International Standard

ISO 9200

Second edition
2024-05

Petroleum measurement systems — Metering of viscous and high temperature liquids

Systèmes de mesurage des produits pétroliers — Comptage des liquides visqueux et à haute température

Reference number
ISO 9200:2024(en)

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

Published in Switzerland

Contents

Page

Foreword .... **iv**
Introduction .... **v**
1 Scope **1**
2 Normative references **1**
3 Terms and definitions **1**
4 Properties of high viscosity liquids **2**
4.1 Viscosity 2
4.2 Reynolds number and flow profile 3
4.3 Density 4
4.4 Effect of temperature on viscosity 4
4.5 Examples of high viscosity liquids and behaviour 5
4.6 Further considerations 6
5 Metering systems **6**
5.1 General 6
5.2 Installation 7
5.3 Heating 8
5.4 System start-up and filling 9
6 Flowmeters **10**
6.1 Differential pressure meters 10
6.2 Displacement meters 10
6.3 Turbine meters 12
6.4 Coriolis mass flowmeters 13
6.5 Ultrasonic meters 14
7 Meter proving **16**
7.1 General 16
7.2 Pipe provers 16
7.3 Volumetric measures 17
7.4 Gravimetric proving 18
7.5 Master meter proving 18
8 Volumetric corrections **18**
8.1 Standard volume 18
8.2 Thermal expansion and temperature effects 19
8.2.1 Overview 19
8.2.2 Temperature effect on Coriolis meters 19
8.2.3 Thermal expansion for ultrasonic meters and differential pressure meters 20
8.2.4 Thermal expansion for displacement and turbine meters 20
Bibliography **21**

Foreword

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

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 document 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).

ISO draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). ISO takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, ISO had not received notice of (a) patent(s) which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at www.iso.org/patents. ISO shall not be held responsible for identifying any or all such patent rights.

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

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*, Subcommittee SC 2, *Measurement of petroleum and related products*.

This second edition cancels and replaces the first edition (ISO 9200:1993), which has been technically revised.

The main changes are as follows:

— mass and volumetric metering is now covered;

— a description and definition of viscosity has been added along with a clarification of high viscosity and high temperature;

— the emphasis on positive displacement meters has been replaced by descriptions of other meter types including ultrasonic, Coriolis and differential pressure devices.

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

This document is intended to guide users in the design, installation, operation, and proving of flowmeters, and their auxiliary equipment, used in the dynamic metering of viscous liquids. It also provides guidance when elevated operating temperatures are used to reduce viscosity. The document applies to Newtonian, hydrocarbon and petroleum liquids. Extra consideration should be given when using other liquids and non-Newtonian liquids.

The objective of this document is to highlight the considerations to be taken into account when metering high viscosity liquids at normal and elevated temperatures, in addition to the normal application of metering less viscous liquids at ambient temperatures.

As the viscosity of a liquid increases, the resistance to flow increases. In a fluid transfer system, this generally means that the maximum flowrate achievable for any given conduit size is reduced to avoid excessive pressure loss. This generally results in lower velocities within the measurement system than would be found in lower viscosity applications. As most flow sensors and meters require a minimum velocity to provide reasonable resolution of measurement, the operational range of the flowmeter chosen can be reduced.

Each flowmeter type and design has different limitations on the viscosity and flow range across which it operates at an acceptable accuracy. For higher viscosities and low velocities, it is probable that for many applications the flow regime is laminar rather than turbulent which again affects the performance of flowmeters.

To provide efficient transport of the fluid within a pipe, viscous liquids are often heated to reduce the viscosity. Measuring systems and the associated flowmeters are therefore selected and operated to suit the chosen operating temperature, taking into account changes in temperature and viscosity from ambient conditions.

The behaviour of the fluid should be considered carefully to recognize the potential for the liquid to solidify during idle periods and also to manage the potential for air, gas, solids, and wax content from damaging or affecting the metering system.

This document supplements the guidance documents applicable to different flowmeter designs and proving methods in the relevant ISO standards referenced in the bibliography.

Petroleum measurement systems — Metering of viscous and high temperature liquids

1 Scope

This document gives guidance for measuring a quantity of primarily viscous hydrocarbon liquid using flowmeters at ambient or elevated operating temperatures.

This document describes the effects of high viscosities and potentially high temperatures, which can induce additional errors in measurement. It also gives guidance on how to overcome or mitigate difficulties.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

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

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

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

3.1
density
mass in a given volume

3.2
performance indicator
derived value which relates the meter output to the quantity measured and can be used to indicate the performance of the meter

EXAMPLE Error, meter factor, K-factor, and discharge coefficient.

3.3
pipe prover
displacement prover
device where the volume of a fluid is displaced from the calibrated length of a pipe and used to provide a calibration reference for flowmeters

3.4
pour point
lowest temperature at which a liquid product loses its flow characteristics and, under specified conditions, ceases to flow

Note 1 to entry: The temperature at which a liquid ceases to flow is based on a standard test.

3.5
Reynolds number
dimensionless number expressing the ratio between the inertia forces and viscous forces within a flowing fluid

Note 1 to entry: The Reynolds number can provide an indication of the flow profile within a pipe. Generally, numbers below 2 000 indicate a laminar flow, while a number higher than 5 000 indicates a turbulent flow.

Note 2 to entry: The Reynolds number and performance indicator for some flowmeters provides a single relationship which accounts for variations in viscosity as well as flowrate.

3.6
viscosity
measure of resistance to flow

3.7
dynamic viscosity
viscosity dynamic
viscosity absolute
ratio of shear stress to shear rate within the fluid, hence the force needed to overcome internal friction

Note 1 to entry: The unit of absolute viscosity is Pascal second (Pa s). The unit of centipoise (cP) is commonly used in practice. 1cP = (1 × 10^{-3} Pa s).

3.8
kinematic viscosity
viscosity kinematic
ratio of *dynamic viscosity* (3.7) to *density* (3.1)

Note 1 to entry: The unit of kinematic viscosity is metre square per second (m^2 s^{-1}). The unit centistoke (cSt) is commonly used in practice. 1cSt = (10^{-6} m^2 s^{-1}) = (1 mm^2 s^{-1}). The unit mm^2 s^{-1} is used throughout this document when giving examples of fluid viscosity.

3.9
performance indicator
derived value which may be used to indicate the performance of the meter

EXAMPLE Error, K-factor, meter factor or discharge coefficient.

3.10
volumetric measure
measure used to provide an accurate measurement of volume to provide a reference for other volume measuring devices

3.11
wax point
cloud point
wax precipitation point
temperature at which wax precipitates from a hydrocarbon liquid

4 Properties of high viscosity liquids

4.1 Viscosity

In this document a viscous liquid is any liquid that requires special treatment or equipment in its handling or storage because of its resistance to flow at either ambient or operating temperature. The liquid is assumed to be Newtonian. If the fluid is non-Newtonian, additional influences on metering should be considered.

Viscosity is typically expressed as being either dynamic or kinematic.

Dynamic viscosity (μ) and kinematic viscosity (υ) are related through density (ρ) by Formula (1).

$$\mu = \nu\rho \tag{1}$$

where

μ is the dynamic viscosity, expressed in Pascal seconds (Pa s);

ρ is the density, expressed in kilograms per cubic metre (kg m^{-3});

ν is the kinematic viscosity, expressed in metre square per second (m^2 s^{-1}).

When applying this conversion, or any other use of a viscosity relationship, consistent and matching units should be used. Using the relevant SI unit as given in Formula (1) helps to avoid error.

4.2 Reynolds number and flow profile

The Reynolds number provides a scale to represent the turbulence within a flowing fluid, hence providing a guide to the velocity profile within a pipe. The Reynolds number is calculated from Formula (2).

$$Re = \frac{VD\rho}{\mu} = \frac{VD}{\upsilon} \tag{2}$$

where

D is the pipe internal diameter, expressed in metres (m);

V is the mean pipe velocity, expressed in m^2 s^{-1};

ρ is the density, expressed in kg m^{-3};

μ is the dynamic viscosity, expressed in Pa s;

ν is the kinematic viscosity, expressed in m^2 s^{-1}.

When calculating the Reynolds number, it is important to ensure the units used are consistent. Using the relevant SI unit as given in Formula (2) helps to avoid error.

Generally, laminar flow is present at Reynolds numbers below 2 000 and turbulent flow at Reynolds numbers above 5 000. Between 2 000 and 5 000, a transitional condition is found where either laminar or turbulent or a changing flow condition exists. Within the transitional range, the condition can switch between regimes. These values are indicative and the Reynolds numbers at which the transition between laminar and turbulent flow occurs is variable and depends on of a variety of factors. These include, but are not limited to, pipe configuration, pipe roughness, temperature, orientation and vibration. Typically, turbulent conditions cannot easily exist below Reynolds number of 2 000, but the transition from laminar to turbulent can easily extend to Reynolds numbers approaching 10 000 and sometimes above.

Increasing viscosity results in a lower Reynolds number for a given velocity. Although most industrial flows of liquids are at a velocity leading to a Reynolds number above 5 000, with higher viscosity liquids a low velocity is often chosen to reduce the pressure losses. Many applications can therefore operate at Reynolds numbers within the transition or laminar region.

Laminar flow results in a parabolic or peaked velocity profile across the pipe, with the highest velocity being at the centre and reducing either side towards the wall. Turbulent flow results in a profile which is essentially flat, or equal, across most of the pipe diameter, and then reduces rapidly to the pipe wall. The flow profile can also be changed due to the viscosity reducing additives or contaminants within the fluid or on the pipe wall. The flow regime and velocity profile have a significant effect on various types of flowmeters.

A stable, predictable and fully developed flow profile (turbulent or laminar) is disturbed by bends and changes in diameter and devices (valves, filters etc.) in the pipe resulting in a swirling or asymmetric flow profile. It takes time and distance to return to a fully developed profile. While a turbulent flow profile can be mostly re-established after a distance of approximately 20 to 30 pipe diameters, a laminar flow profile takes significantly longer to re-establish and in some applications, can take a distance of up to 100 pipe diameters. In laminar flow regimes, temperature difference across a pipe due to sun or wind can modify the profile.

Many flowmeters are designed to perform most effectively with a relatively high flow velocity, resulting in a turbulent flow regime and flat velocity profile. These flowmeters are also significantly affected by a distorted flow profile. Consideration should be given when such flowmeters are used in conditions where there is a laminar flow profile.

When characterizing a meter's performance over its operating range, the Reynolds number can provide an alternative to volumetric flowrate. In some cases, the Reynolds number can be more suitable than the flowrate in providing a single relationship for the performance indicator across the range of the device.

The Reynolds number is not measured directly, however there are techniques available to predict the operational Reynolds number by measuring pressure loss in a straight length of pipe upstream of the flowmeter.

4.3 Density

Density is related to viscosity insofar as high-density hydrocarbon liquids typically also have high viscosity. This is not a linear relationship and can differ between different liquids.

Density should not be used to predict viscosity except when used as a very rough guide.

4.4 Effect of temperature on viscosity

The density of a hydrocarbon liquid varies with temperature in an approximately linear relationship, reducing as the temperature increases. The density and hence volumetric expansion of many hydrocarbon liquids has been defined and the relationship standardized for measurement purposes.

The viscosity of a hydrocarbon liquid also varies with temperature but follows an exponential relationship with viscosity, reducing as the temperature increases. As temperature decreases, the change in viscosity becomes increasingly significant at the lower temperatures.

Viscosity is not required to define the quantity of fluid being measured. It does however, play a significant role in the performance of flowmeters. To specify the viscosity of a liquid, it is common practice to state the dynamic or kinematic viscosity at one specific temperature. It is noted that this temperature is not usually the standard temperature chosen to calculate standard volume. Typically, 20 °C is used to specify viscosity for lower viscosity fluids. For higher viscosity fluids, significantly higher temperatures are used, such as 30 °C, 40 °C or 60 °C, to ensure they are fully liquid when characterized.

There are no common standard formulae relating viscosity to temperature for hydrocarbon liquids. A number of formulae exist, most of which relate kinematic viscosity to temperature. The commonly used formulae all take a similar form and the most common is given in Formula (3).

$$\log\log(\upsilon + A) \cong \log(T) \tag{3}$$

where

log	is logarithm to base 10;
υ	is kinematic viscosity, expressed in $mm^2\ s^{-1}$;
A	is a constant derived from the viscosity measured at two temperatures;
T	is temperature, expressed in degrees Celsius (°C).

NOTE The constant, A, can be derived from measurements using different units from those shown above. In this case, it is expected that units used are carefully recorded and that consistency is ensured when using the formula.

The available formulae, including Formula (3), require the viscosity constant to be derived from measurement. As a minimum, two specific temperatures are used to define the constant *A*. These two values can also be used to generate a viscosity index value which can then be used to predict viscosities at other temperatures.

The temperature at which the fluid or the components within the fluid start to become solid is also important. The wax point is the temperature below which wax or solid components within the liquid precipitate both within the flowing liquid and onto surfaces. The pour point is the temperature below which the liquid effectively no longer flows. If the temperature falls below these points, this has a profound effect on the system and the flowmeter.

If the temperature rises to a point where a component within the liquid can evaporate, boil, or come out of solution, this can lead to gas and two-phase mixture within the system.

4.5 Examples of high viscosity liquids and behaviour

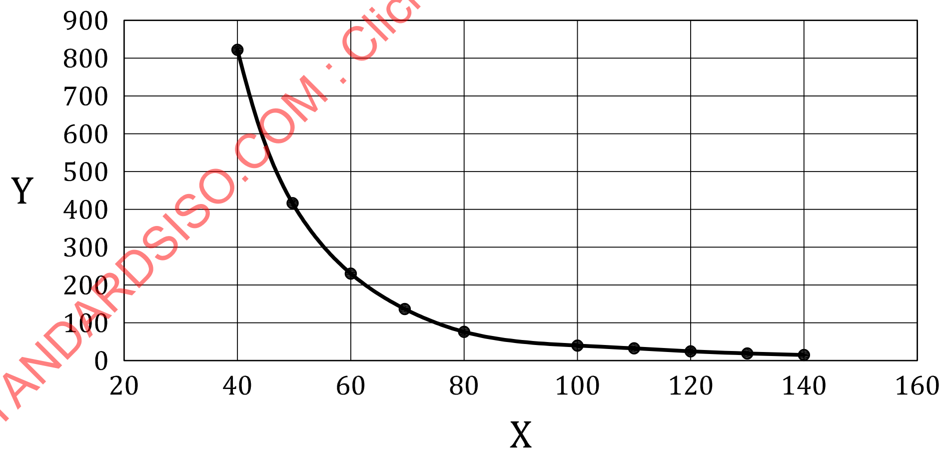
Within this document, high viscosity liquids for measurement are considered to have viscosity at the operating temperature when they are greater than 100 $mm^2 s^{-1}$ and below 2 000 $mm^2 s^{-1}$. Crude oil transport and refining considers the viscosity to be high when it is in the range of 50 $mm^2 s^{-1}$ to 1 000 $mm^2 s^{-1}$.

Operating temperatures are chosen to provide a viscosity within the above ranges, and to allow adequate flow through the system. Temperatures range from ambient through to 150 °C. In some applications, for example, the vacuum refining of residual fuel, the temperature can be as high as 200 °C.

Examples of liquid hydrocarbons which are generally considered as viscous are residual fuels with a viscosity greater than 750 $mm^2 s^{-1}$ (at 50 °C), bitumen, lubricating oils and grease components, and heavy crude oils.

To provide context, water has a viscosity of approximately 1 $mm^2 s^{-1}$ at 20 °C.

Figure 1 shows a graph of viscosity variation with the temperature for a representative high viscosity crude oil. The viscosity at an ambient temperature of 15 °C is estimated to be 1 500 $mm^2 s^{-1}$ and reduces to 800 $mm^2 s^{-1}$ at 40 °C, with further reduction to 200 $mm^2 s^{-1}$ at 60 °C, the specified transport temperature.



Key

X temperature (°C)

Y viscosity ($mm^2 s^{-1}$)

Figure 1 — Representative relationship of temperature to viscosity for a crude oil

4.6 Further considerations

When considering different flowmeter types, the descriptor high viscosity can be significantly lower than the definition applied in this document. For example, the specification of a fiscal turbine meter can suggest a high viscosity application over 20 $mm^2 s^{-1}$.

High viscosity fluids have a number of additional characteristics which should be considered when choosing a metering system. These considerations are listed below.

— Entrained air or gas does not separate easily or quickly from a high viscosity fluid. This results in gas separators or eliminators not being as effective as would be expected when used with low viscosity fluids. Higher pressure losses expected in higher viscosity applications can result in gas formation. Large separators can be specified, however all precautions should be taken to ensure air or gas is not present.

— Solids do not separate or filter easily from high viscosity fluids. Installation of filters or strainers can result in high pressure loss within the system. For this reason, coarse mesh filters are often specified.

— Water or other contaminate liquids do not separate readily when the viscosity is high and can exist as layers, films or emulsions. Emulsions can alter and possibly significantly increase the effective viscosity.

— For some pipeline applications, water or another fluid can be introduced to reduce the friction losses in a pipeline. The water forms a layer on the inside of the pipe wall reducing friction, and thus the pressure loss. Other additives such as viscosity reducers can be introduced to reduce viscosity. The presence and effect of such additives on the flow profile and the flowmeter type should be recognized.

— Cooling below the wax or pour point when the flow is stopped can result in wax formation or solidification within the system.

5 Metering systems

5.1 General

Owing to the various types of meters available and the wide differences in liquids and measurement conditions, it is important that the meter manufacturer be given complete information on the proposed application. The meter manufacturer can make recommendations specifically for the intended operating conditions to minimize possible problems. The manufacturer and system designer should be provided with the following information:

— flow rate range at maximum and minimum operating viscosities;

— maximum and minimum operating pressures;

— maximum and minimum operating temperatures;

— expected ambient conditions and anticipated standby (or off-duty) temperature;

— density or specific gravity of fluid at maximum and minimum operating temperatures;

— viscosity of the fluid at ambient temperature and at the maximum and minimum operating temperatures;

— pour point and wax precipitation temperatures;

— nature and amount of any corrosive elements present;

— nature and amount of any abrasive elements present;

— other fluids such as cleaning and flushing fluids to ensure compatibility;

— presence of additives to reduce friction;

— type of proving method and equipment under consideration.

Certain viscous liquids can contain corrosive materials. This corrosive effect can increase as the temperature increases. Where significant, the metallurgy of the meter, its trim and auxiliary equipment should be capable of resisting this corrosion. At elevated temperatures, special construction materials can be required.

It is important to specify the viscosity at the operating temperature, or across the range of operating temperatures. Providing the single viscosity value given in the fluid specification sheet is not sufficient to adequately design the system.

5.2 Installation

Meters should be installed according to good practice and the manufacturer’s recommendation. Meters and systems should be securely supported. Where the temperature varies significantly from ambient temperature, precautions should be taken to consider thermal expansion of the pipework and avoid resultant stress on the pipework, particularly at the flowmeter.

It is good practice for all meters to allow a minimum distance of five diameters of straight pipe up and downstream to provide a location for additional support for the meter and to allow installation of pressure and temperature measurement. This also provides some degree of profile conditioning.

The manufacturer’s guidance should be sought with regard to an additional straight length of the pipe up and downstream of the chosen flowmeter to provide a suitable flow profile for the meter proposed for the installation. For meters requiring a fully developed profile, e.g. turbine meters, ultrasonic meters and differential pressure meters, a longer length of straight pipe is required following a disturbance. Coriolis meters can require a suitable length of pipe to provide support and stress isolation.

It is recommended to seek guidance from relevant literature and the manufacturers on the effects of both laminar and turbulent flow regimes. Flow straighteners or conditioners can be used to reduce the recommended straight lengths for meters which require a fully developed profile, however the installation of a flow conditioner introduces additional pressure loss and potentially can hold back liquid when draining. Tube bundle type straighteners do not have a significant effect on removing asymmetric flow profile commonly found in laminar flow conditions.

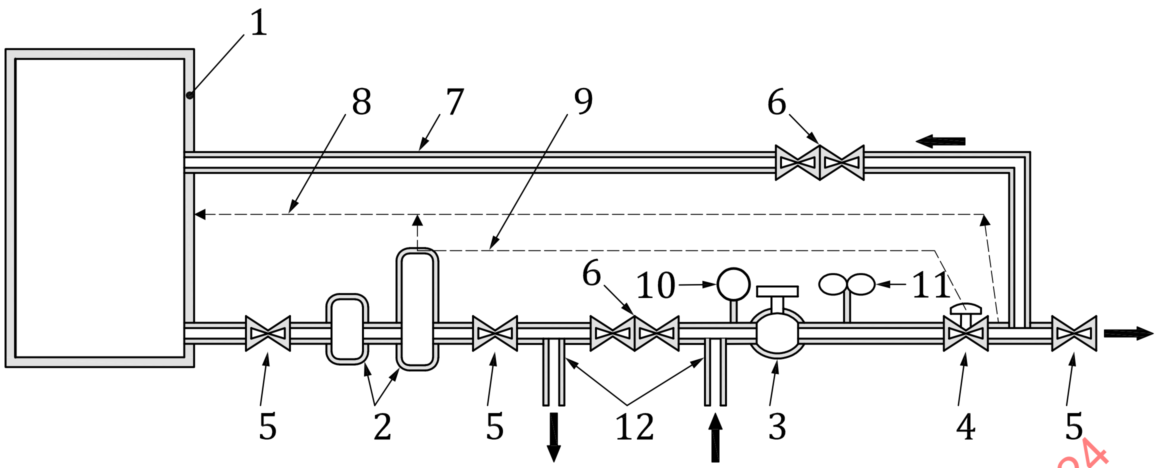
Filtering of the fluid prevents damage to the installed meter. Filters or strainers should be installed upstream of the metering section with a mesh size chosen to protect the meter. Filters introduce pressure loss within a system, particularly when the viscosity is high. A compromise between mesh size, protection, and pressure loss is often required. Filters should be insulated and heated if required to avoid blockage.

The selection of a recommended control valve, installed downstream of the meter, should consider the viscosity of the fluid at operating and ambient conditions. This valve allows control of the flow through the meter and maintains an adequate pressure within the metering section.

Similarly, the connections, and double block valves for a bypass line and for calibration connections should to be sized to suit the viscosity range.

Where an installation has a flowmeter that is required to be calibrated or verified in situ, it is recommended to install connections allowing a prover or other reference device to be connected. It is recommended that such connections be installed downstream of the flowmeter and upstream of the control valve. A double block valve in the flow line between the connections ensures all the flow is diverted to the reference prover.

A schematic diagram showing the main features of an installation is given in Figure 2.



Key

1 insulation and trace heating
2 air/gas/water separator and filter
3 flowmeter
4 control valve
5 shut off isolator valve
6 double block valve
7 return line
8 vent lines
9 air sense and flow control signal
10 temperature sensor
11 temperature and pressure sensors
12 connections to prover reference device

Figure 2 — Schematic diagram of an installation

5.3 Heating

Heating the liquid reduces the viscosity, in turn reducing friction, lowering pressure loss and hence allowing an increase in velocity through the meter.

In a heated system, it is important that the metering section, the flowmeter and upstream and downstream piping are insulated to provide stability.

If the ambient temperature falls below the wax or pour points, cooling can allow waxing or solidification to occur within the system. Waxing or solidification can create a blockage in the system which is difficult to remove, even by re-heating. This can lead to potential damage to the meter or a change in the performance. It is important to maintain an elevated temperature during idle or no-flow periods.

It is common practice to insulate the whole system. Often trace heating is applied to maintain the required temperature and viscosity.

If a system containing a hot product is drained after use, it is good practice to flush with a suitable solvent to prevent residual high viscosity liquid solidifying within a meter body or moving parts.

Accessory equipment such as valves, strainers and air eliminators should also be insulated and heated. This can include venting mechanisms, control valve pilot ports, drain ports, pressure taps and impulse lines.

For systems where the liquid is taken from a heated storage tank, it is possible to keep the liquid in the system hot by continuously circulating the liquid and returning it to the storage. This method is of particular value on tank trucks where auxiliary heating methods are difficult to provide. It is vital to ensure that this re-circulation path is demonstrably closed and sealed so that no fluid can bypass the metering section during a measurement transfer. Double block or twin seal valves should be considered in the return line. An automatic method of controlling circulation and linking to meter registration is suggested.

Trace heating can be applied using steam or hot or warm water flowing through piping or a jacket around the pipework device or flowmeter. Meters are available with jackets fabricated around the body. It should be ensured that variation in pressure from the heating fluid does not affect the meter body.

Alternatively, electric trace heating can be installed under insulation. Precautions to avoid overheating should be put in place for electric trace heating. In smaller installations, the use of electric heating can be adequate and significantly less expensive. Trace heating with self-regulating properties is often used.

It is important that trace heating provides a stable and consistent temperature to the fluid within the body of a flowmeter and around pipework to avoid stratification across the pipe and within the meter. The trace heating should be controlled to avoid variations in temperature resulting in changes in viscosity, hence meter performance.

The liquid temperature should be held below the point where vaporization of the product, or any of its components, can occur at any point throughout the entirety of the system. Precautions should be taken to prevent overheating of the liquid to a point where ignition can occur if exposed to the atmosphere. Overheating can also cause coking or chemical changes in some liquid hydrocarbons, affecting meter performance and thus damaging the meter.

In any heated system, it is important to provide pressure relief for any part of the system which can be isolated. A rise in temperature expands the liquid and hence increases pressure above safe limits. Similarly, cooling a closed sealed system can lead to a reduction in pressure and potentially cause damage.

5.4 System start-up and filling

Initial filling of the system should be carried out carefully following an established procedure. The entire metering system should be filled slowly at a reduced rate until all air pockets have been eliminated from the system. An air pocket flowing through a meter can create a surge pressure resulting in damage if flow is stopped or started quickly. Heating can be applied before starting to ensure no blockage is present in the system.

It is difficult to separate entrained air or vapour from viscous liquids. As viscosity increases, the time required for separating fine bubbles of air or vapour from the liquid increases. The removal of entrained bubbles requires a large air-eliminator to effect separation. In most instances, this approach is uneconomical from the perspective of cost and required space. As a result, precautions should be taken to prevent gas from entering the system. A means to purge the system, by circulating fluid back to the storage tank prior to a delivery, can be considered, in effect using the storage tank as an air eliminator. Circulation should be maintained long enough to ensure that all air or vapour has been carried back to the storage tank. Gas extracted from the system should be vented safely.

The liquid in storage tanks can contain air or vapour bubbles, possibly caused by the method of heating or by pumping liquid into the storage tank at the same time that liquid is being pumped out. Some crude oils foam when heated and should be allowed to settle before withdrawing the product. A sampling or testing method can determine when the air or vapour content is at an acceptable level. If it is not practicable to give sufficient time for separating out the air or vapour from storage, an air eliminator designed for the particular operating conditions is an alternative option. However, this can require a large air eliminator if designed for a high viscosity liquid.

Where air or vapour is not adequately removed during a measured transfer of liquid, a downstream sensor and valve can be used to detect and stop the delivery of liquid, thus avoiding mismeasurement. Detection can be implemented within an air eliminator of moderate size. Examples of installations where this type of system can be required are tank truck meter systems and systems for unloading tank cars, barges, tankers and transport trucks.

Similar precautions are employed to prevent water being drawn through the metering system. Water takes time to settle from a high viscosity liquid and gathers at the bottom of a storage tank. Liquid should therefore not be drawn from the base of a tank.

6 Flowmeters

6.1 Differential pressure meters

The principles of differential pressure measurement and the design, standardization and performance predictions for differential pressure meters are described in the ISO 5167 series. Differential pressure flowmeters are described in the ISO 5167 series and cover orifice plates; nozzles; Venturi nozzles and tubes; and cone and wedge meters. The performance predictions are limited to flows where the Reynolds number is at least 5×10^3 for square edge orifice plates, 7×10^4 for Venturi meters and 8×10^4 for cone meters. This limitation reduces the number of high viscosity applications deemed suitable for standard square edged orifice plates, Venturi and cone meters.

Measurable differential pressure is observed for all differential pressure devices and across a wide range of flowrates and Reynolds numbers. This can extend across turbulent and laminar flow regimes. ISO/TR 15377 provides guidelines for using meters outside the scope of the ISO 5167 series. ISO/TR 15377 covers the performance and discharge coefficient for some designs which extend down to low Reynolds numbers.

While square edge orifice plates are not suitable for high viscosity applications, conical and quarter circle orifice plates have predictable performance for low Reynolds number applications. For conical entry plates, the prediction of discharge coefficient extends down to Reynolds numbers of 80 and for quarter circle plates, 250. It is noted however, that these predictions depend on the diameter ratio selected for the application. The selection of devices requires careful consideration of viscosity, density, acceptable pressure loss and the measurement of differential pressure.

Wedge type meters are specified for applications with high viscosity liquids which are well outside the scope of ISO 5167-6. These applications cover flows where the Reynolds number is as low as 500 and temperatures up to 200 °C. ISO 5167-6 describes the construction and the predicted discharge coefficient for Reynolds numbers greater than 1×10^4. It states that wedge meters can be used outside the stated conditions, but this would require calibration across the operational Reynolds number range. Calibration establishes the discharge coefficient as a function of Reynolds number. It is noted that using water as the calibration fluid at low Reynolds numbers requires measurement of very low differential pressures. It should be ensured that the calibration and subsequent prediction adequately covers the transition from laminar to turbulent flow regimes for the product.

Wedge meters are robust and reduce the chance of damage occurring from solids and erosion. The clear path at the bottom of the pipe allows for good drainage. The manufacturer should be consulted in selecting an appropriate wedge meter for a particular application.

Installing a differential pressure meter requires an adequate upstream and downstream pipe length to provide a developed flow profile. Examples and guidance are given in the relevant parts of the ISO 5167 series, but is generally more applicable to low viscosity and turbulent flow regimes.

As there are no moving parts or sensors in the meter body, the type of meter is suitable for use with high temperatures and allows insulation and trace heating. Wedge meters are available with integral jackets for steam or hot water heating. Thermal expansion is described in 8.2.

Impulse lines and pressure taps are susceptible to blockage by debris or waxing, and should be insulated and heated to prevent blockage and provision made to flush or otherwise clean out a blockage. As the differential pressure generated can be low, great care is required in choosing a pressure transmitter with a suitable range and sensitivity.

It is possible to use axial pressure profile analysis derived from computational fluid dynamics (CFD) to assist in predicting the performance of a cone meter based on a lower viscosity calibration.

6.2 Displacement meters

The design and operation of displacement meters is described in ISO 2714. Positive displacement (PD) flowmeters are devices which continuously divide the flowing stream into volumetric segments, and momentarily isolate these segments for measurement purposes. The total of the volumes contained within the segments as the meter rotates over a period of time is the total volume passed. The frequency at which the segments pass is a measure of the volumetric flowrate. PD meters are driven by the flow, and it is the pressure drop across the meter internals that creates a hydraulic imbalance which causes rotation.

PD meters are available in various designs, the principal ones being sliding vane, oval gear, bi-rotor, tri-rotor, helical gear, and nutating disk. Oval wheel and gear types of meter are generally considered most suitable for high viscosity applications, while sliding vane designs normally specify a lower maximum viscosity limit.

Performance of a displacement meter is affected by slippage of unmetered flow passing through the mechanical clearances between the moving parts of the meter and the body. Slippage varies with the differential pressure across the meter, the viscosity of the fluid and the clearances between the rotors and the body. The differential pressure results from hydraulic losses, drag, and friction in the moving parts. A displacement meter has a reasonably consistent performance indicator across the specified flow range, but becomes nonlinear at extremes of the range due to slippage at higher and lower velocities. Generally, a measurement range of 10:1 can be achieved within a linearity band of 0,2 % for fluids with viscosity less than 20 $mm^2 s^{-1}$. This range can increase to up to 20:1 for higher viscosity liquids.

The flow range is constrained by drag and pressure loss within the meter. This constraint is intended to avoid slippage, prevent cavitation and to reduce the viscous shear load on moving parts. The maximum flow rate limit can vary with different meter types and the viscosity of the fluid. It is noted that the operating range can be reduced to as low as 2:1 due to pressure loss considerations. Manufacturers often provide a derating factor to estimate this reduction in the operating range.

Wider clearances between the rotating element and the meter body, and within rotating elements, can be specified for meters for high viscosity duties. This reduces drag while keeping slippage low. Increasing clearances allows a wider operating range when used with higher viscosity liquids. Widening clearances allows more slippage of fluid through the meter with lower viscosities, leading to variability of performance across different viscosity fluids. A low viscosity calibration liquid is therefore not recommended if clearances have been widened.

For this reason, it is important that any displacement meter is calibrated and characterized for the fluid viscosity where it is subsequently used. When a high degree of accuracy is required, re-proving is recommended to re-establish accuracy for any significant viscosity change.

Where dissimilar metals are used in the construction of the meter, the high temperature can result in mechanical interference caused by differences in metal expansion. This is particularly true where liners or lining sleeves are used.

Lower flowrate limits are governed by slippage and friction. As volumes are physically measured and counted, a displacement meter is not fundamentally affected by the flow regime being turbulent or laminar in the pipe leading to the meter.

Most displacement meters can be specified for higher temperature applications and can be insulated and trace heated if required. Trace heating can be installed using specially designed “jacket case” designs allowing a hot fluid, water, oil or steam, to be introduced to an external casing surround the meter body. The use of devices such as ventilated extensions can separate the meter secondary element(s) and electronic components from the heat source.

When not in use, and if allowed to cool, waxing or deposition can occur within the meter. If the meter is left full, this can solidify and cause a blockage, effectively blocking the flow line. When restarting, solids can seriously damage the meter. PD meters are somewhat self-cleaning in that the movement of the internal components across tight clearances can remove some depositions and soft wax deposits. If the meter is drained and cooled, residual liquid can solidify to a film which alters the internal volume and is difficult to remove. Flushing a meter when drained is recommended.

Care should be taken to ensure pressure relief is provided to the meter, or metering section, if isolated between valves. Excess pressure due to heating a closed section can result in catastrophic failure of the meter while a reduction in pressure due to cooling can damage seals. This advice applies also to any external jacket used for trace heating.

Changes due to expansion of the meter body with temperature result in a change in the internal volume. This is discussed further in 8.2. It is recommended that displacement meters are calibrated or verified in conditions as close to operation as possible, due to the effect of changing temperature and viscosity on the performance indicator.

6.3 Turbine meters

The design and operation of turbine type meters is described in ISO 2715. An axial-flow turbine meter comprises a meter body, normally a section of pipe, containing a free-running rotor assembly mounted on an axial central shaft. The shaft is supported on bearings held within hanger assemblies which align the rotor centrally within the meter body and parallel to the direction of the flow. The rotor is fitted with multiple straight or curved blades, positioned around the rotor and extending outward to the body wall, minimizing blade tip clearance. It is the action of the flowing liquid on the blades which causes rotation of the rotor at a speed proportional to the fluid velocity. Rotor speed is proportional to fluid velocity but is normally considered to be related to volumetric flowrate.

There are two different generic types of turbine flowmeters for liquid duties, multi-blade and helical blade. The first has a multi-bladed rotor with between 5 and 20 straight or slightly curved blades. The rotor can be rimmed or rimless, the former having a rim around the blade tips. This design of meter is relatively sensitive to changes in viscosity and performs best in lower viscosity liquids, however it is claimed that rimmed meters have less sensitivity to viscosity changes. The second generic design of turbine meter has helical blade profile, generally with two or four blades which wrap around the rotor. As the blades in helical turbine meters are generally aligned with the flow, the effect of the stagnant boundary layer at the pipe wall and the hub appears to be lower compared to multi-bladed meter. As a result, helical turbine meters are less sensitive to viscosity changes making them more suitable for higher viscosities. They are also less sensitive to changes in the flow profile entering the meter.

It is important to specify the operating viscosity and Reynolds number range when selecting a turbine meter for an application.

Turbine meters show a performance indicator which has a linear relationship of K-factor across the minimum to the maximum rated flow range. This linear range decreases as viscosity increases, with the minimum flowrate increasing significantly. Below the minimum, the K-factor reduces exponentially until the rotor no longer turns. Increasing viscosity decreases the potential for slippage between the rotor and the pipe wall but significantly increases the drag at the blade tip, thus increasing pressure loss. Increasing viscosity also increases drag within the bearings and across the hub. The turndown ratio of a turbine meter decreases as viscosity increases.

Due to the wide range of designs, no firm guidance on viscosity limits can be defined. For general guidance, multi-bladed and rimmed types of rotor can maintain a linearity band of 0,2 %, for a 10:1 turndown up to around 20 $mm^2 s^{-1}$, dropping to 8:1 at 50 $mm^2 s^{-1}$; the linearity degrades rapidly with increasing viscosity after this limit. This guidance applies to larger sized meters (>150 mm). Smaller sized meters have a more limited viscosity range. Helical-bladed turbines have a significantly wider viscosity range, operating up to 100 $mm^2 s^{-1}$ and meters are available for use with viscosities up to 400 $mm^2 s^{-1}$.

As a change in fluid viscosity has a significant effect on the performance indicator, it is recommended to calibrate with the conditions and fluid to be used.

The "universal viscosity curve" is a commonly used method of presenting the data when a turbine meter is specified for use over a wide range of operational viscosities, or is calibrated with a different viscosity fluid from the operating condition. It can be shown that the K-factor characteristics of turbine meters can approximate to a function of flowrate and kinematic viscosity. For any particular meter, plotting the K-factor against a parameter related to flowrate and viscosity shows that the results of different viscosity calibrations start to overlap to form a continuous curve. There are three parameters, or viscosity indices, suggested in literature, however the simplest is to use the Reynolds number.

Viscosity compensation (correction) can be applied in an associated flow computer. One method is to provide individual K-factors for each product, viscosity or temperature through calibrations. The appropriate values are then chosen for the duty. Values can be interpolated between the values derived from conditions of the calibrations if appropriate. Correction of K-factor for variable viscosities using the Reynolds number does potentially provide a means to compensate for the effect of changes in viscosity.

In addition to changing the viscosity of the liquid, changing temperature expands the pipe body and the rotor, hence the area through which the flow is established. This is discussed further in 8.2.

Where dissimilar metals are used, the high temperature can result in mechanical interference caused by differences in metal expansion. This is particularly true where liners or lining sleeves are used.

Turbine flowmeters are sensitive to disturbances in the flow profile entering the meter. A long straight length of upstream pipe or the use of flow conditioners is recommended. There is little knowledge regarding the effect of changing flow regime in the transition region. It is recommended to calibrate turbine meters across the flow range and conditions in which they are required to be used.

As turbine meters are essentially a simple pipe spool, they are suitable for insulation and trace heating as long as the materials of the sensor has been specified for the required temperature. The meter body can be fabricated with a jacket for steam trace heating. The use of devices such as ventilated extensions can separate the meter secondary element(s) and electronic components from the heat source.

Wax formation, particularly in the bearings, and deposition on the pipe wall can result in a change in performance. It is recommended that meters are not allowed to cool and that they be flushed through with a suitable solvent before being left empty. It has been reported that two or four bladed helical meters can be less susceptible to wax contamination due to a progressive cavity affect and sweeping action of the blade design.

6.4 Coriolis mass flowmeters

The design and operation of Coriolis mass flow meters is described in ISO 10790.

Coriolis flowmeters operate on the principle that inertia forces are generated whenever a particle in a rotating body moves relative to the body in a direction towards or away from the centre of rotation. This inertial force is called the Coriolis force. In a Coriolis meter, the rotating body is a vibrating tube or tubes providing positive and negative rotations.

The generated force is dependent on the mass flowrate though the meter tubes. While providing a wide measurement range of mass flow, the lower velocity gives rise to a reduced sensitivity as the flowrate decreases. Maximum flowrate is limited by pressure loss through the meter.

Generally, two tubes are used to reduce common mode noise in the system. Different designs have tubes formed into a U shape, slightly curved tubes or straight tubes.

The tubes are vibrated at a harmonic frequency which depends on the mass of the tubes. The mass of full tubes is related to the density of the liquid contained. The measured frequency therefore provides a measure of fluid density. From mass flow and density, volumetric flow can be derived. Totalizing provides a measure of quantity, both mass and volume.

Temperature changes affect the stiffness of the tube material. This is very predictable and hence can be corrected by measuring the temperature of the tubes using a sensor on the tube manifold. This temperature approximates the fluid temperature and is often available as an additional output from the meter. Insulation applied to the tubes affects the mass and stiffness of the tubes and is therefore applied at the time of manufacture. Insulation around the casing can be applied retrospectively. Insulation helps to minimize any difference between tube measured temperature and the fluid temperature. It should be noted that this temperature transducer is often not considered accurate enough for custody transfer purposes and an external RTD or other temperature sensor, as for other meter types, can still be specified.

Pressure changes also affect the stiffness of the Coriolis vibrating tubes. Some meter designs allow a pressure input to be entered in the transmitter and an algorithm calculates how much adjustment is required as the pressure changes.

Some Coriolis meters provide a measurement of viscosity which is obtained from either pressure loss across the meter or a diagnostic from the vibration characteristic the tubes.

The secondary electronics carries out all the functions required to provide corrections and can provide outputs of mass flow, volume flow, temperature, density and in some cases viscosity.

The principle of operation is not a function of viscosity, however meter performance can be affected at higher viscosities due to boundary layer effects and damping. Higher viscosity fluids can draw energy from the Coriolis flowmeter excitation system, particularly at the start of flow. This phenomenon can cause the sensor tube(s) to momentarily stall during start up.

The transfer of energy into the tubes when filled with high viscosity fluids can affect the operating range of the meter as the viscosity increases. Manufacturers should be able to provide viscosity correction factors which can be applied to allow for changes in viscosity from the viscosity at calibration. Some manufacturers can apply this automatically from the measurement of viscosity. This correction is not applied as part of a zero-setting process.

There is little evidence to suggest that a Coriolis meter is influenced by the flow regime or profile at the entry to the meter. The viscosity correction can be applied as a Reynolds number effect, as the profile within the tubes affects the transfer of energy and damping.

All the components of a Coriolis meter are contained with a protective enclosure or case. This can be insulated and the trace heating installed. The temperature limits for a meter are limited by the materials used and in particular, the electronic components and sensors within the case. For electronics external to the case, use of devices such as ventilated extensions can be installed to separate the meter secondary element(s) and electronic components from the heat source.

Internal and external stresses can affect the performance of the meter, particularly at the lower end of the flow range. This results in an increase in error at the lower end of the range. For this reason, it is necessary to fully support the meter as advised by the manufacturer and, as far as possible, prevent changes in external stress being transmitted to the meter from the pipework, especially if the temperature changes. It is recommended to reset or check the flow zero of the meter once the operating temperature is stable. When designing the system, a means to ensure there is no flow during this zeroing process is required.

As the tubes are small relative to the line pipe size, this can result in excessive pressure loss. When specified for high viscosities, Coriolis meters can be oversized for high viscosity duties, however this can result in an operational flowrate being at the lower end or even below the linear range.

The meter performance can be affected significantly by deposition within the tubes. This can be observed and the effect alleviated by frequent zero setting of the meter. When the meter is not in use, regular draining and flushing are recommended. Blockage through waxing when cold should be avoided.

6.5 Ultrasonic meters

The design and operation of transit time ultrasonic flowmeters is described in ISO 12242 and, for clamp-on transit time ultrasonic flowmeters, in ISO 24062.

Other types of ultrasonic meters are available i.e. the ultrasonic Doppler method and surface acoustic wave (SAW) type. These types are not addressed in this document.

Transit time ultrasonic meters operate by measuring the velocity of the liquid within a pipe by establishing the time difference between a sound pulse travelling with the flow direction and one travelling against. The sound pulse is usually transmitted at an approximately 45° angle across the pipe. The difference between the times taken for each of these sound pulses gives a measure of the fluid velocity across that transmission path. In the simplest design, a single pair of transducers are positioned across the diameter of the pipe. For higher accuracy, multi-path meters measure velocity for a number of chords across the pipe. Volumetric flowrate is calculated from the velocity(s) and the cross-sectional area of the pipe. The transducers can be mounted on the outside of the pipe wall, i.e. clamp-on meters, or they can be installed in ports through the pipe wall, i.e. wetted transducers.

As the velocity profile is not equal across the diameter of the pipe, the measured velocity, or velocities, are used to estimate the mean velocity based on an assumed flow profile model. The model requires input of fluid velocity, viscosity, and density to provide an estimate of the Reynolds number, and hence an estimate of the flow profile, and if a turbulent or laminar flow profile is expected. This velocity profile model is theoretical and assumes that a fully developed turbulent or laminar profile exists. Using multipath designs provides additional input to modify the model based on the differences in velocity across the pipe.

The transitional regime between laminar and turbulent flow can present a particular challenge to ultrasonic meters as the velocity profile is not stable and switches back and forth between conditions that are broadly similar to turbulent and laminar profiles. The challenge arises because intermittent complex velocity distributions are created when the switching between turbulent-like and laminar-like conditions occurs. If this issue is not properly addressed by meter design and/or flow conditioning, it can lead to lower accuracy and poorer repeatability.

Ultrasonic meters are conventionally calibrated based on a Reynolds number range rather than a flowrate range.

An ultrasonic flowmeter measures velocity from small time differences and this results in reducing sensitivity as the velocity of the liquid is reduced. In addition, the absence of turbulent mixing in the laminar regime can lead to the formation of temperature gradients and corresponding speed of sound gradients that can alter path angles from the values assumed in the meters' electronics. It is therefore necessary to pay careful attention to flows with low Reynolds numbers and whether there is unequal heating or cooling being applied to the pipework upstream of the meter.

Sound attenuation increases with kinematic viscosity and hence the maximum viscosity limits for meter diameters should be established by the manufacturer and transducer model chosen to suit.

When the viscosity of the fluid changes, the thickness of the boundary layer changes, resulting in changes in the effective flow area through the meter. The accuracy of the meter is affected due to changes in the effective cross-sectional area of the meter. This phenomenon is more prominent at high viscosities and particularly when the Reynolds number is less than 10 000. The effect on meter accuracy is manifested in meter factor variation during meter proving. As the thickness of boundary layer is a function of Reynolds number, meter characterization across the range of viscosities and flowrates required can help to reduce effect of changes in the meter factor accuracy due to changes in liquid viscosity.

Depending on the technologies and algorithms employed, meter signal diagnostics can estimate fluid density and viscosity and hence calculate the Reynolds number of the flow stream. If this information is not available within the meter, a manual input of density and viscosity during operation would be required for the meter to operate through the specified range. Based on the sensitivity of these parameters on the performance indicator, these parameters should be updated in the meter as operating conditions changes.

Where characterization is not available within the meter electronics, a characterization by calibration at the relevant temperature and viscosity is recommended.

As an ultrasonic meter consists of a pipe spool with transducers, it is normally acceptable to insulate or trace heat the meter body. Ultrasonic transducers should be specified for the operating temperature. Transducers of standard construction are not suitable for very high temperatures. Specialized transducers are available to work at temperatures up to approximately 200 °C. High temperatures can also be accommodated by using ventilated extensions or wave guides to separate transducers, the meter secondary element(s) and electronic components from the heat source.

The coupling material and method between transducer and pipe wall used for clamp on meters should be specified and maintained for high temperature applications.

It is necessary to account for the expansion due to temperature, for both the pipe area and the sound path length (see 8.2).

Wetted transducers installed in ports set into the pipe wall can potentially be contaminated or the ports filled with solids or wax build up. This reduces the signal strength and can alter the effective path length and path angle. Removal of a transducer can require subsequent recalibration of the meter. Careful consideration should be taken of the fluid wax point in relation to the product temperature in operation and in a shut-down period. Wax or other contamination precipitating onto the pipe walls reduces the diameter, alters the transmission time and potentially alters the flow profile. This is particularly evident on reflective clamp-on types which use the pipe wall as a transmittal or reflective point. Meters and pipework are most effectively maintained at a sufficient temperature and given regular flushing using a suitable solvent particularly after being drained or allowed to cool.

Where there is a known relationship between the meter performance and viscosity, a correction can be applied to the meter output or calculated volume. This relationship can be provided by the meter manufacturer, from literature or from experiment.

The correction can be applied from a fixed, or variable, measure of the viscosity or viscosity temperature relationship. The viscosity can also be measured using an online viscometer.

7 Meter proving

7.1 General

In the petroleum industry, the term proving is used to describe the procedure of calibrating a flowmeter and ensuring it meets specified acceptance criteria. The accepted way to prove a meter is to pass a quantity of liquid through it to an accurate reference device known as a prover.

Several factors determine the choice of proving method. Any comparison of proving methods should consider initial cost, space requirements and ease of operation in relation to the meter accuracy desired.

There are four recognized reference devices and methods employed to prove hydrocarbon liquid flowmeters:

a) Pipe provers

b) Volumetric measures

c) Gravimetric measures

d) Reference (master) flowmeters

The choice of device and method is dependent on the uncertainty required, the value of the product, the nature of the product and the cost. Proving can be carried out in situ, or the meter can be taken to a calibration facility.

A meter measuring a viscous crude oil in a pipeline at a point of custody transfer would very likely require the highest degree of accuracy obtainable and the meter calibrated in situ using a dedicated prover. An example can be a dock installation loading or discharging large quantities. In this case, a dedicated or shared pipe prover, or a mobile prover can be chosen. A master meter method of proving can also be considered where the master meter is removed periodically for calibration in a laboratory.

When the liquid being measured is heated, the proving system should also be heated and insulated.

Although some of the various proving methods discussed above can have apparent advantages for a particular installation, the pipe prover method is generally recommended for best results on viscous fluids.

7.2 Pipe provers

The design, operation and calibration of pipe provers is described in ISO 7278-2. A pipe prover consists of a length of pipe where a displacer travels along the pipe displacing a volume of liquid which corresponds to the synchronised volume measured by the flowmeter. Switches or detectors located on the pipe mark the calibrated volume and trigger the totalization of pulses generated by the meter leading to a measurement of the K-factor. The volume displaced between the detectors positioned at either end of the pipe is defined by calibration. Differences in the volume of fluid due to temperature expansion between the meter and prover are accounted for, as is the expansion of the prover volume from the standard temperature and pressure.

As described in ISO 7278-2, different designs are found. A sphere or conventional prover has usually a significantly large volume. The displacer can be a sphere which travels through a pipe of adequate length and volume. This pipe can be straight or, more commonly, with bends designed to reduce the footprint of the prover. A small volume piston prover has a piston travelling in a straight length of cylindrical pipe which provides for a relatively small displaced volume compared to a sphere prover. In this case, the required volume for calibration is achieved through multiple measurements.