided into two zones, the ‘upper zone’ and the ‘lower zone.

More terminology is found in the relevant technical standards cited in the document.

ACRONYMS

Acronym	**Definition**
ACER	European Union Agency for the Cooperation of Energy Regulators
AGA	American Gas Association
CCA	Constant Current Anemometer
CTA	Constant Temperature Anemometer
DN	Nominal Diameter
DSO	Distribution System Operator
E	Error of Indication
EVC	Electronic Volume Converters
G	Meter size
GERG	Groupe Européen de Recherches Gazières
H2	Hydrogen
HF	High Frequency
ISO	International Organization for Standardization
LCD	Liquid Crystal Display
LF	Low frequency
LRV	Lower Range Value
MEMS	Micro-electromechanical systems
Mid IR	Mid-infrared
MOS	Metal-Oxide-Semiconductor
MPE	Maximum Permissible Error
MID	Measuring Instruments Directive
NDIR	Non-dispersive infrared
NTC	Negative Temperature Coefficient
P	Pressure
PN	Nominal Pressure
ppb	Part per billion
ppm	Part per million
Pt	Platinum
PT	Pressure and Temperature
PTC	Positive Temperature Coefficient
PTZ	Pressure, Temperature and compression factor
RTD	Resistance Thermometer Detectors
Q_{max}	Maximum flow rate
Q_{min}	Minimum flow rate
Q_t	Transitional flow rate
SoS	Speed of Sound

T	Temperature
TDLAS	Tunable Diode Laser Absorption Spectrometers
TSO	Transmission System Operator
URV	Upper Range Value
WME	Weighted Mean Error

The extended name of the THOTH2 partners is reported in the Deliverable D1.1 as indicated in Table 1.

Table 1. Partners' extended name, country and acronym.

Partner extended name (country)	Acronym
SNAM S.P.A. (ITALY)	**SNAM**
ALMA MATER STUDIORUM - UNIVERSITA DI BOLOGNA (ITALY)	**UNIBO**
LE GROUPE EUROPEEN DE RECHERCHES GAZIERES (BELGIUM)	**GERG**
OPERATOR GAZOCIAGOW PRZESYLOWYCH GAZ-SYSTEM SPOLKA AKCYJNA (POLAND)	**GS**
GRTGAZ (FRANCE)	**GRTGAZ**
INSTYTUT NAFTY I GAZU - PANSTWOWY INSTYTUT BADAWCZY (POLAND)	**INIG**
ENAGAS TRANSPORTE SA (SPAIN)	**ENAGAS**
FONDAZIONE BRUNO KESSLER (ITALY)	**FBK**
EIDGENOSSISCHES INSTITUT FUR METROLOGIE METAS (SWITZERLAND)	**METAS**
INRETE DISTRIBUZIONE ENERGIA S.P.A. (ITALY)	**INRETE**
CESAME-EXADEBIT SA (FRANCE)	**CESAME**
AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE (ITALY)	**ENEA**
ISTITUTO NAZIONALE DI RICERCA METROLOGICA (ITALY)	**INRIM**

1. EXECUTIVE SUMMARY

Transporting green hydrogen into existing gas assets requires carefully assessing its effect on the existing components. Since several projects have already been completed or have planned research activities to answer still-existing technical questions, the THOTH2 project focuses on the existing measuring devices. Specifically, the focus of the project regards the identification of the existing gaps in normative standards and the suggestions for solutions to cover them (if any). To contribute the hydrogen readiness of the existing gas transport and distribution infrastructures, new methodologies and protocols have to be developed to perform validated tests for metering devices. Suggestions on the need to change the standards or develop new ones will be based on the results of these experimental tests. Despite the simplicity of the methodological approach, it would be very critical when applying it to measuring devices. Several technologies are available in the market to measure gas properties. Furthermore, the operators can select more than one configuration based on the expected field conditions.

Since limited resources are available, testing all the possible configurations would be impossible. Prioritization is required. Task 1.1 aims to collect all the information to provide a clear overview of the measuring devices installed in the existing gas assets. Specifically, this document includes the state of the art of measuring devices installed in gas assets. Different technologies are available to measure gas parameters. For example, turbine, rotary piston, ultrasonic, diaphragm, thermal mass, orifice, and Coriolis meters are available to measure flow rate. These technologies differ not only for the operating principle but also for the material used, the size available on the market, and the effect that different conditions could have on the metrological performances like, for example, overload conditions, flow rate pulsations, leakages through the clearance and pressure drops. Furthermore, different maintenance activities are usually expected, resulting in different operative costs throughout the lifetime. To date, turbine, rotary piston gas, and ultrasonic meters are used for fiscal gas metering in transmission networks. Specifically, based on the data collected, turbine gas meters are the most installed technologies for medium to high flow rate, followed by rotary piston and ultrasonic (for high flow rate). Few cases of use of Coriolis meters have been found. Regarding distribution, a different situation results. Despite the fact that few answers have been received to date, and only from Italy, it appears that diaphragm gas meters are the prevailing technology installed, even if a greater penetration is expected for thermal mass meters. THOTH2 also includes other measurements like gas quality by chromatographs, pressure and temperature, and trace water dew point. Regarding temperature, it was assumed that since the sensor is not in contact with the fluid but is protected by the thermowell, it can be assumed that no problem would arise. However, further investigation should be performed to investigate if any effect of hydrogen on response time exists. Regarding pressure measurement, many models are commercially available, but attention should be given to the effect of hydrogen on the material with which the fluid is in contact. Specifically, identifying critical materials that can be affected by hydrogen among those available in commercial products should be the next step to identifying the products to be tested. Gas chromatographs are also present in different models and configurations in the existing networks. Usually, different columns are used based on the specific analysis to be performed. Even if the range of the concentration allowed for each molecule is usually known for each model, more details about the configuration of each gas chromatograph are needed to complete the analysis and check the capability to handle hydrogen. Only some models of trace water sensors have been identified in the investigated networks. Specifically, impedance sensors result in the most implemented devices. Other devices are also typically used in the networks. Electronic Volume Converters and Flow Computers convert measurements into standardized gas volumes for fiscal purposes. The main issues to be investigated are the implemented algorithms and their capability to consider hydrogen. The main algorithms are AGA8, SGERG, and AGA-NX19, and the Operators can check the hydrogen limits. The main issue is that many different models are installed in gas transmission and distribution networks. Furthermore, based on the conclusion about pressure and temperature sensors, the potential effects of hydrogen on the metrological performances of those devices that have these sensors integrated have to be carefully assessed not to overcome the limits on errors provided by the standards. Last, leak detection is essential to detect fugitive emissions to the atmosphere and to minimize the risk of failures or accidents . To date, many devices are supplied to the technicians on the field to verify the presence of hazardous substances. Since different sensors can be implemented in the same devices to measure different quantities, attention should be given in Task 2.1 to selecting those sensors that, on the current knowledge, appear to be most critical when being in contact with hydrogen.

2. INTRODUCTION

Based on a factsheet of ACER, i.e., the European Union Agency for the Cooperation of Energy Regulators, almost one-quarter of the energy required by Europe is conveyed as natural gas [1], [2]. Natural gas is transported and distributed to the customers through more than 200,000 km and 2 billion km of transmission and distribution grids, respectively, and 20,000 compressor and pressure reduction stations. Based on the same report, the economic value of the total infrastructure investments can be estimated at around 65 billion euros in EU Transmission System Operators' regulated asset bases, while distribution assets add to that figure at least by a factor of 3. The European natural gas infrastructure is a strategic asset for ensuring energy security. Following the Russian-Ukraine war and the consequent energy crisis, more attention has been put on hydrogen. Following the European hydrogen strategy published in 2020, larger volumes of hydrogen are expected in the gas networks in the following years.

Natural gas infrastructure could support the energy transition to renewable. Intermitted and unforecastable renewable energy can be converted into hydrogen or gaseous e-fuels, and injected into the grid, partly substituting fossil natural gas. However, to date, some questions remain unsolved. Tezel and Hensgens (2021) [3] gave some answers about repurposing the existing gas assets and the impact of hydrogen injection on the main components. Concerning metering, no specific observation was performed, even if the economic impact for replacement or repurposing was assumed to be marginal compared to other components. That is, the impact of hydrogen in metering chain components is essential. Gas metering can be divided into two: fiscal metering and process metering. Fiscal metering ensures the calculation of correct billing, and it would minimize the total value of unaccounted-for gas that must be included in the gas network balancing equation to account for unavoidable measurement errors. Ensuring accurate, reproducible, and stable measurements with hydrogen and natural gas mixtures validated by rigorous and standardized methodologies also supports all the actions that the politics put in place to increase the social acceptability of renewable gases. Process metering includes fiscal measurements of the gas consumption in gas operators' plants but also process measurements for the correct and safe operation of the gas assets. Very complex control systems receive information from the measurement components installed into the field controlling and regulating the components like, for example, valves, compressors, etc. Poor control would result in at least a loss of performance. Furthermore, leak detectors are used to identify fugitive leaks and intervene before a hazardous situation occurs. The verification of the impact of hydrogen on leak detectors' detection performances is essential to ensure that safety performances are not affected or, on the other hand, put in place the proper actions.

Weldon Wright from CGI company identifies several challenges in measuring hydrogen and natural gas mixtures [4] and proper actions have to be performed to make hydrogen injection real:

- To systematically review standards;
- To review analysis procedures and property calculations since many data do not include merchantable concentrations of H2;
- To perform a complete inventory of the field metering components to verify the effect of hydrogen and the actions required;
- The verification of field operation protocols and their updating when necessary;
- The preparation of training processes to inform field operators on the effect of hydrogen.

That is, many projects have already been performed trying to answer the question regarding the metrological effect of hydrogen injection, including, for example, NewGasMet, Decarb , Met4h2 and Mefhysto projects [5]–[8], and many others reported in more detail in Deliverable D1.2 where a summary is reported. The present report fits this framework and answers which measuring component is installed in the gas transmission and distribution grids. Therefore, the report is structured as follows:

- Chapter 3 proposes a review of the main measuring equipment installed in the networks. This section aims to give technical information on the operation and the characteristics of measuring devices to those who are not experts in the field and enter on it for the first time.
- Chapter 4 proposes a schematic overview of the measuring devices installed in the investigated TSOs assets in Italy, Poland, France, and Spain. For privacy and safety motivations, the reported data are anonymized. The same was proposed for two Italian DSOs.
- Chapter 5 gives the conclusions and recommendations for future activities and the connected THOTH2 tasks.

3. NATURAL GAS MEASURING DEVICES: STATE OF THE ART

3.1. Gas meters

Several technologies are commercially available to measure flow rate and total flow. Focusing on measurement in closed pipes, two main categories can be identified: totalizers and flow rate meters (Figure 1). The totalizers are divided into direct and indirect volume totalizers. In the first category (displacement meters), the fluid, a gas or a liquid, fills a known and limited volume. Once the volume is filled, the fluid is isolated and moves towards the outlet of the meters, thanks to the difference in pressure between the inlet and the outlet where it is discharged. This category includes rotary piston and diaphragm (also called bellows) gas meters. The second category, instead, hasn't closed volume chambers but works mechanically or electrically with pulses proportional to the volume that passes through the meter. An example of this category is turbine gas meters.

Flow-rate meters instead measure the volumetric or the mass flow rate using correlations, byan input for the calculation parameters like the fluid velocity or other fluid properties like the kinetic energy. Some examples of volumetric flowmeters are orifice, and gas ultrasonic meters, while for mass flowmeters, typical technologies are Coriolis and mass thermal meters.

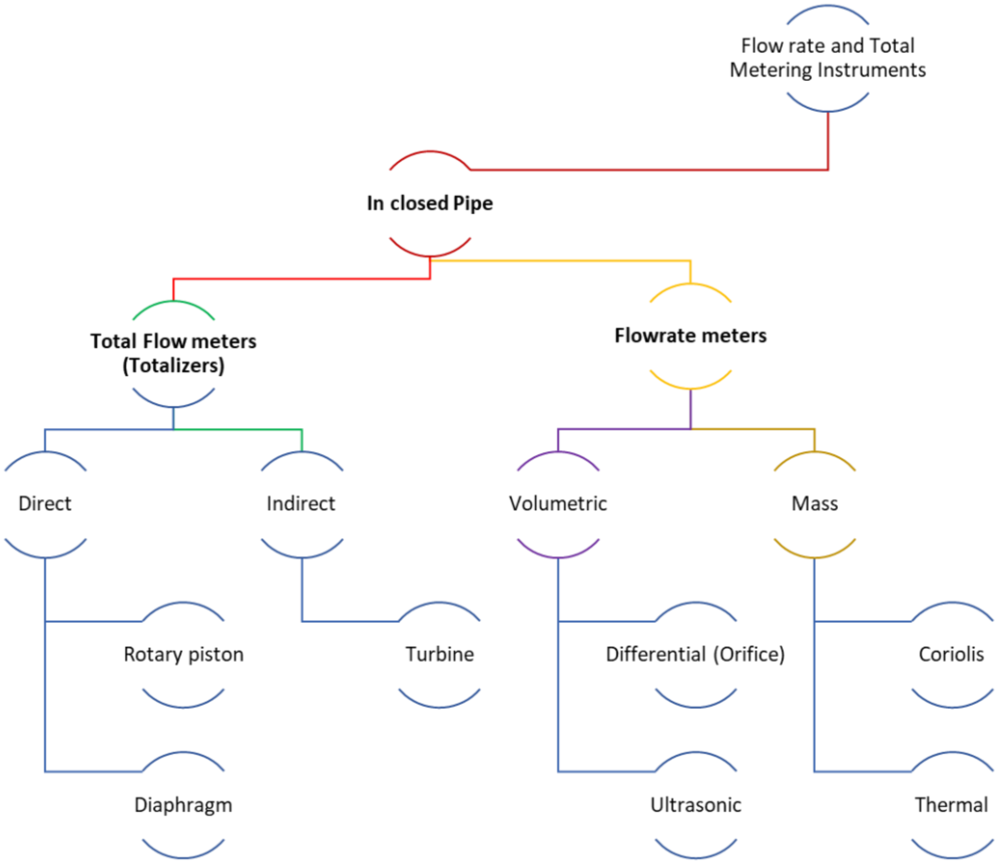


Figure 1. Gas meters' technologies installed and operated in gas TSOs and DSOs grids.

The following sections report the main characteristics of the gas meters installed in gas transmission and distribution networks. At the end of each section, the role of each technology in the grid of the THOTH2 industrial partners is also reported.

3.1.1. Turbine gas meters

Principles of operation

Turbine meters have been commonly used to measure fluid flowrate for several years thanks to their accurate measurement that covers a large flow rate and pressure range. Turbine meters are interferential devices, e.g., measuring devices that do not directly measure the volume, velocity or mass but measure the flow by inferring the value from other parameters that are measured. The first concept of design and realization of a multiblade fan are dated 1790 by the German hydraulic engineer Reinhard Woltmann to measure flowing air and water [5], the origin of the current configuration can be dated at the end of the 1930s for airborne refilling applications.
Focusing to the operating principle, turbine meters consist of a bladed rotor that rotate because of the flow in the measuring chamber [6], [7]. As reported by Baker [6], the rotor design is conceived to realize the minimum disturbances to the incurring flow. However, in practice drag forces appear slightly retard its rotation affecting the metrological performances of the meter, and more specifically the relationship between the volume of fluid that pass through and each rotor revolution, e.g., the linearity. In fact, in ideal condition the number of revolutions would be directly proportional to the flowrate. On the other hand, aerodynamic drag forces appear on the blades, the hub, the faces of the rotor and the tip, but also friction losses on bearings and magnetic drag caused by the means by which the rotation is measured affecting the resulting linearity. That is, the fluid entering the meter is directed through an inlet straightener to the rotor where it encounters the blades triggering the rotation. Higher are the velocity or the pressure or both, better are the metrological performances because of the increase of the driving force that is counteracted by the drag forces previously described. The rotor movement is transferred to the shaft that is supported by lubricated bearings within the measurement chamber and to the counting mechanism (totaliser unit) for the measurement of the volume of gas.

To explain the principle of operation of gas turbine meters, a simplification is made in the description of the following basic equations. Specifically, flat section blades are assumed. The axial velocity of flow that encounters the blades, v_a is written in accordance with Eq. (1):

$$v_a = \frac{W}{\tan\beta} \qquad (1$$

Where:

W is the velocity of the blades
β is the blade angle that in the models commercially available is usually 30° or 45° [8]. It has to be noted that the smaller value ensures larger capacity since a lower velocity of rotation is required to elaborate the same flow rate. This design assures lower loads on the components minimizing the risk of failure and increasing the expected service life.

While the frequency of blade passing, f, is calculated with Eq. (2):

$$\mathrm{f} = \mathrm{N} \times \tan\beta \times \frac{\mathrm{v_z}}{2\pi \mathrm{r}} \quad (2$$

Where:

N is the number of blades in the rotor. Typical values of commercial meters are 16, 20 and 24 blades depending on the size.
r is the radius of the blades where the axial velocity v_a is calculated.

In ideal condition, assuming a perfect linearity between the flowrate Q and the number of pulses measured in the unit of time, i.e., the frequency of blade passing, Eq. (3) is written:

$$\mathrm{f} = \mathrm{K} \times \mathrm{Q} \quad (3$$

Where:

K is the so called "meter constant" usually indicated in the datasheets in pulses per unit of volume. Since nonlinearity affects the response of the meter, some Authors investigated the problem in the past [9], [10] proposing a correction in Eq. (4) where terms referring to viscosity and leakages (a_1) and total torque (a_2) were introduced:

$$\mathrm{f} = \mathrm{Q} \times \left(K + \frac{a_1}{Q} + \frac{a_2}{Q^2}\right) \quad (4$$

More details about the calculation of K factor are described by Chunling et al. (2003) [11].

The design and the main components of commercial turbine gas meters

Compared to liquid meter turbines, gas design is characterized by a large hub and, consequently a smaller flow passage. This design configuration is justified by the need to transmit to the turbine blades the maximum torque by moving the fluid at the maximum radius and velocity as possible. Examples of modern commercial gas turbine are shown in Figure 2 and Figure 3 for the iM-TM model manufactured by Pietro Fiorentini S.p.A., the CGT-02 model manufactured by Common is reported in Figure 4 and Figure 5. The commercial products consist of a main body that supports the load deriving from the gas pressure and the installation stresses coming from the pipe. For example, the EN 12261-2018 [12] suggests using selected value for pressure rating (i.e., PN10, PN16, PN20, PN25, PN40, PN50, PN100, PN150, PN250, PN420). However, the majority of those models used in the gas transmission and distribution sectors indicates a pressure rating up to PN100. Based on the pressure rating, different materials are used by the manufacturers. Typical materials for the body are ductile iron or steel in order of increasing pressure, even if hard anodized aluminium is used for low pressure rating configuration (up to PN16). Regarding the size, a maximum flowrate up to 25.000 m3/h (G16000) can be measured. Nominal diameter depends both on the size of the meter (G) and the allowed gas velocity. For example, three nominal diameters (DN) are available for G100 gas meters (i.e., maximum flowrate equal to 160 m^3/h), i.e., DN50, DN80 and DN100. The complete list of authorized configurations is reported in ISO 12261-2018 [12]. The measurement assembly is included in the main body. Notably, a flow straightener is positioned upstream of the rotor to ensure fluid encounters the blades with the right angle eliminating any undesirable swirl and asymmetry. Typical materials used for the rotor are aluminium (usually for size larger than DN150), polyacetal-Delrin and less frequently stainless steel [6] while the bearings and the main shaft are realized in stainless steel. Also, a gear system reduces and transfers the rotational motion of the rotor to a magnetic coupling with a gas-tight partition that transmits the movement to the counter assembly, which is outside the zone where gas is flowing. Therefore, the components allow to transfer the rotation from a pressurized zone to a non-pressurized zone. The index assembly furtherly reduces the rotational velocity. This assembly aims to move the mechanical counter and the components that induce the low-frequency electric signal emitters. Lastly, a lubrication system is also present to ensure the correct oil lubrication of the rotor bearings as indicated in the maintenance manual by the manufacturers. However, different configurations are commercially available nowadays: maintenance-free models (no external lubrication required), requiring periodical external lubrication with or without a dedicated piston pump. In the case of no piston pump, a dedicated lubrication kit is usually provided by the manufacturer.

Regarding the redout devices and measurement outputs, commercial products usually include mechanical counter with electric signal outputs. The counter is positioned in the index assembly and is maintained visible by the operator through a transparent window (usually realized in polycarbonate) to allow the indication of the gas volume passed in the meter in cubic meters referred to the operative conditions. Therefore, the counter is a non-resettable and non-volatile indicating device. In some case, also a mechanical counter output can be requested to the manufacturer to drive external devices making attention to not overcome the specified maximum torque on the shaft of the connected devices.

As reported also electrical outputs come from the index. Turbine meters can be provided also of devices able to generate electrical pulses and are usually in the form of voltage free contacts or proximity switches. Specifically, two types of signals are usually present in commercial turbine meters both in pressurized and not pressurized zones: low frequency (LF) (1 to 10 pulses/revolution) and high frequency (HF) (in the range between 0.3 kHz and 4 kHz). Furthermore, the main body is configured with sockets to allow the measurement of the gas pressure and temperature. Specifically, the HF emitters can be positioned over the turbine rotor, over the shaft or over the reference wheel, i.e., a component that some models propose as optional to check the condition of the meter.

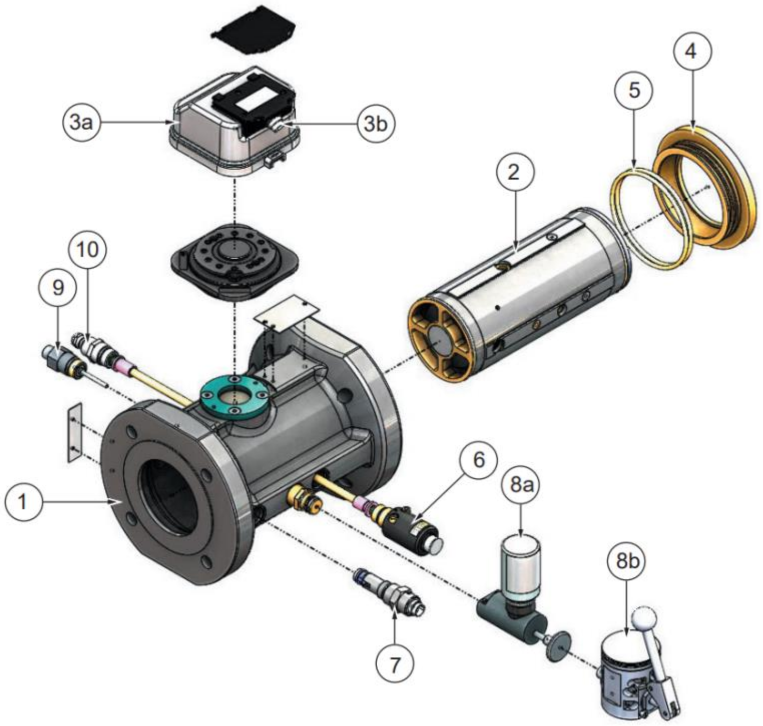


Figure 2. 3D Exploded drawing of a gas turbine meters, e.g., the iM-TM model produced by Pietro Fiorentini for NG or H2NG mixtures up to 20%vol. (1) Body; (2) Measuring cartridge; (3) Totalising group – a) totalise, b) LF connection; (4) Flange ring; 5) O-ring; (6) High frequency sensor on main shaft; (7) High frequency sensor on turbine wheel, (8) Lubrication system – a) piston oil pump; b) hand lever oil pump; (9) Pressure transmitter; (10) Temperature transmitter. Image from Pietro Fiorentini (2023) [13].

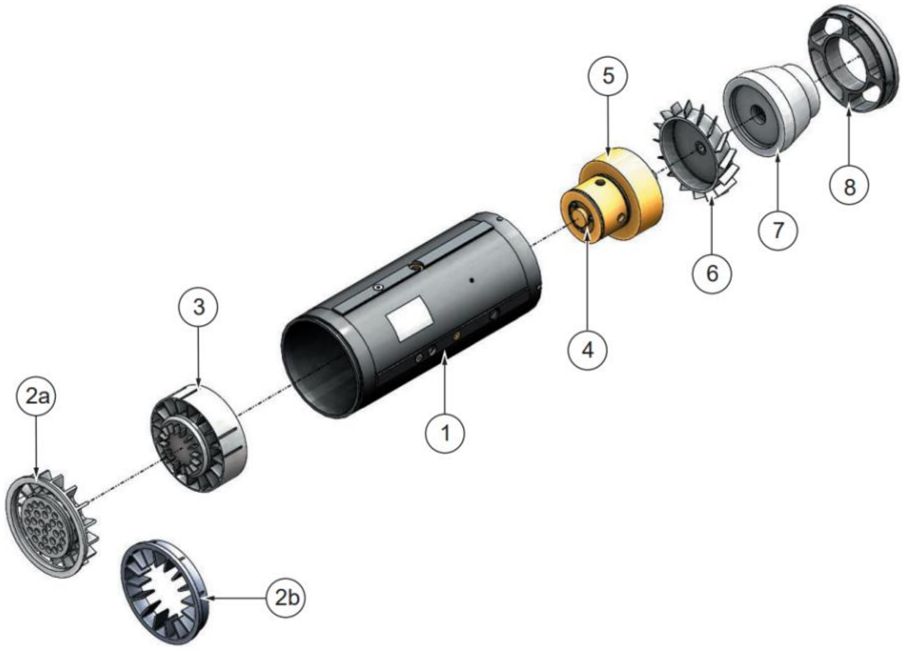


Figure 3. 3D Exploded drawing of a measuring cartridge in the iM-TM model produced by Pietro Fiorentini for NG or H2NG mixtures up to 20%vol. (1) Measuring chamber; (2) First rectifier– a) type 1, b) type 2; (3) Second rectifier; (4) Magnet for high frequency; (5) Bearing housing; (6) Turbine wheel; (7) Pressure compensation ring; (8) Third rectifier. Image from Pietro Fiorentini (2023) [13].

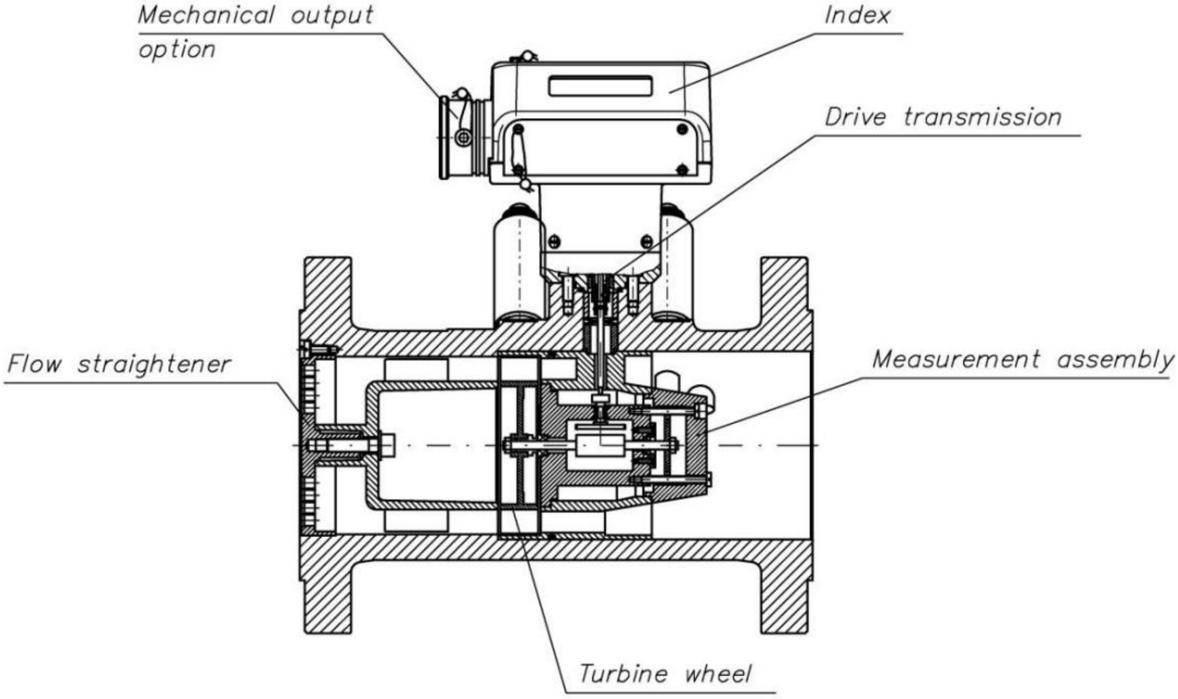


Figure 4. 2D drawing of a gas turbine meters, e.g., the CGT-02 model produced by Common. Image from Common (2018) [14].

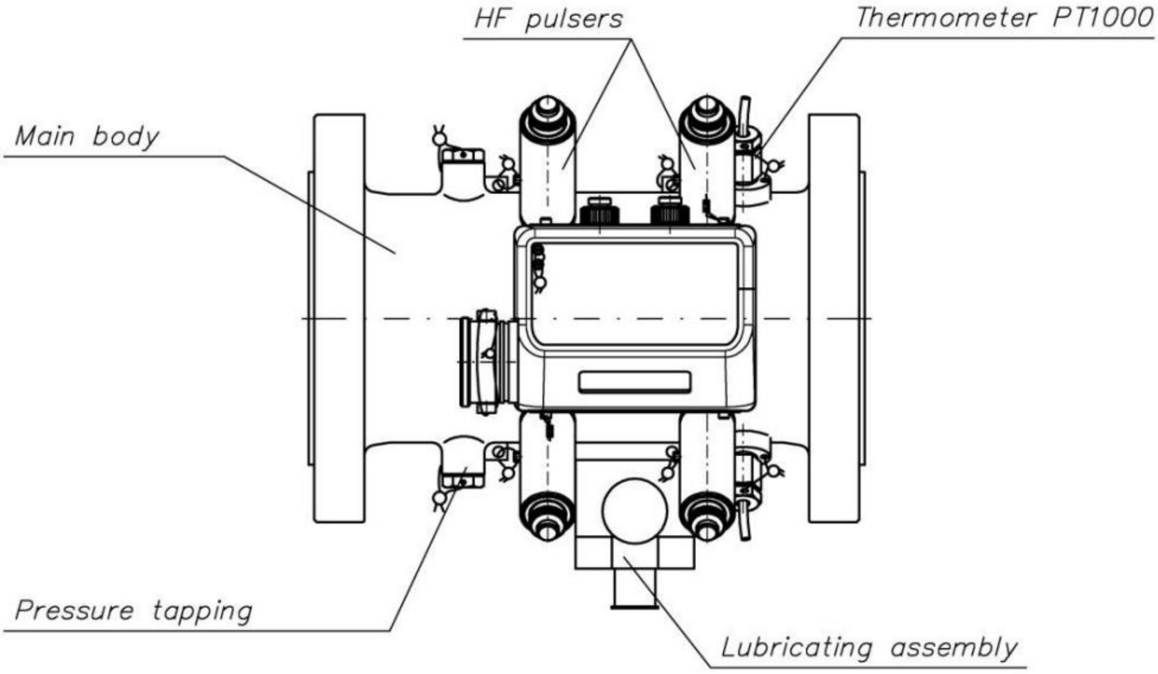


Figure 5. 2D drawing of a gas turbine meters, e.g., the CGT-02 model produced by Common. Image from Common (2018) [14]**.**

Metrological performances

Gas turbine meters are designed to satisfy the metrological performances indicated in the relevant sector technical standards and reports [12], [15], [16]. Several works have been published in the literature describing this technology's main characteristics. For example, Instromet published a complete description of the main features of gas turbine meters [17]. Specifically, the following measuring characteristics are indicated:

- **Measuring accuracy**. The measuring accuracy of gas turbine meters is usually reported by manufacturers in terms of error of indication. The products commercially available in the market ensure performances in line or better of Class 1,0 meter according to the Directive 2014/32/EU (MID) [18]. At low flowrate, the measuring error is mainly affected by friction. On the other hand, at higher flowrate the error of indication is affected by gas pressure since gas viscosity is almost constant for gases. For the same flowrate, a reduction of the error of indication is achieved increasing the gas operative pressure. This condition clearly affects also meter calibration procedures. As described by Ting et al. (1991) [19], on site calibration of turbine meters at operating conditions provides different results respect to factory calibration negatively affecting measurement accuracy. A model to predict the meters' performance at different pipeline operating pressure than those applied during calibration has been proposed by Blagojevic et al. (2021) [20].
- **Rangeability**. For commercial gas turbine meters, the rangeability is typically 1:20 at atmospheric pressure even if higher values, i.e., 1:30 and 1:50, can be achieved by increasing the operative pressure conditions and increasing the DN. The higher the density, the greater the range since more torque can be transferred to the rotor at a minimum flow rate, overcoming the existing drag frictional forces. The minimum flow rate that the meter can satisfactorily measure changes with the square root of the gas density, as reported in Eq. (5):

$$\mathrm{Q}_{min} = \mathrm{Q}_{min,0} \times \sqrt{\frac{\rho_0}{\rho_m}} \quad (5$$

  Where:

  $Q_{min,0}$ is the minimum flowrate at operative conditions
  ρ_0 is the density at reference condition
  ρ_m is the gas density at operative condition and Qmin

  This phenomenon has to be carefully evaluated when verifying the impact hydrogen injection in natural gas networks.
- **Repeatability**. Typical values for commercial gas turbine meters are 0.1% or better.
- **Linearity**. This feature is related to the proportional behaviour between rotor velocity and gas flowrate. Only some of the manufacturers of the meters installed in THOTH2 partners' grid declare in their datasheet the linearity of their model. However, ISO 12261-2018 [12] specifies the allowable differences between the highest and lowest error of indication at each test pressure as a function of the operative pressure (>4 barg or ≤4 barg) and the DN (>DN100 or ≤ DN100).
- **Stability**. Few data are available in the literature about gas turbine meters' stability. Van der Kam & De Jong (1994) [21] investigated the behavior over time of 240 meters installed in high-pressure networks (between 8 barg and 65 barg) by performing recalibration. As a result, the Authors could not identify clear trends between the recalibration interval and the shift of the weighted mean error (WME), suggesting good performances in terms of stability. Similar results were also found by Ting et al. (1991) [19] who performed a long-term

performance test of 18 months between a sales meter and a master meter founding a volume deviation between the two within -0.25% and +0.65%. In 2003, Saglam et al. [22] checked the presence of correlations between metrological performances and construction years of gas turbine meters operated by Gasunie. Meters were divided in different groups based on construction year, pressure class, size and maximum flow rate. Based on the data, they concluded that the drift decreases with increasing time intervals between calibrations.

- **Pressure drops (i.e., energy losses)**. Not recoverable energy losses are due to the pressure drops across the meter. Pressure drop measurement is standardized in ISO 12261-2018 [12]. The test consists of measuring pressure 1DN upstream and 1DN downstream of the meter using atmospheric air as the test medium. Pressure drops in field conditions can be calculated using the real density of the gas passing through the meter. In Figure 6 an example of commercial gas turbine meters produced by two manufacturers is shown. As shown, the pressure drop depends on the flow rate and on the nominal diameter selected.

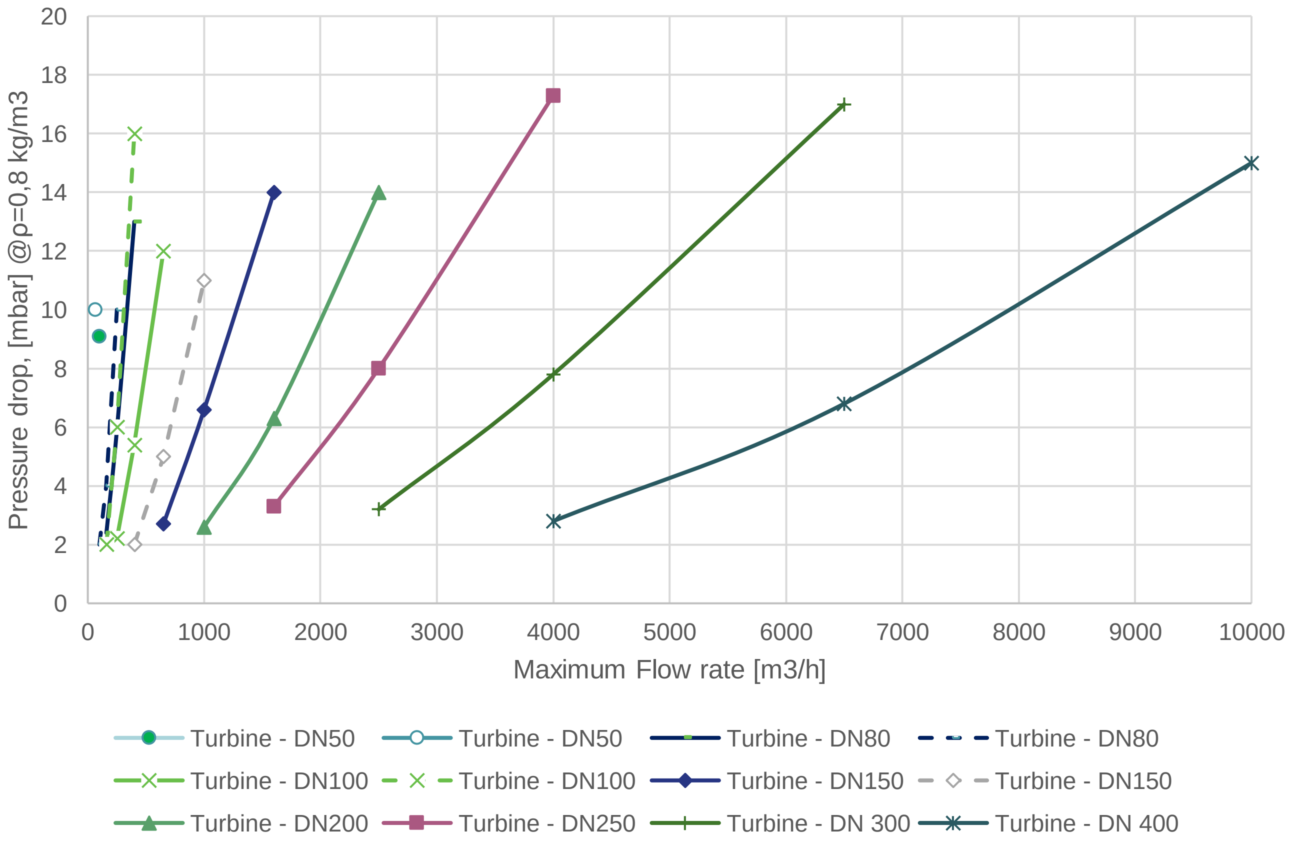


Figure 6. Example of pressure drops for two different models of turbine meters as a function of the maximum flowrate.

- **Influence of flow variations**. Many authors investigate the effect of intermittent flow on gas turbine meter performances. The governing equations to describe the transient phenomena occurring this type of meters can be found for example in Cheesewright et al. (1996) [23] and in [24]. Even if it is not in the scope of the deliverable to investigate the dynamic performance of gas turbine meters, it has to be noted that the turbine wheel experiences a delay in following rapid changes in flow rate because of its inertia. This behaviour is particularly critical when measuring significant and frequent variations in gas consumption. Cascetta & Rotondo (2015 [25] divided variable flows into intermittent and pulsating flows. The first occurs when the profile is rectangular, while the second type occurs with a sinusoidal profile. In intermittent flows, an overestimation of the true flow rate occurs due to the improper rotation of the turbine wheel. Specifically, the phenomenon worsens in the case of high mass moment rotor, ii) low gas density due to low gas pressure or the admixture of a low-density gas like hydrogen, iii) oversized meter selection and the iv) increase of the total number of on-off cycles resulting in an insufficient running time. Continuing the research started by other Authors, Cheesewright et al. (1996) [23] reports the results of site tests to verify the applicability of correction procedures to turbine flow meters when operating in pulsating flows to avoid over-registration so systematic errors. Tonkonogij et al. (2008) [26] tested the performances of three turbines of different sizes and materials in transitional flows to propose a new method for estimating turbine meter response and the measurement error based on the turbine time constant and independently on the pulsation characteristics. A technological solution to minimize the negative effect of flow variability was also investigated by Gacek and Jarowski (2020) [27]. The study focused on Polish gas stations' operation, but the conclusions can be directly extended to other countries. Significant fluctuations occur daily and seasonally, resulting in potential measurement errors when the flow rate is greater than the maximum or smaller than the minimum value. The authors not only proposed substituting the existing turbine with two turbines of different sizes to extend the existing rangeability of the station but also developed a new plant configuration, including an automatic control strategy to operate the two meters.

- **Overload operation**. Since hydrogen injection in the grid could increase the maximum flow rate to transport the same amount of energy, overload operation must be considered when operating a gas meter in the future gas grid. That is, overspeed is accepted by turbine gas meters for a limited time without damaging the rotor. Following ISO 12261-2018 [12], the meter has to be designed to allow overspeed operation of up to 120% of the maximum flow rate for 1 hour, ensuring that the error of indication after the period of overloading is still within the allowed range. Some of the manufacturers of the meters installed in the THOTH2 partners' grid enable them to operate at a higher flow rate. Specifically, one of the manufacturers indicates up to 160% of the maximum flow rate, even if no clear indication of the time is reported. Another manufacturer, instead, indicates up to 125% for 30 minutes. However, as reported by Gacek and Jaworski (2020) [27], no limit to the error of indication is given for overloading operations. Therefore, validated data about the deterioration of the measurement accuracy in overload operation still needs to be included.

Installation requirements

Most of the commercial turbine meters can be installed both in vertical or horizontal configurations without incurring in specific issues or instructions from the manufacturer. In addition, when the gas is free of liquids and dust, no filtration is needed. However, due to the large hub design, the turbine meters are sensitive to the flow profile that encounters the rotor. Therefore, the presence of obstacles or any other devices in the pipes that modify the fluid velocity profile could affect the measurement performances if not properly considered when installing the device. To evaluate the sensitivity of the meters respect to the installation conditions, standards tests are defined, for example, in the Annex B of the ISO 12261-2018 [12] and in Annex E of the ISO 9951:1993 [15], i.e., the low and the high-level perturbation tests. A "free" of straight pipe with a length of 2DN is realized upstream the meter is realized to verify the effect of perturbation and the respect of the metrological performances. In the case that the limits are not respected, the manufacturers have to indicate the additional straight pipe to be maintained or the need to adopt flow conditioners. Different provisions are reported in the

AGA 7-2006 [16] at least 10DN of straight pipe is recommended upstream in-line meters with a flow conditioner located at 5DN. A straight pipe with a minimum length of 5DN is also recommended downstream of the meter. Other installation configurations are also indicated by the AGA mentioned above 7, increasing the measurement uncertainty. For example, the short-coupled installation is shown for those cases where installation space is limited. In this case, at least 4DN of straight pipe with a flow conditioner outlet located at least 2DN of the turbine meters has to be ensured.

In the models installed in the THOTH2 partners' grids, a straight pipe of 2DN length is indicated even if maintaining up to 5DN is recommended to ensure the best metrological performances. On the other hand, no uniform indication appears for the downstream section. If manufacturers don't specify any length to maintain, others recommend keeping a straight pipe up to 3DN to minimize fluid dynamic disturbances.

Maintenance requirements

A lifespan of 25 years is expected for turbine gas meters [28]. To ensure good metrological performances proper maintenance and frequency of inspection has to be ensured in accordance with the indication of the manufacturer. Specifically, the main activities to be performed when operating a gas turbine meter are lubrication, internal inspection and spin testing. Lubrication of the bearings ensure to minimize friction drag caused by the rotation. For this purpose, different configurations are available in the market. While some models can be configured with permanently lubricated bearings, other require periodical lubrication that can be provided by dedicated kit or by special pump. Typical lubrication frequency is between 3-4 months even if the proper period has to be carefully evaluated based on the type of gas and the severity of the application. Each model has to be lubricated with specific oil indicated by the manufacturer.

In addition to oil lubrication, a meter inspection is usually recommended [15]. Common cause of troubles is quite known in the literature as presented by Bunyamin et al (2019) [29] where a general overview of the technology and of its main troubles, cause are reported. Specifically, the absence of visible damages, the accumulation of solids, erosion on the rotor blades, or debris in the internal part of the meter has to be checked. In addition, the presence of noise, the correct tightening of the connections, or the integrity of the connecting cables is performed during field checks. Since internal components are verified, the manufacturers' instructions must be carefully respected to avoid damage and ensure operator safety. Once completed the visual inspection the spin test should be performed. This test aims to evaluate the friction condition in the meter while no precise quantification of the metrological performances can be obtained. However, if the mechanical friction is observed to be significantly increased, the metrological performances of the meter at a low flow rate and pressure are assumed to be degraded. Meters' manufacturer defines the procedure to be respected when performing the spin test and how to elaborate the results. That is, the rotor is put in rotation by a finger or an air jet at a reasonable velocity, and the time required to come to a complete stop is measured and compared with the values provided by the manufacturers and with the one measured when firstly installed. Two possible results can occur. If the time has significantly changed, the metrological accuracy at a low flow rate can be assumed degraded and proper actions be put in place to restore correct working operation, reducing friction. However, other causes, besides friction, could result in unsatisfactory spin test results, such as heavily lubricated bearings, low ambient temperature, draughts, and attached accessories.

3.1.2. Rotary piston gas meters

Basic information

Rotary piston meters are very known in the gas sector from many years. A good overview of their working principle is reported by Schwarz [30]. Starting from 1846 when these measuring devices were designed for applications involving a liquid, their design was developed to manage also gases. Specifically, the first application where gas was treated is dated 1920. That is, the development of the rotary meters continues in the following years by improving, for example, the materials and the mechanical design aiming to minimize the clearance between the rotors and the housing and, so, the internal leakage. The most common and traditional gas rotary meters include two counter-rotating figure "8" shaped rotors called "impellers." The pressure difference between the inlet and outlet imposes a force responsible for rotating the rotors that are geared through external synchronization gears. The measuring operation is simplified in the schematization reported in Figure 7. As shown, four phases can be recognized. Starting from the left, a known gas volume enters in the meter. For this purpose, the entering gas volume is shown in red. In this first step, the gas volume is isolated between the lobs and the meter's body. In the second step (i.e., the second figure from the left), the gas volume starts to move downstream following the rotation of the rotor. In the same stage, the second rotor starts to trap another volume. The gas volume is discharged in the third and fourth steps, and another volume is entrapped to start the cycle again. Therefore, four defined volumes of gas are moved for each complete rotation.

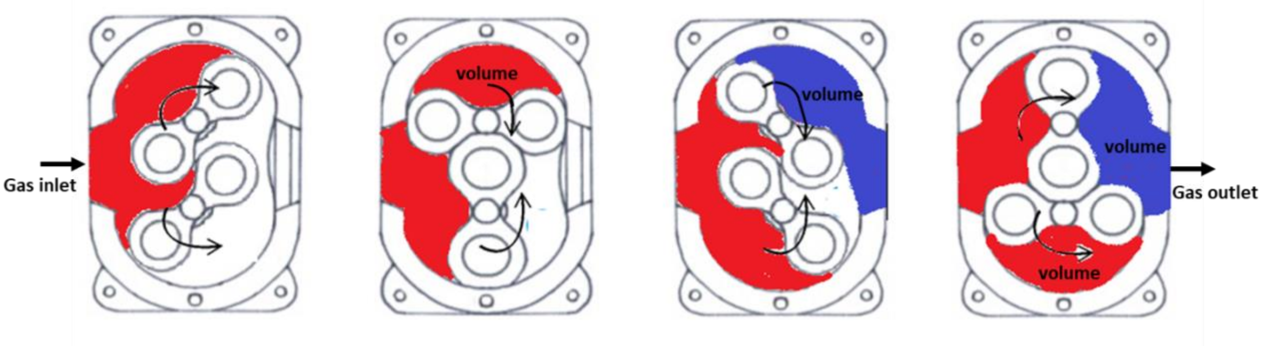


Figure 7. Schematization of the working principle of a rotary piston meter.

Also, leakage occurs through the necessary clearance paths to avoid friction, and so the increase of the pressure drops. Specifically, the leakage flow rate, Q_L, can be calculated through Eq. (6):

$$Q_L = A \times Q + \frac{C \times \Delta p \times h^3}{\mu} \qquad (6$$

Where:
A and C are constant that depend on the meter’s design.
Q is the meter flow rate.
h is the height of the clearance
Δp is the pressure drop over the gap.

µ is the gas viscosity that is 10.9 µPa x s for natural gas and 8.8 µPa x s for hydrogen at 20 C.

The first term is independent of the characteristics of the fluid and of the pressure difference, and it usually results in a small portion of the total leakage. It has to be highlighted that the pressure difference depends on the mechanical friction on the bearings and on the counter. In the second term, instead, these parameters play a crucial role. Therefore, since it is impossible to change the clearance design in existing meters, the impact of the mixture on the leakage and the error curve has to be carefully evaluated. Neglecting the first terms, the ratio between the leakages expected in case of pure hydrogen and methane is shown in Eq. (7):

$$\frac{Q_{L_{H2}}}{Q_{L_{CH4}}} \propto \frac{\mu_{H2}}{\mu_{H2}} = \frac{10.9}{8.8} = 1.24 \qquad (7$$

By transporting a less viscous fluid, theoretically, an increase of Q_L verifies resulting in a reduction of the meter's rangeability.

<u>The design and the main components of commercial gas turbines</u>

Commercial gas rotary piston meters' measuring range is typically included between G10 (Q_{max} = 16 m3/h) up to G1000 (Q_{max} = 1600 m3/h) by coupling two pairs of rotors in the same body. Therefore, rotary piston meters are preferred for medium flow-rate applications. The main components included in a rotary meter are shown in Figure 8. The EN 12480:2018 [31] defines the requirements to be satisfied when designing and manufacturing a gas rotary displacement meter. Typically, aluminium or cast/ductile iron is used for the meter's body medium pressure rating (PN25 / PN40), while steel is the preferred material for higher pressure (up to PN100). The measuring cartridge and the rotors are usually manufactured in aluminium, even if many manufacturers do not specify the material in public datasheets. Cyclic volumes depend on the specific design of the meter and depend on the size of the meter. Typical values for commercial products are in the range between 0.25 dm^3 up to over 5 dm^3 for the standard configuration. Bearings and shafts are usually manufactured in stainless steel to allow the rotation of the rotors at a velocity that for commercial products is between 700 up to 5700 rpm (at the maximum flowrate) depending on the size of the meter. Gas-wetted gears are preferably made in stainless steel, even if Delrin and other synthetic materials are alternatives.

The remaining elements have a role during operation and specifically for maintenance activities. As described in the dedicated section, the gas rotary piston requires lubrication. Therefore, a periodical inspection is necessary to assess and verify the correct oil level within the meter. For this purpose, an oil filler cap, oil level sight glass, and an oil drain plug are installed in the main body.

Lastly, an internal and automatic bypass to the outlet when the pressure drop exceeds a set value can be requested as optional. This solution would ensure the operator satisfies the demand even when damages occur to the meter.

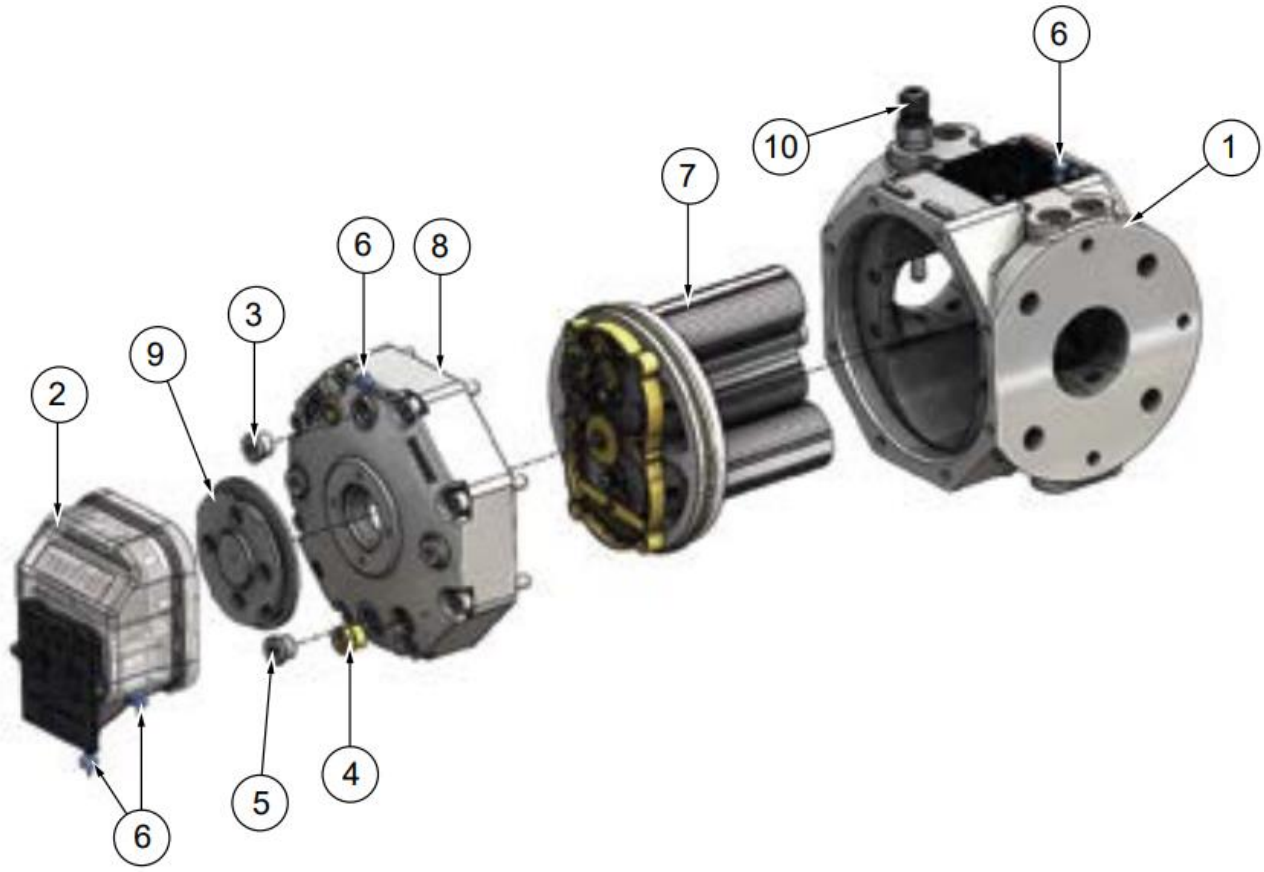


Figure 8. 3D Exploded drawing of the IM-RM rotary piston meter produced by Pietro Fiorentini for NG or H2NG mixtures up to 20%vol. (1) Body; (2) Totaliser group; (3) Oil filler cap; (4) Oil level sight glass; (5) Oil drain plug; (6) Metrological seals; (7) Measuring cartridge; (8) Cover; (9) Magnetic coupling; (10) Thermowell. Image from Pietro Fiorentini (2023) [32].

Rotary meter manufacturers can also provide a more complex meter configuration that ensures higher accuracy and reduced noise. Consisting of two pairs of rotors in the same body, the configuration overcomes the typical operative characteristic of the “8” shaped lobe impeller due to their operative principle, i.e., the flow pulsation. This phenomenon negatively affects the linearity of the calibration curve. Also, it can be responsible for harmonics that limit the achievable maximum flow rate as the pressure in the measuring chamber changes. The pulsation amplitude from the measurement cavity is proportional to the pressure drop across the meter and the rotating speed. In the other configuration, the flow is divided into two measuring chambers realizing cyclic volume up to 14 dm^3 in some commercial products. Furthermore, each pair of impellers is shifted by 45° resulting in a 180° shift in the sine wave, making the pulsation opposing and negligible.

Figure 9. 3D figure of the TWIN IM-RM rotary piston meter produced by Pietro Fiorentini for NG or H2NG mixtures up to 20%vol. Image from Pietro Fiorentini (2023) [32].

Metrological performances

- **Measuring accuracy**. Commercial rotary piston gas meters' accuracy is within the range defined by the EN 12480:2018 [31]. Specifically, an accuracy better than ±1% is expected for flow rate between the maximum and the transitional flow. Reducing the flow rate down to the transitional flow, due to leakages, accuracy in between ±2% are ensured.
- **Repeatability**. Repeatability better than 0.1% can be expected from rotary piston gas meters.
- **Rangeability**. Commercial rotary piston gas meters ensure large turndown. Turndown up to 1:250 is declared by a manufacturer for a gas rotary meter's size greater than G65. However, a typical rangeability for commercial meters of the same size is 1:160.
- **Pressure drops (i.e., energy losses)**. Pressure drops represent an energy loss across the meter. Pressure drop measurement is standardized in EN 12480-2018 [31]. The test consists of measuring pressure 1DN upstream and 1DN downstream of the meter using atmospheric air as the test medium. Pressure drops in field conditions can be calculated using the real density of the gas passing through the meter. An example of pressure drops is shown in Figure 10 for two gas rotary meters produced by two manufacturers (continuous and dotted curves). The different curves are represented as a function of the nominal diameter. As shown,

the selection of the nominal diameter for a specific flow rate impacts on the pressure drop. That is, typical values are in the order of some mbar referred to the maximum flow rate and a fluid density of 0.8 kg/m3.

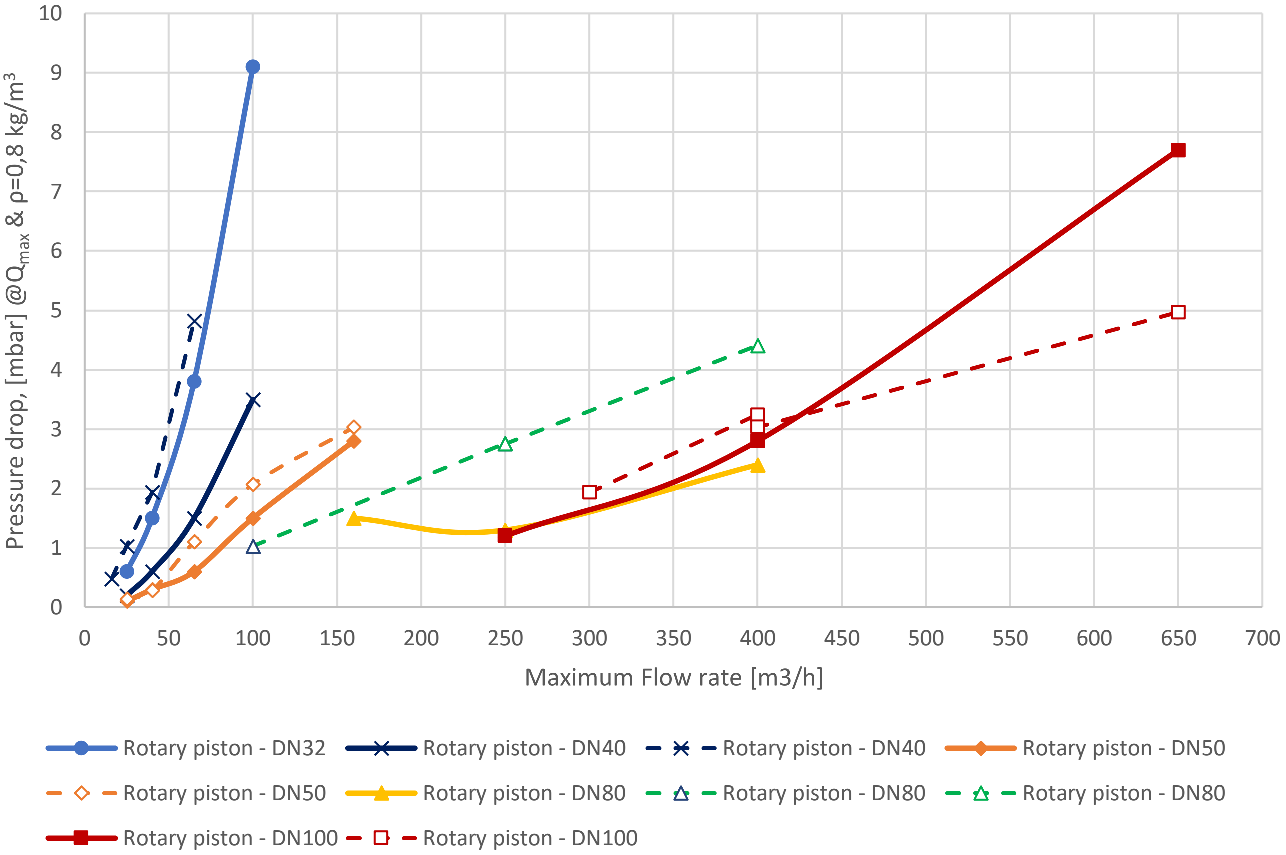


Figure 10. Pressure drops (i.e., energy losses) for a rotary piston gas meter available in the market.

- **Overload operation**. As for turbine gas meters, the EN 12480 [31] requires to test the meters up to 120% of the maximum flowrate for 30 minutes with air at ambient pressure. However, no check of the accuracy is performed during the test exactly as for turbine meters. A manufacturer declares the possibility to operate the meter up to 150% of the maximum flowrate for a “short” period. However, no more information is declared.

Installation requirements

Regarding the installation aspects, it is essential to follow the instruction of the manufacturer. No particular indications exist for rotary gas meters that can be installed horizontally or vertically. However, since the gears must be lubricated, it is very important to maintain the shaft in a horizontal position respecting horizontal installation tolerances defined by the manufacturers that can be up to 1°. Furthermore, in the case of particles transported in the gas, a filter upstream of the meter is suggested to preserve the internal components.

Maintenance requirements

A lifespan of 25 years is expected for rotary gas meters [28]. That is, lubrication of rotor and timing gears has to be ensured in rotary gas piston. Therefore, periodic inspection has to be performed in the field to check the oil level through the dedicated glass installed in the meter's body. The manufacturers suggest the frequency of inspection based on the application and the aggressivity of the gas. Typically, checks should be performed every six months in standard applications. The oil has to be changed after 5 to 8 years with the oil indicated by the manufacturer.

3.1.3. Ultrasonic gas meters

Principles of operation

The ultrasonic gas meters are interferential meters that calculate the gas flow rate by measuring other parameters. Specifically, two measuring methods are used in ultrasonic meters to calculate the volumetric flow rate: the “time difference measurement” or “transit time” and the “Doppler” methods. In the first case, the measurand is the time, while in the second, the change of frequency. The speed of sound is a characteristic of the fluid, and, in the case of gas, it depends on gas temperature and pressure. It is well-known that when a sound wave leaves position "A", it arrives at position "B" at the time "t" as reported in Eq. (8):

$$t = \frac{L_{A-B}}{c} \quad (8$$

Where:

L_{A-B} is the distance between position A and position B
c is the speed of sound in the fluid.

The principle of “*time difference measurement*” has been explained by many Authors in the literature in the past. Some examples are reported in references [33]–[37].

That is, two transducers acting as transmitter and receiver are installed in the body of the meters. Referring to Figure 11 taken from Chen et al. (2020) [37], the transducers are installed in positions indicated as P_{up} and P_{down}. The gas velocity, v, is calculated by measuring the transit time of ultrasonic pulses emitted by the transducers at regular and alternating intervals. The ultrasonic pulses emitted in the same direction of the gas flow, i.e., from P_{up} to P_{down}, are accelerated. On the other hand, those pulses moving in the opposite direction are decelerated proportionally to the gas velocity. Specifically, the calculation is performed by applying Eq. (9):

$$v = \frac{L}{2} \times \cos(\theta) \times \left(\frac{1}{t_{up}} - \frac{1}{t_{down}}\right) \quad (9$$

Where:

L is the distance between position P_{up} and position P_{down}
t_{up} is the time elapsed between the sound wave reaches the position P_{down} from position P_{up}
t_{down} is the time elapsed between the sound wave reaches the position P_{up} from position P_{down}
θ is the angle between the sound wave direction and the pipe wall, i.e., the angle between the measuring path and the gas flow.

In fact, Eq. (10) derives from Eq. (8) and Eq. (9) for the calculation of t_{up} and t_{down}:

$$t_{up} = \frac{L}{c} + \frac{L}{v}\cos(\theta) \quad (10$$

$$t_{down} = \frac{L}{c} - \frac{L}{v}\cos(\theta) \quad (11$$

The gas volumetric flowrate, Q, is lastly calculated by knowing the internal section of the pipe, A, by Eq. (12):

$$Q = v \times A \quad (12$$

While the SoS, c, is calculated by Eq. (13):

$$c = \frac{L}{2} \times \left(\frac{1}{t_{up}} - \frac{1}{t_{down}}\right) \quad (13$$

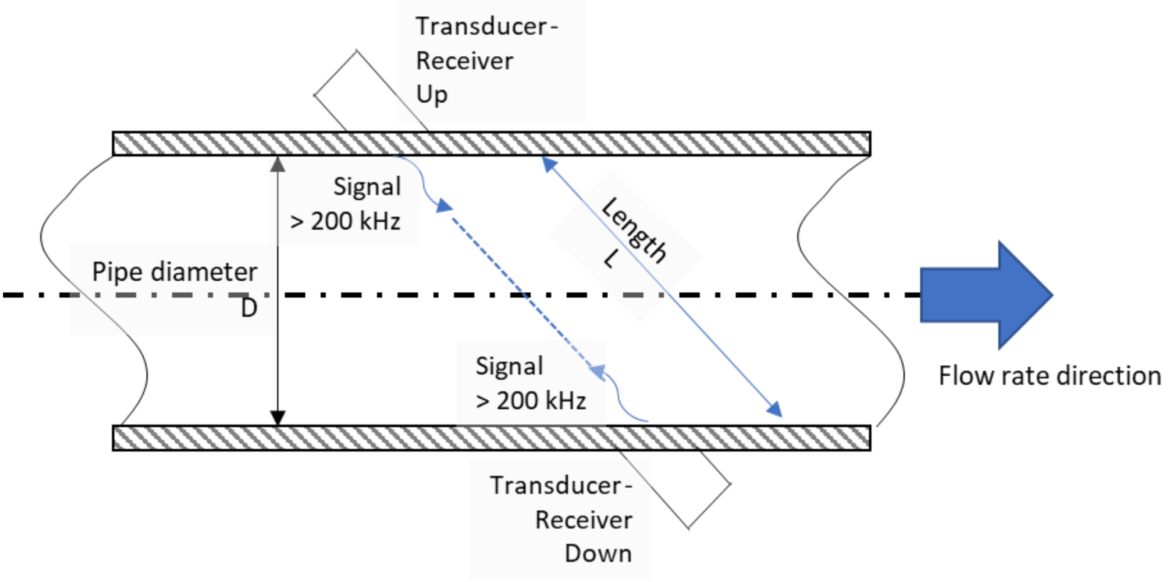


Figure 11. Schematic representation of the "time difference measurement". Ri-elaboration of Figure 1 from Chen et al. (2020) [37].

To improve metrological performances or at least increase the meter's immunity respect not developed flows, multipath configurations have been developed and are commercially available [34], [38], [39]. In this case, the volumetric flow rate is calculated as the weighted sum of the velocities calculated as in Eq. (14):

$$Q = A \times \sum_{i=1}^{N_p} v_i w_i \quad (14$$

Where:

N_p is the number of measuring paths. Commercial solutions with up to 5 paths are available in the market for high accuracy measurements.

v_i is the velocity calculated in the i-th path

w_i is the weighted factor for the i-th path.

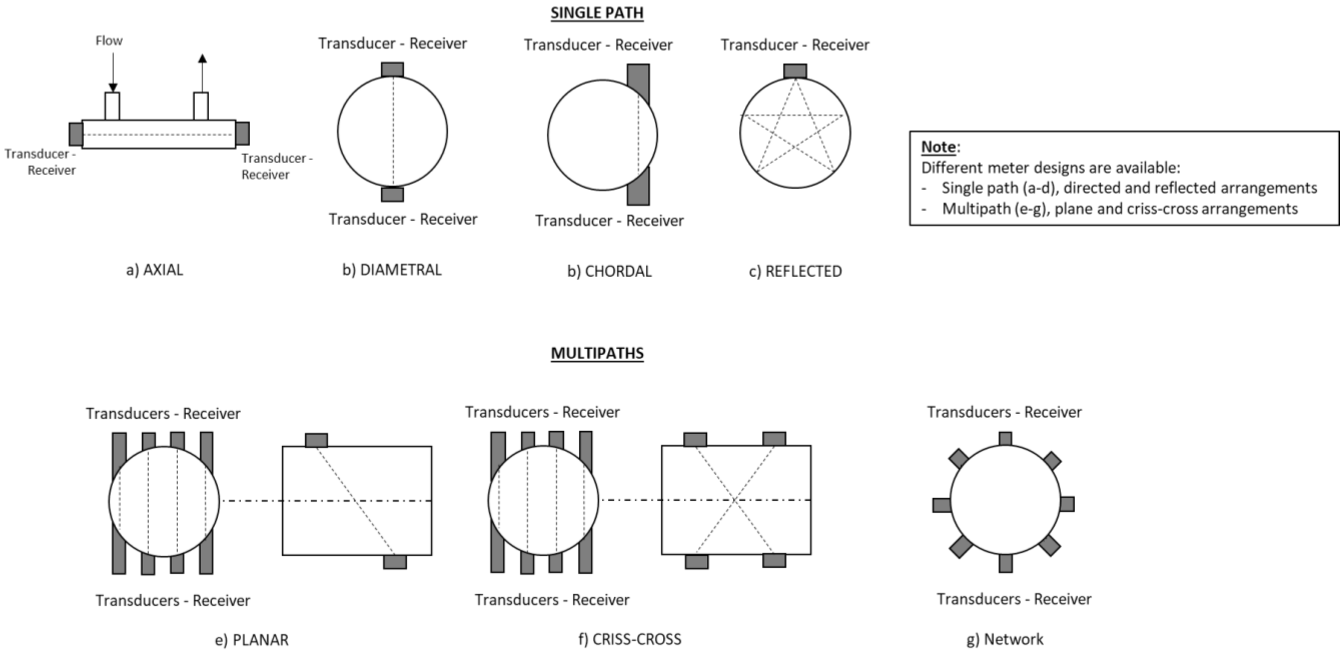
The metrological performances are affected by several factors that can be summarized as below:

- The geometry of the meter and the location of the transducers.
- The accuracy and the quality of the components used to produce the ultrasonic wave, to measure the quantity and to calculate the velocity.
- The flow velocity profile and the presence of any disturbance.
- The temperature distribution since the SoS depends on the fluid density.
- The presence of a flow pulsation.
- The presence of noise that impacts the operation principles.

“Doppler effect” based measuring devices works on the well-known principle. Inhomogeneities or impurities (dispersers) in the fluid reflect the sound wave that is emitted by a transmitter. These inhomogeneities reflect the sound wave acting as moving transmitters. The frequency change of the reflected signal is a function of the flow rate and of the SoS.

The design and the main components

The main requirements for ultrasonic gas meters are included in ISO 17089-1 [40], EN 14236 [41] (for domestic applications) and AGA-9. That is, for large flow rate applications, inline and clamp-on configurations are available in the market while for domestic applications only inline meters are implemented. Inline meters include several components. The main ones are the transducers, the meter body, the electronics and the data processing and presentation unit. The transducers are responsible for the transmission and the receipt of the sound wave at a frequency between 100 kHz and 300 kHz. Typically, frequencies greater than 200 kHz are selected being less impact by any noise effect occurring in the system. A small piezoelectric ceramic disk sends the signal from the transducer's front. This active element is usually included in an arrangement of metal parts and high-grade epoxy within a titanium housing to protect it. Stainless-steel or Hastelloy can also be used in applications characterized by very aggressive environment. That is, different number of transducer pairs, of reflections per path, and attachment method into the conduit can be selected by the manufacturers. Examples of available configurations in commercial products include horizontal, V-shape paths, diagonal paths, single and double reflections even if more configurations are described in the ISO 17089-1 [40]. However, higher uncertainty due to contamination or change in wall roughness can characterize reflected path configurations. Furthermore, as reported by Herrmann et al. (2004), more energy is required in bounced configurations making it more technically challenging to realize products being certified for intrinsically safe operations or able to measure low-density gases such as H_2 [38]. Furthermore, Dell’Isola et al. (1997) [33] reviewed the sensitivity of each configuration for potential flow disturbances like, for example, swirl and pulsating flow.



Note:
Different meter designs are available:
- Single path (a-d), directed and reflected arrangements
- Multipath (e-g), plane and criss-cross arrangements

Figure 12. Principal acoustic paths configuration. Image elaborated from Dell'Isola et al. (1997) [33].

2 double reflection
+
1 single reflection

2 double reflection
+
2 single reflection

2 double reflection
+
3 single reflection

Figure 13. Multi-path configuration for the Q.Sonic© ultrasonic gas meter. Image from Elster-Instromet (2005) [42].

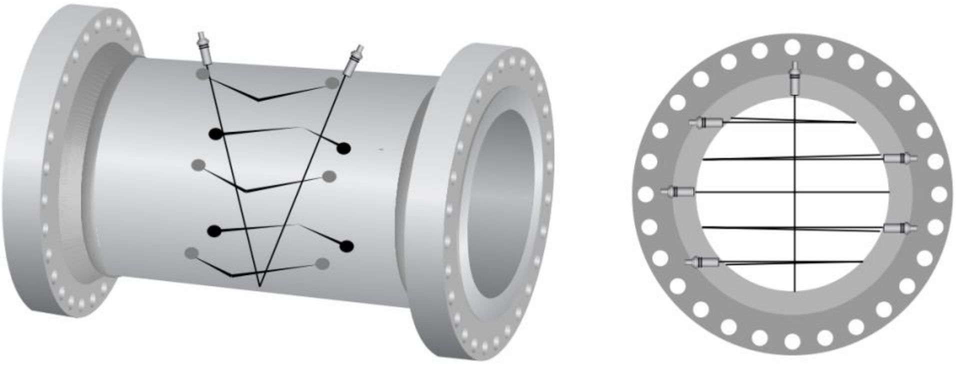


Figure 14. Multi-path configuration for the Altosonic V12© ultrasonic gas meter. Image from Krohne (2017) [43].

Regarding the meter body, similarly with turbine gas meter, length down to 3DN are available in the market (2DN for turbine gas meters). Carbon steel and 316 stainless-steel are the preferred material to realize body able to withstand high pressure rating up to PN 420 and to convey large flow rate (DN up 1600).

For domestic ultrasonic gas meters, usually the single path configuration is used due to space and cost limits. Furthermore, other materials are used because of the different operative conditions between gas distribution and transmission. The clamp-on ultrasonic meters are installed outside the pipeline in different configurations like, for example, those shown in Figure 15 for a commercially available clamp-on meter. As shown in the figure, reflection and diagonal arrangements are available with different number of paths. Even if the increase of the path number would usually improve the accuracy [39], a signal attenuation occurs. Therefore, attention has to be made in the selection of the correct transducers. Two typologies are available, i.e., the lamb and the shear wave transducers, and are selected based on the wall thickness, the gas velocity within the pipe and the nominal diameter of the pipe.

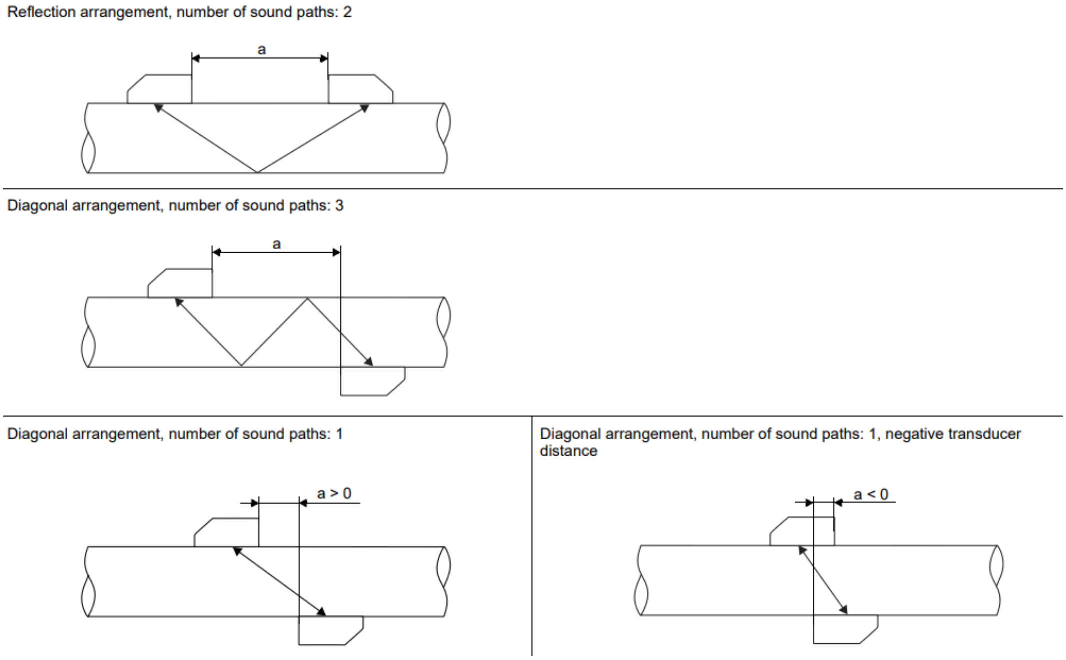


Figure 15. Possible arrangements of the transducers in the clamp-on installation. (a) is the transducers' distance. Image from Flexim (2021) [44].

Metrological performances

- **Measuring accuracy**. Ultrasonic gas meters installed in transmission networks in accordance with ISO 17089-1 are classified as “Class 1” and “Class 2” accordingly with ISO 17089-1 [40]. “Class 3” and “Class 4” are defined with the ISO 17089-2 but are not considered in the present report. Specifically, “Class 1” meters, requiring an accuracy class equal to 0.5 or 1.0 (as defined in section 5.8.2 of the ISO [40]) are used for custody transferability applications. “Class 2” meters are used for process application and include measuring devices with an accuracy class equal to 2.0 or better. State of the art ultrasonic gas meters are able to satisfy more stringent conditions. Specifically, products with an accuracy up to ± 0.1% of the measured flow rate for high pressure flow calibrated and linearised are available in the market. Less accurate measurements can be achieved in absence of linearisation (up to ±0.2% with some models available in the market) or in the case that only the SoS is calibrated (up to ±0.5%). However, it has to be remembered that once it is installed in the field additional measurement uncertainty finally occurs. Regarding clamp-on measuring devices, an uncertainty up to 1-2% of the measuring value is declared by some manufacturers in the market, while for domestic gas meters ensures accuracy in accordance with Class 1.5 meters as defined in EN 14236 [41] or better. In fact, several manufacturers declare error curves within the 1% for the entire measuring range. It has to be noted that EN 14236 indicates that these meters are designed to operate on gases with speeds of sound in the range 300 m/s to 475 m/s ($SoS_{CH4,27°C}$ = 450 m/s; $SoS_{H2,27°C}$ = 1320 m/s)
- **Repeatability**. State of the art inline ultrasonic meters declare repeatability up to ±0.05%-0.1% of the reading in the range between 5% to 100% of the maximum flowrate for uncontaminated gases. Slightly higher values are declared for clamp-on devices (up to ±0.15% of the measured value).
- **Rangeability**. State of the art inline ultrasonic meters declare large turndown up to 1:150.
- **Pressure drops**. Having no moving part, ultrasonic gas meters are characterized by low or zero pressure drops.
- **Response time**. Few manufacturers declare the response time of their products in public datasheets. Those that do it declare performance of 1 update per second.
- **Influence of pulsating flow**. As reported by Durke et al. (2016) [45], few data are available in the literature regarding the performances of ultrasonic gas meters in pulsating flow. However, overestimation and underestimation errors have been reported in the literature because of different causes like, for example, an inadequate sampling time of the meters unable to detect flow pulsation, and velocity profile variations or distortions. Furthermore, pulsating sound waves produced by pressure regulators can also disturb the metrological performances of the ultrasonic meters.

Installation requirements

A proper length of the straight tube is required upstream and downstream of the gas ultrasonic meters to ensure accurate measurements. Swirl and distortion of the flow profile have to be avoided when measuring with an ultrasonic gas meter. That is, the length of these pipeline sections is a function of the accuracy class of the meter and the referring technical standard like the ISO 17089-1, the AGA 9 or the OIML R137. For example, “Class 1” meters require upstream and downstream length of 5 DN and 3DN respectively. These lengths will ensure that the accuracy does not deviate more than ±0.3% from the calibration once the meter is installed in the field. However, longer straight pipelines could be defined by the manufacturer. The installation of a flow conditioner upstream the meter, however, allows the reduction of the upstream length while the downstream one remains unchanged. For clamp-on configurations, since the measuring devices are installed outside the pipe, damping materials can be positioned below the transducers to minimize the noise that would affect the measurement.

Maintenance requirements

A lifespan of 15 years is expected for ultrasonic gas meters [28]. Ultrasonic gas meters are usually considered low-maintenance meters. Since no internal moving parts are present within the body, there should be no need to disassemble the meter during its lifetime, if not in exceptional cases. For example, in the case of contamination growth within the meters, the meter must be opened, verified for corrosion and cleaned. In the case of a transducer malfunction, it is usually suggested to substitute the pair on the same acoustic path. Last but not least, if the electronic unit is power supplied by a battery, substitution has to be performed when discharged. Regarding domestic ultrasonic gas meters, only the substitution of the main battery when completely discharged has to be completed. Other actions would be possible only by damaging the metrological seals.

3.1.4. Diaphragm gas meters

Principle of operation

Diaphragm gas meters have been the only used technology until some decades ago for the domestic gas distribution sector as reported by Cascetta & Vigo (1994) [46]. A diaphragm gas meter is a mechanical volumetric flowmeter in which the gas volume is measured using measuring chambers with deformable walls. Its metrological performance often deteriorates due to the abrasion of moving parts and material aging over time. It is also likely affected by temperature and pressure because of the compressibility and expansibility of the diaphragm. As described by Bennet [47], a fixed gas volume is displaced for each stroke of the diaphragm. The principle that regulates the operation of diaphragm meters consists in isolating, during each single measurement, a known volume of gas (measurement volume) in two measuring chambers. The size of each one coincides with the measurement volume and is exactly equal to a quarter of the cyclic volume; for example, a meter with a maximum flow rate of 6 m^3/h, having a cyclic volume equal to the minimum allowed (2 dm^3) has the volume of each measuring chamber equal to 0.5 dm^3. The measurement consists both in the continuous repetition of the operations of filling and emptying the gas from the chambers and in taking into account the number of times this cyclic operation is performed. The figure below schematizes the diaphragm gas meter and is taken from Tsankov et al. (2021) [48].

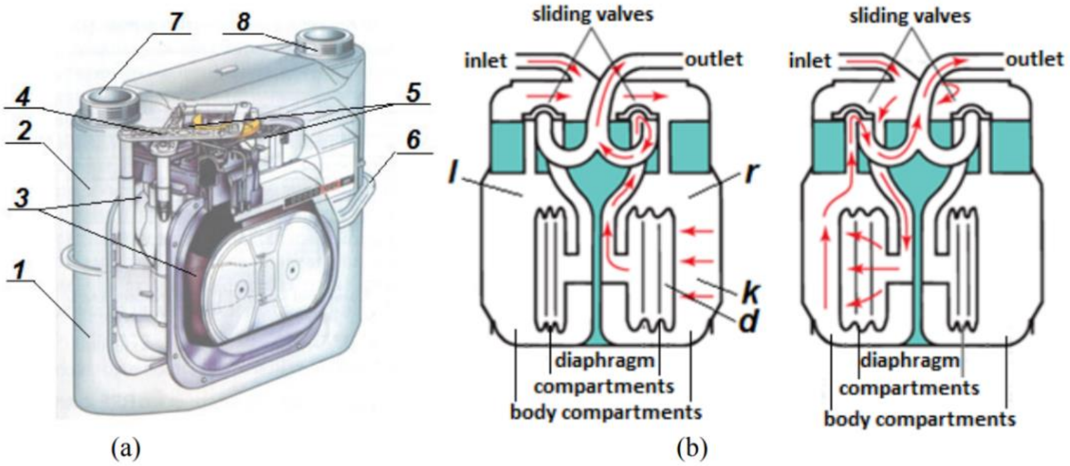


Figure 16. Diaphragm flow meter with sliding valves and built-in temperature corrector (a) device: (1) housing; (2) cover; (3) membranes; (4) measuring mechanism; (5) gas distribution sliding valves; (6) tightening hoop; (7) gas inlet; (8) gas outlet; (b) Principle of operation - left (l) and right (r) compartments, in which there are two chambers: diaphragm (d) and body (k). Image from Tsankov et al. (2021) [48].

The design and the main components

Only "essential" components are described in the report. Since gas diaphragm meters are used to deliver gas to domestic customers, different national regulations exist and apply through Europe. To date, for example, a dichotomy exists between traditional and smart gas meters which deployment started some years ago. Many references exist in the literature reviewing the topic such as, for example, [49], [50], [51]. Since the main difference between the two configurations is related to data communication, no further focus will be proposed. However, it has to be noted that some European countries require also the installation of an automatic shut-off valve and a temperature sensor in the smart meter. The impact of hydrogen on these two components has to be carefully investigated.
That is, a diaphragm meter is composed of:

- A body containing the gas pressure and forming part of the compartments that measure the gas.
- Diaphragms that move as gas pressure fluctuates on either side.
- Valve covers and seats that regulate the gas flow into each side of the diaphragm.
- Linkage to connect the diaphragm with the valves and index.
- The components to account the gas that in traditional meter is the mechanical register while in smart meters the electronic unit

Due to the manufacturing tolerances, some differences can verify respect to the design. In this case, a correction action can be taken during the calibration. It should be remembered that until the beginning of the 1990s, the membranes were typically built with animal skin, usually lambskin in small gauges and more resistant leather in medium-large gauges. After that period, membranes were made of synthetic materials, such as cotton or nylon, and vulcanized with resistant rubbers (nitrile rubber, neoprene, Viton, or other types). However, synthetic membranes have drawbacks, including the possible deterioration caused by hydrocarbons, flexibility and bending capacities smaller than previously used materials, and decreased mechanical resistances at temperatures below -5°C.

Metrological performances

Ficco (2014) [52] and Li et al. (2019) [53] experimentally investigated the performances of diaphragm gas meters installed in gas distribution networks. Specifically, Ficco (2014) assessed the degradation of the metrological performances as a function of the age, the installation conditions and the manufacturing technology while Li et al. (2019) focused on the effect of the use age on the error of indication.
The following information refers to diaphragm meters that satisfy the conditions of EN 1359 [54]:

- Elaborates gases of the 1st, 2nd and 3rd family in accordance with EN 437.
- Maximum working pressures not exceeding 0,5 barg
- Maximum actual flow rates not exceeding 160 m^3/h over a minimum ambient temperature of −10 °C to 40 °C and a gas temperature range as specified by the manufacturer with a minimum range of 40 K. It has to be noted that a wider ambient temperature range can be indicated by the manufacturer with a minimum temperature of −10 °C, −25 °C or −40 °C and a maximum temperature of 40 °C, 55 °C or 70 °C.

Measuring accuracy: The maximum permissible error (MPE) when using air has to be within the limit defined by the EN 1359 or better. It has to be noted that typically better performances are indicated by the manufacturers. Factors that impact meter accuracy include:

- Internal friction. Excessively unclean or sticky valves or binds in the meter will cause higher differential pressures.
- Diaphragm displacement. A precise and stable diaphragm displacement is required for each meter stroke. Therefore, the effective cross-sectional area of the diaphragm and the diaphragm stroke must remain constant.
- External Leaks. Any opening, such as cover gaskets, index seal box, or meter connections that lets gas escape, will affect its accuracy.
- Internal leaks. These leaks cause the meter to run slowly and are usually found in areas such as the diaphragm assembly, valves, or flag rod seals.
- Wear. The phenomenon at either end of the short flag arm or in the tangent bearing will cause the check rate proof to decrease while not appreciably affecting the open rate proof. Wear of the crank or crank arms will affect the timing of the valves, which will increase the open rate proof.

Turndown: Rangeability up to 1:160 can be achieved by diaphragm meters as declared by manufacturers.
Pressure drops: the maximum allowed pressure drop allowed by EN 1359 is 3.0 mbar. However, typically, smaller pressure drop is declared by manufacturers.

Maintenance requirements

The diaphragm meter does not require much upkeep other than a periodic proof test.

3.1.5. Coriolis gas meters

Principle of operation

The first experience to use Coriolis flow meter in natural gas sector for custody transfer applications can be dated in 1995 [55]. Ten years later, Riezebos et al. (2004) [55] reported that the through the results of calibration for CMF300 Coriolis meters produced by Micro Motion it can be claimed that the tested meters showed very good performances even if in the duration tests some challenges were found because of the limited rangeability for meters operated at low pressure (i.e., 9 barg). However, as reported by Buttler [56], the performances of Coriolis meters improve through the years making them as a reliable way to measure natural gas flow rate.

That is, the measurement principle is based on the controlled generation of Coriolis force. This force is always present when there are translational and rotational motions. Specifically, the Coriolis force is written as in Eq. (15):

$$\overrightarrow{F_c} = -2M \cdot (\vec{w} \times \vec{v}) \qquad (15$$

Where:

F_c is the Coriolis force
M is the mass
ω is the angular velocity vector
v is the radial velocity vector

The primary measurement in a Coriolis flow meter is the mass flow rate. The meter can be designed with one or multiple balanced meter tubes interconnected at the extremities. The tube system, also known as the Sensor, utilizes a centrally positioned electromechanical setup to induce vibrations in the tubes. The tubes' motion is directly proportional to the energy applied to the exciter coil. A feedback loop regulates the tube's vibration amplitude by adjusting the excitation current to maintain the tube's motion and oscillation at its resonant frequency when interacting with the fluid. Therefore, instead of a constant angular velocity ω, the flow sensor based on the Coriolis effect uses oscillation. The Coriolis forces in the measuring tube cause a phase shift in the tube's oscillations, as shown in Figure 17:

- When no flow rate is present, the tube oscillates in phase, and the displacements of points A and B in the figure are symmetrical.
- On the other hand, when the flow rate is different from zero, the mass flow rate causes a deceleration of the oscillation at the inlet of the tube and an acceleration at the outlet. The pipe oscillation is no longer symmetrical with respect to the centreline, so the displacements of points A and B are different, i.e., out of phase.

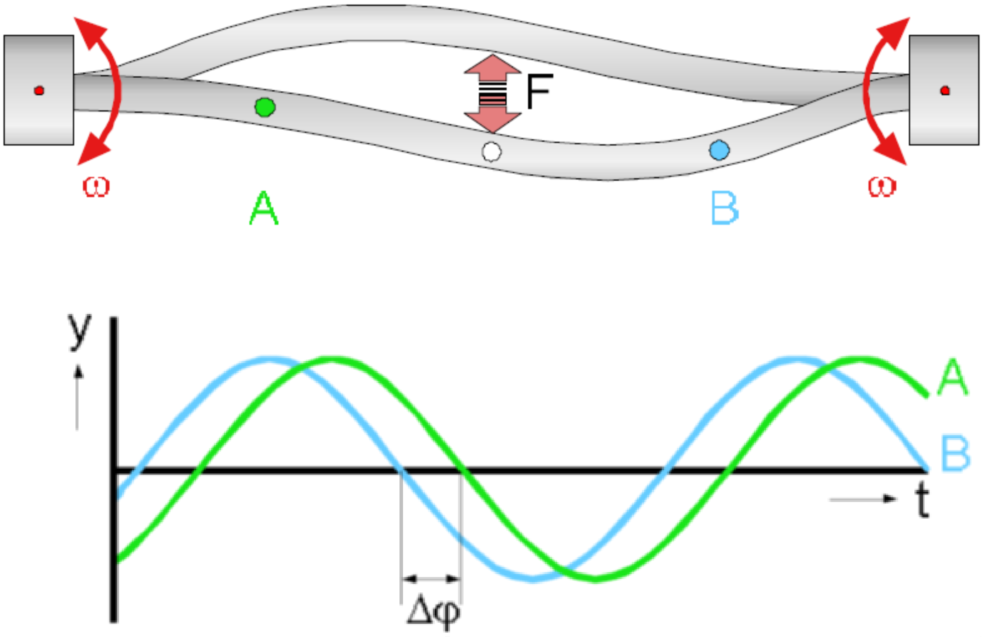


Figure 17. The working principle of a Coriolis flow meter. Image taken from Endress & Hauser [57]

The phase difference (A-B) increases with higher mass flow rates. Electrodynamic sensors installed in the meter detect the oscillations in both the inlet and outlet pipes. This measuring principle is unaffected by temperature, pressure, viscosity, conductivity and fluid velocity profile. That is, the measuring tube is continuously excited at its resonant frequency. When there is a change in the density, an automatic adjustment of the oscillation frequency occurs. In fact, Eq. (16-17) apply:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{c}{M_T + M_F}} \qquad (16$$

$$f_r = \frac{1}{2\pi}\sqrt{\frac{c}{M_T + \rho_F \cdot V_F}} \qquad (17$$

Where:

M_T is the mass of the measuring tubing.
M_F is the mass of the fluid within the sensor.
c is a constant that depends on the geometry and physical characteristics of the measurement system.
V_F is the fluid volume.
ρ_F is the fluid density.

The design and the main components of thermal mass meters

A Coriolis meter is comprised of two main components, a sensor (primary element) and a transmitter (secondary). The sensor has a design that varies drastically from one manufacturer to another. Typically, stainless steel is used as material for natural gas sector application. There are single and dual tube designs, varying degrees of bent tubes, and some that are straight. Some examples are shown in Figure 18 from Hu et al. (2021) [58]. Other images can be found in AGA (2013) [59]. Furthermore, single and double tube designs are also possible. Specifically, the double tube design allows a balance against external disturbances. The frequencies that are used between manufacturers and the drive systems can vary. The various designs often were developed to get the maximum benefit for an application or an industry. Even with the variance of designs, the Coriolis meter offers many advantages over other flow technologies. Processes that may affect other styles of flow meters have minimal effect on Coriolis. Coriolis meters are not intended to be used in multiphase fluids, specifically mixtures of liquids and gases. It is important to look at pressure drop when sizing a meter. When the pressure drop takes the product too close to the vapor pressure, this can cause flashing that leads to poor meter performance, cavitation, and possibly damage to the meter.

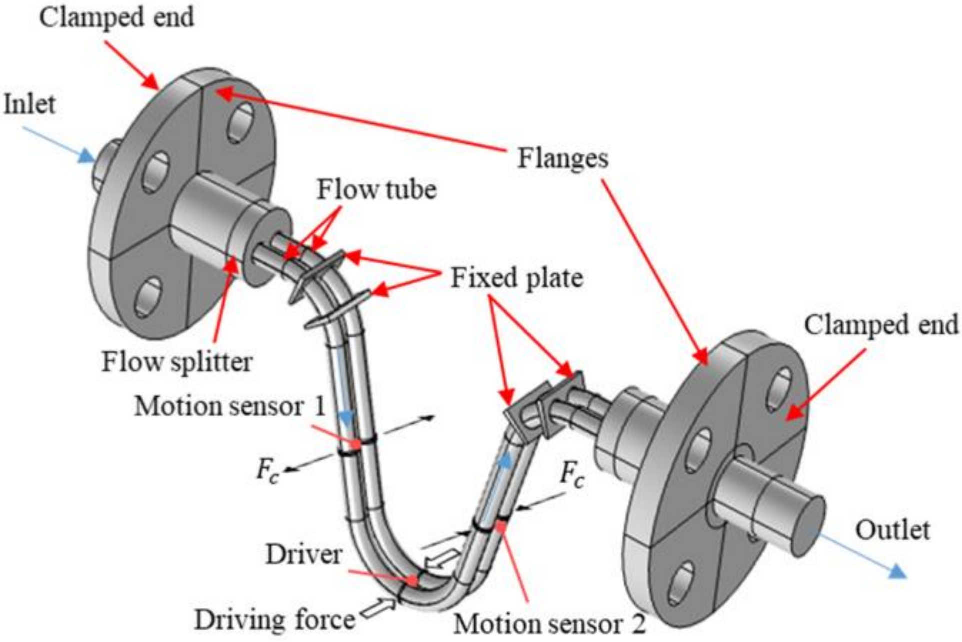


Figure 18. Main components of a bent tube configuration. Image from Hu et al. (2021) [58].

Coriolis transmitters supply power and control signals to sensors, interpreting raw signals and providing process information. Outputs can be pulse, frequency, analog, or digital signals that are transmitted through protocols like HART, Modbus, Ethernet, or Device net. Transmitters can also trigger fault alarms and offer diagnostic information to assess meter performance and process insights. They calculate net quantities and concentrations and can be remote or direct-mounted based on the application. Advancements in technology have reduced transmitter size and power requirements, primarily for process applications and not custody transfer. The transmitter's internal processor can be programmed with meter calibration information, required outputs, and units of measure. Some transmitters have additional features to meet specific industry or application needs and may offer special outputs. As reported by AGA {X] the measurement of gas density is inadequate for gas measurement. To calculate gas volume flow rate measurements accurately, the mass flow must be input into a flow computer along with the relative or base density for proper calculations. Methods like AGA8 Gross Method 1, Gross Method 2, or Detail Method are used for this purpose. Inputting a fixed value directly into the Coriolis sensor for output is possible but not recommended, as it may result in erroneous measurements due to changes in the actual gas composition without updating the meter's settings accordingly.

Metrological performances

- **Measuring accuracy (mass flow rate)**. Typical values for accuracy can achieve ±0.35-0.5% of the reading for gases medium at reference calibration conditions even if better performances can be achieved. Therefore, a correction has to be considered to simulate in field conditions.
- **Rangeability**. Rangeability usually depends on the meter nominal diameter. Values up to 1:500 are available in the market for commercial products.
- **Repeatability (mass flow rate)**. Typical values can achieve ±0.25% of the reading for gases medium.
- **Influence of flow variations**. Coriolis meters are declared to maintain accuracy over a wide range of pulsating conditions, even if some issues can appear when flow pulsation approaches the resonant frequency of the measuring sensor. As indicated by [X], Coriolis meters typically operate at resonant frequencies above 100 Hz in gas applications. That value is typically far away than expected in actual cases.
- **Overload operation**. Coriolis meters are typically designed to measure fluid with high velocity. In fact, some meters are to operate up to sonic or choke conditions. Therefore, no particular issue appears.

Installation requirements

Proper installation of Coriolis meters is crucial for optimal performance. Even if they don’t require long straight tubes upstream and downstream, following the manufacturer's installation requirements and best practices is advised to ensure the declared metrological performances. For gas applications, horizontal up and flag positions are common. Horizontal up prevents liquid accumulation, and the flag position ensures condensate drainage. Proper piping alignment without rotational torque or mechanical binding is crucial for accurate meter performance. In case of accuracy issues, unstable zero, or varying meter factor, checking for binding or torque problems is recommended. Ensuring the meter is installed independently of the piping system can help address these issues. Installing a spool piece during new construction can also be helpful.

Maintenance requirements

No special maintenance actions are usually expected for Coriolis gas meters. The field maintenance of a Coriolis meter is an inspection process consisting in the verification of the correct operation of transmitter, sensors and “zero” measurement condition.

3.1.6. Thermal mass gas meters

Principle of operation

Thermal mass gas meters monitor the cooling effect of the moving fluid on a heated element. The electric power supplied to maintain the sensitive element at a constant temperature, or the temperature difference ΔT from the set-point value, is proportional to the gas mass flow rate. The fluid inside the measuring section passes through two temperature transducers. One of the two resistance thermometers is used as a standard temperature-sensing device and monitors the current process values. The other is used as a heater.

The heater can operate in two ways, e.g., constant current anemometer (CCA) and constant temperature anemometer (CTA). In the first mode the heater is kept at a constant differential temperature and higher than the process temperature by varying the electrical energy consumed by the sensor. The higher the mass flow, the greater the cooling effect and the energy required to maintain the difference. By measuring the electric current supplied to the heater, the mass flow rate of the gas is calculated. This configuration is the most employed in industrial application. In the second case, the heater is powered with a constant electric current, while the temperature difference is measured. In this case, the variation measured in the temperature difference is proportional to the mass flow rate change.

The relationship between the mass flow m and the power spent Q on the heater is given by Eq. (18):

$$G = K \times \frac{Q}{c_p \times \Delta T} \qquad (18$$

Where:

G is the mass flowrate.

c_p is the specific heat of the fluid

ΔT is the temperature difference

K is a calibration constant that depends on the fluid's characteristics, e.g., more specifically on density and thermal conductivity.

The design and the main components of thermal mass meters

The work of Bekraoui & Hadjadj (2020) [60] describes the main components included in the market configurations of thermal mass flow meters, e.g., the inline and the insertion configurations. Inline configuration meters up to DN 100 (4") are usually present in the market, while insertion type also covers greater diameter application. It has to be noted that other authors distinguish between immersible and capillary tube configurations. The capillary tube mass meter, as described by Parvizi et al. (2016) [61], is usually used for low flow rate application, e.g., for distribution gas measurement billing purposes.

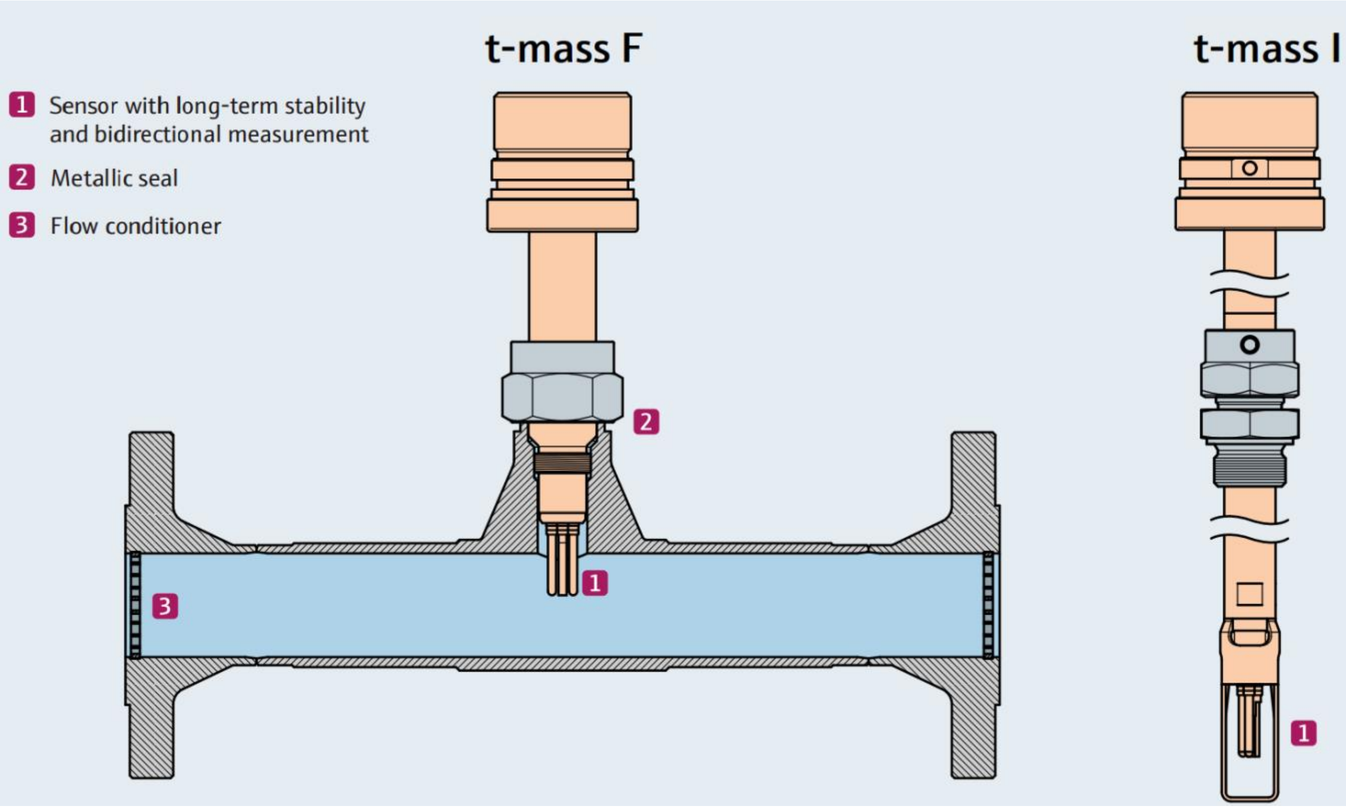


Figure 19. 2D drawing of the T-mass thermal mass flow meter: inline configuration (left) and insertion configuration (right) produced by Endress Hauser. Image from Endress & Hauser (2020) [62].

The thermal flow meters comprise a heater resistor and one or more temperature sensors immersed in the gas. Because of the potential leakage path, pressure ratings up to PN 40 are available in the market based on the material adopted even if temperature derating has to be also considered when operating at high temperature. Transmitter enclosure is usually realized in aluminum. The wetted components' casing, e.g., those components that are directly immersed in the medium, is realized in C-276 or C-22 Hastelloy, and stainless steel. Temperature sensor is usually a PT100 while the heating resistor is also manufactured in platinum. A flow conditioner can also be installed to reduce the fluid-dynamic disturbances, the pressure drops, and the required straight length upstream and downstream of the sensor. Gas meters' market is plenty of manufacturers having thermal mass meters in their portfolio. However, a distinction has to be made between the distribution and transmission sectors. In the distribution case, thermal mass meters range from G4 to G40 and are usually of the capillary type. Thermal meters are usually integrated in more complex devices that include other additional functionalities to be compliant with domestic billing purposes.

Metrological performances

- **Measuring accuracy**. The measuring accuracy of gas thermal mass meter is usually reported by manufacturers in terms of error of indication while the technical standard EN 17526 [63] indicates a Class 1.5 meters. Ficco et al. (2016) [64] experimentally evaluated the accuracy of capillary and inline full bore thermal mass meters changing different parameters like, for example, the flowrate, the gas composition. Specifically, five different compositions characterized by a Wobbe Index between 45.7 and 54.7 MJ/kg were investigated. The Authors find that gas composition change negatively affect the metrological performances of capillary configuration. Better metrological performances were measured for full bore design even if the error always exceed the limit for Class 1.5 measuring device at the minimum flowrate. That is, standard products declaring an accuracy up to 1% of the reading value and 0.1% of the full scale exist on the market. On the other hand, Class 1.5 devices are usually commercialized for the distribution market even if error deviation smaller than 1.0% are declared by some manufacturers.

- **Rangeability**. For commercial thermal mass meters, a rangeability up to 1:100 is achieved in standard products with a resolution up to 1:1000. However, some commercial products declare a rangeability up to 1:1000.
- **Repeatability**. The technical standard EN 17526 defines two thresholds for allowed repeatability as a function of the flowrate. That is, performances down to ± 0.25% are found in commercial products.
- **Pressure drops**. Since the fluid-dynamic interference of thermal mass meters is limited, relatively small pressure drop can be achieved down to 1-2 mbar. However, a greater pressure drop would results reducing the DN while increasing the gas flowrate.
- **Influence of flow variations**. Response to unsteady flows have to be tested in accordance with the EN 17526 and metrological performances verified. In fact, as discussed by Han et al. (2005) response time of the meter play a key role in accurately measure unsteady flow [65].
- **Overload operation**. As for turbine gas meters, the EN 17526 [63] require to test the meter up to 120% of the maximum flowrate for 20 minutes. However, no limit to the error of indication is given for overloading operations also in this case.

Installation requirements

No specific requirements are reported in EN 17526 for installation that has to be specified by the manufacturer in the datasheet. Typically, a defined length of straight tubes upstream and downstream the meters are usually indicated by the manufacturer.

Maintenance requirements

Maintenance activity only result in periodical annual checks of the measuring devices. The check list includes the verification of the environmental conditions, of the process connections, the seals components (O-rings) and electrical wiring. In case of dirty gases, it could be necessary to periodically clean the wetted components with non-corrosive solutions. The cleaning frequency depends obviously on the gas conditions and has to be carefully check to avoid inaccurate measure.

3.1.7. Calibrated orifices

Principle of operation

Orifice plates are pressure differential devices. They are well known measuring devices with decades of operation in natural gas sectors thanks to their relatively low cost, the absence of moving parts and no limits on temperature, pressure and size. The first example of pressure differential devices, in fact, can be dated in 1779 when Giovanni Venturi realized the so-called technology. However, calibrated orifices are invasive measuring devices. In fact, the calibrated orifice (or orifice plate) induces a concentrated pressure drop Δp generated by a sudden narrowing of the section in the duct given by the passage from the diameter D of the pipe upstream of the diaphragm to the diameter d of the orifice. The static pressure drop through the orifice and the gas velocity can be calculated by Eq. (19) and Eq. (20):

$$\Delta p = \frac{1}{2} \times \rho \times \zeta \times v^2 \tag{19}$$

$$v = \frac{Q}{A} \tag{20}$$

Combining Eq. (19) and Eq. (20), Eq. (21) is written:

$$\Delta p = \frac{1}{2} \times \rho \times \zeta \times \left(\frac{Q}{A}\right)^2 \propto \rho \times \zeta \times Q^2 \tag{21}$$

Where:

ζ is the local pressure drop coefficient that depends on the nature of local resistance
ρ is the fluid density
v is the gas velocity through the orifice
A is the section of the orifice
Q is the volumetric flowrate

Different configurations are commercially available for the measuring plate that can be realized in any material with the condition to remain unchanged during operative conditions. However, stainless steel is the most common material used for gas application. Furthermore, from a design point of view, in addition to the classic single hole, multiple holes configuration also exists [66], [67].

Mass flowrate calculation

The EN ISO 5167-1 and 5167-2 standards define the rules to be followed for the measurement of the flow rate of fluids using differential pressure devices inserted in ducts with a full circular section [68], [69]. Specifically, the mass flow rate q_m is calculated by Eq. (22):

$$q_m = C \times \varepsilon \times d^2 \times \left(\frac{\pi}{4}\right) \times \frac{(2 \times \Delta p \times \rho)^{0.5}}{(1 - \beta_4)^{0.5}} \tag{22}$$

Where:

C is the discharge coefficient that depends on the flow rate
ε is the expansibility [expansion] factor used to take into account the compressibility of a fluid
β is the diameter ratio, i.e., a geometric factor, equal to the ratio between d and D

To properly calculate the mass flowrate geometrical and operative conditions indicated by the ISO 5167-2 have to be carefully ensured and satisfied.

However, since the discharge coefficient C depends on flowrate q_m through the Reynolds number, the iterative calculation process reported in Annex A of ISO 5167-1 has to be applied. Specifically, the well-known Reader-Harris/Gallagher correlation is implemented for the calculation of the discharge coefficient [67]. Since the Reynolds number depends on the gas velocity, density and viscosity, the effect of the introduction of H2NG mixtures in the grid has to be carefully checked.

Metrological performances

Respecting the design and installation requirements defined by the cited standards ensures the achievement of expected metrological performances. As reported by Kis et al. (2013) [70], the typical accuracy of a correctly installed pressure differential devices range between 0.6%-2% of the measured range. Some examples of degraded metrological performances are shown in the paper by Kawakita (2003) [71]. In the paper, Kawawita during inspections to real plants listed different cases like, for example, the respect of upstream and downstream length of straight tube, the internal diameter of the pipe near to the device, the incorrect eccentricity of the orifice plate respect to the tube centreline, the incorrect internal pipe roughness, the wrong calibration of the measuring devices, and the presence of leakages through piezometric tubing, the quality of the gas.

Respect to previous measuring device, the pressure drop through the orifice plate is an input parameter for the design of the meter that has to be verified and the end of the sizing approach.

Influence of flow variations

Respect to other gas meter technologies, a small rangeability is ensured by the orifice plate and usually from 1:3 to 1:10 [27].

Installation requirements

Specific requirements in terms of installation are indicated by ISO 5167-2 to ensure the required metrological performances.

Maintenance requirements

No extensive work is available in the literature about orifice plate maintenance. However, since the conditions of the orifice plates are critical to correctly calculate the flowrate, inspection activity focuses on it [72]. Specifically, a typical check list includes, for example, the verification of the orifice plate bore size, the visual examination of plate and, more specifically, of the bore edges to avoid any type of flow pattern deformation, and the inspection of the seals. Last, pressure differential transmitter should be annually calibrated [28].

3.2. Gas volume converters

Introduction

No review is present in the literature about gas volume converters. As reported by the name, their purpose is the conversion of the measured volumes at operative conditions to standardized base conditions for fiscal purposes. Operative conditions change during operations. Therefore, it would be impossible to calculate the correct amount of energy transferred by measuring the volume flow rate. As a solution, the gas temperature and pressure are measured. Also, the gas composition can be measured when unknown. The gas density is calculated through well-known laws or correlations in the literature. The gas mass flow rate is finally computed from these inputs. By connecting the volume conversion device to a calorific value determination device, as outlined in EN 12405-2, energy calculation is performed.

Two different devices characterized by different metrological performances are available to gas Operators cover the scope: Electronic Volume Converters (EVC) and Flow Computers.

3.2.1. Electronic Volume Converters (EVC): T, PT and PTZ conversion

Basic information

Three types of EVC are usually installed and operated in the gas grids. As reported by EN 12405-1:2022 [73], they differ for the components installed and the functionalities implemented:

1. Conversion as a function of the temperature (the so called "T conversion"): this device includes a calculator, i.e., the electronic device that receives the signal from the meter and the temperature measuring device, and the temperature sensor. Platinum resistance thermometer sensors or temperature transducers can be used. The calculator and the temperature sensor work together to convert the gas volume to base conditions. The pressure measurement is not directly performed. On the other hand, predefined values can be implemented in the software to calculate the conversion factor. Also, the compression factor can be included as initial set value. T-conversion devices are usually used for domestic gas meters
   For this type of volume converter, the volume at base conditions is calculated through Eq. (23-25)

$$V_b = C \times V \qquad (23$$

$$C = \frac{K}{T} \qquad (24$$

$$K = \frac{p}{p_b} \times T_b \times \frac{Z_b}{Z} \qquad (25$$

Where:

C is the conversion factor
V is the measured gas volume
T is the measured absolute temperature
P is the absolute pressure at the measurement conditions
P_b is the absolute pressure at the base condition
Z is the compressibility factor of the gas at the measurement conditions

2. Conversion as a function of the temperature and the pressure (the so called "PT conversion"): respect to the previous configuration, a pressure transducer is added. According to the technical standards, absolute pressure transducers should be preferred for absolute pressures below 21 bar. For higher values of pressure, also gauge transducer can be integrated. However, in this case, to derive the absolute pressure, the average atmospheric pressure at the installation site has to be implemented in the software as pre-set value. Regarding the compression factor, as for before, it can be considered a fixed value calculated from the average measurement conditions and the determined gas compositions. The volume at base conditions is calculated through Eq. (26-28)

$$V_b = C \times V \qquad (26$$

$$C = \frac{K'}{T} p \qquad (27$$

$$K' = \frac{1}{p_b} \times T_b \times \frac{Z_b}{Z} \qquad (28$$

3. Conversion as a function of the temperature, the pressure and the compression factor (the so called “PTZ conversion”): respect to the previous configuration, only a different approach is used to calculate the compressibility factor. Specifically, known equations in the literature are implemented in the software and specified in technical documentation by the manufacturer while the gas properties and components are used as inputs. The main equations for the calculation of the volume at base conditions are shown in Eq. (29-31)

$$Z = f(p, T) \quad (29$$

$$V_b = C \times V \quad (30$$

$$C = \frac{p}{p_b} \times \frac{T_b}{T} \times \frac{Z_b}{Z} \quad (31$$

Some models include also the possibility of compensating for the gas meter's error based on the calibration certificate at the operative conditions. In this case, the corrected volume, V_c, is calculated from the measured volume, V_m, using a function called f(Q) calculated by linear or nonlinear interpolation of the measured calibration points and provided by the meter manufacturer. The corrected volume is calculated as shown in Eq. (32):

$$V_c = V_m \times f(Q) \quad (32$$

The conversion factor shall be recalculated at intervals between the volume pulses not exceeding 1 min for a temperature conversion device and at intervals not exceeding 30 s for the other types of gas volume conversion devices.

Main components

Several components are integrated to achieve volume conversion [74]. However, a preliminary distinction has to be made between “Type 1” or “Type 2” configurations. In “Type 1”, the converter and the pressure and temperature measuring devices are approved together resulting a complete device. Differently, in “Type 2” devices, the converter and the measuring instruments are approved separately.

The selection of the components has to be performed to ensure the respect of the EN 12405-1 requirements.

That is, to achieve the functionalities described in the previous section, the corrector, the temperature sensor and, potentially, the pressure transducer are the main components. Some requirements defined by the technical standard impact their selection and have to be carefully investigated by the manufacturer in the certification of the product. The most important ones are reported below. However, the reader is invited to carefully check the above cited standard for the complete list of requirements:

- Gas group or family of the fluid in contact with the measuring devices: to be identified in accordance with the EN 437.
- Gas temperature range: three different ranges can be identified, e.g., normal ([-20 C, 50 C]), limited, and extended.
- Range of the pressure transducer: the ratio between the maximum and the minimum pressure has to be greater than 2 (p_{max} / p_{min} > 2).

- Maximum ambient temperature: different values are available potentially impacting ATEX analysis, i.e., 30 °C, 40 °C, 55 °C or 70 °C.

Other components are also usually present in an EVC:

- **Enclosure**: designed to withstand various weather conditions and is suitable for outdoor use. Most of the enclosure features provisions for attaching security seals on the door or adding a lock.
- **Processor board:** it is the central processing unit of an electronic volume corrector. It contains all the necessary electronic components for volume correction. Appropriate connectors and terminals connect this part with other accessories, such as pressure transducers, temperature transducers, index wiring, and displays. The processor board essentially functions as a microprocessor-based computer on a board, incorporating power supply regulators, a microprocessor, memory, analog/digital converters, analog inputs, digital inputs, analog outputs, digital outputs, counters, signal conditioning, and various supporting circuitries. Internally, the processor board is powered by either 5 or 3.3 VDC (Volts Direct Current), depending on the technology used. On-board lithium batteries or external supply are options available in the market.
- **Display**: the display allows users to view relevant parameters directly at the corrector. It typically consists of a Liquid Crystal Display (LCD) that may be integrated into or connected to the processor board. Most LCDs are designed to display a limited number of characters, and parameter values are often preceded by a letter designator. Different parameters can be scrolled through by pressing a button or using a magnet on a designated area.
- **Keypad**: usually present in the EVC, the keypad allows for local data entry and is used to configure or select the parameters to be displayed on the local screen.
- **Antenna**: an antenna is integrated in the device to allow data communication in the case of wireless data communication protocols, e.g., as, for example, GSM or GPRS protocols
- **Power supply**: The internal or external power supply can be provided in EVC. One or more non-rechargeable D-size lithium batteries (3.6 Vdc) are usually installed in the devices to satisfy the energy demand for a useful life. The external power supply at 200-240 Vac is also possible in the market.

Metrological performances

To respect also the condition about the maximum permissible error (MPE), expressed as relative values and applicable to the volume at base conditions or to the conversion factor at the net of the gas meter error, is another compulsory condition. The values that are valid for “Type 1” and “Type 2” conversion devices are shown in Table 1 and Table 2. It has to be noted that reference conditions refer to the conditions of use prescribed for testing the performance while the rating operating ones refer to the expected working conditions.

Table 2. Maximum permissible errors (%) for conversion device type 1 in accordance with [73].

Indication or element	Reference conditions	Rated operating conditions
Main indication for PT or PTZ conversion	± 0.5	± 1
Main indication for T	± 0.5	± 0.7

Since “Type 2” components are approved separately, the specific errors are indicated distinctly. Specifically, the error is calculated as the sum of the individual errors as reported in Eq. (33):

$$|e| = |e_f| + |e_p| + |e_t| \leq |MPE| \tag{33}$$

Where:
e is the total conversion factor error.
e_f is the error on the calculation of conversion factor.
e_p is the error on the pressure measurement.
e_t is the error on the temperature measurement.

Table 3. Maximum permissible errors (%) for conversion device type 2 in accordance with [73].

Indication or element	Reference conditions	Rated operating conditions
Main indication (ec) for PT and PTZ conversion	± 0.5	± 1
Calculator (ef)	± 0.2	± 0.3
Temperature (et)	± 0.1	± 0.2
Pressure (ep)	± 0.2	± 0.5
Main indication for T conversion only	± 0.5	± 0.7

Based on the values reported in Table 2 and in Table 3, the limit error defined by the technical standard for volume converters “Type 1” and “Type 2” is 0.5%

3.2.1. Flow computers

Basic information

Flow Computers are high accuracy volume converter devices with a calculator integrating data processing and monitoring functions. Four main functionalities are included in these devices as described in the reference technical standard [75]:

- Sensor signals’ acquisition functions: to process signals from physical quantity provided by sensors and transducers to measurands;
- Sensor functions: to convert measurands to correct measurements, mostly based upon calibration results and filtering procedures. Regarding temperature sensors and pressure transducers similar requirements to EN 12403-1 apply. In this case, however, if gauge pressure transducer is used, also an atmospheric pressure transducer is required to calculate the actual gas pressure;
- Metering functions: to calculate derived values such as volume, calorific value, compression factor, etc., based upon international standards and formulas and to take care of the supervision and monitoring for the purpose of high accuracy and substitution values;
- Long Term Data Storage functions: to keep all relevant information necessary to construct or reconstruct calculated values.

A schematic drawing taken from the technical standard is reported in Figure 20.

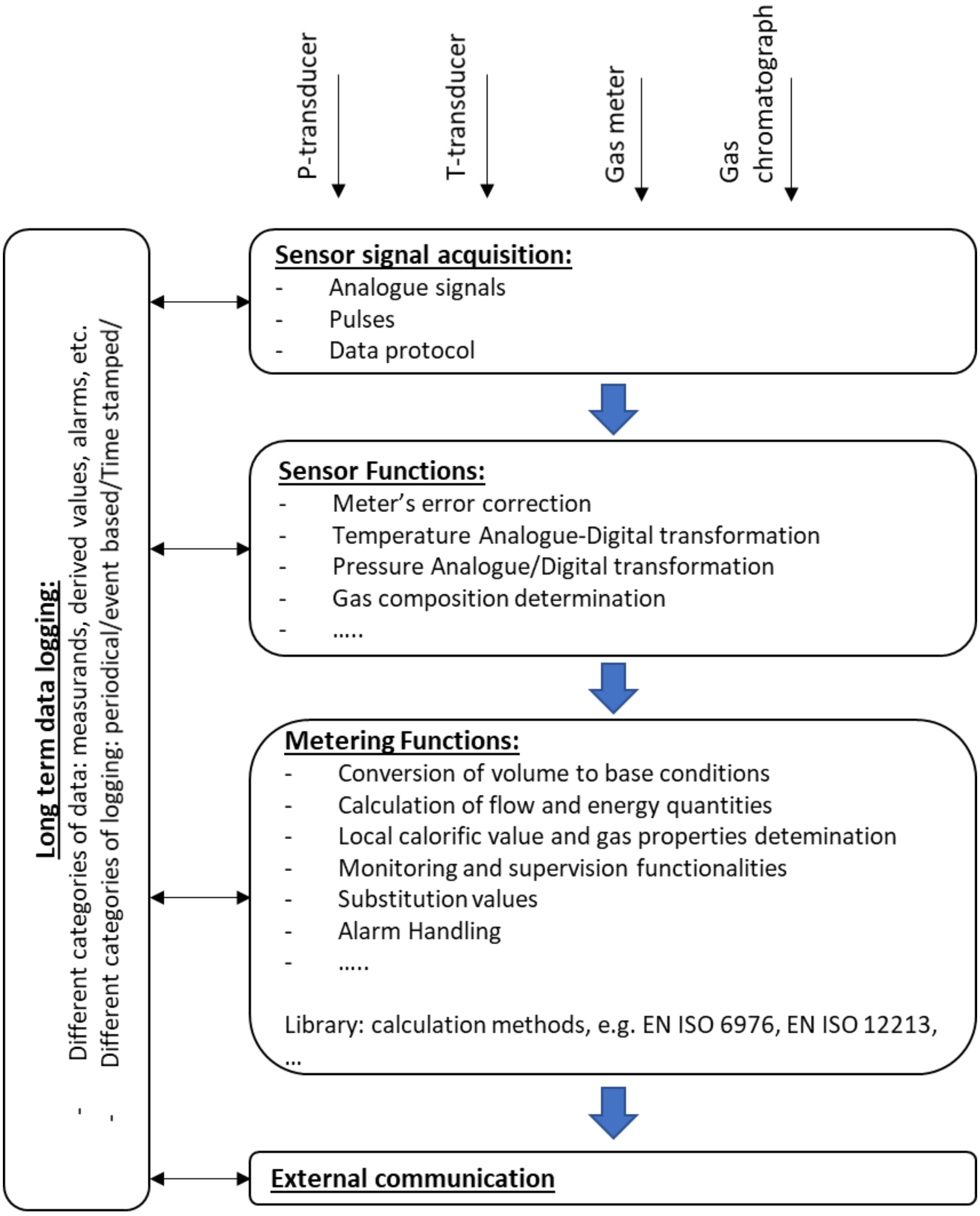


Figure 20. Main functionalities of a Flow Computer. Image elaborated from ISO 12405-3 [75].

Metrological performances

Regarding the selection of the components to be integrated in Flow Computers, as for volume converters, the selection has to be completed by satisfying the requirements reported in the technical standards. Maximum

Permissible Error (MPE) is also identified at the net of the gas meter error. The values are reported in the following table.

Table 4. Maximum permissible errors (%) for conversion device type 2 in accordance with [73].

Indication or element	Reference conditions	Rated operating conditions
Main indication (ec) for volume conversion	± 0.3%	± 0.5%
Calculator (ef)	± 0.1	± 0.1
Temperature (et)	± 0.1	± 0.2
Pressure (ep)	± 0.1	± 0.2

The total error is calculated as in Eq. (33) for "Type 2" volume converters. Based on the values reported inTable 4, the limit error for Flow Computer is 0.3%, e.g., a lower value than "Type 1" and "Type 2" converters.

Gas compressibility equations

The gas compressibility factor allows the calculation of the gas density in accordance with the real gas law. The Eq. (34) applies at measured and base conditions:

$$\mathrm{P_{m/b}V_{m/b} = Z_{m/b}NRT_{m/b}} \qquad (34$$

Where:

$P_{m/b}$ is the absolute pressure at measured or base conditions;
$V_{m/b}$ is the gas volume at measured or base conditions
$Z_{m/b}$ is the compressibility factor at measured or base conditions,
N is the number of moles of gas,
R the Universal gas constant
$T_{m/b}$ the absolute temperature at measured or base conditions.

Combining the equations for measured and base conditions, Eq. (35) apply:

$$\mathrm{V_b = V_m\left(\frac{P_m}{P_b}\right)\left(\frac{T_b}{T_m}\right)\left(\frac{Z_b}{Z_m}\right)} \qquad (35$$

The super compressibility factor F is defined as in Eq. (36):

$$\mathrm{\left(\frac{Z_b}{Z_m}\right) = \left(F_{pv}\right)^2} \qquad (36$$

Several approved methodologies are available in the literature to calculate the real gas conditions and implemented in volume converters devices like for example, AGA NX19, EN 12213-2 (AGA 8), EN 12213-3 (SGERG-88), GERG-88. More details about the applicability of these equation are reported in the literature as, for example, but not limited to references [76]–[79]. The applicability with hydrogen is discussed in Deliverable D1.2.

Maintenance requirements

Usually, no maintenance is performed in field without breaking the metrological seals. Especially for those converters power supplied by primary batteries, abnormal power consumption due, for example, to bad data communication, can be responsible for a reduction of the expected lifetime. In these cases, the substitution of the converter is the solution usually adopted by the operator.

3.3. Gas chromatographs

Basic information

Gas quality analysis is essential to correctly assess the energy transported and delivered to the final end-users. For this purpose, gas chromatographs are used. Several papers have been written as, for example, but not limited to Gawale et al. (2022) [80], Cordero et al. (2020) [81], Bartle & Myers (2002) [82]. Gas chromatography is a technique used to analyse a hydrocarbon mixture and, more specifically, its components. Gas chromatographs are available both for fixed installation and portable applications. However, the main components and functionalities are the same. Typically, a gas chromatographs include the following main components:

- A sample system.
- A chromatograph oven.
- A GC controller.

A schematic representation of the main components is reported in Figure 21 and described below.
The sample system is connected to the process usually stainless-steel tubing. Sample system is the first component that the gas encounter in the various steps before being analyzed. In this stage, the extracted gas is appropriately manipulated. First of all, the gas has to be clean and dry. Solids and humidity could damage the internal components. Secondly, gas pressure has to be controlled and regulated to the set point value indicated by the manufacturer, which is usually between 1-2 barg. However, due to the pressure drop, by the Joule Thomson effect, the gas temperature would reduce, increasing the risk of condensation of the heavier hydrocarbon. Heated pressure regulators or other components are implemented to maintain the gas temperature higher than the hydrocarbon dew point value, minimizing condensation risk. Inline filters are also installed to separate solid particles with a hydraulic diameter of 1-2 microns. Since it is essential to reduce the sample lag time, i.e., the time required for the gas sample to reach the analyzer, the filters' volume should not be minimized. Filters should be in ceramic or porous metallic type to avoid the absorption losses of fibre or paper filters. Special membranes can remove liquid droplets that would leave the gas to pass, weeping the liquid away. Since the gas chromatographs are very sensitive to temperature variations, all the components are typically enclosed within a heated oven compartment to maintain the temperature within a range of ±3 °C across to the set-point that, for natural gas applications, is usually maintained at 80 °C.
However, the main components of gas chromatographs are the columns that separate the gas mixture into its components. The gas to be analysed is sent to the columns with another gas, i.e., the so-called carrier gas, that acts as a background and facilitates the detection of the main components. Different gases like helium, argon, nitrogen, and hydrogen can be used as carriers. The selection of the gas carriers depends on the application and on the components to be identified. Once the gas enters the column, the different components are separated. In fact, selective retardation of the components of the sample takes place in the column causing each component to move through the column at a different rate. However, since much time and long columns could be required to complete the separation, multiple columns are used to split the analysis into smaller and faster column applications. Last, the components pass over the detector when the separation is completed. Different technologies are available on the market, for example, flame ionization detectors (for ppm-level hydrocarbons),

flame photometric detectors (for ppb to ppm level sulfur detection), and the thermal conductivity detector (TCD) (from ppm levels to 100%vol).

The TCDs are the most implemented in the gas sector. Specifically, TCD uses two thermistors in a Wheatstone bridge. Once the temperature increases, the electrical resistance reduces. Heat is removed from the thermistor bead when the gas passes due to heat convection. The higher the thermal conductivity of the gas, the higher the heat removed and so the temperature reduction. In TCDs, the carrier gas is sent to one of the two thermistors, i.e., the reference thermistor, while the gas mixture (i.e., the gas that has to be analyzed plus the carrier gas) is sent to the other. Due to the difference in thermal conductivity, a different amount of heat is removed in the two thermistors unbalancing the Wheatstone bridge. The resulting signal is sent to the controller for processing. As a result, each component in the gas sample causes a different peak shown in the chromatogram. To associate the component to the peak, the controller verifies the retention time, i.e., the time from the beginning of the analysis cycle to when the peak has appeared. On the other hand, the concentration is calculated by using the area below the peak or, as an alternative, from the height of the peak. However, calibration with a known gas mixture is required. In fact, a unique response factor for any component is required to calculate its concentration. Eq.(37) is used by knowing the peak area, while Eq. (38) is used by knowing peak height:

$$\mathrm{A_{F,n}} = \frac{\mathrm{A_n}}{\mathrm{c_n}} \quad (37$$

Where:

$A_{F,n}$ is the area response factor for component n-th in area per mole percent (%).
A_n is the area associated to the component n-th during calibration.
C_n is the amount of the n-th component in the calibration gas ($\%_{mol}$).

$$\mathrm{H_{F,n}} = \frac{\mathrm{H_n}}{\mathrm{c_n}} \quad (38$$

Where:

$H_{F,n}$ is the height response factor for component n-th in area per mole percent (%).
H_n is the heigh of the peak associated to the component n-th during calibration.
C_n is the amount of the n-th component in the calibration gas ($\%_{mol}$).

These response factors are stored in the memory of the device and can be also printed in the calibration reports.

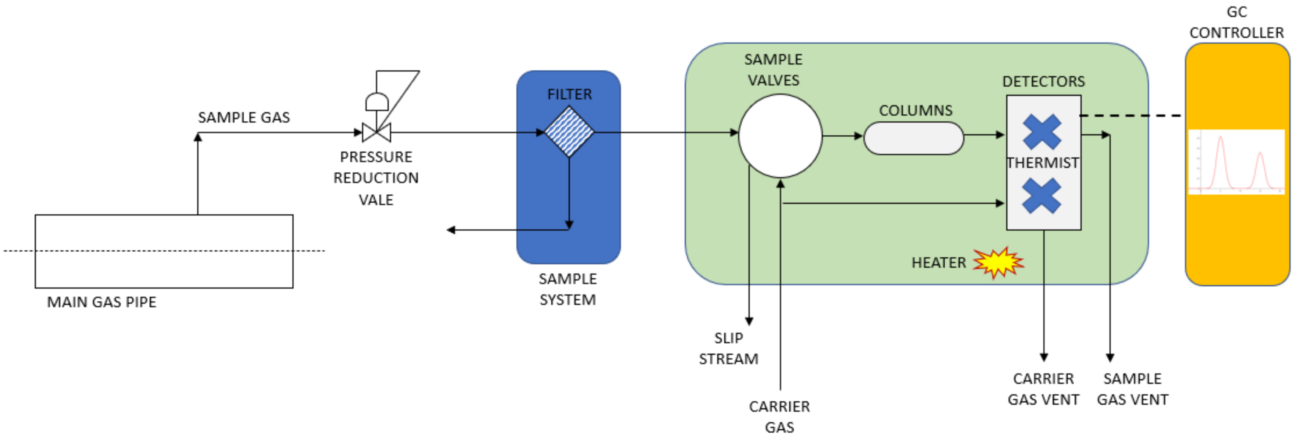


Figure 21. Working principle of gas chromatographs. Elaboration of the figure published by Emerson [83].

Regarding technical standards, ISO 6974, ISO 6975 and ISO 6976 are considered relevant for the technology [84]–[86]. Furthermore, the GPA-2261-20 "*Analysis for Natural Gas and Similar Gaseous Mixtures by Gas Chromatography*" [87] applies to gas cromatography.

Installation requirements

Gas chromatographs should be installed the nearest as possible with the process to avoid the need of high flow rates through the sample line to minimize the lag time. Furthermore, attention has to be given in the selection of the correct sampling point location. In fact, zone where stratification or separation could occur have to be avoided.

Maintenance requirements

Typical maintenance for gas chromatographs includes visual inspection of the device and periodical calibration using a reference mixture.

3.4. Gas pressure transmitters

Basic information

Pressure measuring devices measure the fluid pressure. Different measures can be obtained with different sensor configurations based on the expected purpose, e.g., absolute, gauge, and differential pressure measurement. Pressure sensors are realized with two surfaces: the first is in contact with an environment of unknown pressure, while different configurations are available for the second. When it is in contact with a «zero» pressure environment (vacuum), the absolute pressure of the fluid is measured. The gauge pressure is measured when it is in contact with ambient pressure. Last, the differential pressure is measured when it is in contact with an environment with known or unknown pressure. Several sensors are commercially available, such as strain gauge, capacitance and resonant sensors.

The requirements and the procedures to measure the fluid pressure in natural gas transmission and distribution are reported in ISO 15970 [88].

Capacitance sensors

The measurement of a force or a pressure incident on an object can be obtained by measuring the deformation. This object is usually a diaphragm that can be realized in different materials like the 316L stainless steel, Alloy C-276, tantalum, gold plated, ceramic based on the aggressivity (abrasion and corrosion) of the fluid. Specifically, in the case of differential or gauge pressure measurement, the process pressure caused the deformation of the diaphragm. The diaphragm is typically in contact with a filling fluid (usually a silicone oil or an inert fluid) that transmits the pressure signal to the sensing element. Even if not discussed in the cited standard, some ceramic diaphragms do not require any filling fluid.

Strain gauge

These instruments essentially consist of an elastic diaphragm subjected to variations in the inlet pressure on which they are glued or deposited as a thin film. Usually, four strain gauges are installed. Two are subjected to traction, while the remaining are subjected to compression. Therefore, following the deformation of the diaphragm, two strain gauges lengthen while the remaining ones shorten. An output signal proportional to the pressure and temperature compensated is obtained with a suitable connection of the four to a Wheatstone bridge.

Resonant sensors

The structure is kept vibrating at the resonant frequency utilizing eccentric coils. The frequency is detected through detecting coils inserted in an electronic circuit. When no pressure is applied, the resonant frequency is that of the structure. On the other hand, when pressure is applied, a variation occurs. These instruments ensure high resolution and accuracy when operated within a certain temperature range and with the same fluid used during calibration. In fact, the fluid's temperature and composition influence the resonant frequency.

Metrological performances

Many parameters have to be checked when selecting a pressure transducer. Some of the most important are reported below:

- *Accuracy*. The accuracy of the pressure measuring devices is expressed as a function of the span, i.e., the difference between the upper and the lower measuring range limit. Pressure measuring devices with an accuracy of 0.075% or better (up to 0.025%) are commercially available.
- *Stability*. A stability between 0.1% and 0.2% is declared by the state-of-the-art measuring devices. It has to be noted that stability is declared for a certain period of time (usually 12 months) after which different performances can verify.
- *Time constant and dead time*. The time constant identifies the time the transducer takes to adjust the detection of the input quantity to a certain percentage of the new value it assumes when this quantity undergoes a variation. The time constant is measured in seconds (s). This parameter is detected by imposing an instantaneous step variation of the physical quantity and detecting the time taken by the transducer to detect the new value assumed by the quantity. The dead time, instead, is the time that elapses between the input variation and the moment the system reaches 5% of the rated value; in this interval, the system does

not respond, so this time must be as short as possible. The order of magnitude for the time constant and the dead time are hundreds and tens of milliseconds.

Installation requirements

Installation requirements are defined by the manufacturers in the datasheet. However, no specific conditions are usually indicated expect to install the measuring device over the pipe to avoid any drains into the measuring element.

3.5. Gas temperature transmitters

Introduction

The measure of temperature has a long history. The first known instrument for measuring temperature based on the expansion of air is dated 125 before Christ. After this first example, several famous researchers developed more accurate devices [89].

Several measurement methods are commercially available to measure the temperature of a fluid: mechanical thermometers, indicator thermometers, thermocouples, resistance thermometers with metal resistors, semiconductor resistance thermometers, radiation thermometers, and optical methods. In the following section, however, only those indicated in the ISO 15970 [88] to measure the fluid temperature in natural gas transmission and distribution custody operations will be reported in detail.

Few works are available in the literature investigating temperature measurements in the natural gas industry. For example, Ficco et al. (2023) [90] investigated the accuracy of temperature measurement in a gas-closed pipe by experimental measurements both in the laboratory and the field. Summer and winter conditions have been considered to verify the effect of the ambient temperature, gas velocity, and pressure on the measurement error. As a result, for pressure up to 30 bar, the Authors identify a potential overestimation of the gas temperature in the summer due to the combined effect of the piping wall's internal radiation and low gas velocity. To mitigate this effect, practical countermeasures have been indicated.

As reported in the ISO, gas temperature is widely measured by means of Resistance Thermometer Detectors (RTDs) that links the gas temperature to the sensor's electrical resistance of the sensor.

3.5.1. Resistance thermometer Detectors (RTDs)

Basic information

This measurement method exploits the change in resistivity of certain materials as temperature changes. Two categories of RTDs are commercially available: the Positive Temperature Coefficient (PTC) sensors and the Negative Temperature Coefficient (NTC). In the PTC, the measured electrical resistance increases with the temperature. The simplified empirical law that represents the physical phenomenon is reported in Eq. (39):

$$\mathrm{R(T)} = \mathrm{R_0}\big(1 + \alpha(\mathrm{T} - \mathrm{T_0})\big) \qquad (39$$

Where:

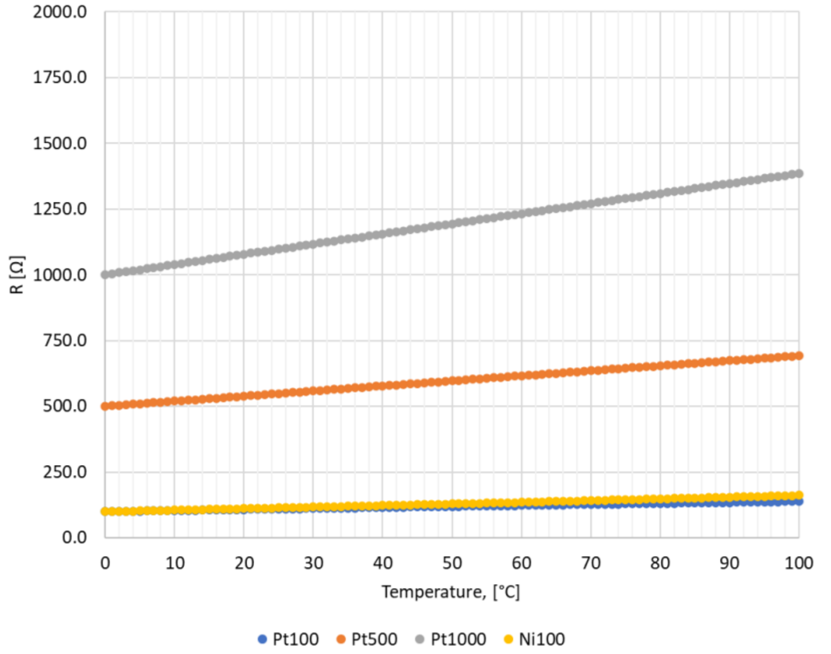
- R(T) is the electric resistance of the sensor at temperature T

- R_0 is the electrical resistance at the reference temperature T_0
- T_0 is the reference temperature
- α is the average temperature coefficient between T and T_0

Corrections to the above equation can be required based on the measured temperature range and as a function of the material. In fact, even if ideally all materials can be used, few of them would ensure a reliable measurement system. In fact, specific features have to be checked before the selection of a specific material:

- Appreciably variable resistance with temperature (sensitivity).
- Linearity
- Long term stability
- Repeatability
- Ductility and mechanical strength
- High temperature coefficient

To date, the most industrially used material is platinum (Pt). The Pt resistance is placed in a stainless-steel protective sheath electrically connected to other components with electrical wiring. As for other models, platinum resistors are identified by the resistance at 0°C. Therefore, Pt100 and Pt1000 have an electrical resistance equal to 100 Ohm and 1000 Ohm at 0 °C. For cost reasons, platinum can be replaced by nickel (but not above 300°C) and copper for low temperatures, while tungsten can be used for high temperatures.



Pt:
From T = 0 °C to T = 850 °C
$R_t = R_0 \times [1 + A \times T + B \times T^2]$

$A = 3{,}9083 \times 10^{-3}$
$B = -5{,}775 \times 10^{-7}$
$R_{0,Pt\_100} = 100\ \Omega$ @ 0°C
$R_{0,Pt\_500} = 500\ \Omega$ @ 0°C
$R_{0,Pt\_1000} = 1000\ \Omega$ @ 0°C

Ni:
From T = -60 °C to T = 250 °C

$R_t = R_0 \times [1 + A \times T + B \times T^2 + C \times T^4 + D \times T^6]$

$A = 0{,}5485 \times 10^{-2}$
$B = 0{,}665 \times 10^{-5}$
$C = 2{,}805 \times 10^{-11}$
$D = -2 \times 10^{-17}$
$R_{0,Ni\_100} = 100\ \Omega$ @ 0°C

Figure 22. Resistance of the PT resistors as a function of the measured temperature. Image elaborated from ABB Automation Products GmBH [89].

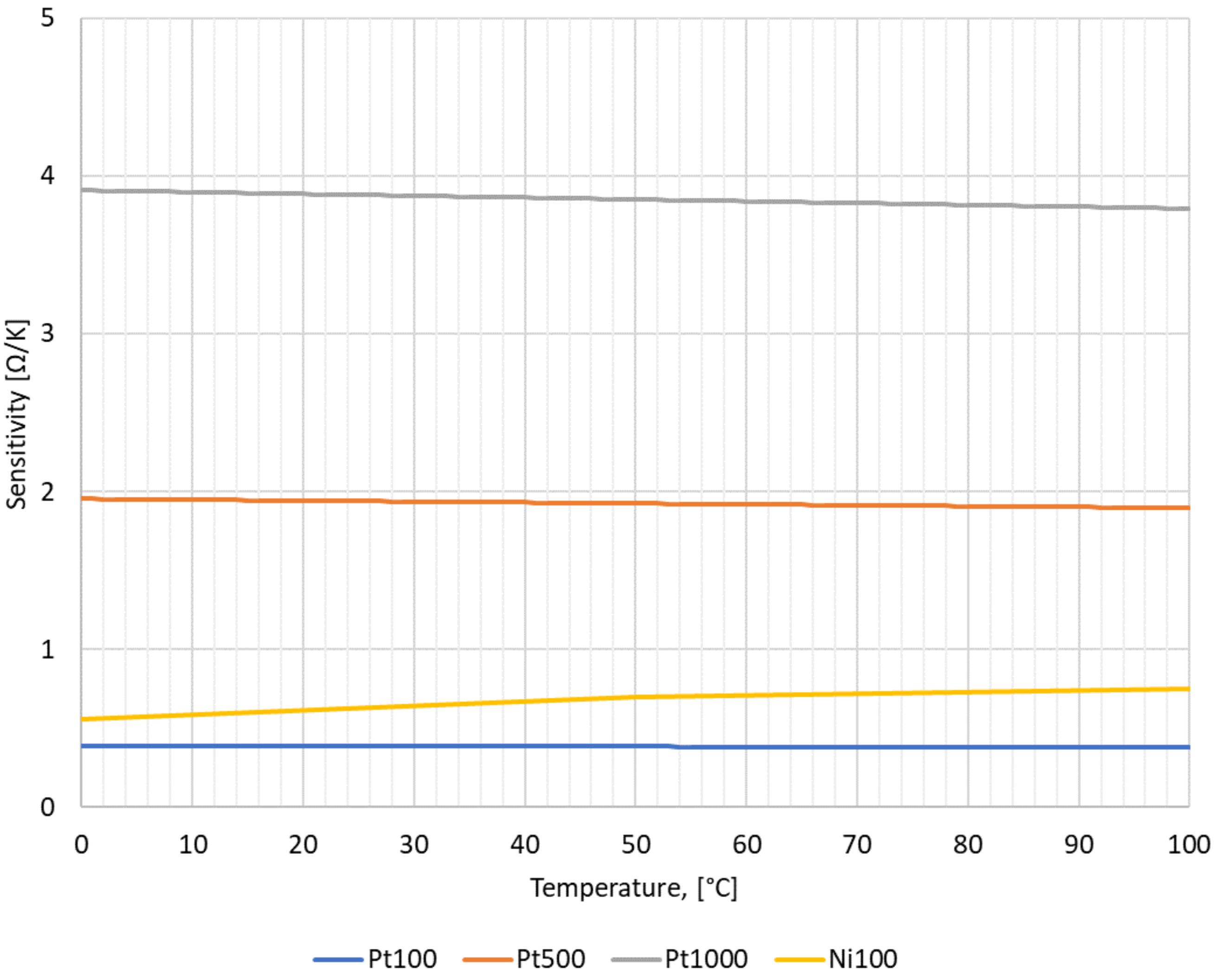


Figure 23. Sensitivity of PT resistors as a function of the measured temperature. Image elaborated from ABB Automation Products GmBH [89].

In the NTC, instead, the electrical resistance decreases.

To measure the resistance, a constant current is applied to the circuit and the occurring voltage drop is measured in accordance with the Ohm's law. To perform it, the RTD is installed in a Wheatstone bridge. Three different configurations are commercially available: two-wire, three-wire or four-wire circuit as shown in Figure 24.

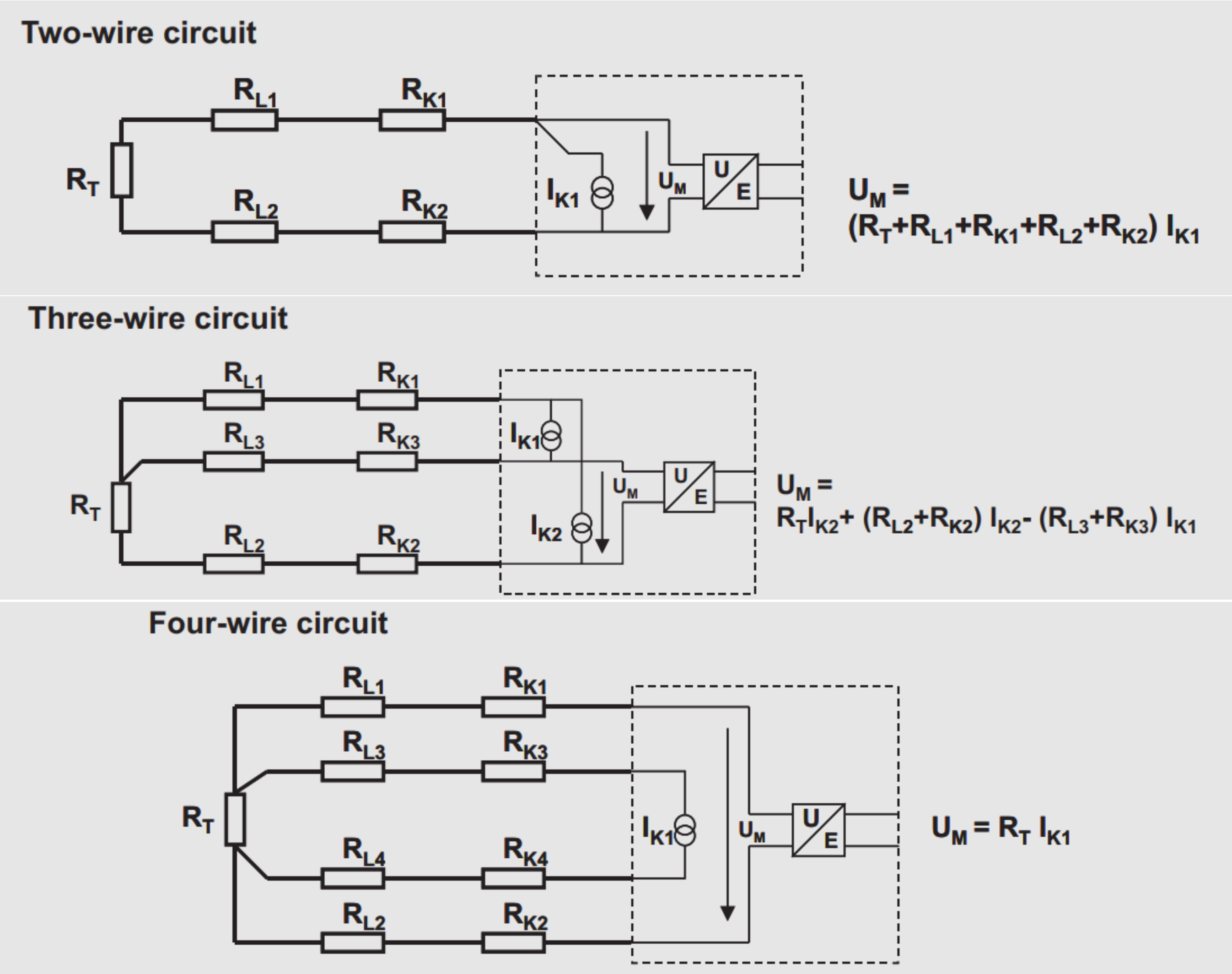


Figure 24. The three configurations available for the measurement of the resistance. Image from ABB Automation Products GmBH [89]. RTD is indicated as R_T in the schematics, connection leads and terminals resistance are indicated as R_L and R_K respectively.

- Two-wire circuit: as shown in the figure, when constant current is applied, the measured voltage takes into account also leads and terminals' voltage drop. Therefore, this configuration is not adequate for accurate measurement.
- Three-wire circuit: in this configuration, two current sources are used to compensate the effect of the voltage drops in the circuit. Solving the circuit by applying Kirchhoff laws, the effect of the other components (leads and terminals) vanishes remaining the contribution of the RTD. However, to realize identical elements is not always possible in the reality. So, some errors remain also in the three-wire configuration.
- Four-wire circuit: usually implemented in the gas grids, a constant current source is used. The voltage drop through the RTD is measured at the terminals of two high resistance connection leads reducing the amount of current and so the impact on the measurement.

One aspect to be considered in RTD sensors is the self-heating caused by the currents in the circuit. In fact, the resistance value is obtained by dividing the voltage drop that occurred when a known supplied current is supplied to measure the voltage variation. However, ISO 15970 requires an appropriate shape of the protective sheath and low supply current. Therefore, the effect is negligible for commercial products since an error of less than 0.02 °C would result at 1 mA.

Measurement performances

The measuring range of RTD is between -200 C to 1000 C for platinum materials while Nickel RTDs are limited to -60 C and 250 °C.

Two accuracy classes are available for Pt resistors: Class A and Class B according to EN 60751 in accordance to Eq. (41-42):

$$\text{Class A: } \Delta\text{T} = \pm(0.15\ °\text{C} + 0.002 \times |T|) \quad (41$$

$$\text{Class B: } \Delta\text{T} = \pm(0.30\ °\text{C} + 0.005 \times |T|) \quad (42$$

Assuming a PT100, for a “Class A” resistor when measuring 100 Ohm, the effective temperature has a tolerance of 0.15°C, i.e., between -0.15°C to +0.15°C. On the other hand, for a “Class B”, the actual temperature would be between -0.30°C to +0.30°C.

The thermal response time depends on the inertia of the thermowell. However, typical values for the T90 are in the order of some seconds.

Installation requirements

The rules for the installation of temperature sensors are reported in ISO 15970. The most important indications are reported below:

- The sensor is not in direct contact with the fluid. However, it is usually inserted within a thermowell (DIN 43772) to reduce potential damages due to corrosion, static load due to pressure, and vibration.
- While this configuration reduces the degradation of the probe, potential adverse effects on the measurement can verify. As indicated in the technical standard, when the thermowell is inserted into the moving fluid, heat transfer could be reduced due to dispersion if not minimized adequately using thermal insulation for 5DN upstream and downstream the location of the thermowell.
- The thermowell should be fitted into the pipe to almost 1/3 of the nominal inside diameter, even if a different length can be selected for a large nominal diameter pipe to reduce the vibration effect due to the flow if the cylindrical thermowell design is preferred to conical.
- The probe has to be completely inserted in the thermowell with a liquid filling the remaining volume to avoid the presence of air responsible for bad metrological performances and an increase in the response time.
- The RTD sensors are usually mounted perpendicular to the pipe wall. However, severe vibrations can verify, resulting in bending forces and resonant vibrations (ref. TR 61831) that have to be verified based on the wake frequency calculation.

3.5.2. Semiconductor Resistance thermometers

Thermistors have the sensing element consisting of a semiconductor (usually a mixture of sintered oxides) that has, as with resistance thermometers, an electrical resistance that varies with temperature. The difference is that the resistance varies nonlinearly with temperature but very markedly (for example, about ten times more than copper).

The working range of a thermistor is limited to 100÷200°C, much smaller than that of thermocouples and RTD sensors. For example, a thermistor with a resistance R_0 of 5,000 Ω at 25°C and a change in that resistance of the order of 4%/°C will have, for one degree of temperature change, a resistance change of 200 Ohm/C.

Thus, the big advantage of the thermistor is the high sensitivity, which allows for the reduction of the sensing element, which is miniaturized. The thermistor must be powered to measure its resistance change, and therefore, it is subject to the phenomenon of self-heating by the Joule effect, which must therefore be duly contained.

3.5.3. Thermocouples

The thermocouple consists of two different conducting metals welded together at one end. Placing the junction at a different temperature from that of free ends, a voltage appears between them (Seebeck effect). The higher the temperature difference, the greater the voltage. Assuming a constant Seebeck coefficient, a linear relationship between f.e.m. and the temperature differential is obtained.
Thus, the voltage measured on the thermocouple is proportional to a temperature difference. To have temperature indications referring to zero (i.e., zero degrees, a value typically provided by the manufacturer), it would be necessary for the cold junction to always be at the temperature of melting ice (0°C), a condition that can be replicated in the laboratory, but not for industrial measurements. Compensation circuits are used to overcome this limitation.

Measurement performances

The measuring range of thermocouples is between -200 C to 1800 C based on the combination of metals selected while the deviation limits depend on the measuring device Class (i.e., class 1; class 2 or class 3 defined in accordance with EN 60584).

3.6. Trace water humidity sensors

Basic information

The presence of trace water in the flow can be detrimental since a potential risk of water condensation or ice formation exists following a pressure reduction. The temperature of natural gas decreases due to the Joule-Thomson effect. For this reason, some plant configurations include a heater to reheat the gas upstream or downstreamthe pressure reduction valve. While hydrogen behaves contrarily to natural gas, water presence would still be critical since it negatively affects the heating value of the gas, reacts with reactants in the mainstream (like carbon dioxide or hydrogen sulphide) to produce acid products that worsen corrosion. Therefore, the presence of water has to be measured appropriately.

The measuring devices used for the purpose are based on two different measurands: the water dew point and the concentration of water in the natural gas. The correlation to calculate the water content from water dew point is well known and defined in the EN ISO 18453:2004 [91]. A lot of research is available in the literature regarding this topic. For example, Mckeogh (2020) [92]and Løkken (2013, 2015) [93], [94] reviewed the main technologies:

1. Reference methods:
    a. Chilled mirror
    b. Karl Fisher titration
2. Online measures:
    a. Impedance sensors
    b. Quartz microbalance
    c. Optical fiber Fabry-Perot interferometer
    d. Tunable diode laser.
    e. Electrolytic sensor.

Concerning the classification above, online measures require the connection to the gas pipe. Before to inject the gas samples in the measuring chamber, proper gas treatment is required. As shown in Figure 25 taken from Løkken (2015) [94], the treatment section can include:

- A heated sampling line between the main pipe to the measuring device to avoid condensation due to the operation in low ambient temperature. The measuring device's housing can be also provided by an internal heater for the same reason.
- Filters to avoid that any solid particle that can damage the sensor reach it.
- A downstream pressure regulator to properly control the gas sample pressure avoid overpressure within the sensor. A safety valve is also provided downstream to intervene in the case of a malfunction of the regulator venting the pressure outside.

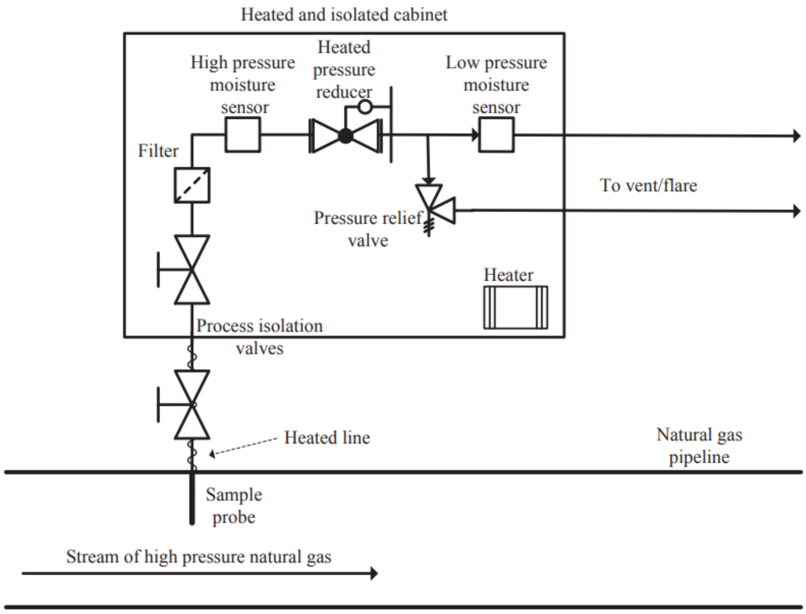


Figure 25. Schematic of a typical section installed upstream the trace water humidity sensor in online configuration. Image from Løkken (2015) [94].

The main characteristic of each category will be discussed in the following sections. No further comments will be reported for developing technologies like, for example, the one developed by Burgass et al. (2021) [95] that even if an accuracy of ±0.1 C is declared for the dew point, it is not commercially available yet.

3.6.1. Chiller mirror hygrometers

Basic information

The chilled mirror hygrometers measure the water or the hydrocarbon dew point temperature directly by cooling a surface, i.e., the mirror, until water condensation occurs. Reached the equilibrium between the water condensation and evaporation, the temperature of the mirror surface equals the dew point temperature. Automatic and manual models are available in the market.

As shown in Figure 26, thermoelectric cooling based on the well-known Peltier effect is usually implemented in automatic configurations. However, other cooling techniques can be implemented. In the case of thermoelectric approach, a multi-stack stage arrays of P-N junctions are arranged in a back-to-back orientation. Applying direct current to the P-N junctions, electrons leave the P junctions and a thermal flux occurs from the mirror to the junctions. Changing the polarity of the current, the mirror would be heated. The cooling process has to be stopped once the condensation equals the evaporation. To achieve this goal, visible or infrared light is emitted and reflected by the mirror to a photodetector. Due to the vapour condensation, liquid water deposits in the surface of the mirror creating a film. Usually, rhodium mirrors are used even if other materials (like platinum) are available in the market depending on the specific application. A variation of light reflections occurs as a consequence of the accumulation of water on the surface due to absorption and scattering. Therefore, less light is received by the photodetector that control a feedback control loop to maintain constant the mass of water, e.g., the equilibrium between the condensation and the evaporation. Finally, a four-wire platinum thermistor measures the mirror temperature. As shown in the figure, chilled mirrors require a defined gas flow rate (some litres per min) to ensure satisfying dew/frost formation and response time.

Automatic chilled measuring devices allow also the measure of hydrocarbon dew point. However, the optical surface of the mirrors has to be changed to take into account the different properties respect to the water.

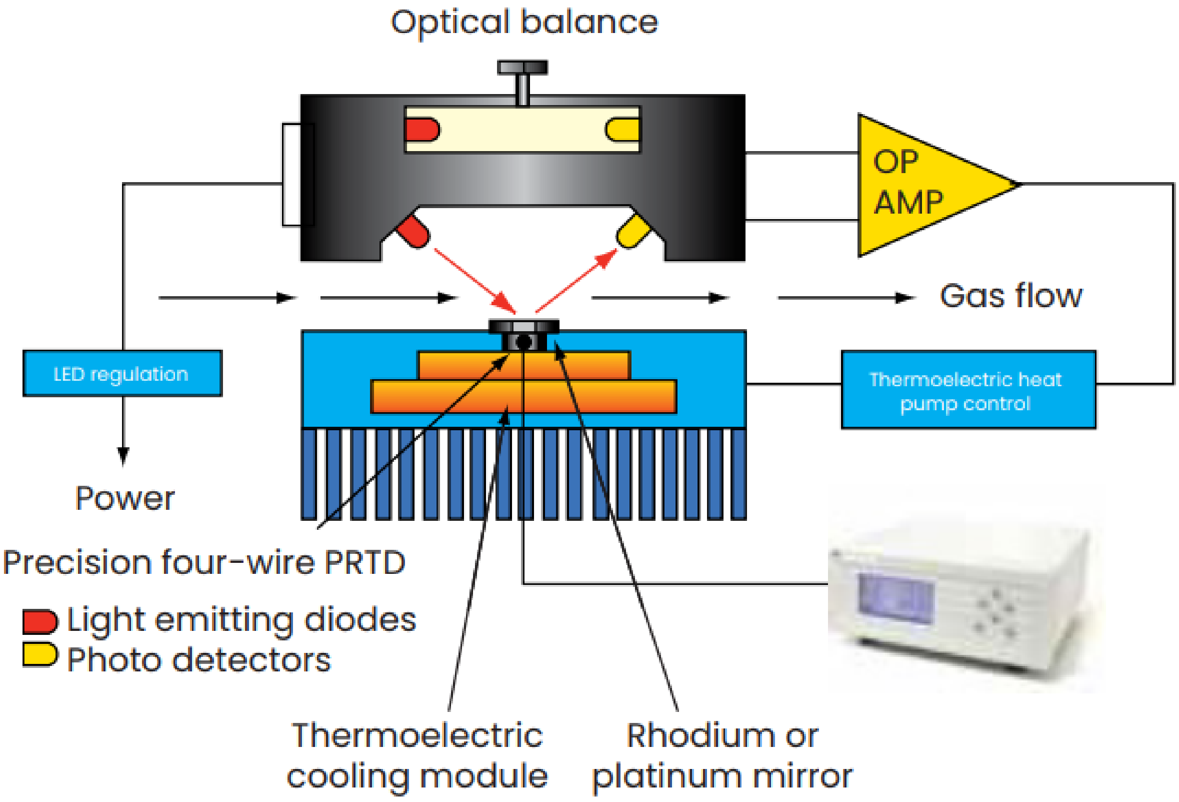


Figure 26. Schematic drawing of the working principle of an automatic chilled mirror. Image from Panametrics – Baker Hughes (2021) [96].

Manual chilled mirrors are cooled by a gas which temperature have been reduced exploiting the Joule-Thomson effect. Two examples of manual chilled mirrors are shown in Figure 27. In the manual configurations, no objective automatic control of water condensation occurs. On the other hand, the equilibrium between condensation and evaporation is only confirmed by the experience and knowledge of the operators in charge of the test. Even if several repetitions of the test are required to avoid outliers, the obtained results highly depend on the ability of the operator that has also to distinguish between water and hydrocarbon dew points [97]. So, manually chilled mirrors are not continuous measuring devices and are usually used for spot check of the automatic ones that are installed in the grid.

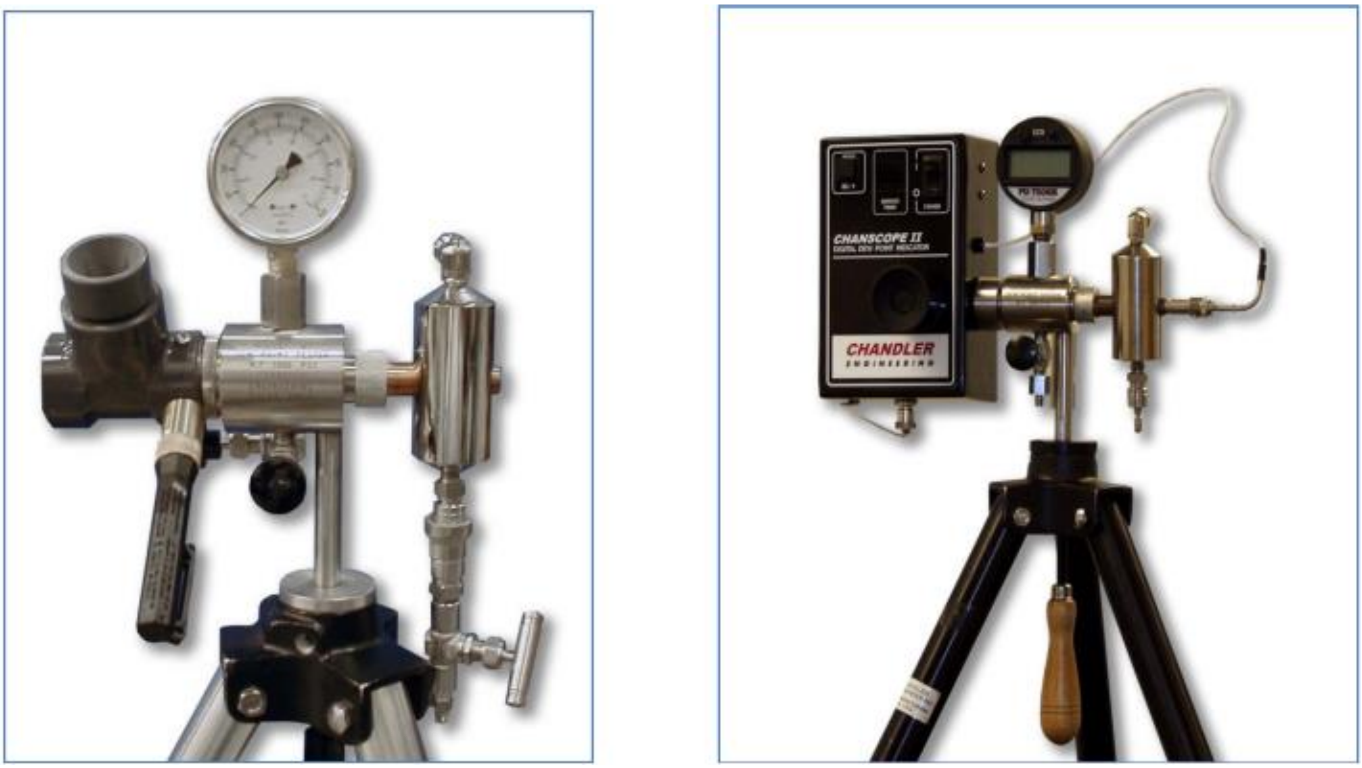


Figure 27. Two chilled mirrors in manual configuration. Image from Potter (2011) [97].

Detection performances

Commercial chiller mirror hygrometers measuring range usually reaches values down to -100 °C. Dew point accuracy, repeatability and sensitivity can achieve values of the order of ±0.5 °C or better, ±0.01 °C and ±0.03 °C. No or few measurements drift expected during the expected lifetime.

Maintenance requirements

Manual cleaning could be required due to the deposition of solid materials that tends to aggregate on the mirror when it is heated to the dry state after being cooled.

Installation requirements

These products are usually available for safe areas. Therefore, the measuring device has to be installed in a containment or in an inert purged volume to avoid the presence of flammable and/or explosive gases.

3.6.2. Karl Fisher titration

Basic information

The operation principle of Karl Fisher titration is based on the Bunsen reaction used to determine the sulphur dioxide content in aqueous solutions. Volumetric and coulometric titration are the two main methods for Karl Fischer titrations. When all the water is consumed, an excess of iodine is detected by an indicator electrode. The titrating agent is an iodine-containing solution in a burette for volumetric configuration. The water content is calculated using the titration volume and the mass of the water titrated. For coulometric titration, the iodine (I_2) is generated electrochemically by anodic iodide (I^-) oxidation in the titration cell. The water in the sample is calculated measuring the required current to complete the oxidation. The volumetric titration method is preferred for higher water contents between 1 and 100 mg). Coulometric titration is preferred for lower water contents in the range between 10 µg and 10 mg.

More details about the Karl Fisher titration methods for the measure of trace water in natural gas are included in ISO 10101 series [98].

3.6.3. Impedance sensors

Basic information

Impedance sensors are based on the capability of the water vapour to permeate through pores of a top film material varying the dielectric constant of the medium. The most used measuring devices in the natural gas sector are those based on the aluminium oxide sensors. Specifically, the sensor is realized with an aluminium base where a metallic oxide, like aluminium or silicon oxide, is deposited. On the top, a porous gold thin film is integrated. A schematic of the sensor is shown in Figure 28.

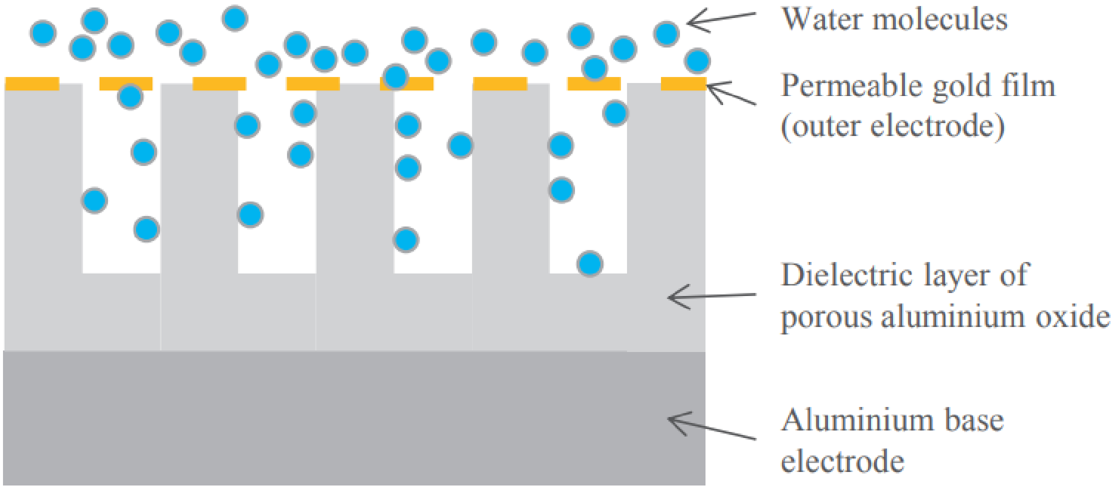


Figure 28. Schematic of an impedance sensor. Image from Løkken (2015) [94].

By applying a low AC voltage at fixed frequency, the resulting impedance is proportional to the partial pressure of the water. A calibration process is performed for each sensor to link the measured impedance with the dew point temperature.

Detection performances

Impedance sensors' range usually reaches values down to -110 °C. However, metrological performances in terms of accuracy, repeatability lower than chilled mirror are shown (i.e., ±3 °C or better based on the range; ±0.5 °C).

A typical annual drift up to ±2 °C is expected in these measuring devices requiring calibration.

Maintenance requirements

The measuring devices require frequent periodical calibration as a countermeasure of the measuring drift.

Installation requirements

Impedance sensors can be installed directly on the process withstanding high pressures up to 345 bar with no minimum flow requirements. Respect to the chilled mirror, explosion proof configurations that can be installed directly on the process exist minimizing the distance from the analyser, so the lag time. However, in the case of aggressive conditions, sample conditioning systems upstream the measuring devices are suggested to protect them.

3.6.4. Quartz microbalance hygrometers

Basic information

Quartz microbalance devices includes a quartz substrate coated with a hygroscopic polymer film. The quartz vibrates at its resonant frequency when a voltage is applied. When the sensor is immersed in humid air, water vapour is adsorbed by the hygroscopic film and resonant frequency changes accordingly. Higher is the humidity, greater is the adsorbed amount and the reduction of the resonant frequency. A schematic representation of the measuring device is shown in Figure 29.

Detection performances

State of the art standard measuring ranges reach Lower Range Value (LRV) down to 0.1-1 ppm$_v$. The Upper Range Value (URV) can easily extend up to 1000 – 2000 ppm$_v$. The typical accuracy of quartz microbalance devices is 10% of the reading up to 1-2500 ppm$_v$ and they can achieve very short response time thanks to the fact these devices do not require to reach the equilibrium conditions, i.e., steady state.

Maintenance requirements

The microbalance sensors require to be periodically re-zeroed due to hysteresis phenomenon. To do so, a "reference dry" gas mixture is used alternatively to the sampled gas. Measuring the frequency difference, the water vapour concentration is measured. The typical maintenance plan also includes periodic inspection and replacement of sample system filters and annual or bi-annual planned calibration checks.

Installation requirements

When operating a quartz microbalance, care has to be made in controlling gas sampled flowrate, temperature and pressure.

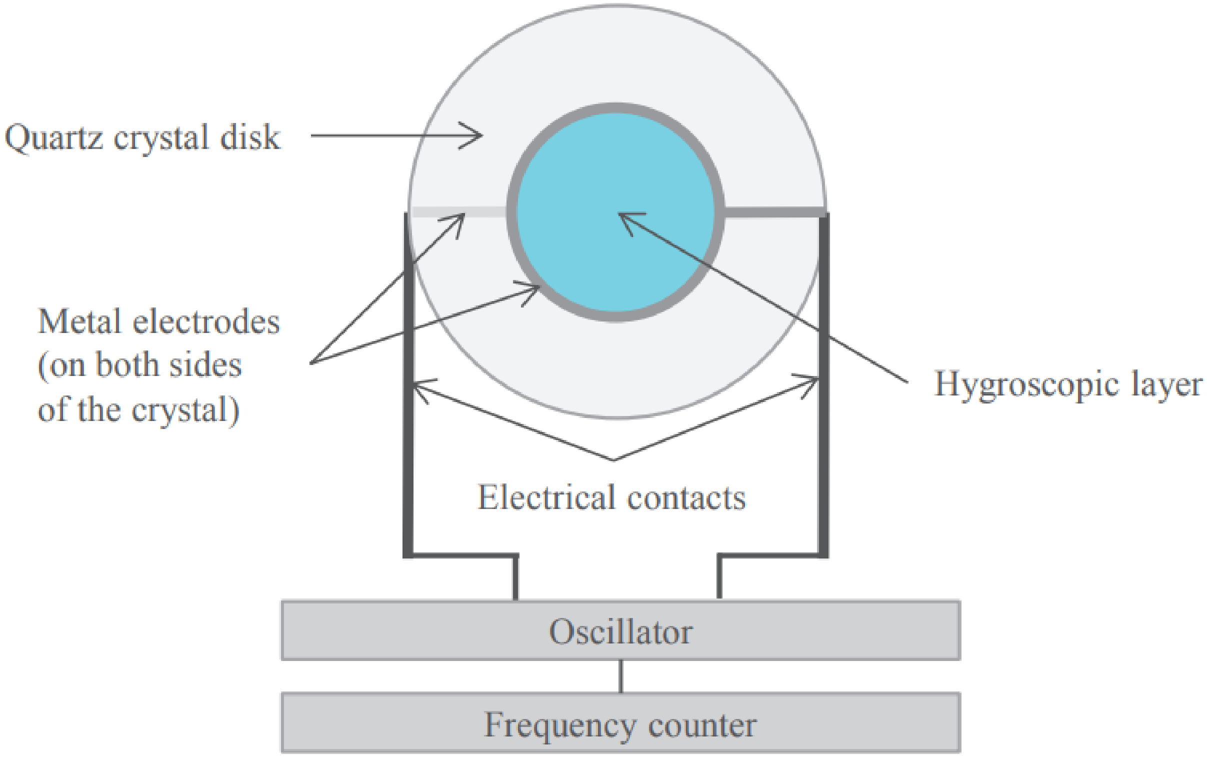


Figure 29. Schematic of a quartz microbalance hygrometer. Image from Løkken (2015) [94].

3.6.5. Optical fiber Fabry-Perot hygrometers

Basic information

Yeo et al. (2008) [99] reviewed this technology. Multi-layered structure including materials with high and low refractive indices like, for example, SiO_2 and ZrO_2 are used in the sensor head that is glass coated to selectively leave to permeate the water vapour. The optical signal is reflected by the mirrors at the ends. By increasing the water vapour pressure, more water molecules are absorbed in the pore structure of the sensor. The water that is adsorbed changes the refraction index of the layers, shifting the wavelength of the light beam in the fiber respect to reference value. A Polychromator detects the refracted light while the dew point is calculated on the base of the measured shift. A schematic representation of the principle of operation is shown in Figure 30.

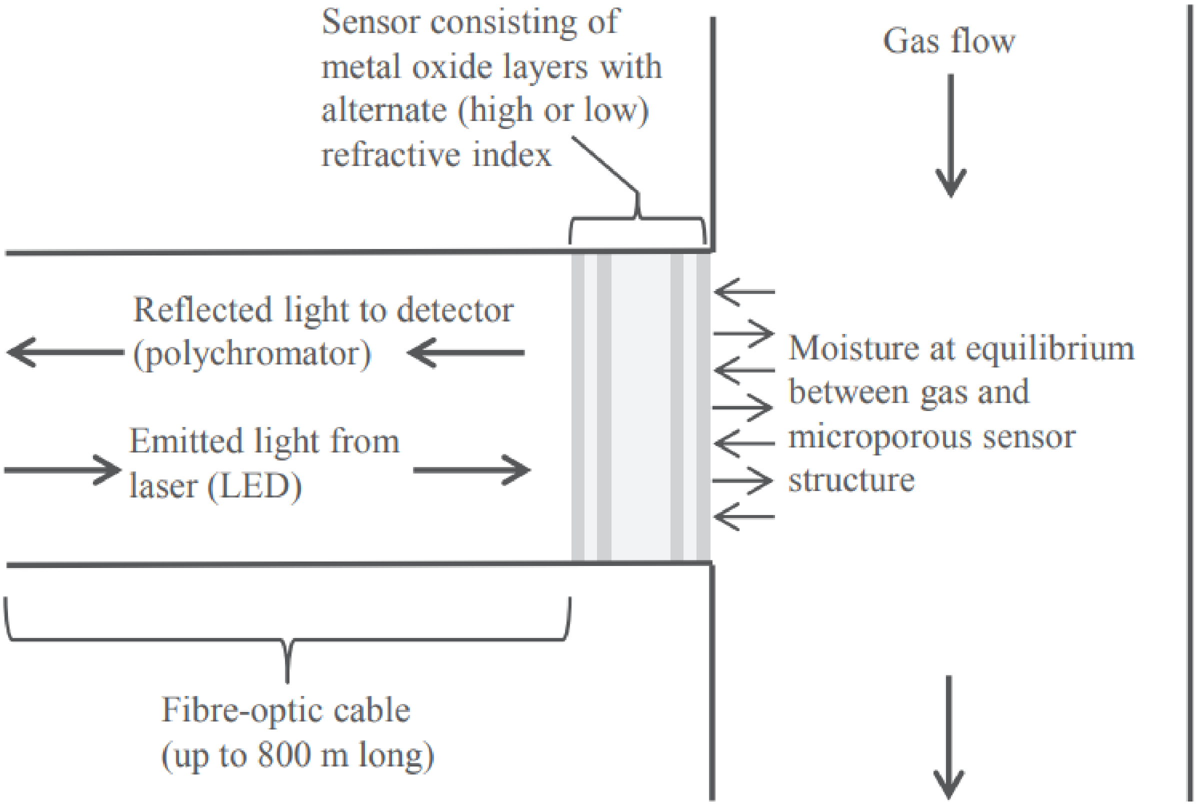


Figure 30. Schematic of optical fiber Fabry-Perot hygrometers. Image from Løkken (2015) [94].

Detection performances

The measuring devices can be applied to a range up to 80% ensuring an accuracy up to ± 2C and a response time of less than a minute.

3.6.6. *Tunable Diode Laser Absorption Spectometers*

Basic information

Tunable Diode Laser Absorption Spectrometers (TDLAS) are continuous trace water measuring devices based on the Beer-Lambert law. The Beer-Lambert law states that the intensity of light moving through an absorbing medium is attenuated. In the case of TDLAS, a diode laser installed in a hermetically sealed and dry chamber stimulates the release of photons by recombining electrons and holes by supplying a current into a p-n junction. The diode laser is controlled to produce light with a wavelength near the infrared. The light moves through a stainless-steel chamber, and a gold-plated mirror reflects it down to a photodetector, where the attenuation is measured. A schematic representation of the principle of measure is shown in Figure 31.

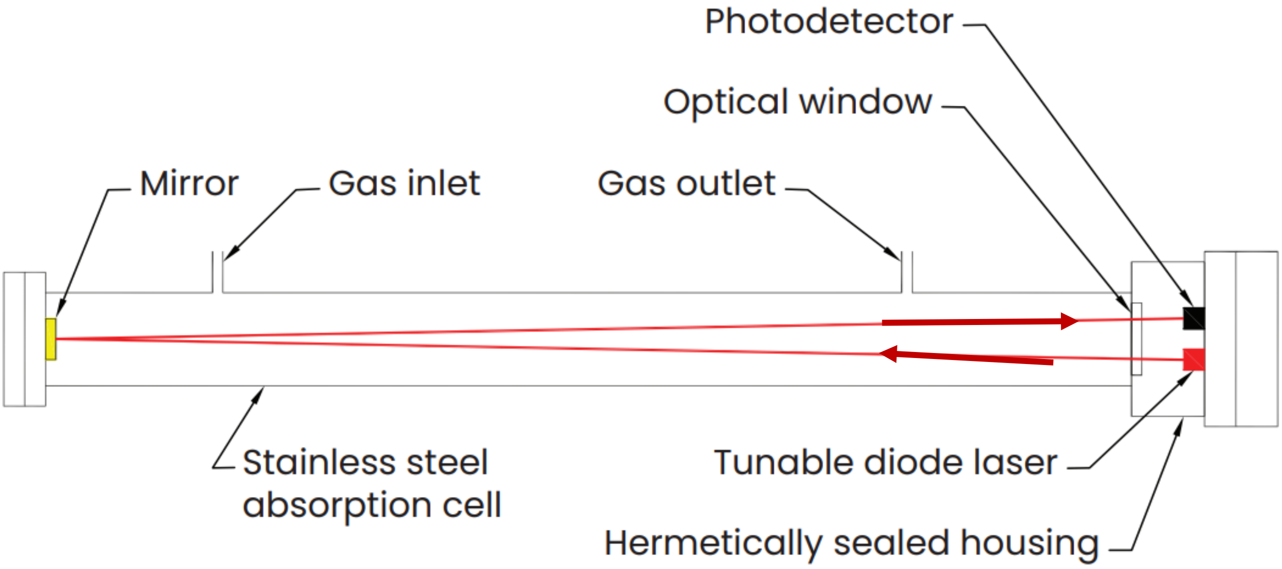


Figure 31. Principle of operation of a TDLAS. Image from Panametrics – Baker Hughes (2021) [100].

The higher is the water concentration in the sampled gas, the greater is the attenuation. When a water molecule impacts with a photon characterized by a specific energy proportional to its wavelength, the photon is absorbed. Therefore, the measure assesses the energy absorbed when light is passed through a sampled gas. However, since methane absorbs in the same frequency range as water, the technique has yet to be so employed in the natural gas industry requiring very high-resolution devices to detect the difference in absorption peaks. Combining the information about the gas temperature and pressure, the water concentration is calculated.

Detection performances

State of the art standard measuring ranges reach lower range values (LRV) down to 5 ppm_v even if some special devices can extend down to 100 ppb_v. The URV can easily extend up to 2000 – 5000 ppm_v. Standard accuracy is ± 2% of the reading (mole fraction or ppm_v). Furthermore, TDLAS measuring devices are characterized by very short response time (< 2 sec), even if time is required to complete absorption cell purging when changing the sampled gas. Therefore, the system response time depends on the total length of the sampling tube that connect the process to the measuring devices.

High long-term stability is ensured by the absence of sensing surface is degraded due to exposure to the gas.

Pressure reduction is required upstream to reduce the pressure of the sampled gas down to values in the order of 200 kPa, e.g., 2 bara.

Maintenance requirements

Low efforts are expected for TDLAS if the gas samples are cleaned. However, the presence of liquid contaminants could be responsible for signal dispersion causing erroneous measurements. The typical maintenance plan includes periodic inspection and replacement of sample system filters and planned calibration checks every three to five years.

Installation requirements

The length of the tubing connecting the process and the measuring device must be as small as possible to minimize the system response time. Other proper installation suggestions include the use of tubing of stainless-steel material and avoiding other materials like, for example, copper to prevent that ambient humidity from permeating through the wall and affecting the measurement. Also, attention has to be given to avoiding water condensation in the sampling tubing upstream of the devices. For this purpose, heaters can be installed when very low temperatures are expected.

3.6.7. Electrolyte sensors

Basic information

Electrolytic sensors have been a well-known technology since the 1950s when Dr. Keidel described the operation principle, and they can be considered the first measuring devices to be used for the online measurement of trace water. Also known as phosphorous pentoxide (P_2O_5) sensors, they consist of two wire platinum or rhodium electrodes helically wound around an insulating quartz tube core and coated with P_2O_5. Since it shows a hygroscopic behaviour, P_2O_5 coating absorbs the water vapor transported by the sampled gas. Water electrolysis is obtained by applying a DC voltage to the two electrodes. Due to the voltage difference, water is divided into hydrogen (at the negative anode) and oxygen (at the positive anode). Simply, water electrolysis occurs. The gases finally diffuse back into the gas stream where they are carried out of the cell.

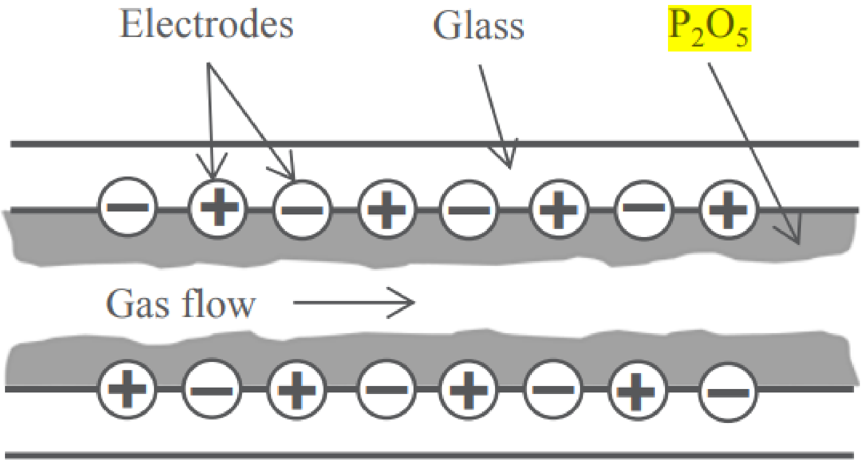


Figure 32. Schematic of an electrolytic cell hygrometer. The symbols "+" and "-" schematically represents the two wounded electrodes. Image from Løkken (2015) [94].

The higher the amount of water, the greater the current required to complete the electrolysis phenomenon under the Faraday law. To ensure accurate measures, the sampled gas's temperature, and pressure must be carefully controlled.

Detection performances

Measuring accuracy of almost ±10% of the reading are declared in the state of the art. Long response times are also expected for this technology.

Maintenance requirements

The P_2O_5 coating deteriorates in the presence of high trace water concentrations. To recover the metrological performances, the cell has to be cleaned and recoating by the manufacturer.

3.7. Leak detectors

Leakages in pressurized systems are responsible for energetic losses to a remarkable extent. Therefore, estimations concerning leakage losses are of economic and societal importance. In addition, leakage from the natural gas grid is estimated to be a major source of CH4 in the atmosphere, contributing significantly to the greenhouse effect. Current natural gas leak detection techniques mainly include diverse techniques, each with advantages and disadvantages.

One approach includes using chemical sensors, such as chemiresistive sensors, that are based on the change of electrical properties of the devices and are part of the electrochemical sensor class. Other leak detectors integrate sensors working with different operating principles with respect to chemiresistive devices, including pellistors, photoacoustic sensors and devices that exploit optical transduction mechanisms. These different sensors are widely used by the companies that produce leak detectors, including SENSIT Technologies, INFICON, Fluke, etc. Below are brief descriptions and characteristics of the most used technologies currently employed for monitoring leaks in natural gas transmission and distribution pipelines. Further information can be found in standard BS EN 60079-29-2:2015.

3.7.1. Metal-Oxide-Semiconductor (MOS) sensors

Basic information

The Metal-Oxide-Semiconductor (MOS) gas-sensing mechanism is based on the change in the conductivity of the device-sensing component in the presence of reducing or oxidizing gasses. The sensing layer is directly exposed to the target analytes in these sensors. The interaction between the sensing layer and analytes results in changes in the physical and chemical properties of the sensing material at elevated temperatures, leading to a device conductivity change. More details are included in the work of Barsan et al. (2007) [101].

MOS sensors can be manufactured as portable devices that are operated at elevated temperatures and used in a large variety of applications. The sensing material is usually deposited as a polycrystalline film or layer on a substrate with integrated electrodes and heating. Chemiresistive sensors generally provide the advantages of high sensitivity, measurement simplicity, stability, and low cost.

Detection performances

The concentration of CH_4 that can be detected with high accuracy is in the range of 1-50.000 ppm. However, elevated operating temperature (150°C–500°C) and the electrical nature of the device make this technique potentially dangerous for the detection of flammable and explosive compounds. Furthermore, the presence of O_2 is fundamental for the working principle of MOS gas sensors, and its absence prevents the sensor from operating correctly. The potential cross-sensitivity with other environmental gaseous compounds (CO, VOCs, etc.) might affect the performance on the detection of CH_4.

Maintenance requirements

Due to baseline drift, lack of performance stability over time, and the possibility of being poisoned, chemoresistive gas sensors must often be recalibrated and their detection capabilities verified over the time using a specific methane/GN standard.

Market

This kind of sensor is integrated by several companies on their monitoring devices. The cost of a MOS gas sensor is in the range between 20-150 € while the cost of a leak detector based on these sensors can be of the order between 500-2.500 €.

3.7.2. Photoacoustic gas sensor

Basic information

Turbulence in fluids turns out to be an acoustic source. That means that leaks can be acoustically found and have a specific acoustic signature. Ultrasound frequencies are used (relatively narrow bands around 40 kHz). Some providers on the market offer testing equipment based on relatively simple technologies. A pragmatic reason for the simple technology is the availability of cheap sensors. The users accept some disadvantages. A further important feature of leakage testing is the transformation of the (narrowband) ultrasound to audible frequencies [102], [103]. The ultrasound signal is heterodyned to the audible range giving just qualitative information. Any spectral information is lost. This heterodyned signal is used to estimate (quantify) the loss by leakages. It should be emphasized that there is no physical relationship for this kind of quantification. However, it may, empirically, work in some very special situations.

Detection performances

The fast and high sensitivity give advantages in this method compared to others. In addition, this method also offers accurate leak location and low false alarm rate. For instance, acoustic sensors can detect a 2.5 cm^3/sec leak at 7 bars from up to 10 meters. On the other hand, high background and noise condition will affect the actual leak and produce false alarm when the leak is too small.

Maintenance requirements

A periodic recalibration of the device should be planned. In addition, a routine verification of the sensing performance over time should also be foreseen, due to potential failure or breakage of some of the MEMS microphones that compose the array.

Market

This kind of device (MEMS microphone for gas detection) is used and sold by several companies. MEMS microphone array cost is about 50-500€, while the cost of the final device based on the MEMS microphone array is about 5.000-25.000 €.

3.7.3. Pellistors

Basic information

A pellistor is a solid-state device that is employed to detect gases that are either flammable or have a notable variation in thermal conductivity compared to air. The term "pellistor" is coined by combining the words "pellet" and "resistor". The detection element is composed of small ceramic pellets loaded with a catalyst, and their resistance changes when exposed to gas. Many pellistors require gentle heating during usage, hence they are designed as four terminal devices with two connections for a small heating element and two for the sensor itself. To ensure safety and prevent explosions, the sensitive element is typically enclosed in a housing made of wire mesh, where gas can penetrate the permeable mesh, but the passages are too lengthy and narrow to support the spread of a flame. Pellistors are divided in two main categories, depending on the working principle: i) the catalytic pellistor, employed in the catalytic bead sensor, works by combusting the target gas. The resulting heat generates a proportional change in the resistance of the detecting element of the sensor, indicating the gas concentration; ii) the thermal conductivity pellistor works by measuring the change in heat loss detecting element in the presence of the target gas, which is transduce to an electrical resistance change.

Detection performances

This kind of sensors can be used for detecting a high range of CH_4 concentration, which depends on the device calibration. Usually, they are employed for detecting high CH_4 concentration, from 2.2% to 100%, with a resolution of 0.1% and an accuracy of ±5%. The lack of selectivity of the pellistor involves the potential cross-sensitivity with other explosive or environmental gaseous compounds (H_2, propane, VOCs, etc.), which might affect the performance of the device on the detection of CH_4

Maintenance requirements

A periodic recalibration of the device should be planned, due to the lack of sensor response reproducibility over the time.

Market

This kind of device is used and sold by several companies. The simplicity of pellistor makes this sensor extremely cheap, whose cost is typically in the range of 1-20 €. The cost of the final device based on pellistor is much higher (several hundred €), because it should include a specific and accurate air sampling tool and a sophisticate algorithm able to overcome the pellistor performance drawbacks and improve the accuracy of the data collected.

3.7.4. Tunable Diode Laser Absorption Spectroscopy gas sensors

Basic information

Trace gas sensing and analysis by Tunable Diode Laser Absorption Spectroscopy (TDLAS) has become a robust and reliable technology for industrial process monitoring and control, quality assurance, environmental sensing, plant safety, and infrastructure security.

TDLAS measures the wavelength-dependent absorption of light through a gas medium. As the name implies, the technique usually employs a tunable-wavelength diode laser as the light source. When the wavelength of light matches one absorption line of a gas species present in the sample, the photodetector records a reduction in the light intensity. When the gas concentration is ultra-low, the induced change in transmission becomes extremely small and difficult to detect sufficiently fast. The sensitivity of TDLAS is significantly enhanced by modulating the current of the laser, which leads to a modulation of the wavelength and light intensity. The information about the absorption response is then recovered by demodulating a signal from the photodetector at the modulating frequency and its second-order harmonic [104].

Detection performances

Sensors incorporating well-packaged wavelength-stabilized near-infrared (1.2 to 2.0 µm) laser sources sense over a dozen toxic or industrially-important gases. A prominent emerging application for TDLAS is standoff sensing of gas leaks, e.g., from natural gas pipelines. The methane detection range depends on the device calibration and settings and usually ranges from 1 to 50.000 ppm.

Maintenance requirements

A periodic recalibration of the device should be planned. Routinary maintenance of the laser source should be foreseen.

Market

TDLAS gas sensors are used by different companies. The approximate cost for TDLAS device for CH_4 detection is about 10.000-25.000 €.

3.7.5. Non-dispersive infrared gas sensors

Basic information

Non-dispersive infrared (NDIR) is an effective method for measuring methane since it does not rely on the presence of oxygen. It is non-dispersive in that no dispersive element (e.g., a prism or diffraction grating as is often present in other spectrometers) is used to separate (like a monochromator) the broadband light into a narrow spectrum suitable for gas sensing. Most NDIR sensors use a broadband lamp source and an optical filter to select a narrow band spectral region that overlaps with the absorption region of the gas of interest. In this context, the narrow may be 50-300 nm bandwidth.

Detection performances

Modern NDIR sensors may use Microelectromechanical systems (MEMs), or mid-IR LED sources, with or without an optical filter. Methane monitoring can be achieved with infrared gas sensors because the gas absorbs IR light at a specific wavelength, specifically in the ranges of 3.2-3.5 µm and 7.3-8.2 µm. The detection range of an NDIR sensor depends on the device calibration and settings. Usually, it goes from 0 to 10% vol.

Maintenance requirements

A periodic recalibration of the device should be planned. A routinary maintanance of the NDIR source and detector should be planned.

Market

NDIR gas sensors for methane detection are produced by different companies, including Hamamatsu and Edinburgh Sensors. Differently to other technologies, the cost range of sensors and related detectors are not easily quantifiable.

4. GAS METERING IN TRANSMISSION AND DISTRIBUTION GAS NETWORKS

4.1. Methodology: data collection and analysis

Data and information about the measuring devices currently installed in gas transmission and distribution networks have been recovered from the industrial partners within the Consortium during the activities of Task 1.1. In this phase, the investigation has been limited to information such as model, manufacturer, etc., that have been considered easy to be recovered and compared. To date, each partner manages data differently, resulting in different databases and available data. Through the data, it is possible to create a preliminary overview that will be used as input for the selection and prioritization of the measuring devices to be tested together with the information deriving from Task 1.2.

All the reported data have been anonymized and normalized for confidentiality and security reasons.

4.1.1. Gas transmission networks' data collection

Regarding gas transmission infrastructure the following data were asked:

- Gas meter:
    - Model;
    - Manufacturer;
    - Size (i.e., maximum flowrate)
    - Nominal diameter (when available)
    - Installation year (when available)
    - Assumption:
        - Process vs Fiscal gas meters: both types are installed in the networks. For the purpose of the document, process gas meters include all gas meters installed by the gas operators and used to control/regulate a process in the plant or to provide a fiscal measure of the gas that is consumed in operators' plants like for example, to reheat the gas stream to avoid hydrate formation due to the pressure drop in the pressure reducing valves. Because of the different data available in the database owned by the partners, in this stage, only fiscal meters have been considered. This assumption relies on the fact that the ratio between the number of process and fiscal gas meters is between 1:10 and 1:50. Furthermore, the impact of hydrogen on those meters has less importance with respect to billing issues deriving from an erroneous measurement in fiscal gas meters.
        - Some discrepancies between models, manufacturers and size appear during the data analysis. Where possible, based on technical information on the datasheet, the discrepancies were solved. In those case where it was not possible, the data have been collected as "unknown".
- Electronic volume converters and Flow Computer, gas chromatographs, trace water humidity sensors and leak detectors:
    - Model

- Manufacturer

Even though the Consortium is aware that having more information would have increased the level of detail of the investigation, this process would have more time available to recover the data from specific site visits in the field. For example, since almost 20.000 fiscal gas meters are currently operated by the four TSOs directly involved in the project as consortium partners (Snam, Enagás, GRTgaz, Gaz-System), the time required to proceed with a deeper analysis would have been too much challenging. Furthermore, the proposed approach would not impact the connected tasks. For example, the measuring devices in Task 2.1 will be selected based on the information derived from these activities. When no information is available for selecting a specific condition, the worst operative condition will be considered based on the knowledge of the Consortium and the Stakeholders Advisory Board members, as well as the knowledge derived from task 1.2.

4.1.2. Gas distribution networks' data collection

Regarding gas distribution a different approach was necessary. First of all, only one gas DSO is involved as a partner in the THOTH2 consortium. In addition, since each country has specific regulations, extending the results to other countries would result in an inaccurate picture of the state of the art. Last but not least, at least in Italy, the meters installed in the grid are periodically selected by tender. Therefore, the gas DSOs market is continuously evolving, resulting in very challenging to design a static picture. To counteract this situation, it was decided to design a simplified survey to obtain information from relevant stakeholders also outside the Consortium aiming to collect information, leveraging on the THOTH2's Stakeholders Advisory Board, participated also by relevant European technical associations (e.g., Marcogaz). More details about the survey are reported in the Appendix. To increase the possibility of success, it was asked to the association Marcogaz to share the survey with its members discovering the importance of collecting the greatest number of answers as possible. To date few answers have been received by the Consortium. Therefore, since the development of the methodology has been the most important product of Task 1.1 activities, it was decided to maintain open the survey and to stress again the importance of collecting the information. An updated version of this report will be made available if relevant answers will be collected in the next weeks.

4.2. NG transmission system

4.2.1. Fiscal gas meters

4.2.1.1. Installed technologies

According to the previous chapter, different gas meter technologies can be installed in the gas networks to perform fiscal purposes (turbine, rotary piston, ultrasonic, and other). Based on the collected information, 0.114-0.356 fiscal meters per km are installed in the investigated TSO networks. The value reduces to 0.003-0.03 for gas meters used for process purposes. As shown in Figure 33 and in Figure 34, gas turbine meters are the most installed technology for all four TSOs. This result can be explained by this technology's extended flow rate range and metrological performances summarized in the previous dedicated chapter. Transmission networks are characterized by high flowrate, and flow pulsations typically occur when directly connected to large industrial customers and seasonal (or periodical) gas consumers. The maximum percentage has been calculated for TSO2, where the 95% of the installed fiscal gas meters are turbine type, followed by ultrasonic meters. A similar result has also been calculated for TSO4. However, in this case, also rotary gas meters play a role, even negligible, in the total market, with 7% of the meters installed. A different market share has been identified for TSO1 and TSO3. Turbine meters remain the most installed technologies, but the percentage of rotary piston gas meters in those two cases is significant. Furthermore, ultrasonic gas meters overcome 10% of in TSO3 case while also Coriolis meters are installed. It has to be noted that, even if not represented, two of the four TSOs indicated also fiscal meters for own purposes. The most used technologies in this case are diaphragm/bellows, rotary piston and quantometers. Focusing on TSO3, the percentage of installed gas meters as a function of the technology and the manufacturing year was investigated. More than 21.8% of the installed meters are in operation from before 2010, i.e., 13 years ago. Of these, turbine meters represent almost 15% of the total share. Therefore, the information about substitution philosophy should be carefully considered when selecting and prioritizing the meters to be tested in Task 2.1.

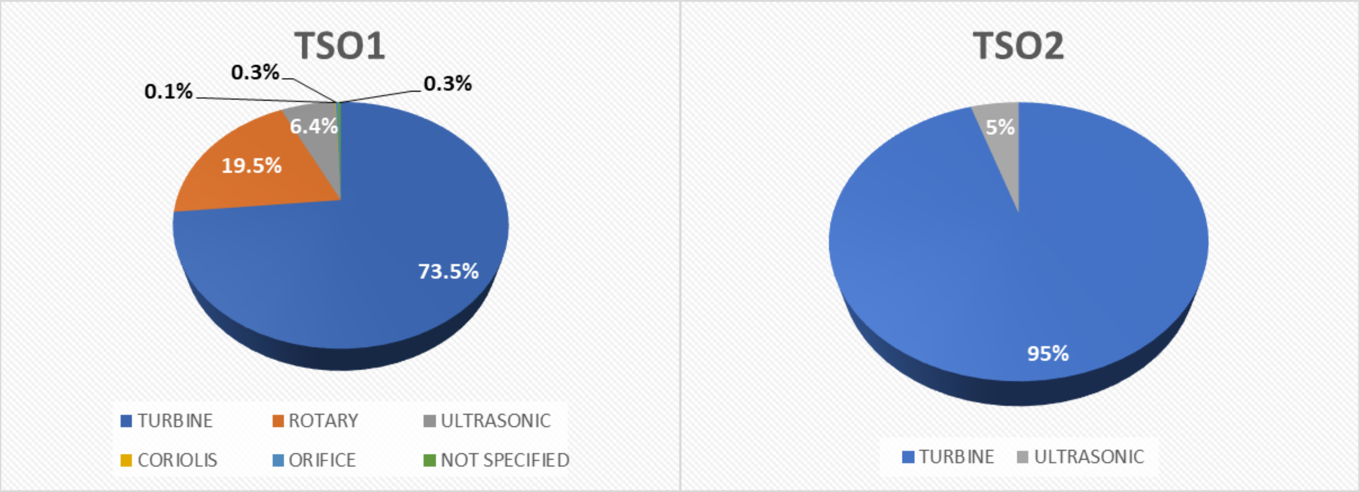


Figure 33. Installed gas meters divided per type of measuring technology for TSO1 and TSO2.

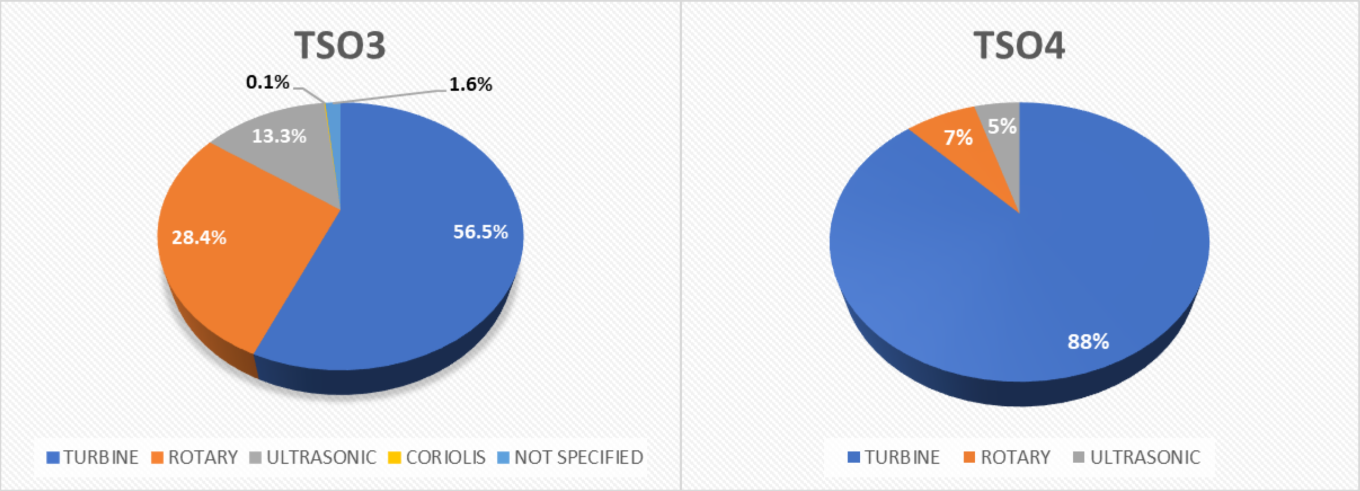


Figure 34. Installed gas meters divided per type of measuring technology for TSO3 and TSO4.

A similar trend has been also recognized by Walter et al. (2021) [105] during the HIGGS project. Specifically, Walter et al. (2021) recognized that turbine gas meters as the most implemented technology (66.3%) in Europe, followed by rotary piston gas meters (20.6%), venturi, ultrasonic and diaphragm/bellows type (5-7%). However, Walter et al. (2021) indicated an average European concentration equal to 35 gas meters per 1000 km, i.e., quite smaller than that calculated based on the data provided by the four TSOs members of the THOTH2 Consortium.

4.2.1.2. Installed gas meters' models

Several gas meters' models are currently installed in gas transmission networks. Table 5 shows the models of fiscal gas meters currently operated by the four investigated TSOs for each measuring technology. The distribution between the manufacturers is reported in Figure 35. For confidentiality reasons, the models are not specified in the figure. As shown in the Figure, a wide distribution appears for TSO3 for turbine and rotary gas meters.

Table 5. Main models of fiscal gas meters implemented in gas TSO grids. Gas meters used for process applications not indicated.

Turbine meters		**Rotary meters**	
Manufacturer/Vendor:	Model:	Manufacturer/Vendor:	Model:
COMMON	CGT	COMMON	CGR
ELSTER-INSTROMET-HONEYWELL	SM-RI-X	ELSTER-INSTROMET-HONEYWELL	RMT
ELSTER-INSTROMET-HONEYWELL	TRZ	ELSTER-INSTROMET-HONEYWELL	RVG
ELSTER-INSTROMET-HONEYWELL	TRZ2	ELSTER-INSTROMET-HONEYWELL	RABO
FMG	FMT	FMG	FMR
ITRON-ACTARIS-SCHLUMBERGER	FLUXI 200/TZ	ITRON-ACTARIS-SCHLUMBERGER	DELTA
PIETRO FIORENTINI-DRESSER	IMTM-CT	PIETRO FIORENTINI-DRESSER	IM-RM
RMG	TRZ03	ROMET	IRM
SENSUS	MARK II TURBOMETER	ROMET	RM
TANCY	TBQM	VEMMTEC	OMEGA VI
VEMMTEC	IGTM		
Ultrasonic meters		**Coriolis meters**	
Manufacturer/Vendor:	Model:	Manufacturer/Vendor:	Model:
CALDON	CAMERON LEFM 380Ci	ENDRESS HAUSER	PROMASS F300
DANIEL	UNKNOWN	ENDRESS HAUSER	PROMASS F500
ELSTER-INSTROMET-HONEYWELL	QSONIC		
ELSTER-INSTROMET-HONEYWELL	SENIOR SONIC		
EMERSON	T200		
EMERSON	UNKNOWN		
ENERGO FLOW	GFE-202		
FMC TECHNOLOGIES-INTERGROTECH-TECHNIP FMC	MPU		
KHRONE	ALTOSONIC V12		
KROHNE	OPTISONIC 7300		
PIETRO FIORENTINI-DRESSER	FIOSONIC		
RMA	ECO SONIC X12		
SICK	FLOWSIC500		
SICK	FLOWSIC600		
TRANSUS INSTRUMENTS	UIM 4F		

As shown in the figure, some models prevail over others for each measuring technology type. For example, "model 1" turbine meters manufactured prevail in TSO1, while "model 3" is the most installed for TSO2 and TSO3. "Model 2" is instead the most installed in TSO4's grids. About rotary piston gas meters, while TSO2 uses the technology only to supply internal process and so it has been excluded in the investigation, "model 1" is the most present in TSO1, while "model 2" and "model 5" are the most implemented in the grid managed by TSO3 and TSO4. Regarding ultrasonic gas meters, the predominant technologies are the same in all four TSOs. Specifically, "model

1" and "model 3" appear to be the most installed. However, "model 2" also has a significant market share in TSO1 grids. Last, Coriolis meters for fiscal purposes are installed only by TSO3.

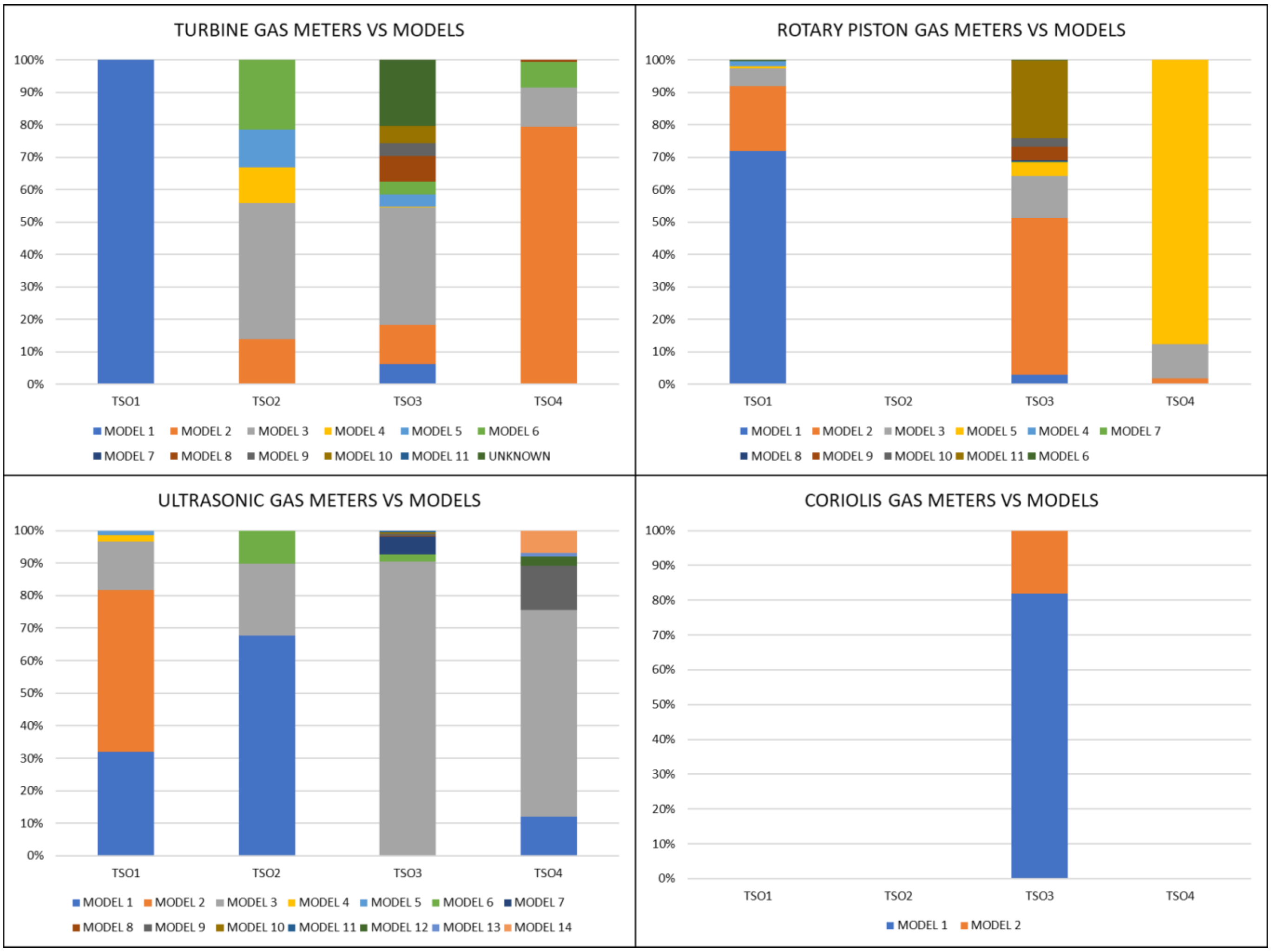


Figure 35. Market share for the four analysed gas TSOs.

4.2.1.3. Installed size (G)

A graphical summary of the size of the fiscal gas meters installed in the gas grids is shown in Figure 36 and in Figure 37. As shown in Figure 36, the main percentages of meters are in the range between G100 and G2500. Furthermore, ≤G65 gas meters are relevant only for TSO1 and TSO2. It has to be remembered that this percentage doesn't take into account the data regarding fiscal gas meters or process meters used for own purposes but only the gas fiscal meters that allow gas delivering from the transmission grid.

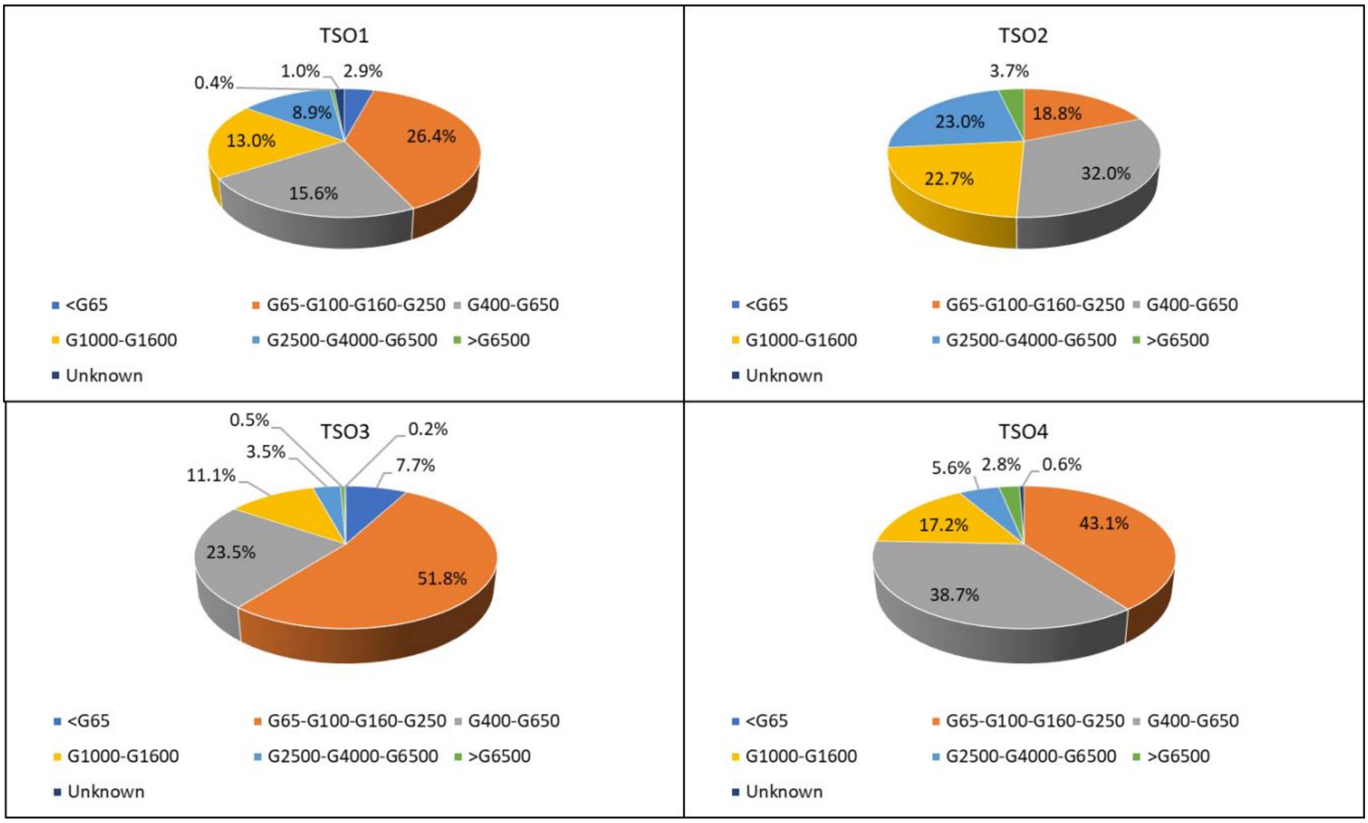


Figure 36. Fiscal gas meters' fiscal size.

Focusing on measuring technology types, a similar trend is present for all four TSOs as shown in Figure 37. A part from TSO2, where rotary gas meters are limited to size ≤G65, in other TSOs, rotary meters are installed up to G650 (TSO3). However, in the range between G100 and G2500, turbine gas meters are the most implemented technology in the grid, followed by rotary gas meters in the lower range and ultrasonic gas meters in the upper range. Over G6500, ultrasonic gas meters are the most present technology, while in G4000 and G6500 sizes, in two of the investigated TSOs (TSO1 and TSO4), ultrasonic meters are the most implemented.

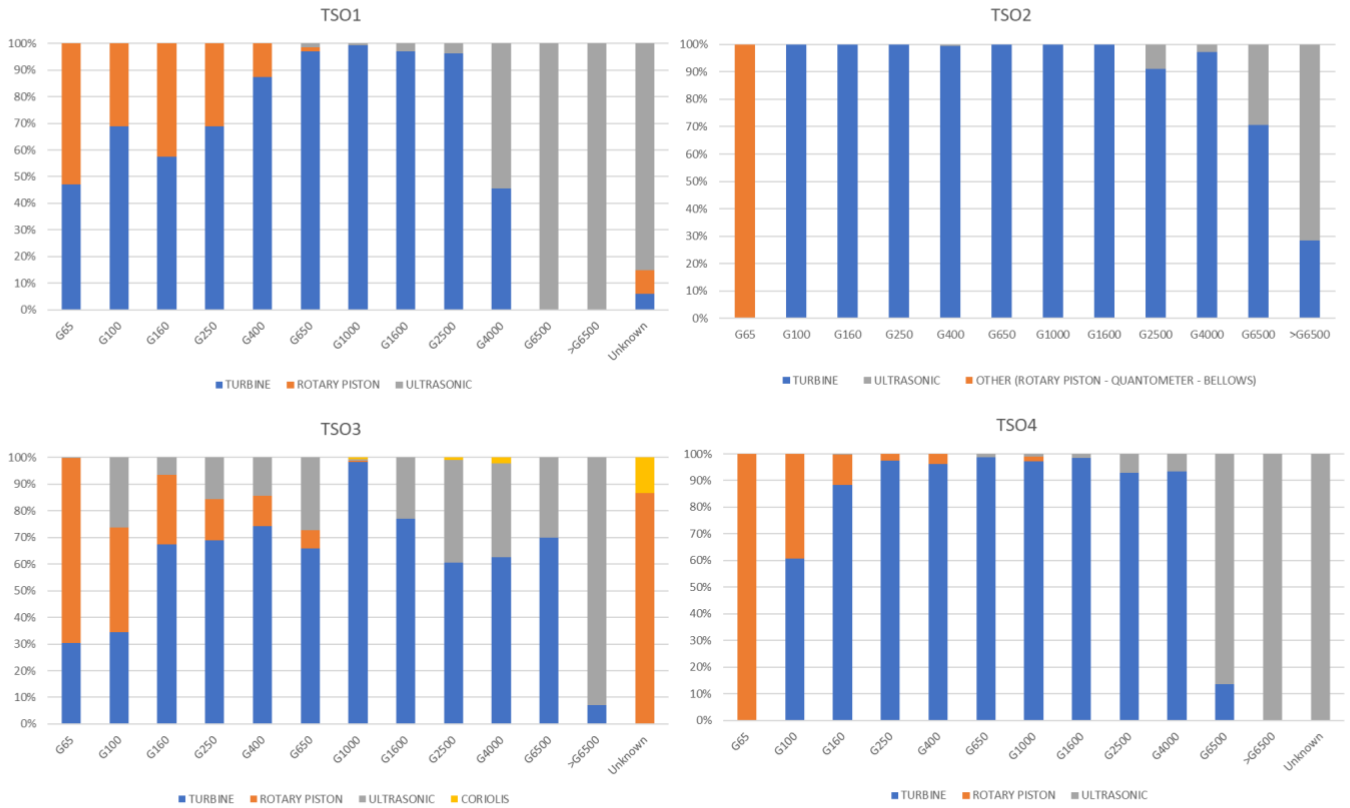


Figure 37. Size of the fiscal gas meters installed in the gas grid of the four investigated TSOs.

4.2.2. Gas volume converters and Flow computers

Almost 100 different models of converters are installed in the four transmission grids that have been investigated. The complete list of volume converters declared by the four TSOs is reported in Deliverable D1.2. Regarding gas volume converters and Flow computers' distribution, a very different situation appears among the four investigated TSOs in terms of number of models. The complete list of models is reported in Table 6. Since many of these models are installed in a minimal percentage, the analysis has been limited only to those models installed in a significant number. Specifically, the penetration of the different models in the analysed gas transmission networks have been investigated by applying Eq. (43):

$$P = \frac{\sum_{i=1}^{4} p_{k,i}}{4}$$

(43

Where:

P is the weighted percentage [%]. The value of P can range between 0 and 100%. The value of zero is assumed in the case that the model is not installed in no one of the four grids. On the other hand, "100%" means that the model is installed in all the networks, representing 100% of the share.
$p_{k,i}$ is the percentage of the k-th model in the grid of the i-th operator [%].

As shown in Figure 38, only a limited number of models reach a significant market share. Furthermore, it has to be noted that those models that do not reach a value for P greater than 0.20% are not included in the figure. That is, almost 60 models (i.e., 60% of the total) are not shown.

Focusing on the remaining forty models, “model 74” reaches the highest penetration but is installed only TSO3. The same conclusion is derived for “model 47” and “model 64” which have a high penetration even if they are mainly installed in the grid operated by TSO2. In conclusion, a difference appears with respect to the situation analysed for the gas meters. In that case, several models are used by different TSO, while it seems that the market is more distributed for the gas volume converters – flow computer.

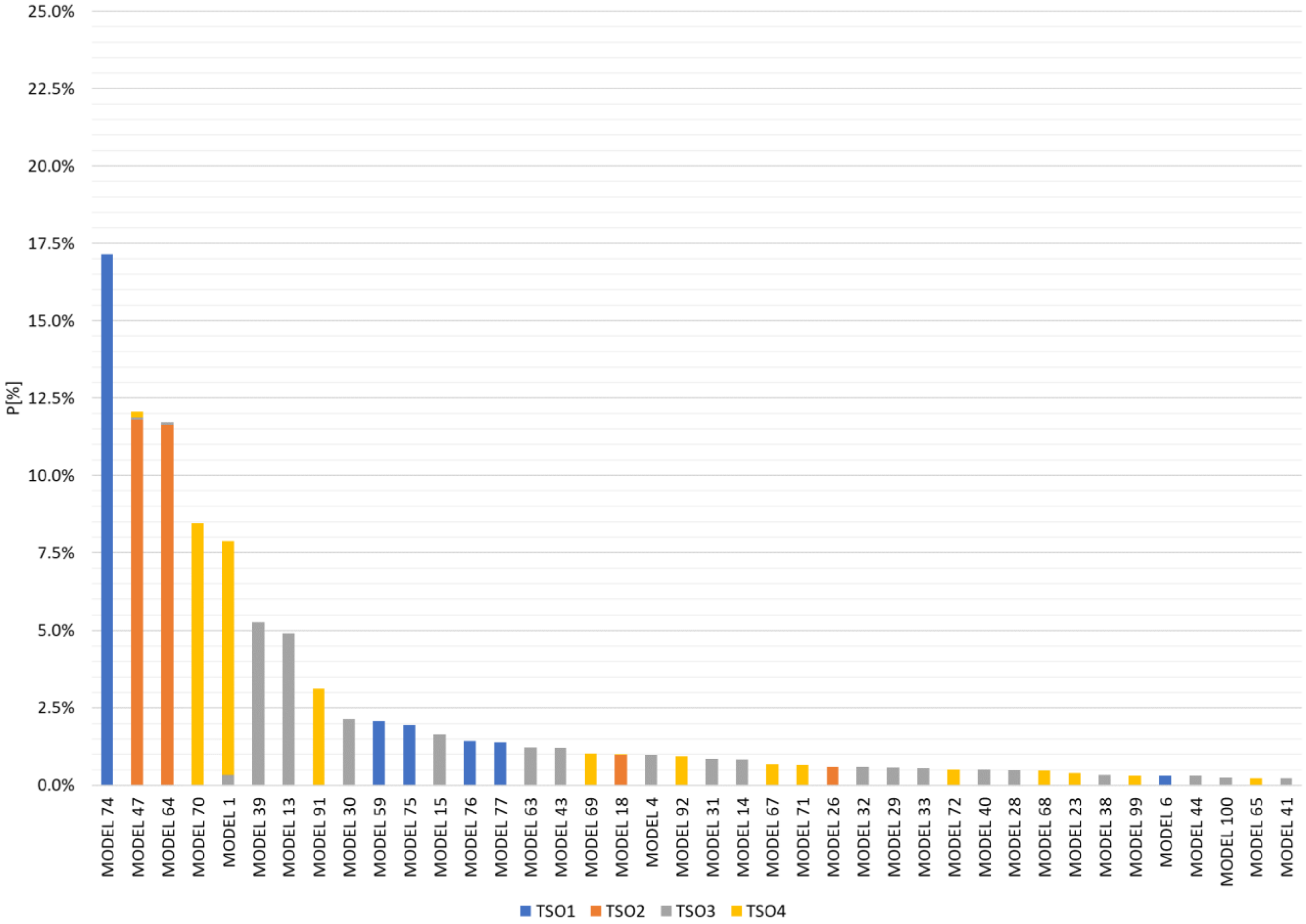


Figure 38. Models of the converters / flow computers installed in the gas grid owned by THOTH2 TSOs.

Regarding the compressibility factor, several algorithms are implemented in the devices. Based on a preliminary investigation, different correlations are currently implemented and the most applied are SGERG, AGA-NX19, AGA8, GERG88, GERG-2008.

Table 6. List of models of electronic volume converters and Flow computers.

Manufacturer/Vendor	Model	Manufacturer/Vendor	Model
ACTARIS	CORUS	INSTROMET / HONEYWELL	782/10-VE
ACTARIS	SEVC-D	INSTROMET / HONEYWELL	999
ACTARIS	COMPLEX 3V	INSTROMET / HONEYWELL	782/8Z
ACTARIS	COMPLEX 3C	INSTROMET / HONEYWELL	782/2X
CAMCO	VEM	INSTROMET / HONEYWELL	901
COMMON	CMK-02	INSTROMET / HONEYWELL	444
COMMON	CMK-01	INSTROMET / HONEYWELL	782/5
COMMON	CMK-03	INTEGROTECH	MSP-02-FC
COMMON	UNKNOWN	INTEGROTECH	MSPR-4.0-FC
CPL	ECOR3	ITRON	CDV 15-3B
CPL	ECOR2	ITRON	UNKNOWN
CPL	EFLO	KAMSTRUP	UNIGAS 300
D&D ELETTRONICA	IMP-8FC	KROHNE	SUMMIT 8800
D&D ELETTRONICA	IMP-FC-1/PS	MECI	CDN 12-3
D&D ELETTRONICA	IMP-FC2	MECI	CDN 12-6
ELGAS	ELCOR 95	MECI	CDN 16
ELSTER	UNKNOWN	MECI	CDV 12
ELSTER / HONEYWELL	ENCORE FC1	MECI	CDV 15
ELSTER / HONEYWELL	EK230	MECI	CDV 15 - 3B
ELSTER / HONEYWELL	EK 220	MECI	CDV 15 - 3H
ELSTER / HONEYWELL	EK260	MECI	CDV 15 - 3L
ELSTER / HONEYWELL	EK-88	MECI	UNKNOWN
EMERSON	FloBoss S600	PLUM	MACMAT II
EMERSON	FloBoss S600+	PLUM	MACMAT IV
EMERSON	UNKNOWN	PLUM	MACMAT III
EX-I FLOW	SFC3000	PLUM	MACBAT II
FAST	Genius3	PLUM	MACBAT IV
FIMIGAS	ICARUS	PLUM	MACMAT
FIMIGAS	VESCOM 3	PLUM	MACBAT
FIORENTINI	Explorer plus	PLUM	MACBAT III
FIORENTINI	FIOMEC 12	RMG	ERZ 2000
FIORENTINI	FloWEB	SCHLUMBERGER	COMPLEX 3C
FIORENTINI	EXPLORER	SCHLUMBERGER	COMPLEX C
FIORENTINI	FIOMEC 10	SCHLUMBERGER	COMPLEX 3V
FIORENTINI	FIOMEC 22	SCHLUMBERGER	SEVC-D
FIORENTINI	FIOMEC	SCHLUMBERGER	PTZ EX
FIORENTINI	FIOMEC 21	SCHLUMBERGER	COMPLEX V
FLONIDAN	UNIFLOW 1200	SCHLUMBERGER	CORIN
I.G.S. DATAFLOW	FLOWTI 702-1	SCHLUMBERGER	CT 2100
I.G.S. DATAFLOW	FLOWTI 704	SEVME	UNKNOWN
I.G.S. DATAFLOW	FLOWTI T702	SICK	Flow-X/P
I.G.S. DATAFLOW	LOGTI L222	SIS	ENVOL
I.G.S. DATAFLOW	FLOWTI T600	SIS	MEDITEL
I.G.S. DATAFLOW	FLOWTI T502	SIS	UNKNOWN ECV
I.G.S. DATAFLOW	FLOWTI T500	SOLARTRON	7925
I.G.S. DATAFLOW	FLOWTI T504	SOLARTRON	7951
INSTROMET / HONEYWELL	FC2000	TECHNOTRADE	TBOX MS
INSTROMET / HONEYWELL	782/10-VO	TTC	EMMS
INSTROMET / HONEYWELL	782/2XF	UNKNOW (OR UNCLEAR)	UNKNOWN
INSTROMET / HONEYWELL	555	UNKNOWN	UNKNOWN ECV
INSTROMET / HONEYWELL	782/5X	WIGERSMA&SIKKEMA	Unigas 300

4.2.3. Gas chromatographs

As for other measuring devices, gas chromatographs also are present in the gas TSO networks in several different models as listed in Table 7.

Table 7. List of manufacturers and models of gas chromatographs.

Manufacturer/Vendor	Model	Manufacturer/Vendor	Model
ABB	BTU 8000	EMERSON	700 XA
ABB	NGC 8206	EMERSON	500 FPD
ABB	PGC 1000	EMERSON	700XA FPD
ABB	TOTALFLOW 8100	EMERSON	UNKNOWN
AGILENT	490	EMERSON	500
AGILENT	990	EMERSON	UNKNOWN
CHROMPACK-THT	CP2002	MECI	CVM16
DANIEL	500	MECI	MGC16
DANIEL	500/2350	MECI	PES15
DANIEL	700	MECI	UNKNOWN
DANIEL	DANALYSER 571	REGAS	ChromEx 400 PCS + H2
DANIEL	DANALYSER 575 E	SIEMENS	SITRANS CV
DANIEL	UNKNOWN ANALYSER	SRA INSTRUMENTS	A-3000 NGA+
ELSTER-INSTROMET-HONEYWELL	ENCAL3000	VARIAN	CP-4900
EMERSON	370 XA	VARIAN	CP4900-PRO
EMERSON	700	YAMATAKE	HGC 303

The total number of models installed in the investigated gas grid is twenty-eight. Since many of these models are installed in a minimal percentage, the analysis has been limited only to those models installed in a significant number. Specifically, the penetration of the different models in the analysed gas transmission networks have been investigated by applying the same approach used for gas volume converters-flow computers. Eq. (44) was used:

$$P = \frac{\sum_{i=1}^{4} p_{k,i}}{4} \qquad (44$$

Where:

P is the weighted percentage [%]. The value of P can range between 0 and 100%. The value of zero is assumed in the case that the model is not installed in no one of the four grids. On the other hand, "100%" means that the model is installed in all the networks, representing 100% of the share.
$p_{k,i}$ is the percentage of the k-th model in the grid operated by the i-th TSO.

The result is shown in Figure 39. As shown several models are used by all the TSOs. The number of TSOs that currently have installed a specific model can be checked by the number of colours of the bar. For example, three TSOs have currently installed model 23. Specifically,, “model 23” reaches a weighted penetration of almost 17% and it is installed in TSO2, TSO3 and TSO4 grids. On the other hand, only one TSO has installed the model 21. The “model 21” achieve a similar weighted penetration but it is installed only in TSO3 grids. Differently as for previous measuring devices, the 90% of the TSO3 installed gas chromatographs is covered by four models. The same percentage is covered by six, and eight models respectively for TSO1, TSO2 and TSO4.

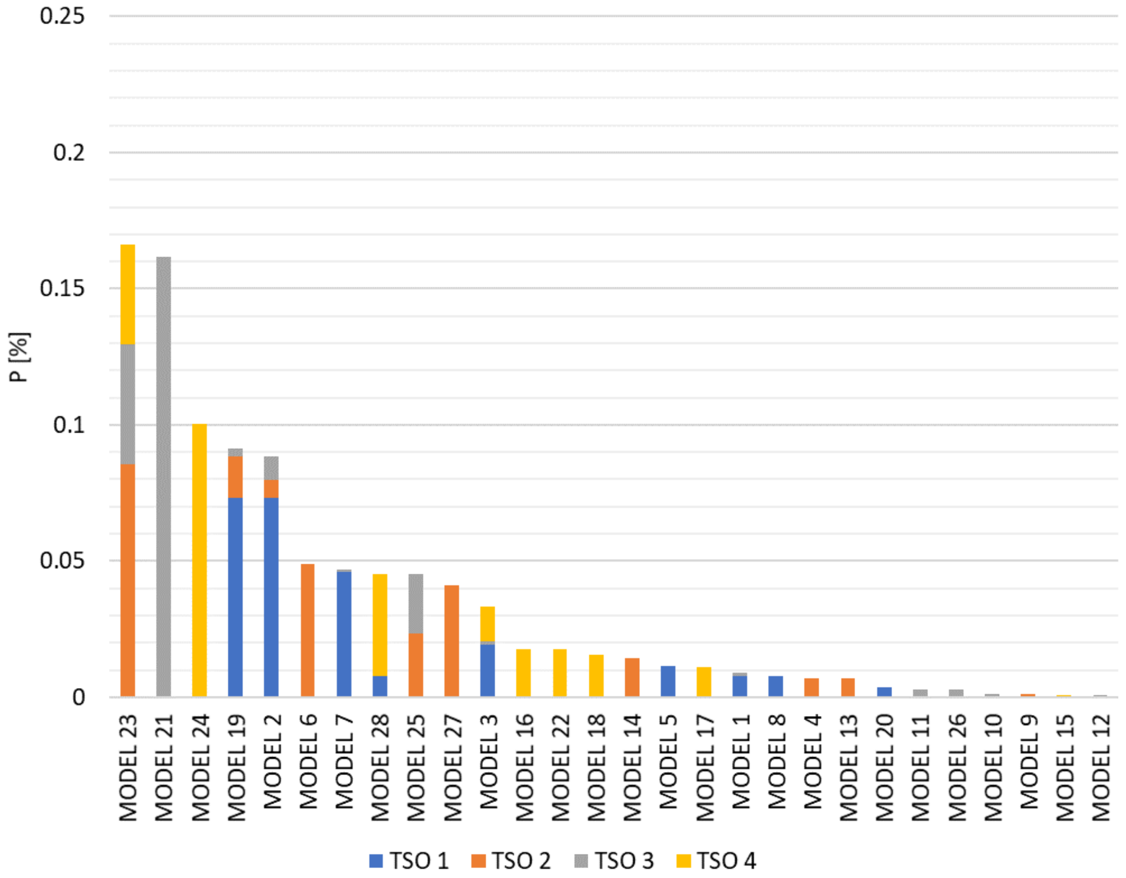


Figure 39. Models of the gas chromatographs installed in the gas grid owned by THOTH2 TSOs.

4.2.4. Other measuring devices

Other measuring devices include pressure and temperature transmitters, trace water humidity sensors, and leak detectors. While pressure and temperature transmitters are also used for fiscal purposes by sending signals to the gas volume converters and flow computers to convert the measured volume in reference conditions, the other measuring devices are used for process applications. The most updated list of measuring devices used in the gas TSOs grids is reported below. It must be noted that the same models can also be purchased from vendors that do not coincide with the manufacturer and are not written in the following tables. It has to be highlighted that no data are available for TSO4 grids to date. Therefore, the deliverable will be updated if and when these data will be shared.

Pressure transmitters. The exact number of pressure transmitters was given only by two TSOs and ranges between 0.29 and 0.42 measuring devices per km of network. Many different models characterized by several configurations to measure absolute, differential and gauge pressures are currently implemented in the gas networks resulting very complex the analysis of all of them. The list of the identified manufacturers and models is reported in Table 8. To shorten the table, it was decided to indicate only the brand without specifying the configuration. It has also to be noted that no data are available for almost the 50% of the installed pressure transmitter in TSO3 gas system. For TSO1, for the 3.4% is not possible to identify the exact model and it is discarded from the analysis. Therefore, these measuring devices have been excluded from the analysis. The penetration of the different models in the analysed gas transmission networks have been investigated by applying the same approach used for gas volume converters-flow computers:

$$\mathrm{P} = \frac{\sum_{\mathrm{i}=1}^{3} \mathrm{p}_{\mathrm{k,i}}}{3} \tag{45}$$

Where:

P is the weighted percentage [%]. The value of P can range between 0 and 100%. The value of zero is assumed in the case that the model is not installed in no one of the three grids which TSO provided data. On the other hand, "100%" means that the model is installed in all the networks, representing 100% of the share.
$\mathrm{p}_{\mathrm{k,i}}$ is the percentage of the k-th model in the grid operated by the i-th TSO. Compared to previous analysis the index of the sum “i” ranges from 1 to 3 because TSO4 has not been included in the analysis.

In Table 8, the identified models are shown as a function of the number of TSOs that currently operate them. The number of TSOs that currently have installed a specific model can be checked by the number of colours of the bar. As shown, four models, “model 31”, “model 29”, “model 30”, and “model 41” are installed in all the three gas transmission networks. Focusing to the models that are implemented in at least 2 TSOs, as shown in Figure 40, only “model 31” has a good penetration in all the investigated TSOs. “Model 6”, “model 13” and “model 42” are also interesting models to be tested because of the large penetration in the network.

Table 8. Manufacturers and models of pressure transmitters.

Manufacturer/Vendor	Model:	Manufacturer/Vendor	Model:
ABB-HARTMANN	ASD 800	HONEYWELL	ST 120
ABB-HARTMANN	AMD 200	HONEYWELL	ST 924
ABB-HARTMANN	ASD 810	HONEYWELL	ST 170
ABB-HARTMANN	AMD 230	HONEYWELL	STG (UNSPECIFIED)
ABB-HARTMANN	266NH	JUMO	P30
APLISENS	APC-2000 / APR-2000	ROSEMOUNT-EMERSON	300S
APLISENS	PC-28	ROSEMOUNT-EMERSON	1151
APLISENS	PC-50	ROSEMOUNT-EMERSON	2051
APLISENS	PS-28 SMART	ROSEMOUNT-EMERSON	2088
DRUCK	PTX 611	ROSEMOUNT-EMERSON	3051
DRUCK	PTX 610	ROSEMOUNT-EMERSON	3052
ENDRESS-HAUSER	CERABAR (UNSPECIFIED)	ROSEMOUNT-EMERSON	3053
ENDRESS-HAUSER	CERABAR PMP-51	ROSEMOUNT-EMERSON	3054
ENDRESS-HAUSER	CERABAR PMP-71	SIEMENS	SITRANS P
FUJI	FKP	TRAFAG	8852
FUJI	FKH	VEGA	UNSPECIFIED
FUJI	FKKX	WIKA	S-10
HONEYWELL	ST 3000	YOKOGAWA	EJA310 / EJX310
HONEYWELL	ST 800	YOKOGAWA	EJA510 / EJX510
HONEYWELL	ST 974	YOKOGAWA	EJA430 / EJX430
HONEYWELL	ST 944	YOKOGAWA	EJA530 / EJX530
HONEYWELL	ST 97L	YOKOGAWA	EJX610A
HONEYWELL	ST 940	YOKOGAWA	EJX110A

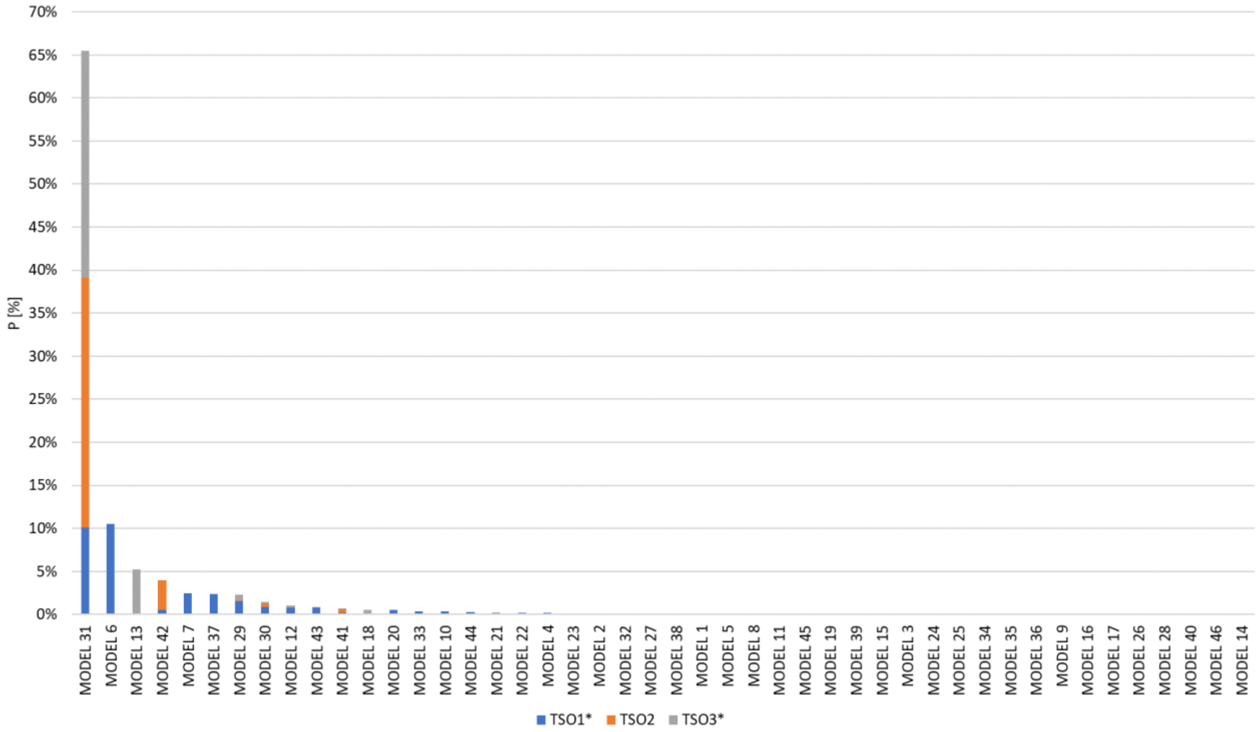


Figure 40. Percentages of the pressure transmitters models installed in the networks. For TSO1 and TSO3 the unknown measuring devices are excluded from the analysis.

Temperature transmitters. Temperature transmitters are not considered so critical respect to the injection of hydrogen in the grid because the sensor is not directly in contact with the fluid but protected by the thermowell. Therefore, it was decided to not proceed in father analysis.

Trace water humidity sensors. Only one TSO indicated the total number of trace water humidity sensors in the network. A value of 0.012 devices per km of network results even if more investigation is required to confirm the data. That is, other TSOs indicated the list of models and manufacturers implemented in the network. Compared to other measuring devices, a limited number of models are currently operated in the grid for trace water humidity measurement. In the list, the measuring devices that only measure the hydrocarbon dew point are not included in this report.

Table 9. Manufacturers and models of trace water humidity sensors. Hydrocarbon dew point analysers have been excluded.

Manufacturer/Vendor:	Model:	Manufacturer/Vendor:	Model:
AMETEK	OLV 3050	MICHELL	TDL600
BARTEC	L1660	MICHELL	EASIDEW PRO I.S.
GE INDUSTRIAL - PANAMETRICS	MIS-2	MICHELL	PROMET EExd
GE INDUSTRIAL – PANAMETRICS	MMS3	MICHELL	Transmet I.S.
GE INDUSTRIAL – PANAMETRICS	AURORA	MICHELL	SF-52
GMACX	MCM	MICHELL	QMA 401
HONEYWELL	4112	SPECTRASENSOR/ENDRESS+HAUSER	SPECTRASENSOR (UNSPECIFIED)
MICHELL	CONDUMAX II		

As shown in Figure 41, "model 7", "model 8" and "model 9" are the most present in the investigated gas grids. As shown in Figure 42, the preferred technology implemented in the trace water humidity sensors is the "impedance sensor" type (≈61%), followed by TDLAS (≈23%), and optical and quartz (≈8%). It has to be noted that one model also implements a patented solution similar to chilled mirror technology to measure the hydrocarbon dew point.

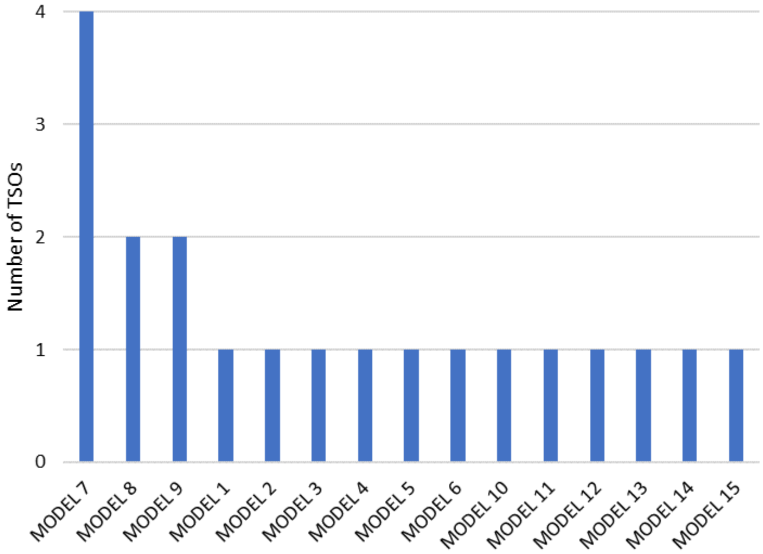


Figure 41. Models of trace water measuring devices vs the number of TSOs that implement the model in the network. The analysis doesn't take into account the models of TSO4 that are not available to date.

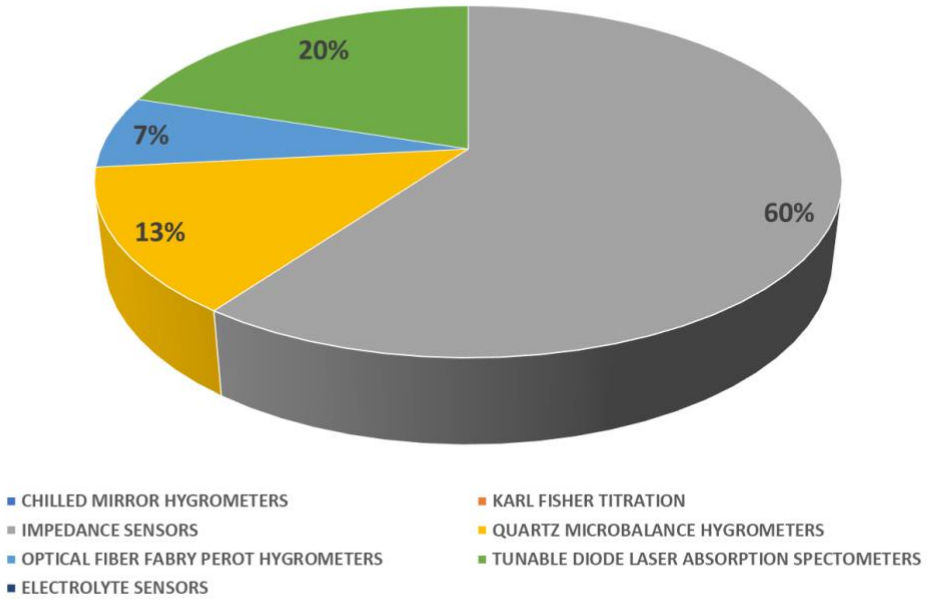


Figure 42. Measuring technology implemented in the investigated transmission grids. The analysis doesn't take into account the models of TSO4 that are not available to date.

Regarding the metrological performances ensured by the installed devices, from the analysis of public datasheet, it was discovered that the majority of the installed impedance sensors ensure a calibrated range for the dew point down to -110 °C, even if some models have a reduced range down to -60 °C or -40 °C. Furthermore, the accuracy ranges between ±1 °C and ±3 °C based on the measured dew point. TDLAS-based measuring devices typically have a mearing range up to 6.000 ppm_v even if a model declares up to 23.000 ppm_v and an accuracy than range between ±1 % and ±2% of the reading or ±1 ppm_v and ±2 ppm_v. The Quartz based technology declares a measuring range up to 2500 ppmv while the fibre optic based one a measuring range down to a dew point of -80 °C.

Leak detectors. Only portable leak detectors have been included. So, the analysis excludes static leak detectors in the current version and only include mobile devices. Two TSOs defines the number of own leak detectors resulting in a range between 0.02-0.08 devices per km of networks. Many different models result from the data shared by the partners. Only two models have been identified in more than one partner. The complete list of the models and manufacturers is reported in Table 10.

Table 10. Mobile leak detectors' models and manufacturers

Manufacturers/Vendor:	Models:	Manufacturers/Vendor:	Models:
ALARM-EX	Alex D/02	HONEYWWELL	GasAlertMicroClip XT
ALTER	GAS HUNTER	HONEYWWELL	MultiPro-1
ALTER	GD-7	HONEYWWELL	MultiPro-2
ALTER	GD-8	HONEYWWELL	MultiPro-4
ALTER	LD-100 Ex	HONEYWWELL	MultiRAE Lite
ALTER	UNKNOWN	HONEYWWELL	QRAE II
BACHARACH	LEAKATOR-10	HONEYWWELL	QRAE PLUS
CROWCON	TRIPLE PLUS+	HONEYWWELL	TOXIPRO
CROWCON	GASMAN	HUBERG	RIVELGAS PLUS
CROWCON	GASMAN II	INDUSTRIAL SCIENTIFICS	M40
DRAEGER	XAM-5000	INDUSTRIAL SCIENTIFICS	MX6 IBRID
DRAEGER	XAM-7000	M.S.A.	ALTAIR 5
DRAEGER	XAM-2500	M.S.A.	ALTAIR 4
DRAEGER	X-am 5600	M.S.A.	ALTAIR PRO
DRAEGER	X-zone 5500	M.S.A.	EX-METER
DRAEGER	X-xone unspecified	M.S.A.	TITAN
ESDERS	ELLI	NEOTRONICS	MINIGAS MK5
ESDERS	HUNTER	RDTECH	JJB30 Ultra-Light
ESDERS	SIGI EX	SENSIT	HGX-3P
ESDERS	MULTIGAS III	SENSIT	GASTRACT LZ-30
EWIMAR - WB	UNKNOWN	SENSIT	UNKNONW
FLUKE	ii900	SEWERIN	EX-TEC HS 660
GFG	Microtector II G450	SEWERIN	EX-TEC HS 680
GFG	Polytector III G999	SEWERIN	EX-TEC PM300
GMI	GT-41	SEWERIN	EX-TEC PM4
GMI	GT-42	SEWERIN	EX-TEC Snooper 4
GMI	GT-43	SEWERIN	PORTAFID M3K
GMI	PS200	SEWERIN	VARIOTEC 450-Ex
HFSC	RMLD	TOPSKY	JJB30
HONEYWWELL	GasAlertMax XT	TOPSKY	JJB30 ULTRA LIGHT

The penetration of the different models in the analysed gas transmission networks have been investigated by applying the same approach used for other measuring devices:

$$P = \frac{\sum_{i=1}^{3} p_{k,i}}{3} \qquad (46$$

Where:

P is the weighted percentage [%]. The value of P can range between 0 and 100%. The value of zero is assumed in the case that the model is not installed in no one of the three grids which TSO provided data. On the other hand, "100%" means that the model is installed in all the networks, representing 100% of the share.
$p_{k,i}$ is the percentage of the k-th model in the grid operated by the i-th TSO. Compared to previous analysis I ranges from 1 to 3 because of TSO4 has not been included in the analysis.

The results are shown in Figure 43. The number of TSOs that currently have installed a specific model can be checked by the number of colours of the bar. In this case only two models are in common between two TSOs ("Model 30" and "model 12"). The bars of TSO2 have been represented with dotted lines because TSO2 divided its measuring devices into detection and quantification devices, making it impossible to evaluate each model's percentage on the total. It also must be noted that many of the leak detectors implemented more than one of the sensor types described in the previous chapter to measure different gases. Therefore, it would be necessary to evaluate in Task 2.1 which of these measurements could be more affected by hydrogen to focus the experimental activities.

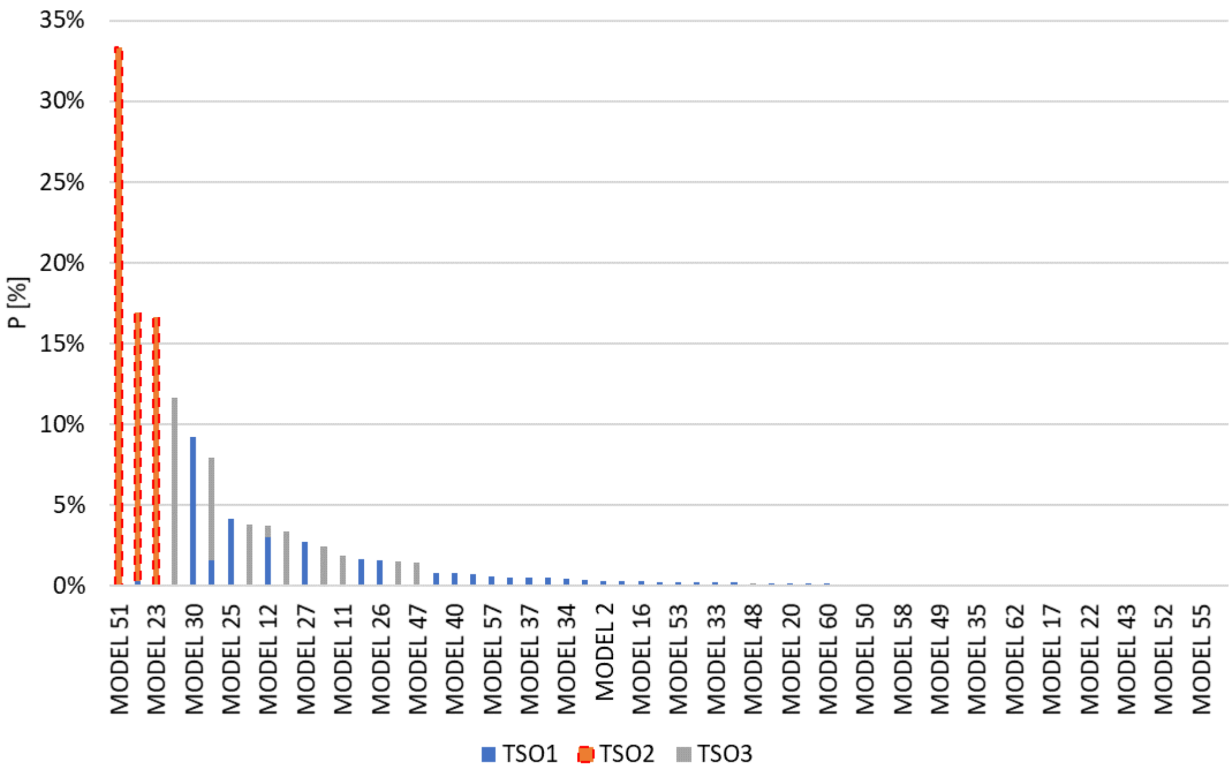


Figure 43. The average penetration of different models in the market.

4.2.5. Answers received from the survey and literature review

To date one additional TSO outside the THOTH2 Consortium provide information about the measuring devices installed in its network, answering the survey that has been shared through Marcogaz. The answers are reported in the following Table. As shown in Table 11, The most significant percentage has a size greater than G2500. This condition differs from the situation depicted by the four THOTH2 TSOs. Regarding the technology, a turbine gas meter is preferred above G65, while below rotary piston gas meters are preferred. However, some doubts arise regarding the range above G650, where rotary piston gas meters are considered the second choice. In fact, to the best knowledge of the Authors, no rotary piston gas meters are available for this size, so further investigation is required. Concerning the implemented technologies, no additional models have been identified respect to those already identified.

Regarding the other measurement devices, no answers have been provided by the participant to the survey.

Table 11. Received answers from participants to the survey outside the THOTH2 consortium.

Meter Size	**<G40**	**G65-G100-G160-G250**	**G400-G650**	**G1000-G1600**	**≥G2500**
Operative pressure - please indicate a range [barg]	**[0,10]**	**[0,80]**	**[0,80]**	**[0,80]**	**[0,80]**
Number of installed meters [%]	**0.8%**	**13.4%**	**18.3%**	**28.3%**	**39.2%**
Please rank the following technology from the most used to the less used in the identified range size (e.g., 1 - the most implemented in the grid; 7 - the less implemented. Use "NA" if the technology is not used)					
Turbine meters	**2**	**1**	**1**	**1**	**1**
Ultrasonic meters		**2**	**2**	**2**	**2**
Rotary piston meters	**1**	**3**	**3**	**3**	**3**
Thermal mass meters					
Diaphragms meters	**3**				
Coriolis meters					
Other					
Please indicate the manufacturer and the model of the installed meter	Elster-Instromet, ITRON, FMG	Elster-Instromet SM-RI-X-K, RVG, ACTARIS Fluxi 2080 TZ,..	Elster-Instromet SM-RI-X-K, RVG, ACTARIS Fluxi 2080 TZ, RMG	Elster-Instromet SM-RI-X-K, RVG, ACTARIS Fluxi 2080 TZ RMG	Elster Intromet Q-SONIC plus, Flowsick, Krohne V12
Please indicate the list of manufacturers and models of gas converters	Corus, S-EVCD, EK-220, EK260, Instromet 2000, Elster F1, Krohne 8800, Gavilar				

4.3. NG distribution system

As reported at the beginning of chapter four, few answers were received. Specifically, the answers give a preliminary overview of the scenario in Italy (covering only almost the 30% of the Italian distribution market), Denmark. An answer was received also from the Netherlands but due to confidentiality reasons, few data were indicated. Therefore, the following considerations have to be considered as preliminary and to be confirmed with more replies will arrive from the invited participants. The received answers have been divided between smart and traditional gas meters. Table 12 shows the answers received for smart gas meters. Considering the answers from participants no. 1-2 from Italy, between 67-75 domestic meters (G4-G6) are installed per km of networks. The value drops down to almost 1.0 meter per km in the size (G10-G16-G25). Regarding the measuring technologies implemented, both the participants answer that diaphragm gas meters are the most installed technology followed by thermal mass meters and ultrasonic gas meters. In the upper sizes (G10-G16-G25), ultrasonic gas meters have been not indicated by the participants. Participant no. 2 indicates rotary piston meters and turbine gas meters for size greater than G40. In this case, a gas volume converter is installed for the conversion of the gas volume to the reference conditions. Regarding additional functionalities compared to a traditional meter, it has to be noted that domestic gas smart meters (G4-G6) are required to integrate an internal shut-off valve. The participant no.3 from Denmark indicates the presence of intelligent meters only for size ≥G65. The potential impact of hydrogen concerning the potential leakages and material degradation should be assessed since no information was found in the literature. One of the three participants also indicates to have developed a G4 ultrasonic meter, with a declared materials compatibility to the hydrogen until 30%vol and suitable for metrological tests above 10%vol.

Table 13 includes the main data regarding traditional meters still installed. As shown, few traditional meters are still operated in the networks. Respect to the smart meters, ultrasonic and thermal mass meters are not present. In this case, regarding the main manufacturers, the following have been indicated:

Table 12. Answers received from gas DSO regarding own gas smart meters.

	Participant no 1	**Participant no 2**	**Participant no 3**
Country	Italy	Italy	Denmark
QUANTITY (meters/km)			
G4-G6	74.50	66.88	0
G10-G16-G25	1.05	0.89	0
G40	0.00	0.13	0
≥G65	0.00	0.17	0.088
MAIN MEASURING TECHNOLOGIES			
G4-G6	1° DIAPHRAGM 2° THERMAL MASS 3° ULTRASONIC	1° DIAPHRAGM (≈48%) 2° THERMAL MASS (≈45%) 3° ULTRASONIC	-
G10-G16-G25	1° DIAPHRAGM 2° THERMAL MASS	1° DIAPHRAGM (≈55%) 2° THERMAL MASS (≈45%)	-
G40	-	1° DIAPHRAGM (≈98%) 2° ROTARY (*) only converter	-
≥G65	-	1° DIAPHRAGM (≈42%) 2° TURBINE (≈31%) 3° ROTARY (≈27%) (*) only converter	1° TURBINE 2° ROTARY 3° ULTRASONIC 4° OTHER
PRESSURE&TEMPERATURE COMPENSATION?			
G4-G6	Only T compensation	Only T compensation	Only T compensation
G10-G16-G25	Both T,p compensation	Both T,p compensation	
G40	-		Both T,p compensation
≥G65	-	Gas converters installed for ≥G40	
IS AN INTEGRATED VALVE REQUIRED?			
G4-G6	YES	YES	NO
G10-G16-G25	NO	NO	NO
G40	NO	NO	NO
≥G65	NO	NO	NO
COMMUNICATION PROTOCOLS			
G4-G6	RF169, NB-IoT	RF169, GPRS, NB-IoT	GSM – GPRS (in the next two years only GPRS)
G10-G16-G25	GSM, GPRS (soon available NB-IoT)	GSM, GPRS (soon available NB-IoT)	
G40			
≥G65			

Table 13. Answers received from gas DSO regarding own gas traditional meters.

	Participant no 1	**Participant no 2**	**Participant no 3**
Country	Italy	Italy	Denmark
QUANTITY (meters/km)			
G4-G6	0.959	3.85	12.4
G10-G16-G25	0.063	-	0.57
G40	0.026	-	-
≥G65	0.034	-	0.053
MAIN MEASURING TECHNOLOGIES			
G4-G6	1° DIAPHRAGM	1° DIAPHRAGM	1° DIAPHRAGM
G10-G16-G25	1° DIAPHRAGM	-	1° DIAPHRAGM 2° ROTARY
G40	1° DIAPHRAGM (*) 2° ROTARY (*) 3° TURBINE (*)	-	-
≥G65	1° DIAPHRAGM (*) 2° ROTARY (*) 3° TURBINE (*)	-	1° TURBINE 2° ROTARY 3° ULTRASONIC 4° OTHER
(*) remote reading provided by the converter			

Regarding the main manufacturers, the following have been indicated:

- *Gas meters*: Actaris, AEM SA, Alesia, American Meter Company, CPL, Dresser, Elster, Ermaf, Flonic, Flonidan, FMG, Honeywell, Itron, Landys + Gyr, Magnol, Meter Italia, Metersit, Metrix, Nuovo Pignone, Pietro Fiorentini, Rombach, Sacofgas, Sagemcom, Samgas, Schlumberger, Simbrunt, Siconia.
- *Electronic volume converters*: CPL - ECOR3, CPL & Siconia/Sagemcom - ECOR4, D&D, Elster - EK220 + MTU155-I, Elgas - Elcor+, Fast teclab – GENIUS, Honeywell – EK280, Itron, Kamstru, Metrix, Pietro Fiorentini, Sagemcom, Wigersma & Sikkema - Unigas300.

Other data regarding the distribution of gas meters in the German gas grids have been reported by Gotze (2020) [106]. In the report, it is written that the 99.25% of the gas meters are diaphragm type. The remaining percentage is covered by rotary piston (0.39%), turbine (0.32%), ultrasonic (0.02%) and Coriolis (0.01%).

Regarding the other measuring devices included in the report, only two participants answered. The preliminary information provided are the following:

- Gas analysers: ABB – PGC1000 using helium as gas carrier; BAKER HUGHES – XMTC, HONEYWELL - ENCAL 3000 (C6+; Co2, H2S, O2, N2, CH4),
- Densimeter: Solatron – 3098A; Solatron – 3096C
- Pressure transmitters: Endress & Hauser – CT30; Honeywell – STD 120; Honeywell – STD 140; Rosemount – 1151; Rosemount – 3045; Rosemount – 3051 series.
- Trace water detector: BARTEC
- Leak detectors. The reference standard is the CEI - EN 61779-1 "*Electrical apparatus for the detection and measurement of flammable gases - Part 1: General requirements and test methods*" and the Linea Guida CIG N.16 (to be respected in Italy even if it is not an actual regulation) "*Esecuzione delle ispezioni programmate e localizzazione delle dispersioni sulla rete di distribuzione per gas con densità ≤ 0,8 e gas con densità* > 0,8" (i.e., execution of planned inspection and localization of leaks on the distribution for gas with density ≤ 0.8 gas with density > 0.8), paragraph 7.2.2 "*Instrumentation characteristics*" and

paragraph 7.3.3 “*Characteristics of the instrumentation for the localization and classification of gas leaks on underground pipelines*” [107]: Huber Günther & C. – Protheo IR compact (leak detection on vehicle); Huber Günther & C. – METREX 2 (pedestrian inspection).

Since only one participant provided the information about other measuring devices than gas meters, it was decided to maintain open the survey and to encourage European gas DSOs through the European gas sector Association to provide additional data to design an exhaustive overview.

5. CONCLUSIONS AND FUTURE ACTIVITIES

Based on the performed state of the art, prioritization is necessary to identify the measuring devices to be tested. However, a premise is necessary. The databases of gas operators are not standardized, so data collection and analysis resulted challenging. Therefore, the design of a comprehensive inventory was limited to essential information to correctly perform the activities of Task 1.2, Task 2.1, and Task 4.2. Specifically, the Consortium agreed that proceeding with a higher detail analysis would have been not necessary for the definition of the expected inputs to Task 2.1. In fact, in case of missing information, the selection of the configuration/s to be tested will be discussed and prioritized based on the THOTH2 partners' know-how and on the expected impact of H2NG mixtures and pure H_2.

That is, the main conclusions to be taken from the activity are:

- *Fiscal gas meters*: rotary-piston, turbine, and ultrasonic are the most installed technologies in the transmission gas grids. Specifically, turbine gas meters are the most installed. Regarding the size, the rotary piston prevails at a relatively low flow rate, the turbine at medium-high ranges, while ultrasonic are prevalently installed at a very high flow rate. This selection could be justified because the ultrasonic meters have no wetted components resulting in lower pressure drops (i.e., energy losses), negligible maintenance, and high metrological performances. Regarding the size, the most percentage of gas meters is included between G100 and G650. Some specific models are implemented in all the transmission networks, and the verification of their metrological performances should be prioritized in future THOTH2 activities. In addition to the investigation of the effect on the measuring accuracy regarding turbine and rotary piston meters, the following elements should also be carefully investigated when hydrogen is injected:
    - Gas turbine meters: effect on the rangeability due to the reduction of gas mixture density, the experienced accuracy in overload operations, and the compatibility with wetted materials and lubrication oils.
    - Rotary piston meters: effect on the leakage due to internal clearance at low flow rate, compatibility with the lubrication oil.

  Regarding distribution networks, to date, other answers from the survey participants are expected in the next weeks. Furthermore, answers come only from Italy. Therefore, the analysis should be updated once collected more answers. That is, it is clear that for distribution networks, the prevalently installed meters are diaphragm meters followed by thermal mass and ultrasonic. Specifically, for small sizes, diaphragm, and thermal mass meters are almost equivalent in the number of installed devices.

- *Electronic volume converters and Flow computers*: Many different models are installed in the investigated grids. However, the issues identified prevalently refer to the algorithm for calculating the compressibility factors. AGA8, AGA 19NX, and SGERG algorithms are examples of the most implemented.
- *Gas chromatographs*. Also, many models are installed in the investigated grids in this case. Some models are implemented by more than one TSO, even if a large penetration characterizes some models installed by a single TSO. The verification of these devices should be prioritized.
- *Other measuring devices*. Regarding the other devices, it can be concluded that some of the models are installed by all the investigated TSOs for pressure transmitters. Regarding trace water humidity sensors, the models on the market are more limited, and the networks commonly operate many devices. Specifically, the preferred technology is the impedance-based sensors, followed by TDLAS. Microbalanced

quartz and fiber optic are also present. Regarding leak detectors, the analysis focused on portable ones. Many models are currently available in the grids, and only two models are used by more than one TSOs. Furthermore, based on public datasheets, it was found that some models allow more than one measurement by installing different sensors ensuring the detection of hazardous molecules in a defined response time. Therefore, response time is one of the most performances that should be considered when defining the KPIs to be assessed with experimental tests. The selection of the configuration and the sensors to be tested with the presence of hydrogen has to be carefully checked in Task 2.1.

The Task 1.1 activities have also been prodromal to discuss the content of R&D hub activities as expected in subtask 5.3.1, "Creation of R&D+i Hub for research on HNG metering". The R&D+i Hub should allow the discussion of common doubts and the updating of state-of-the-art technology and become a moment to exchange experiences and opinions. The R&D+i Hub would also be the best place to discuss future initiatives, putting together the different players of the sectors, i.e., the gas operators, the manufacturers, the academia, the research institutes, and all that would be interested.

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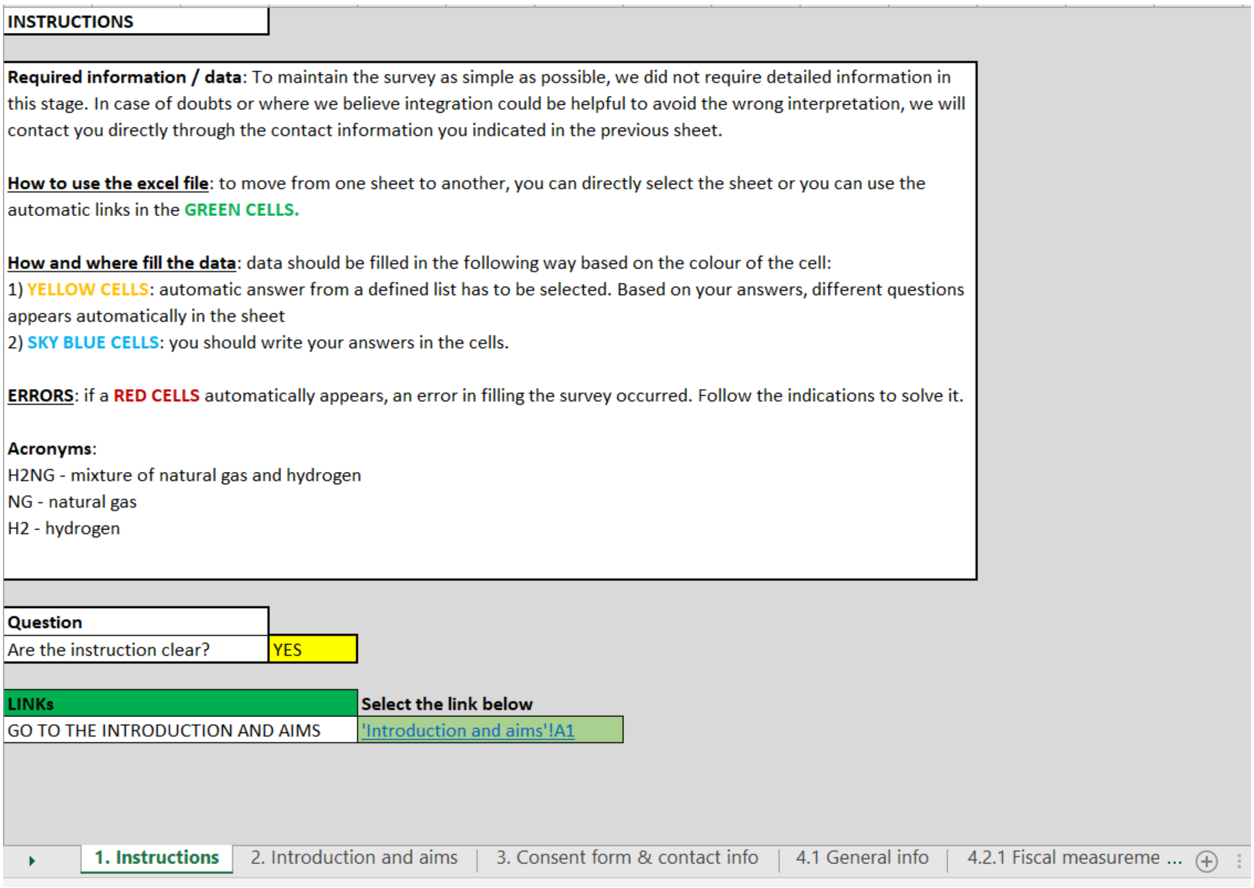
7. APPENDIX – MEASURING DEVICES' SURVEY

To collect information about gas measuring devices from gas distribution and transmission operators also outside the Consortium, a dedicated survey was designed to be answered by sector experts from gas DSOs and gas TSOs. The survey was developed in .xls format. Despite the fact it is not an open format, Excel has been selected being commonly used by experts in the addressed market. The survey includes five sections:

1. Instructions. In the instruction sheet, the main information about how to compile the survey are provided. It has to be noted that since some sections of the survey are automatically compiled, it is very important to inform the respondents (Figure 44).
2. Introduction and aims. In the second sheet, an introduction to the THOTH2 project and the main aims are described. This information is considered useful to disseminate the project main info through the sector community (Figure 45).
3. Consent form and contact info. In the "consent form" sheet, the respondents are informed about data will be managed (Figure 46).
4. General info. In the sheet no. 4 (Figure 47), general data about the operated gas grid are asked in order to calculate average Key Performance Indicators:
    a. Length of the gas distribution/transmission network
    b. Annual transported / distributed gas volume
    c. Active users connected to the transmission / distribution grid
    d. Number of operated Pressure Regulated and Metering Gas stations
5. Fiscal measurement_DSOs. Regarding fiscal gas meters, the following data are asked (Figure 48):
    a. Number of installed meters per size-G.
    b. Qualitative ranking of the technologies per size-G.
    c. Indication of gas meters and volume converters' manufacturers and models per size-G.
    d. Any available information about the compatibility of hydrogen with the own installed meters.

    It has to be noted that the sheet has been divided into two parts, i.e., traditional and smart meters.
6. Fiscal measurement_TSOs. Regarding fiscal gas meters, the following data are asked (Figure 49):
    a. Operative pressure
    b. Number of installed meters per size-G.
    c. Qualitative ranking of the technologies per size-G.
    d. Gas meters and volume converters' manufacturers and models per size-G.
    e. Any available information about the compatibility of hydrogen with the own installed meters.
7. Other measurement devices. Data are asked also for other measurement devices including: process gas meters (so those meters not used for fiscal purposes), gas chromatographs and quality measuring devices, leaks detectors, pressure transmitters (Figure 50).
8. End of the survey. In the last sheet of the survey, general comments about the expectation on the project results and suggestions are asked to the participants (Figure 46).



INSTRUCTIONS

Required information / data: To maintain the survey as simple as possible, we did not require detailed information in this stage. In case of doubts or where we believe integration could be helpful to avoid the wrong interpretation, we will contact you directly through the contact information you indicated in the previous sheet.

How to use the excel file: to move from one sheet to another, you can directly select the sheet or you can use the automatic links in the **GREEN CELLS.**

How and where fill the data: data should be filled in the following way based on the colour of the cell:
1) **YELLOW CELLS**: automatic answer from a defined list has to be selected. Based on your answers, different questions appears automatically in the sheet
2) **SKY BLUE CELLS**: you should write your answers in the cells.

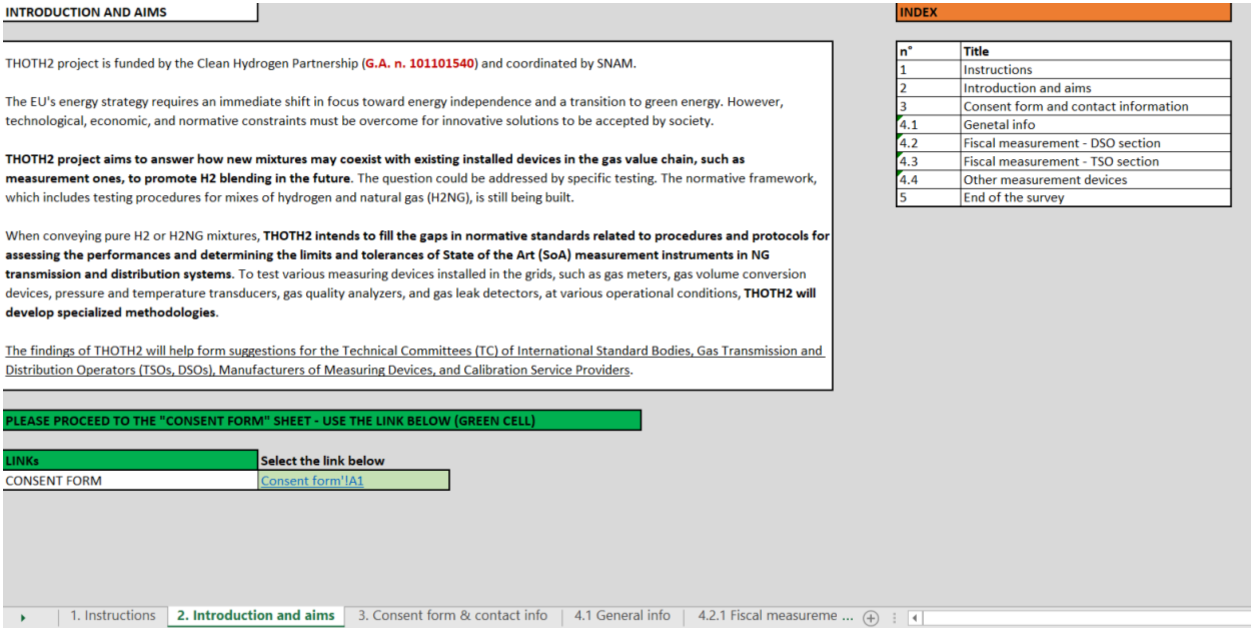
ERRORS: if a **RED CELLS** automatically appears, an error in filling the survey occurred. Follow the indications to solve it.

Acronyms:
H2NG - mixture of natural gas and hydrogen
NG - natural gas
H2 - hydrogen

Question	
Are the instruction clear?	YES

LINKs	**Select the link below**
GO TO THE INTRODUCTION AND AIMS	'Introduction and aims'!A1

Figure 44. Sheet no. 1 of the developed survey: Instructions.



INTRODUCTION AND AIMS

THOTH2 project is funded by the Clean Hydrogen Partnership (**G.A. n. 101101540**) and coordinated by SNAM.

The EU's energy strategy requires an immediate shift in focus toward energy independence and a transition to green energy. However, technological, economic, and normative constraints must be overcome for innovative solutions to be accepted by society.

THOTH2 project aims to answer how new mixtures may coexist with existing installed devices in the gas value chain, such as measurement ones, to promote H2 blending in the future. The question could be addressed by specific testing. The normative framework, which includes testing procedures for mixes of hydrogen and natural gas (H2NG), is still being built.

When conveying pure H2 or H2NG mixtures, **THOTH2 intends to fill the gaps in normative standards related to procedures and protocols for assessing the performances and determining the limits and tolerances of State of the Art (SoA) measurement instruments in NG transmission and distribution systems**. To test various measuring devices installed in the grids, such as gas meters, gas volume conversion devices, pressure and temperature transducers, gas quality analyzers, and gas leak detectors, at various operational conditions, **THOTH2 will develop specialized methodologies**.

The findings of THOTH2 will help form suggestions for the Technical Committees (TC) of International Standard Bodies, Gas Transmission and Distribution Operators (TSOs, DSOs), Manufacturers of Measuring Devices, and Calibration Service Providers.

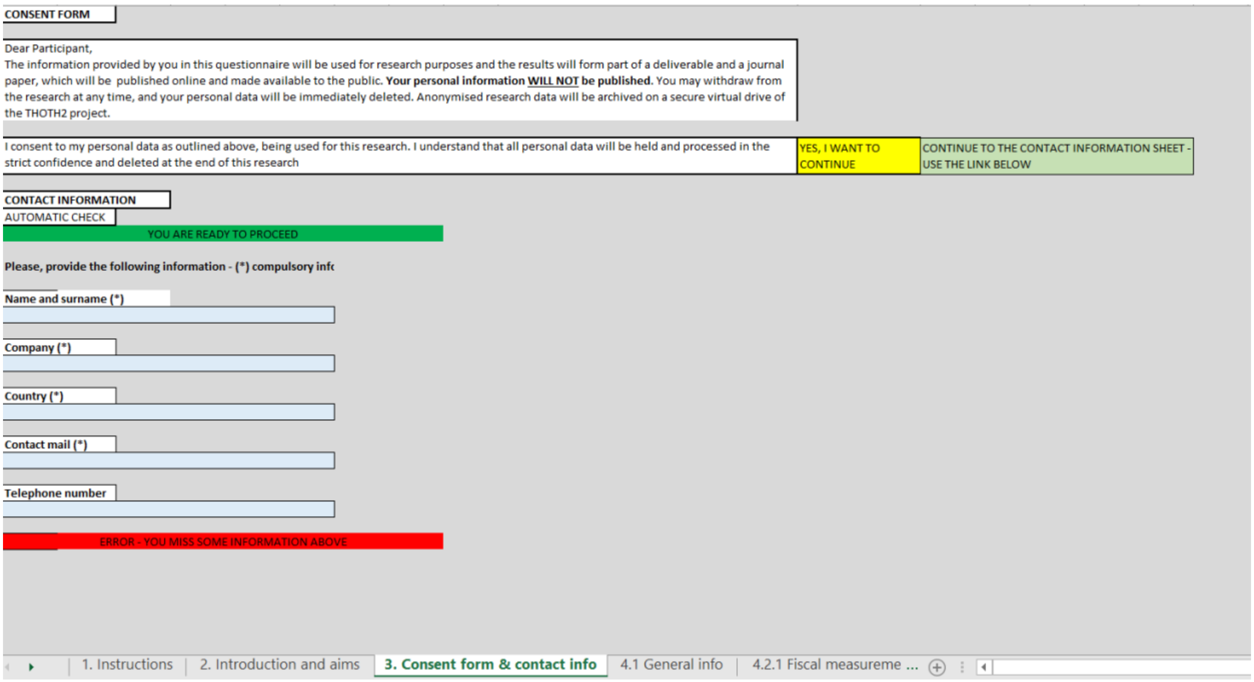
PLEASE PROCEED TO THE "CONSENT FORM" SHEET - USE THE LINK BELOW (GREEN CELL)

LINKs	**Select the link below**
CONSENT FORM	Consent form'!A1

INDEX

n°	**Title**
1	Instructions
2	Introduction and aims
3	Consent form and contact information
4.1	Genetal info
4.2	Fiscal measurement - DSO section
4.3	Fiscal measurement - TSO section
4.4	Other measurement devices
5	End of the survey

Figure 45. Sheet no. 2 of the developed survey: Introduction and aims.



CONSENT FORM

Dear Participant,
The information provided by you in this questionnaire will be used for research purposes and the results will form part of a deliverable and a journal paper, which will be published online and made available to the public. **Your personal information <u>WILL NOT</u> be published.** You may withdraw from the research at any time, and your personal data will be immediately deleted. Anonymised research data will be archived on a secure virtual drive of the THOTH2 project.

I consent to my personal data as outlined above, being used for this research. I understand that all personal data will be held and processed in the strict confidence and deleted at the end of this research	YES, I WANT TO CONTINUE	CONTINUE TO THE CONTACT INFORMATION SHEET - USE THE LINK BELOW

CONTACT INFORMATION

AUTOMATIC CHECK

YOU ARE READY TO PROCEED

Please, provide the following information - (*) compulsory infc

Name and surname (*)

Company (*)

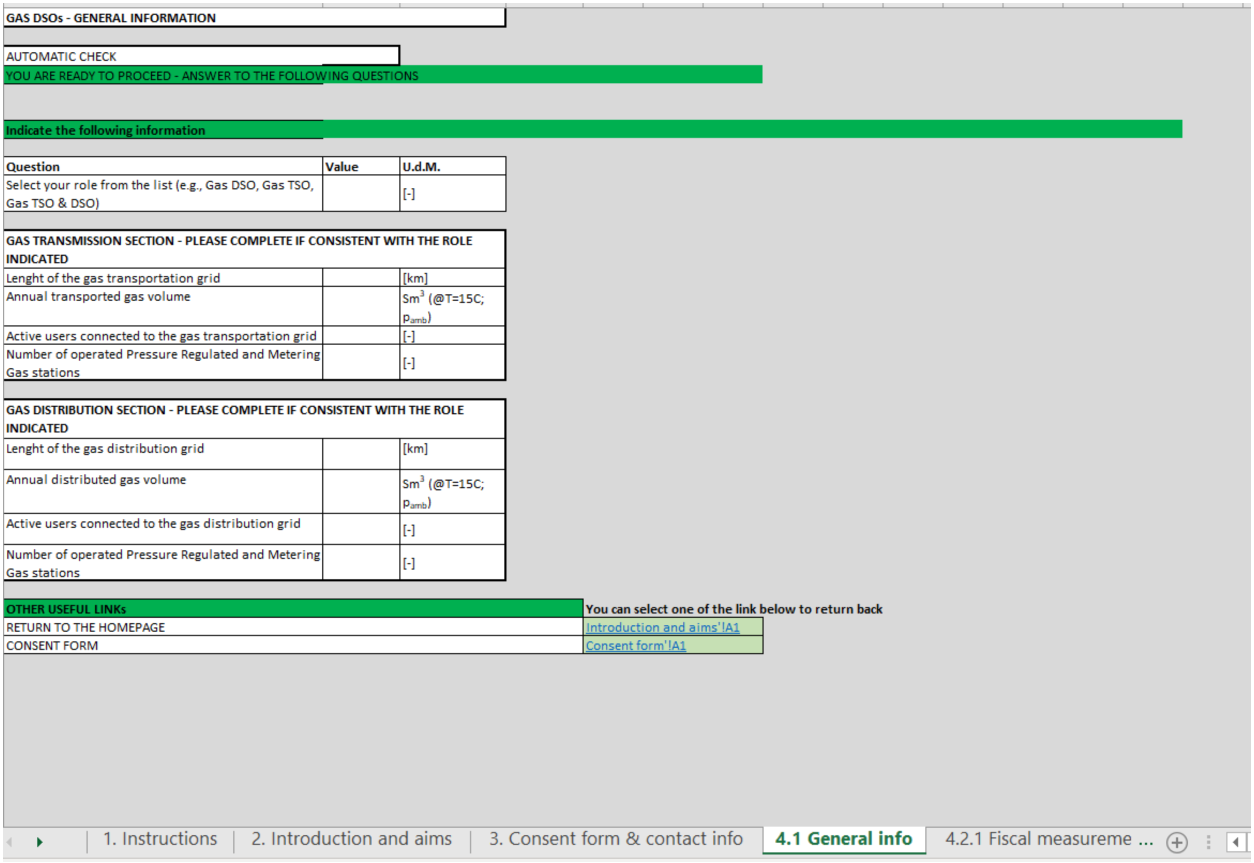
Country (*)

Contact mail (*)

Telephone number

ERROR - YOU MISS SOME INFORMATION ABOVE

Figure 46. Sheet no. 3 of the developed survey: Consent form & contact info.



GAS DSOs - GENERAL INFORMATION

AUTOMATIC CHECK

YOU ARE READY TO PROCEED - ANSWER TO THE FOLLOWING QUESTIONS

Indicate the following information

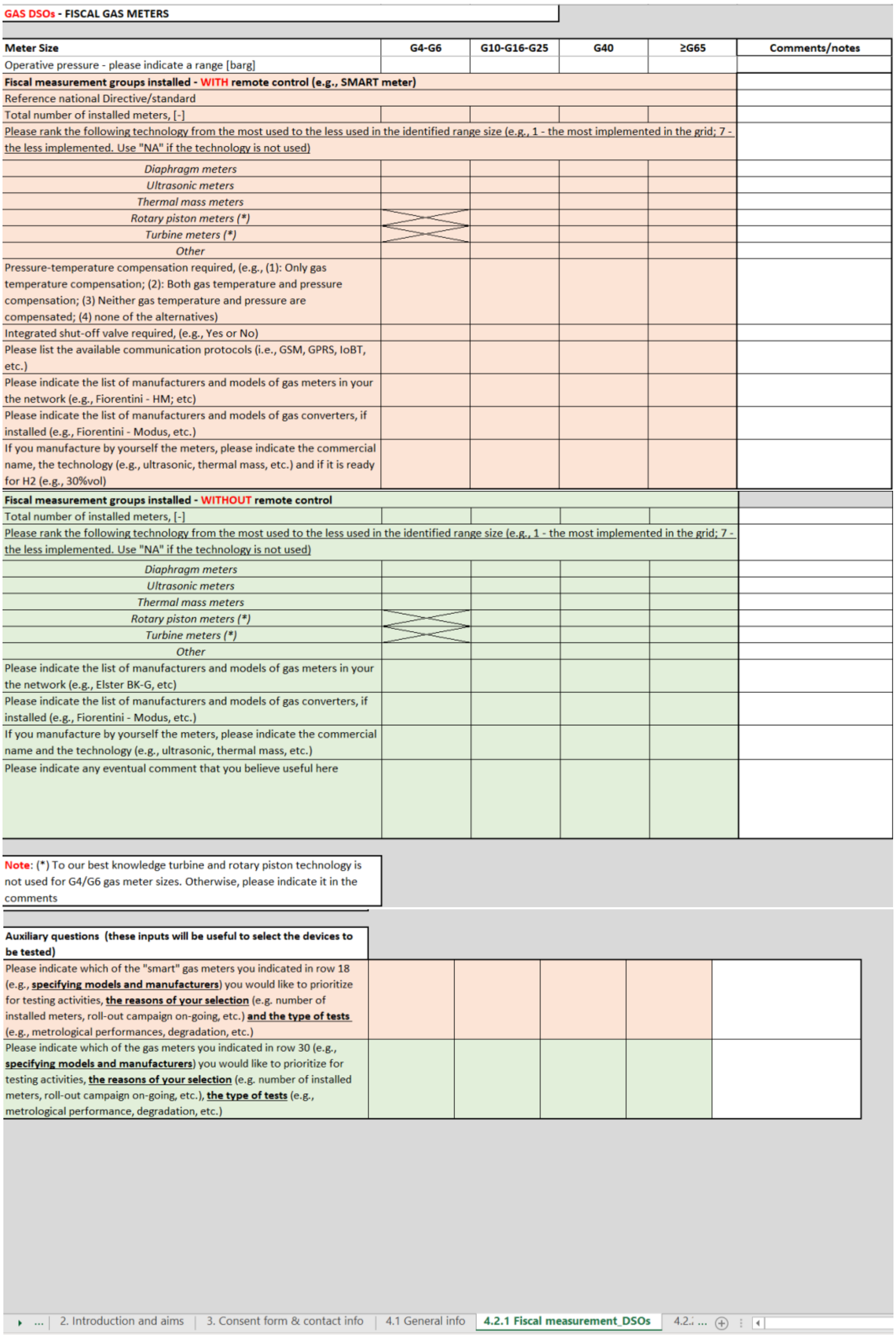
Question	Value	U.d.M.
Select your role from the list (e.g., Gas DSO, Gas TSO, Gas TSO & DSO)		[-]

GAS TRANSMISSION SECTION - PLEASE COMPLETE IF CONSISTENT WITH THE ROLE INDICATED		
Lenght of the gas transportation grid		[km]
Annual transported gas volume		Sm^3 (@T=15C; p_{amb})
Active users connected to the gas transportation grid		[-]
Number of operated Pressure Regulated and Metering Gas stations		[-]

GAS DISTRIBUTION SECTION - PLEASE COMPLETE IF CONSISTENT WITH THE ROLE INDICATED		
Lenght of the gas distribution grid		[km]
Annual distributed gas volume		Sm^3 (@T=15C; p_{amb})
Active users connected to the gas distribution grid		[-]
Number of operated Pressure Regulated and Metering Gas stations		[-]

OTHER USEFUL LINKS	**You can select one of the link below to return back**
RETURN TO THE HOMEPAGE	Introduction and aims'!A1
CONSENT FORM	Consent form'!A1

Figure 47. Sheet no. 4.1 of the developed survey: General info.



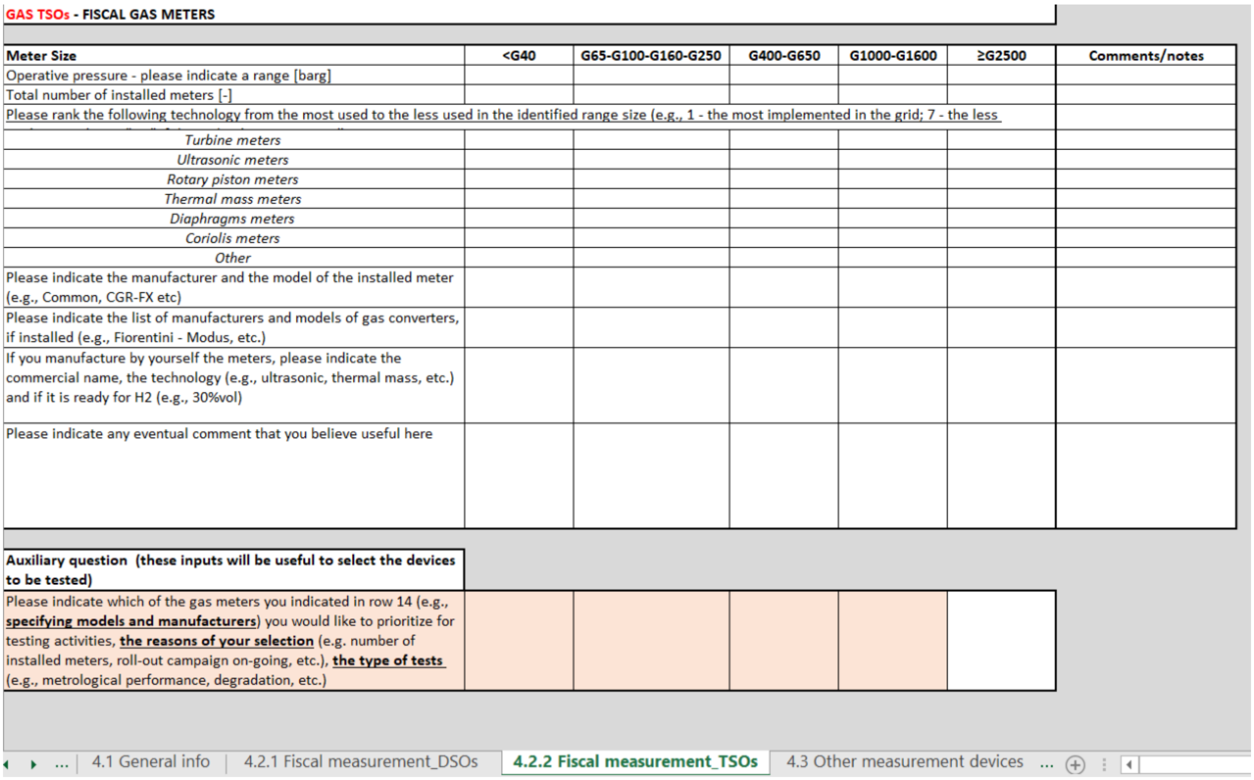
GAS DSOs - FISCAL GAS METERS

Meter Size	**G4-G6**	**G10-G16-G25**	**G40**	**≥G65**	**Comments/notes**
Operative pressure - please indicate a range [barg]					
Fiscal measurement groups installed - WITH remote control (e.g., SMART meter)					
Reference national Directive/standard					
Total number of installed meters, [-]					
Please rank the following technology from the most used to the less used in the identified range size (e.g., 1 - the most implemented in the grid; 7 - the less implemented. Use "NA" if the technology is not used)					
Diaphragm meters					
Ultrasonic meters					
Thermal mass meters					
Rotary piston meters (*)	☒				
Turbine meters (*)	☒				
Other					
Pressure-temperature compensation required, (e.g., (1): Only gas temperature compensation; (2): Both gas temperature and pressure compensation; (3) Neither gas temperature and pressure are compensated; (4) none of the alternatives)					
Integrated shut-off valve required, (e.g., Yes or No)					
Please list the available communication protocols (i.e., GSM, GPRS, IoBT, etc.)					
Please indicate the list of manufacturers and models of gas meters in your the network (e.g., Fiorentini - HM; etc)					
Please indicate the list of manufacturers and models of gas converters, if installed (e.g., Fiorentini - Modus, etc.)					
If you manufacture by yourself the meters, please indicate the commercial name, the technology (e.g., ultrasonic, thermal mass, etc.) and if it is ready for H2 (e.g., 30%vol)					
Fiscal measurement groups installed - WITHOUT remote control					
Total number of installed meters, [-]					
Please rank the following technology from the most used to the less used in the identified range size (e.g., 1 - the most implemented in the grid; 7 - the less implemented. Use "NA" if the technology is not used)					
Diaphragm meters					
Ultrasonic meters					
Thermal mass meters					
Rotary piston meters (*)	☒				
Turbine meters (*)	☒				
Other					
Please indicate the list of manufacturers and models of gas meters in your the network (e.g., Elster BK-G, etc)					
Please indicate the list of manufacturers and models of gas converters, if installed (e.g., Fiorentini - Modus, etc.)					
If you manufacture by yourself the meters, please indicate the commercial name and the technology (e.g., ultrasonic, thermal mass, etc.)					
Please indicate any eventual comment that you believe useful here					

Note: (*) To our best knowledge turbine and rotary piston technology is not used for G4/G6 gas meter sizes. Otherwise, please indicate it in the comments

Auxiliary questions (these inputs will be useful to select the devices to be tested)					
Please indicate which of the "smart" gas meters you indicated in row 18 (e.g., **specifying models and manufacturers**) you would like to prioritize for testing activities, **the reasons of your selection** (e.g. number of installed meters, roll-out campaign on-going, etc.) **and the type of tests** (e.g., metrological performances, degradation, etc.)					
Please indicate which of the gas meters you indicated in row 30 (e.g., **specifying models and manufacturers**) you would like to prioritize for testing activities, **the reasons of your selection** (e.g. number of installed meters, roll-out campaign on-going, etc.), **the type of tests** (e.g., metrological performance, degradation, etc.)					

Figure 48. Sheet no. 4.2.1 of the developed survey: Fiscal measurement_DSOs.

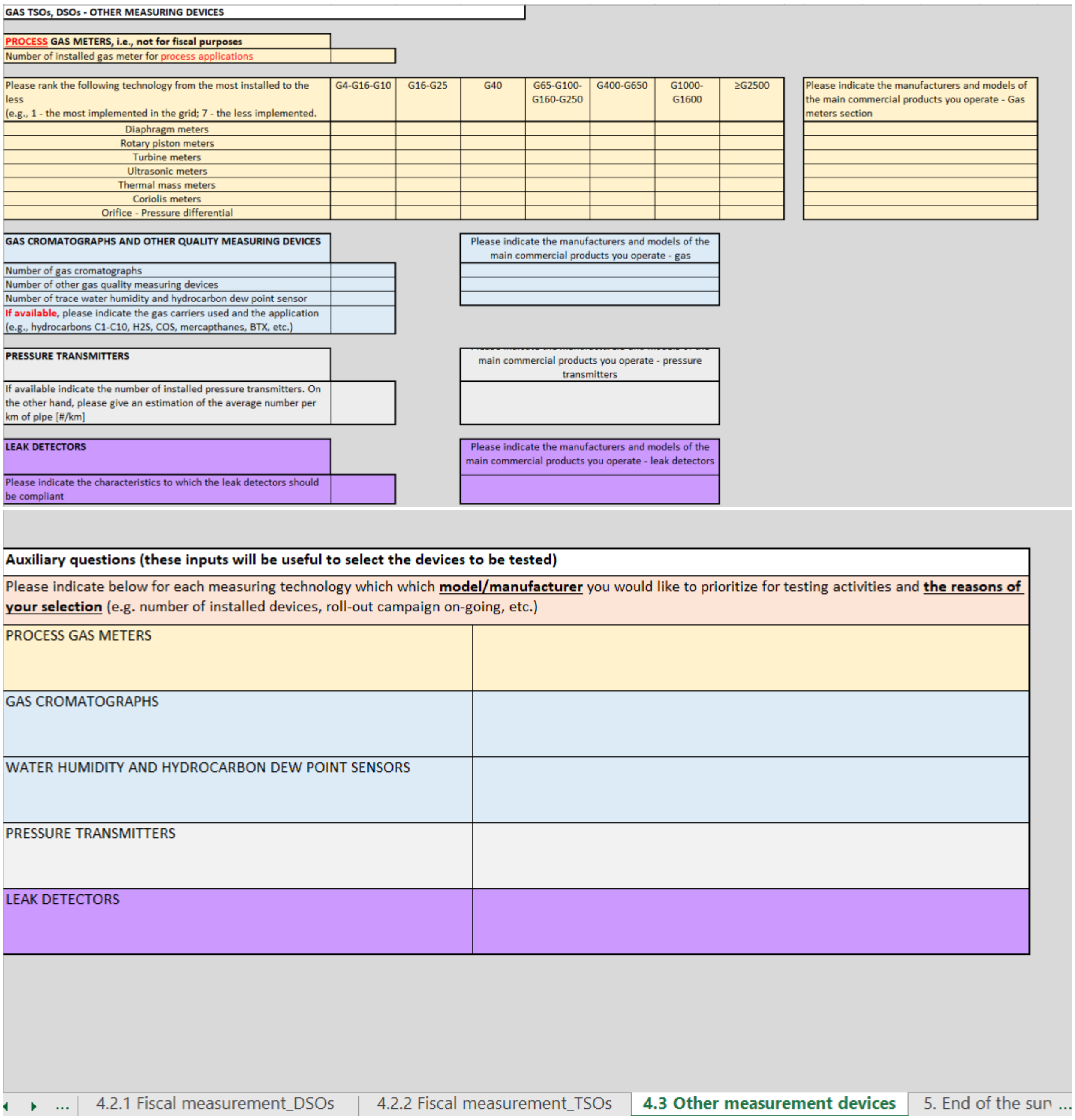


GAS TSOs - FISCAL GAS METERS

Meter Size	**<G40**	**G65-G100-G160-G250**	**G400-G650**	**G1000-G1600**	**≥G2500**	**Comments/notes**
Operative pressure - please indicate a range [barg]						
Total number of installed meters [-]						
Please rank the following technology from the most used to the less used in the identified range size (e.g., 1 - the most implemented in the grid; 7 - the less						
Turbine meters						
Ultrasonic meters						
Rotary piston meters						
Thermal mass meters						
Diaphragms meters						
Coriolis meters						
Other						
Please indicate the manufacturer and the model of the installed meter (e.g., Common, CGR-FX etc)						
Please indicate the list of manufacturers and models of gas converters, if installed (e.g., Fiorentini - Modus, etc.)						
If you manufacture by yourself the meters, please indicate the commercial name, the technology (e.g., ultrasonic, thermal mass, etc.) and if it is ready for H2 (e.g., 30%vol)						
Please indicate any eventual comment that you believe useful here						

Auxiliary question (these inputs will be useful to select the devices to be tested)					
Please indicate which of the gas meters you indicated in row 14 (e.g., **specifying models and manufacturers**) you would like to prioritize for testing activities, **the reasons of your selection** (e.g. number of installed meters, roll-out campaign on-going, etc.), **the type of tests** (e.g., metrological performance, degradation, etc.)					

Figure 49. Sheet no. 4.2.2 of the developed survey: Fiscal measurement_TSOs.



GAS TSOs, DSOs - OTHER MEASURING DEVICES

PROCESS GAS METERS, i.e., not for fiscal purposes	
Number of installed gas meter for process applications	

Please rank the following technology from the most installed to the less (e.g., 1 - the most implemented in the grid; 7 - the less implemented.	G4-G16-G10	G16-G25	G40	G65-G100-G160-G250	G400-G650	G1000-G1600	≥G2500
Diaphragm meters							
Rotary piston meters							
Turbine meters							
Ultrasonic meters							
Thermal mass meters							
Coriolis meters							
Orifice - Pressure differential							

Please indicate the manufacturers and models of the main commercial products you operate - Gas meters section

GAS CROMATOGRAPHS AND OTHER QUALITY MEASURING DEVICES	
Number of gas cromatographs	
Number of other gas quality measuring devices	
Number of trace water humidity and hydrocarbon dew point sensor	
If available, please indicate the gas carriers used and the application (e.g., hydrocarbons C1-C10, H2S, COS, mercapthanes, BTX, etc.)	

Please indicate the manufacturers and models of the main commercial products you operate - gas

PRESSURE TRANSMITTERS	
If available indicate the number of installed pressure transmitters. On the other hand, please give an estimation of the average number per km of pipe [#/km]	

main commercial products you operate - pressure transmitters

LEAK DETECTORS	
Please indicate the characteristics to which the leak detectors should be compliant	

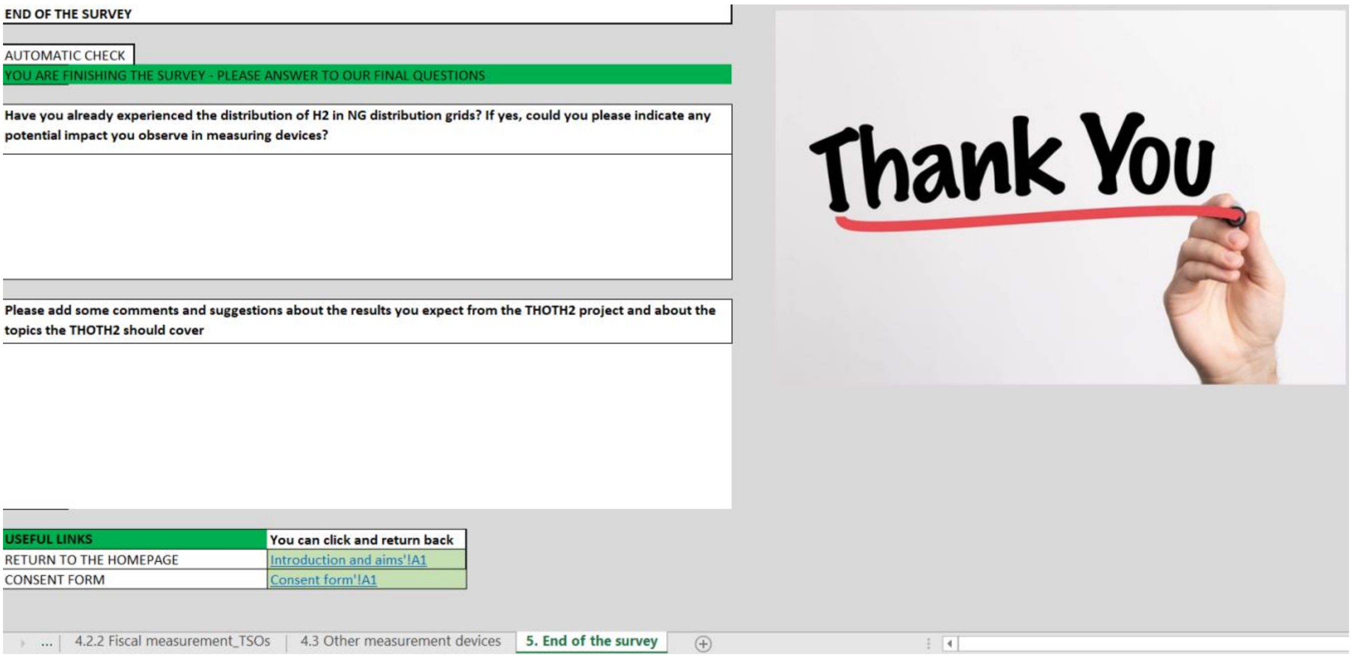
Please indicate the manufacturers and models of the main commercial products you operate - leak detectors

Auxiliary questions (these inputs will be useful to select the devices to be tested)

Please indicate below for each measuring technology which which **model/manufacturer** you would like to prioritize for testing activities and **the reasons of your selection** (e.g. number of installed devices, roll-out campaign on-going, etc.)

PROCESS GAS METERS	
GAS CROMATOGRAPHS	
WATER HUMIDITY AND HYDROCARBON DEW POINT SENSORS	
PRESSURE TRANSMITTERS	
LEAK DETECTORS	

Figure 50. Sheet no. 4.3 of the developed survey: Other measurement devices.



END OF THE SURVEY

AUTOMATIC CHECK

YOU ARE FINISHING THE SURVEY - PLEASE ANSWER TO OUR FINAL QUESTIONS

Have you already experienced the distribution of H2 in NG distribution grids? If yes, could you please indicate any potential impact you observe in measuring devices?

Please add some comments and suggestions about the results you expect from the THOTH2 project and about the topics the THOTH2 should cover

USEFUL LINKS	You can click and return back
RETURN TO THE HOMEPAGE	Introduction and aims'!A1
CONSENT FORM	Consent form'!A1

Figure 51. Sheet no. 5 of the developed survey: End of the survuey.