INTERNATIONAL STANDARD

ISO 21903

First edition
2020-02

Refrigerated hydrocarbon fluids — Dynamic measurement — Requirements and guidelines for the calibration and installation of flowmeters used for liquefied natural gas (LNG) and other refrigerated hydrocarbon fluids

Hydrocarbures liquides réfrigérés — Mesurage dynamique — Exigences et lignes directrices pour l'étalonnage et l'installation de débitmètres utilisés pour le gaz naturel liquéfié (GNL) et autres hydrocarbures liquides réfrigérés

Reference number
ISO 21903:2020(E)

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 28, *Petroleum and related products, fuels and lubricants from natural or synthetic sources*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Reliable, accurate and commonly agreed measurement methods are a first requirement for the trade of goods. In the LNG distribution chain, there is a commonly agreed measurement practice, as described in various International Standards and in the GIIGNL *Custody transfer handbook*[10]. The LNG industry is committed to improve measurement accuracy to reduce financial risks and to optimize mass and energy balances throughout the LNG measurement chain. Dynamic measurement technologies have the potential to reduce measurement uncertainty. As an extension of the traditional distribution chain for LNG, a new market of professional consumers for LNG is developing related to transport fuel and metrological infrastructure. In this respect, the availability of the following tools for dynamic flow measurement is essential:

— primary standards for the determination of the amount of an LNG substance and calibration of working standards;

— LNG test and calibration facilities (for volume and mass flow) for the calibration of equipment for custody transfer, allocation or process control under operational conditions;

— stable meters for the determination of volume and mass flow under cryogenic conditions;

— guidelines for the selection and installation of cryogenic flowmeters;

— guidelines for zeroing and adjusting cryogenic flowmeters, including tips and traps;

— guidelines for the further dissemination of traceability by (master meter) calibration techniques, including correction methods for parasitic metrological effects;

— guidelines for the calibration of volume and mass flowmeters with alternative fluids such as water.

This document provides designers of metering stations and end-users with a set of valuable guidelines to enable a better performance of liquid flowmeters under cryogenic operating conditions. The document focuses on LNG as a medium, however, it is assumed that much of the information is also directly applicable to other cryogenic fluids.

Refrigerated hydrocarbon fluids — Dynamic measurement — Requirements and guidelines for the calibration and installation of flowmeters used for liquefied natural gas (LNG) and other refrigerated hydrocarbon fluids

1 Scope

This document specifies the metrological and technical requirements for flowmeters intended to be used for the dynamic measurement of liquefied natural gas (LNG) and other refrigerated hydrocarbon fluids. For LNG static volume measurement used in custody transfer, see ISO 10976.

This document sets the best practice for the proper selection and installation of flowmeters in cryogenic applications and identifies the specific issues that can affect the performance of the flowmeter in use.

Moreover, it offers a calibration guideline for laboratory and on-site conditions (mass or volume) by either using LNG or other reference fluids. The choice of calibration fluid will depend on the capabilities of the available flow calibration facilities and the ability to achieve the required overall measurement uncertainty demanded by the intended application.

This document is applicable, but is not limited, to the use of Coriolis and ultrasonic flowmeters for dynamic measurements of LNG.

In principle, LNG and other refrigerated liquid hydrocarbons are considered in this document. Recommendations in this document are based on the available test results with LNG. These results are probably applicable to other cryogenic fluids.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

ISO 12242, *Measurement of fluid flow in closed conduits — Ultrasonic transit-time meters for liquid*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1.1
master meter
MM
flowmeter calibrated against a primary standard with sufficiently low uncertainty and used to calibrate the meter under test

3.1.2
measurement error
measured quantity value (3.1.3) minus a reference quantity value

3.1.3
measured quantity value
quantity value representing a measurement result

3.1.4
measurement uncertainty
non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used

Note 1 to entry: A list of metrological definitions can be found in ISO/IEC Guide 99.

3.1.5
stored zero value
S_{ZV}
value stored in the flowmeter transmitter representing a meter reading at a no flow condition

3.1.6
turndown ratio
ratio of maximum and minimum flow rates

3.1.7
zero adjustment
dedicated procedure to set a new *stored zero value* (3.1.5), with the aim to keep the flowmeter within its *zero offset limit* (3.1.9)

3.1.8
zero offset
Z_0
average mass or volume flow rate reading observed under zero (no) flow conditions

Note 1 to entry: In this instance, the (Coriolis) flowmeter's low flow cut-off filter is disabled, and the flow direction in the electronics is set to bi-directional.

3.1.9
zero offset limit
$Z_{0\mathrm{L}}$
maximum permissible *zero offset* (3.1.8) specified by the manufacturer

Note 1 to entry: Some Coriolis mass flowmeter manufacturers also state a specific zero offset for verification and adjustment.

3.1.10
zero verification
procedure to check that the actual *zero offset* (3.1.8) of the flowmeter has not exceeded the *zero offset limit* (3.1.9)

3.2 Abbreviated terms

CMF Coriolis mass flowmeter

LNG liquefied natural gas

MM master meter

MUT meter under test

USM ultrasonic flowmeter

4 Flowmeter selection

4.1 Considerations of meters specific to LNG metering

Table 1 gives an overview of the considerations for the selection of the appropriate flowmeter for a specific situation.

Table 1 — Flowmeter selection considerations

Parameter	Coriolis flowmeter	Ultrasonic flowmeter
Type of measurement	Mass flow measurement, density measurement.	Volumetric flow measurement (at actual conditions).
Diameter of the meter	Limited line size.[a]	Availability for larger lines.[b]
Required space to install the meter	Relative large meter body dimensions.	Relative small meter body dimensions.[c]
Pressure drop	Considerable pressure drop at high flow rates. Possibility of LNG flashing.	Low pressure drop.
Turndown ratio	Large rangeability; the flowmeter can be applied to a large range of flow rates.	Large rangeability; the flowmeter can be applied to a large range of flow rates.
Diagnostics	Density, gain of excitation (gas detection), tube temperature.	Multiple paths flow profile, speed of sound, gain, signal to noise ratio (gas detection).
Straight length requirements (flow profile)	Not required to have a straight length upstream of the flowmeter. This is because CMFs are typically not affected by swirling and non-uniform flow velocity profiles induced by upstream or downstream piping configurations.	For meters with a small number of paths (< 4) a significant straight length up and downstream of the meter is required to achieve sufficient accuracy. This is because meters with small number of paths may be sensitive to swirl and non-uniform flow velocity profiles induced by upstream or downstream piping configurations. Multipath types may not be sensitive to swirling and non-uniform flow velocity profiles induced by upstream or downstream piping configurations.
Bi-directional flow	Suitable for bi-directional flow.	Suitable for bi-directional flow.

[a] Typically meters with a diameter up to 12" are available.

[b] Typically meters with a diameter up to 36" are available.

[c] The total setup could be relatively large due to a long upstream straight pipe length.

[d] The stiffness change of the vibrating tube due to cryogenic temperatures has a significant impact, however, it can be corrected for by the temperature model.

Table 1 *(continued)*

Parameter	Coriolis flowmeter	Ultrasonic flowmeter
Reynolds number sensitivity	Generally low sensitivity to Reynolds number for low viscosity fluids such as LNG. For very high viscosity fluids the flowmeter error is dependent on the Reynolds number, especially for laminar-turbulent transition. The viscosity changes due to changes in the composition are anticipated to be negligible.	Depending on the number of paths there is a moderate to high sensitivity on the Reynolds number. The viscosity changes due to changes in the composition are anticipated to be negligible.
Sensitivity to vibrations	Could be affected by vibrations when the frequency is near the vibration frequency of the tube.	Insensitive to vibrations.
Mechanical stress	Sensitive to mechanical stress. Impact of mechanical stress can be monitored for zero flow conditions.	Insensitive to mechanical stress.
Pressure	Small effect for pressures up to roughly 30 bar. Can be corrected for based on available correction models and internal or external pressure measurement.	Smaller effect, can be corrected for based on available correction models and internal or external pressure measurement.
Temperature	Thermal expansion of the meter body may be compensated for based on internal/external temperature measurement.[d]	Thermal expansion of the meter body may be compensated for by an internal/external temperature measurement.
Others	Measured flow and density can be influenced by bubbles caused by (local) boiling and/or cavitation in the flow.	Measured flow can be influenced by bubbles caused by (local) boiling and/or cavitation in the flow. Consider velocity limits to prevent cavitation around transducers.

[a] Typically meters with a diameter up to 12" are available.

[b] Typically meters with a diameter up to 36" are available.

[c] The total setup could be relatively large due to a long upstream straight pipe length.

[d] The stiffness change of the vibrating tube due to cryogenic temperatures has a significant impact, however, it can be corrected for by the temperature model.

4.2 Coriolis flowmeter

The CMF is a device that measures mass flow rate as well as fluid density. Its fundamental operational principle is based on vibration mechanics and its interaction with the fluid dynamics. Because of its working principle, the flowmeter is capable of determining the density of the fluid when it matches a resonance frequency that corresponds to the fluid mass enclosed in the measuring tube's finite volume.

The mass flow rate is directly linked to the Coriolis force that is present when the fluid moves at a certain velocity and in combination with the measuring tube's angular motion. As this occurs, a secondary oscillation mode will take place, thus generating a phase shift in the measuring tube displacement. Such a phase shift is proportional to the mass flow rate, and is therefore used as a primary output signal to determine flow.

NOTE More information on the CMF is given in Annex A.

4.3 Ultrasonic flowmeter

The ultrasonic transit-time flowmeter is a sampling device that measures discrete path velocities using one or more pairs of transducers. Each pair of transducers is located at a known distance apart such that one is upstream of the other. The upstream and downstream transducers send and receive pulses of ultrasound alternately. The times of arrival are used in the calculation of average axial velocity. At any given instant, the difference between the apparent speed of sound in a moving liquid and the speed of sound in that same liquid at rest is directly proportional to the liquid's instantaneous velocity. As a consequence, a measure of the average axial velocity of the liquid along a path can be obtained by transmitting an ultrasonic signal along the path in both directions and subsequently measuring the transit-time difference.

The volumetric flow rate of a liquid flowing in a completely filled closed conduit is defined as the average velocity of the liquid over a cross section multiplied by the area of the cross section. Thus, by measuring the average velocity of a liquid along one or more ultrasonic paths (i.e. lines, not the area) and combining the measurements with knowledge of the cross-sectional area and the velocity profile over the cross section, it is possible to obtain an estimate of the volumetric flow rate of the liquid in the conduit.

NOTE More information on the ultrasonic flowmeter is given in Annex B.

5 Process conditions

5.1 Temperature effects

5.1.1 Loading procedures

Both CMF and USM applications require a stable and consistent single-phase flowing medium in order to correctly measure the flow. It is particularly important to consider this requirement when loading at cryogenic temperatures as potentially large temperature variations and heat gain increase the likelihood of a two-phase flow. This will at least be the case if the meter/pipes connecting the meter are at ambient temperature prior to loading.

Several mitigating actions may be employed to increase the likelihood of maintaining a cryogenic single-phase liquid flow. One effective way to accomplish this is by keeping the meter cooled down, not only during loading operations, but at all times, e.g. by using a proper circulating loop. A disadvantage is the increased cost of cooling the cryogenic medium as the circulation will increase the heat gain. In general, a low-flow velocity, large pipe diameter, and poorly insulated meter and flow lines should be avoided as this will add to the probability of boiling and two-phase flow.

Maintaining the temperature of the meter at cryogenic conditions will minimize stresses on the pipe material, which is desirable.

Depending on the loading product, it is common practice to cool down the meter and pipes from ambient to cryogenic conditions prior to transfer. For LNG application, gas and liquid nitrogen are often used for this purpose. Starting from an ambient temperature, cold nitrogen gas can be introduced to gradually lower the temperature and avoid stress from temperature shock. Small amounts of liquid nitrogen are then injected to boil off and further cool down the system.

For some applications (e.g. in a small-scale LNG transfer), it is not possible to cool the meter and pipes with liquid nitrogen because it is not accessible at the location. In this case, purging the system with cold natural gas is allowed.

After loading, the temperature will have to change from cryogenic to ambient conditions. It is common to let the remaining liquid boil off from meter/pipes and this can cause a two-phase metering condition.

Depending on the conditions, at loading, both the CMF and USM can apply compensation to account for changes in process conditions such as temperature. Any such compensation can increase the measurement uncertainty and shall be considered specifically for the actual application. Therefore, it is advisable to consult the flowmeter manufacturer.

5.1.2 Temperature effects on CMF measurements

One fundamental design parameter for CMFs at cryogenic temperatures is the consideration of the measuring tube's material properties and its behaviour at very low temperatures. This is quite relevant, since the Young's modulus of elasticity of tube material at standard conditions (e.g. water at laboratory temperature) is significantly different from the cryogenic conditions, and, more importantly, its value is defined by a nonlinear relationship with the temperature. Further, because of the cryogenic temperatures, the volume of the measuring tubes changes significantly. Disregarding these effects can cause a shift in the calibration curve and thus a measurement bias.

Since CMF manufacturers are aware of these effects, a dedicated algorithm is implemented in CMF software to correct for the Young's modulus dependence on temperature, thermal contraction and any other relevant parameters, if applicable.

In general, straight-measuring tube CMFs are more sensitive to cryogenic temperatures, as the axial stress created in the tube can be very high and can exceed the material strength. A bent-measuring tube CMF is a more robust sensor, since the axial stress generated at cryogenic temperatures is much smaller, i.e. within the allowable material strength, and thus it gives a better zero-point stability.

Some independent studies on the performance of CMFs under cryogenic conditions indicate that most meters are suitable for cryogenic flow measurements. However, the closeness of the flow measurement to the reference value will vary according to the correction algorithm developed by the manufacturer, and the data concerning the sensor's material properties obtained from a fitted polynomial curve. It is worth noting that, despite having a reliable source of data, the tube material properties and/or the influence of the manufacturing process can cause a shift from the reference data, thus causing unaccountable axial stress on the sensor.

5.1.3 Temperature effects on USM measurements

For all ultrasonic meters, the flow correction factor due to changes in meter geometry at cryogenic temperatures can be given as a straightforward analytical solution, see ISO 12242. Owing to this, the correction has a very small uncertainty and the only uncertainties related to this correction are those associated with the material constants.

The flow correction factor due to a change in the meter body temperature, ΔT, is shown by Formula (1):

$$K_{bt} = (1+\alpha\Delta T)^3 = \left(1+3\alpha\Delta T+3(\alpha\Delta T)^2+(\alpha\Delta T)^3\right) \quad (1)$$

where

K_{bt} is the thermal correction factor;

ΔT is $T_{operating} - T_{calibration}$;

α is the thermal expansion coefficient.

Formula (1) may be simplified without a significant loss of accuracy to Formula (2):

$$K_{bt} = 1+3\alpha\Delta T \quad (2)$$

5.2 Pressure effects

5.2.1 Coriolis flowmeter

Operating a CMF at fluid pressures higher than the calibration reference conditions will lead to changes in the mechanical characteristics of the measuring tube, thus modifying the CMF fundamental vibration frequency, and, if not corrected, could create significant flow measurement errors.

The fluid pressure effect may be interpreted in mechanical terms as an additional axial stress acting on the measuring tube. From manufacturers' data and independent tests, it has been found that pressure effects can differ with measuring tube geometry. For most bent-tube CMFs, the sign of the pressure sensitivity (percentage of error per bar) is negative, while for most straight-tube CMFs it is positive.

Currently, the majority of CMFs have a relatively small sensitivity to pressure changes. However, if there is a need to quantify the CMF's impact on the measurand, then the end-user is advised to follow the manufacturer's recommendations. Alternatively (if applicable), a pressure sensor may be employed to make a real-time correction to the measurand, thus minimizing the CMF's pressure sensitivity. The latter shall be taken into consideration only if the CMF pressure-induced error exceeds the maximum error tolerated by the process measurement, or if the operational pressure is so significantly high that the manufacturer advises using an auxiliary pressure sensor.

5.2.2 Ultrasonic flowmeter

The influence of pressure on the performance of a USM, if operated at fluid pressures different than the calibration pressure, is almost negligible. Only an expansion caused by the meter body due to a pressure difference will affect the internal diameter, and hence will cause an under- or over-reading. This will only be significant if the pressure difference is substantial. In this case, the flowmeter should have the capability to correct for it. A general formula to calculate the pressure correction factor is shown by Formula (3):

$$K_{pb} = 1 + \frac{C_{pb}}{100} \times \left(P_{process} - P_{cal} \right) \quad (3)$$

where

K_{pb}	is the correction factor used for the pressure expansion;
C_{pb}	is the linear pressure coefficient, in %/kPa;
$P_{process}$	is the process pressure, in kPa;
P_{cal}	is the reference pressure, in kPa.

A typical pressure correction factor for a pressure difference is C_{pb} = 0,000 04 %/kPa.

NOTE A generic formula to calculate the effect of volume increase due to pressure is shown by Formula (4):

$$\frac{\Delta A_i}{A_i} = \frac{D_i + w}{w} \times \frac{P}{E} \quad (4)$$

where

ΔA_i	is the difference of the internal cross-sectional area;
A_i	is the internal cross-sectional area;
D_i	is the internal pipe diameter;
w	is the wall thickness;
P	is the pressure;
E	is the elasticity modulus.

5.3 Mechanical vibrations

5.3.1 Coriolis flowmeter

In some cases, CMFs are exposed to external vibrations or pulsations. Such vibrations can be induced by mechanical means (i.e. a pumping system), the environment or by the fluid dynamics in the pipeline.

In general, a CMF is designed in such a way so that the effect of the external vibration is minimized, whereby it has no relevant impact on the CMF measurement.

In cases where the end-user deals with a severe vibration application, it is recommended to use flexible piping or isolation pipe supports to minimize the vibration, or to contact the manufacturer for further assistance.

5.3.2 Ultrasonic flowmeter

USMs are built out of a robust metal body and the principle of operation is based on measuring the time differences between two ultrasonic pulses travelling across the pipe diameter in opposite directions. Currently, there is no proof of sensitivity of the meter reading to mechanical vibration.

5.4 Cavitation

5.4.1 Coriolis flowmeter

Cavitation in CMFs is defined as the process of formation of the vapour phase of a liquid within the measuring tube. This phenomenon occurs when the hydrostatic pressure is decreased, which is caused by a reduction in the cross-sectional area. The decrease in hydrostatic pressure causes a decrease in the boiling point, which can cause the liquid to start boiling. This phenomenon is also known as “cavitation”.

As the liquid cavitates within the measuring tube, it forms tiny vapour bubbles, which grow as they collapse on one another (implosion). If the fluid velocity at the measuring tube continues to increase (the pressure continues to fall), then the vapour bubbles will continue growing in the same manner (see Figure 1).

In terms of linearity, the cavitation effect plays a significant role, since the two-phase condition can generate a significant measurement error depicted by a nonlinear response at the upper flow range of the CMF.

Unlike other nonlinear effects upon CMFs, this is perhaps the easiest to handle, since cavitation can be prevented by setting the operating process conditions properly. In this respect, there are six fundamental recommendations to avoid cavitation:

a) use the correct size of the CMF according to the process conditions;

b) avoid low upstream pressure;

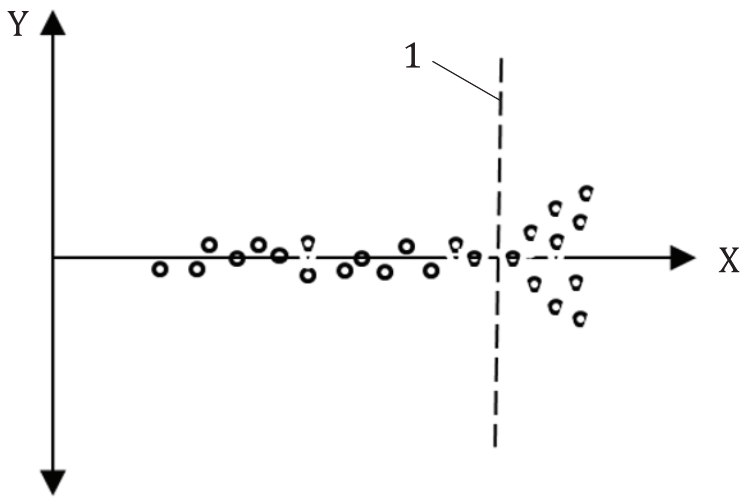
c) avoid fluid velocities out of the manufacturer’s specifications;

d) use the correct operational window and pressure/temperature relation (see the phase envelope);

e) ensure proper venting at a high point to prevent vapour pockets growing over time;

f) ensure enough recirculation (cooling) over the line piece to minimize the influence of ambient heat gain.

Figure 1 depicts a sudden spread of the measurement error in the CMF response, due to the early presence of cavitation in the measuring tube(s).



Key

1 early presence of cavitation

X flow, in kg/h

Y relative error, in %

Figure 1 — Early presence of cavitation in a Coriolis flowmeter

5.4.2 Ultrasonic flowmeter

Cavitation in the USM is unlikely to happen when the transducers are built-in in such a way that no cavities are present (the transducers are flush with the inner pipe wall). If cavitation takes place in the meter, the readout will be unstable and, in some cases, will completely stop due to the attenuation of the sound pulse.

5.5 Thermodynamic properties of LNG

The fluid properties for density and viscosity for LNG can be found in the tables in Annex F.

6 Installation

6.1 Valves

For both CMFs and USMs, it is recommended to use valves that are fully leak-tight. Flow regulating valves (control valves) should be installed downstream to ensure that the fluid remains in a single phase and no flashing or cavitation occurs.

6.2 Swirl and non-uniform profiles

6.2.1 Coriolis flowmeter

The performance of a CMF in single-phase flow is not affected by swirls or non-uniform velocity profiles induced by upstream or downstream-piping configurations.

Caution shall be exercised with respect to inducing external stress or vibration on the flow tubes when planning and carrying out the installation of Coriolis meters as explained in ISO 10790.

