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NORWEGIAN SOCIETY FOR OIL AND GAS MEASUREMENT
NORSK FORENING FOR OLJE OG GASSMÅLING

HANDBOOK
of
Water Fraction Metering

Revision 2, December 2004

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Water Fraction Metering

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Produced for

The Norwegian Society for Oil and Gas Measurement
ConocoPhillips Norge
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Preface

The Norwegian Society for Oil and Gas Measurement is an independent society for personnel engaged in measurement of oil and gas in the Norwegian oil and gas business.

In the technical area the Society's activities include flow measurement, sampling and online quality measurement in processing and transportation systems.

The society shall contribute to:

- promote the understanding of flow measurement and sampling.
- co-ordination of Norwegian activities within international standardisation of oil and gas metering.
- exchange metering experience between experts from different companies and government bodies.
- support new technology and issue technical documents/handbooks.

Svein Neumann
Chairman

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1. INTRODUCTION

This handbook has been prepared as a direct result of the need to perform continuous measurements of the water fraction in quantities of both produced and transported hydrocarbon liquids.

The increased availability of water fraction meters (WFM) for continuous measurements, presents a new challenge. It is of the utmost importance to obtain reliable data when making fiscal measurements. The uncertainty associated with water fraction measurement is a fundamental consideration of total crude oil measurement and assessing the quality aspects of production. It is also important to be able to continuously monitor and analyse the water content of the crude oil during the optimising process for both operation and transportation.

Until recently, representative sampling of the oil/water flow has been used for the calibration and adjustment of WFMs. Utilising sampling and analysis techniques as a reference has restricted the performance of the new technology, i.e. the applied technology in the WFMs has the potential for less uncertainty than the reference techniques. An analytical and practical approach has led to an independent calibration and adjustment procedure for the water fraction measurements, as outlined in this handbook.

This handbook addresses the operational aspects of the measurement technology. In addition to meeting the demand for a more reliable operation procedure, it is also the intention to initiate a process for international standardisation on this topic. The NORSOK standard I-105 describes the inquiry requirements and associated equations for the flow computer. The NORSOK equations also describe the conversion from measured volume percentage to mass percentage.

2. SCOPE

This handbook sets out recommendations to be used for the continuous determination of water fraction in hydrocarbon liquids. It describes the recommended installation, calibration and adjustment methods. The procedures and installations described have been prepared for both fiscal and allocation water fraction measurements.

As integral part of the work undertaken by Christian Michelsen Research for revision 1 of this handbook, a scientific evaluation of the theoretical uncertainty for two different WFMs was carried out. Both the Fluenta WIOM-350 (no longer marketed) [1] and the MFI WaterCut Meter (now marketed as the Roxar WaterCut Meter) [2] underwent a theoretical evaluation of the combined uncertainty in accordance with the "*Guide to the expression of uncertainty in measurement*" [3]. The recommendations outlined in this handbook are based on these reports.

The problems of multiphase mixtures are pointed out and the precautions for minimising them are described. However, it should be noted that all fiscal aspects of this handbook are founded on the base line conditions that the flow has no water slugs and that the water and oil are homogeneously distributed.

3. NORMATIVE REFERENCES

The following standards are considered as normative references with respect to continuous water fraction measurement.

NORSOK Standard, I-105	*Fiscal Measurement Systems for hydrocarbon liquid.* This standard describes the functional and technical requirements for water fraction measurement.
ISO 3171	*Automatic pipeline sampling*. Representative sampling criteria and stream conditioning can be referred to when planning installation of a WFM.
ASTM D4928	*Standard test methods for water in crude oils by coulometric Karl Fisher Titration (correspond to IP 386/90).* The standard covers the determination of water in the range from 0.02 to 5 % by mass in crude oil by a laboratory.
NORSOK Standard, P-001	*Process design* Chapter 3.1 Definitions describe the Double Block & Bleed valves.

4. DEFINITIONS

Two categories of terms are defined below. The first section defines terms that are commonly used to characterise fluid flow in a conduit, and in particular terms related to two-phase oil/water flow. As the presence of a small fraction of free gas may also have to be considered, terminology related to three-phase oil/gas/water flow has also been defined. The second section defines meteorological terms that may be useful in characterising the performance of a water fraction meter.

4.1 Terms related to two-phase oil/water flow

Dissolved water	Water in solution in petroleum and petroleum products.
Emulsion	Colloidal mixture of two immiscible fluids, one being dispersed in the other in the form of fine droplets [5].
Entrained water	Water suspended in oil. Entrained water includes emulsions but does not include dissolved water.
Flow regime	The physical geometry exhibited by a multiphase flow in a conduit; for example, in two-phase oil/water, free water occupying the bottom of the conduit with oil or oil/water mixture flowing above [5].
Fluid	A substance readily assuming the shape of the container in which it is placed; e.g. oil, gas, water or mixtures of these [5].
Full bore	An in-line device, which measures over the full cross-section of the pipe, as opposed to an insertion device, which only measures locally around a probe. Also refers to the act of measuring over the full cross-sectional area of the pipe.
Gas	Hydrocarbons in the gaseous state at the prevailing temperature and pressure [5].
Gas volume fraction (GVF)	The gas volume flow rate, relative to the multiphase volume flow rate, at the pressure and temperature prevailing in that section. The GVF is normally expressed as a percentage [5].
Homogeneous flow / mixture	A two-phase oil/water flow or mixture in which both phases are evenly distributed over the cross-section of a closed conduit; i.e. the composition is the same at all points [5].
Mass flow rate	The mass of fluid flowing through the cross-section of a conduit in unit time [5].
Multiphase flow	Two or more phases flowing simultaneously in a conduit; this document deals in particular with multiphase flows of oil and water [5].
Oil	Hydrocarbons in the liquid state at the prevailing temperature and pressure conditions [5].
Oil-continuous two-phase flow	A two-phase flow of oil/water characterised in that the water is distributed as water droplets surrounded by oil. Electrically, the mixture acts as an insulator.
Phase	In this document, “phase” is used in the sense of one constituent in a mixture of several. In particular, the term refers to oil, gas or water in a mixture of any number of the three [5].
Phase area fraction	The cross-sectional area locally occupied by one of the phases of a multiphase flow, relative to the cross-sectional area of the conduit at the same local position [5].

Phase flow rate	The amount of one phase of a multiphase flow flowing through the cross-section of a conduit in unit time. The phase flow rate may be specified as phase volume flow rate or as phase mass flow rate [5].
Phase mass fraction	The phase mass flow rate of one of the phases of a multiphase flow, relative to the multiphase mass flow rates [5].
Phase volume fraction	The phase volume flow rate of one of the phases of a multiphase flow, relative to the multiphase volume flow rates [5].
Sample loop	A bypass to the main pipeline being sampled, through which a representative portion of the total flow is circulated.
Slip	Term used to describe the flow conditions that exist when the phases have different velocities at a cross-section of a conduit. The slip may be quantitatively expressed by the phase velocity difference between the phases [5].
Slip ratio	The ratio between two-phase velocities [5].
Slip velocity	The phase velocity difference between two phases [5].
Superficial phase velocity	The flow velocity of one phase of a multiphase flow, assuming that the phase occupies the whole conduit by itself. It may also be defined by the relationship (Phase volume flow rate / Pipe cross-section) [5].
Volume flow rate	The volume of fluid flowing through the cross-section of a conduit in unit time at the pressure and temperature prevailing in that section [5].
Water-continuous two-phase flow	A two-phase flow of oil/water characterised in that the oil is distributed as droplets surrounded by water. Electrically, the mixture acts as a conductor.
Watercut (WC):	The water volume flow rate, relative to the total liquid volume flow rate (oil and water), both converted to volumes at standard pressure and temperature. The WC is normally expressed as a percentage [5].
Water Fraction Meter (WFM)	A device for measuring the phase area fractions of oil and water of a two-phase oil/water flow through a cross-section of a conduit expressed as a percentage.
Water-in-liquid ratio (WLR)	The water volume flow rate, relative to the total liquid volume flow rate (oil and water), at the pressure and temperature prevailing in that section [5].

4.2 Terms related to metrology

The accuracy of water fraction meters should be specified by terms, which are in conformance with "The international vocabulary of basic and general terms in metrology" issued by ISO [4].

Other standards based on the above document may also be used, e.g. BS 5233 (1986): "Glossary of terms used in metrology" [6].

Some of the definitions of BS 5233, which may be particularly relevant to water fraction measurement, are quoted below (or form part of the definitions).

Accuracy (of measurement)	Accuracy of measurement is the closeness of the agreement between the result of a measurement and the value of the measurand [7]. *NOTE 1:* The value of the measurand may refer to an accepted reference value [1]. *NOTE 2:* "Accuracy" is a qualitative concept, and it should not be used quantitatively. The expression of this concept by numbers should be associated with (standard) uncertainty.
Adjustment	A tuning of the measuring instrument or measuring system in order to operate according to a reference or standard. The tuning may include software, mechanical and/or electrical modifications.
Calibration	Set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or certified reference material, and the corresponding values realised by standards [4]. The result of the calibration may indicate a need for adjustment of the measuring instrument or measuring system in order to operate according to a reference or standard. *NOTE 1:* The result of a calibration permits either the assignment of values of measurands to the indications or the determination of corrections with respect to indications. *NOTE 2:* A calibration may also determine other meterological properties such as the effect of influence quantities. *NOTE 3:* The result of a calibration may be recorded in a document, sometimes called a calibration certificate or a calibration report.
Certified Reference Material (CRM)	Reference material, accompanied by a certificate, one or more of whose property values are certified by a procedure which establishes traceability to an accurate realization of the unit in which the property values are expressed, and for which each certified values is accompanied by an uncertainty at a stated level of confidence [4].
Conditions of use	The conditions, which must be fulfilled in order to use a measuring instrument correctly, taking account of its design, construction and purpose [5].

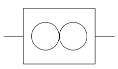
[1] In some documents it also points to the "true value" or "conventional true value". However, according to the *Guide* this definition should be avoided since the word "true" is viewed as redundant; a unique "true" value is only an idealised concept [3] and "a true value of a measurand" is simply the value of the measurand.

	NOTE: The conditions of use can refer, among other things, to the type and condition of the subject of the measurement, the value of the quantity measured, the values of the influence quantities, the conditions under which the indications are observed, etc.
Deviation	Value minus its reference value [4].
Error (of measurement)	Error of measurement is the result of a measurement minus the value of the measurand. In general, the error is unknown because the value of the measurand is unknown. Therefore, the uncertainty of the measurement results should be evaluated and used in specification and documentation of test results [7].
Footprint	A number, a set of numbers, a table, an equation or a curve representing the raw measurement (usually a frequency) of the meter, with a specific, uniquely defined content in the sensor section. The footprint shall be recorded as part of factory calibration, so that it can later be used as a reference during a reproducibility check to verify that the meter has not changed its response.
Influence quantity	Quantity that is not the measurand, but that affects the result of the measurement [7].
Measurand	Particular quantities subject to measurement [7].
Primary calibration	A calibration that is carried out with the purpose of adjusting a WFM to operate according to a certain reference, as well as recording the footprint of the WFM. The footprint may typically be recorded using a reproducible Certified Reference Material, while the adjustment may be performed using a stabilised crude oil sample, whose water content should be less than 0.1 % by volume and documented by traceable Karl Fischer titration method.
Random error	The result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatable conditions [7]. *NOTE:* Because only a finite number of measurements can be made, it is possible to determine only an estimate of the random error. Since it generally arises from stochastic variations of influence quantities, the effect of such variations is referred to as <u>random effects</u> in the *Guide* [3].
Range	The interval between the minimum and maximum values of the quantity to be measured, for which the instrument has been constructed, adjusted or set [7].
Reference material (RM)	Material or substance one or more of whose property values are sufficiently homogeneous and well established to be used for the calibration of an apparatus, the assessment of a measurement method, or for assigning values to materials. *NOTE:* A reference material may be in the form of a pure or mixed gas, liquid or solid. Examples are water for the calibration of viscometers, sapphire as a heat-capacity calibrant in calorimetry, and solutions used for calibration in chemical analysis. [4].
Reference value	A particular value of an influence quantity stated in the specification of a measuring instrument as a basis for determining its intrinsic error [7].
Repeatability (of results of measurements)	Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same measurement conditions, i.e. by the same measurement procedure, by the same observer, with the same measuring instrument, at the same location at appropriately short intervals of time [4].
Reproducibility (of results of measurements)	Closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement, e.g. changed principle of measurement, method of measurement, observer, measuring

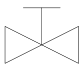
	instsrument, reference standard, location, conditions of use or elapsed time [4].
Reproducibility check	A test that is carried out as often as may be required to verify whether the meter has changed its footprint or not, and thus whether adjustment of the meter is required or not. The installation of the WFM shall allow for reproducibility check without removing the meter from the piping.
Result of measurement	Value attributed to a measurand, obtained by measurement. It is an estimated value of the measurand [7].
Span	The algebraic difference between the upper and lower values specified as limiting the range of operation of a measuring instrument, i.e. it corresponds to the maximum variation in the measured quantity of interest[2] [7]. Example: A thermometer intended to measure over the range -40 ^{0}C + 60 ^{0}C has a span of 100 ^{0}C.
Uncertainty (of measurement)	That part of the expression of the result of a measurement, which states the range of values within which the true value or, if it is appropriate, the conventional true value, is estimated to lie [7]. *NOTE:* In cases in which there is adequate information based on a statistical distribution, the estimate may be associated with a specified probability. In other cases, an alternative form of numerical expression of the degree of confidence to be attached to the estimate may be given.

4.3 Symbols

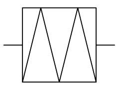
List of symbols used in the schematic drawings in the handbook.



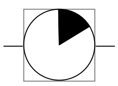
Flow meter



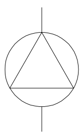
Valve



Static mixer



Water Fraction Meter



Pump

[2] E.g. a flow metering system which covers the range 50-200 m^3/h, has a span of 150 m^3/h.

5. TWO-PHASE OIL/WATER FLOW

Based on the theory behind most of the known WFMs, the optimum performance is achieved at a flow regime where the water concentration is the same at every point over the cross-sectional area. In addition the slip ratio should be equal to 1.

The water "budget" for an oil/water mixture can be expressed as:

Total water = free water + suspended water + dissolved water

Free water is completely separated from the oil-phase. By sufficient mixing, most free water may be converted to suspended water. The amount of free water at the WFM’s location will affect its performance.

Suspended water (or entrained water) is water dispersed as small droplets and includes water in emulsion. Leaving a suspension undisturbed over a period of time, some suspended water will become free or dissolved water. Water in emulsion does normally not readily separate. Demulsifier / emulsion breaker additives will however affect this equilibrium.

The amount of dissolved water in an oil/water mixture is generally very low; typical in the range of 0.01 % - 0.1 %, and is mostly dominant by interfacial properties and the interaction between the oil and the water. The mixture temperature and pressure have minor effect on the content of dissolved water.

In a homogeneous water-in-oil mixture, the concentration of the water is by definition the same over the entire pipe cross-section. This requires that the water is finely dispersed as small droplets in the continuous oil phase. Even if this is the case, a concentration gradient may exist, especially in horizontal lines, and ±5 % deviation from the mean is in practise considered as a homogeneous mixture [8].

The turbulence, which exists naturally in a pipeline, can be sufficient to provide adequate mixing of water in the oil phase. The minimum natural turbulent energy for adequate mixing depends on the oil and water flow rates, pipe diameter, viscosity, water concentration, density and interfacial tension.

Sections 5.1 and 5.2 give a brief description of two prediction methods that can be used to determine whether a water-in-oil mixture is homogeneous or not in horizontal and vertical flow. Section 5.1 describes the method appointed for horizontal flow, which is based on a procedure given by the ISO 3171 standard [8]. Section 5.2 outlines a prediction method based on flow pattern models developed by Flores et al. [10]-[11] for vertical and inclined pipes, though it is claimed that the model is independent of inclination angle. Generally, the two methods predict that the degree of dispersion of water-in-oil is promoted by high velocity, high oil viscosity, high oil density, low interfacial tension and small pipe diameter.

5.1 Horizontal pipes

This method is based on the ISO 3171 standard [8] for predicting the degree of homogenisation in horizontal water-in-oil dispersions. Adequate oil and water mixing is, according to ISO 3171, characterised by uniform dispersion. i.e., the water concentration at the top C_1 and the bottom C_2 in a pipe is approximately equal. The degree of dispersion in a horizontal pipe can be estimated by a simple equation formed by balancing the downward flux of water droplets due to gravity with the upward flux due to turbulent diffusion:

$$\frac{C_1}{C_2} = \exp\left(\frac{-W}{\varepsilon/D}\right) = \exp\left(-\frac{1}{G}\right) \tag{1}$$

where

C_1/C_2	Ratio of water concentration at the top C_1 to that at the bottom C_2.
W	Settling velocity of the water droplets
ε/D	Turbulence characteristic, where ε is the particle eddy diffusivity and D the pipe diameter
$G = \dfrac{\varepsilon/D}{W}$	Parameter indicating the dispersion degree

A C_1/C_2 ratio of 0.9 to 1.0 indicates very good dispersion, which respectively correspond to G = 10 and $G \to \infty$. A ratio of 0.4 or smaller indicates poor dispersion with a high potential for water stratification.

Semi-empirical models for the settling velocity W and the turbulent characteristic ε/D can be used to estimate the concentration ratio or the parameter G. The semi-empirical models depend on other models, and the step procedure given in the ISO 3171 standard becomes quite elaborate.

However, by combining all the equations W and ε/D depend on, it is possible to arrive at a single analytical expression that relates the liquid velocity in the pipe and the fluid properties with the parameter G, i.e.

$$\boxed{\begin{array}{l} V_c = K_1 \cdot G^{0.325} \cdot \sigma_{ow}^{0.39} \cdot \dfrac{(\rho_w - \rho_o)^{0.325}}{\rho_o^{0.283}} \cdot \dfrac{D^{0.366}}{\mu_o^{0.431}} \\ \beta < 10\text{-}15\,\% \end{array}} \qquad (2)$$

where

V_c	Critical (minimum) velocity for maintaining a dispersion degree G
K_1	Constant depending on unit system (SI or field units)
G	Parameter defining the degree of dispersion (usually G = 10)
σ_{ow}	Interfacial (surface) tension between oil and water
ρ_o, ρ_w	*Oil* and water density, respectively
D	Inner pipe diameter
μ_o	Oil viscosity
β	Volumetric water fraction in per cent

The numerical constant K_1 depends on the unit system being used, and Table 5.1 gives the value of K_1 when the parameters in Eq. (2) are given in SI units and practical field units.

Table 5.1. Values of the numerical constant K_1 in SI and field units.

Parameter	**SI units**	**Field units**
V_c	m/s	m/s
G	-	-
σ_{ow}	N/m	mN/m [1]
ρ_o, ρ_w	kg/m^3	kg/m^3
D	m	cm
μ_o	Pa·s	cP [2]
K_1	2.02	0.50

[1] mN/m = 10^{-3} N/m

[2] cP = mPa·s =10^{-3} Pa·s

By using Eq. (2), with the value of K_1 from Table 5.1, it is possible to calculate the critical (minimum) liquid velocity corresponding to a defined degree of dispersion G when the fluid properties and the pipe diameter are known quantities.

The value G = 10 gives a concentration ratio 0.9, and is recommended by ISO 3171 [8]. This corresponds to ±5 % deviation from the mean concentration and it is in practise considered as a homogeneous mixture.

A set of ”typical” values for fluid properties and pipe diameter has been chosen as a basis for the calculations, see Table 5.2. The critical velocity is then calculated and plotted by varying a single parameter in turn. Figure 10.1 to Figure 10.4 in Appendix A show the variation in the critical velocity as a function of the fluid properties and the pipe diameter, where only a single parameter is varied in each plot, and the others are held fixed with values given in Table 5.2.

Table 5.2. ”Typical” values for fluid properties and pipe diameter selected for calculations and graphical presentations.

Parameter	**Value**
D	10.16 cm (4")
ρ_w	1025 kg/m^3
ρ_o	800 kg/m^3
μ_o	5 cP
σ_{ow}	25 mN/m

The diagrams in Figure 10.1 to Figure 10.4 in Appendix A show that the minimum liquid velocity to maintain a dispersion corresponding to a concentration ratio of 0.9 (G = 10) decreases with the oil density and the oil viscosity, and increases with the interfacial tension and the inner pipe diameter.

The method described here should be used with care since it is based on a simplified concentration model, as well as other simplified and semi-theoretical models. The water concentration model is only valid for small water volume fractions, i.e. less than approximately 10–15 % water in oil. A conservative approach is strongly recommended when estimating acceptable limits for adequate dispersion, i.e. use the worst-case conditions expected (lowest liquid velocity, lowest oil density, lowest oil viscosity and highest interfacial tension).

If additional turbulence is introduced to the system in form of bends, valves, contractions etc, the critical velocity may be reduced considerable. Confer the ISO 3171 standard [8] for procedures to handle such cases.

5.2 Vertical and inclined pipes

In vertical pipes, the dispersion is normally better than in horizontal lines due the absence of a gravity component normal to the flow direction. In horizontal flows the gravity component in the transversal flow direction promotes stratification. In inclined pipes, the gravity plays a role depending on the inclination angle.

The approach used in horizontal pipes can also be used for vertical and inclined pipes if a very conservative estimate is desired. However, a flow pattern model for vertical and inclined pipes has recently been developed and tested by Flores *et al*. [10]-[12] in the multiphase flow loop at the University of Tulsa.

Flores *et al.* developed a mechanistic model to predict the transition to the flow regime *Very Fine Dispersion of Water in Oil* (VFD W/O). This *flow regime* is characterised by a flow with very small water droplets distributed in a continuous, fast moving, oil phase over the entire cross sectional area of the pipe. Hence, this flow can be considered as homogeneous mixture. The transition to VFD W/O occurs at relatively high flow rates of the oil phase and is essentially independent of inclination angle in the range 45° – 90° from the horizontal.

The transition mechanism to the VFD W/O flow regime is following: The turbulent forces in the oil phase have to be sufficiently large to overcome the interfacial tension forces of the water droplets, with the restriction of a minimum droplet diameter to keep the spherical droplet shape. The transition criterion can then be mathematically obtained (see Flores *et al*. [10]-[11] for details):

$$\frac{V_{os}}{V_{ws}} = 12.65 \cdot \frac{Y_o}{\sqrt{Eo}} \tag{3}$$

where Y_o is a dimensionless parameter given by

$$Y_o = \frac{(\rho_w - \rho_o)g}{\dfrac{2C_o}{D}\left(\dfrac{\rho_o V_{os} D}{\mu_o}\right)^{-n} \rho_o V_{os}^2} \tag{4}$$

and Eo corresponds to the Eötvos number, modified as

$$Eo = \frac{(\rho_w - \rho_o)gD^2}{\sigma_{ow}} \tag{5}$$

where

V_{os}, V_{ws}	Superficial oil and water velocity, respectively
σ_{ow}	Interfacial tension between oil and water
ρ_o ρ_o	Oil and water density, respectively
μ_o	Oil viscosity
D	Inner pipe diameter
g	Constant of gravity (9.81 m/s^2)
C_o, n	Constants: C_o = 0.046, n = 0.2

Inserting the values of the constants and rearranging Eq. (3) to Eq. (5), one arrives at the following expression in SI units that relates the superficial velocities, fluid properties and pipe diameter:

$$V_{ws} = 0.00232 \cdot \left(\frac{\mu_o}{D}\right)^{0.2} \cdot \frac{\rho_o^{0.8}}{\sigma_{ow}^{0.5}\left(\rho_w - \rho_o\right)^{0.5}} V_{os}^{2.8} \qquad (6)$$

Eq. (6) can be used to calculate the maximum superficial water velocity that still gives a homogeneous flow condition for a given oil rate, fluid properties and pipe diameter.

However, it may be more convenient to express the homogeneous flow criterion in terms of the mixture velocity and the volumetric water fraction instead of the superficial velocities as in Eq. (6). The mixture velocity (average total velocity) V corresponds to the measured flow rate from a fiscal metering station, while the water fraction β corresponds to the output from a water fraction meter.

The superficial velocities can be defined in terms of the mixture velocity V and the water fraction β *[%]* in the following way:

$$V_{ws} = \frac{\beta}{100} \cdot V \qquad (7)$$

$$V_{os} = \left(1 - \frac{\beta}{100}\right) \cdot V \qquad (8)$$

Substituting Eqs. (7)-(8) for the superficial velocities in Eq. (6) yields the following formula for the critical (minimum) velocity V_c which is required to maintain a homogeneous flow in a vertical, or inclined pipe:

$$\boxed{\begin{array}{l} V_c = K_2 \cdot \dfrac{\beta^{0.556}}{(100-\beta)^{1.556}} \cdot \sigma_{ow}^{0.278} \cdot \dfrac{(\rho_w - \rho_o)^{0.278}}{\rho_o^{0.444}} \cdot \left(\dfrac{D}{\mu_o}\right)^{0.111} \\ \beta < 20\text{ - }25\,\% \end{array}} \quad (9)$$

The numerical constant K_2 depends on the unit system being used, and Table 5.3 gives the value of K_2 when the parameters in Eq. (9) are given in SI units and practical field units.

Table 5.3. Values of the numerical constant K_2 in SI and field units.

Parameter	**SI units**	**Field units**
V_c	m/s	m/s
β	%	%
σ_{ow}	N/m	mN/m [1]
ρ_o, ρ_w	kg/m^3	kg/m^3
D	m	cm
μ_o	Pa·s	cP [2]
K_2	2910	550

[1] mN/m = 10^{-3} N/m

[2] cP = mPa·s =10^{-3} Pa·s

Eqs. (6) and (9) are not expected to be valid beyond 20 - 25 % water content in *oil*, since the water droplets would not remain spherical, but forming larger droplets that causes the mixture to be inhomogeneous when the water fraction exceeds approximately 25 %. See Flores *et al.* [10]-[11] for more details about the *flow regime* model, as well as *flow regime* maps for inclined and vertical pipes.

By using Eq. (9) with the value of K_2 from Table 5.3, it is possible to calculate the critical (minimum) liquid velocity for a given water fraction when the *fluid* properties and the pipe diameter are known quantities.

Eq. (9) is plotted in Figure 10.5 to Figure 10.8 in Appendix for different values of *fluid* properties and pipe diameter with the water fraction as a parameter. The values in Table 5.2 have been used as a basis, and a single parameter is varied in each plot for five selected values of the water fraction β. As can be inferred from the diagrams, the critical (minimum) liquid velocity that can be allowed in order to maintain homogeneous flow increases with the oil density and viscosity, and decreases with increasing interfacial tension and pipe diameter. These trends are similar to the trends observed in horizontal flow, though the two models are based on different physical principles.

It is noteworthy to recognise from Figure 10.1 to Figure 10.8 that the vertical model predicts an appreciable lower critical (minimum) velocity than the horizontal model, and that the dependency on the different fluid properties and pipe diameter is more pronounced for the horizontal model. This is mainly due to the stratification effect in horizontal flow, which makes the horizontal model more sensitive to variation in fluid properties and pipe diameter than the vertical model.

A major difference between the two models is the dependency on the water fraction. The horizontal model does not depend on the water fraction, except that the water fraction should be small, and not greater than approximately 10 – 15 %. The water fraction is an important parameter in the vertical model, which is valid at higher water fractions (approximately 20-25 %).

5.3 Concluding remarks

Models for predicting homogeneous water-in-oil mixtures in horizontal and vertical pipe flow have been described and illustrated in diagrams (Figure 10.1 to Figure 10.8 in Appendix A). The models can be used to estimate the critical (minimum) liquid velocity that is necessary to obtain a homogeneous water-in-oil mixture.

The model for horizontal flow is based on a procedure given by ISO 3171 [8], where the settling rate of water droplets is balanced with the turbulent rate in the pipe. This model is limited to small water volume concentrations, i.e. below 10-15 %. The model for vertical flow is based on the transition to the flow regime *Very Fine Dispersion of Water in Oil* (VFD W/O). This flow regime can be regarded as a homogeneous flow regime and the model describing this regime has recently been derived and tested by Flores et al. [10] – [12]. The criterion for homogeneous water-in-oil mixture is that the turbulent forces in the oil phase have to be sufficiently large to overcome the interfacial tension forces of the water droplets. This model is valid for vertical and inclined pipe flow (45° - 90° from the horizontal plane). Furthermore, the model is valid for low to moderate high water concentrations, i.e. 20 – 25 %.

It is important to emphasise that both models are based on simplified models and semi-theoretical models that may have restricted validity. A conservative approach is therefore recommended when estimating acceptable limits for adequate dispersion. i.e., use the worst case conditions expected (lowest liquid velocity, lowest oil density and viscosity and highest interfacial tension).

6. APPLICATIONS

The dynamic measurement of water fraction as described and analysed in this Handbook may find its application in the following main areas:

- Fiscal applications – sales & allocation measurement.
- Test separator applications.

This chapter will discuss briefly the operational conditions such on-line meters will experience and also indicate the operational advantages that can be obtained by using this technology compared to traditional manual sampling and analysis.

6.1 Fiscal applications

6.1.1 Sales metering

This application can be characterised by the following: Fiscal metering of stabilised crude oil; either continuous operation (pipeline) or batch loading (offshore/onshore tanker loading).

Main process devices for water removal are separators and/or electric static coalescers. In addition chemicals may be injected in order to speed up the settling rate. Typical operating conditions are:

1. Low water content (typical < 0.5%). Optimal conditions with homogenous oil/water mixture.
2. Medium water content (0.5% < typical < 2%).
3. High water content (2% < typical < 10%). Difficult operating conditions.

Under certain abnormal situations, continuous water phase may also be present in the line, however it should be noted that the WFMs in this case will be outside their defined operating range.

Normal operating conditions for sales metering are: 30 - 70 °C at a pressure range of 10 - 25 barg.

6.1.2 Fiscal / allocation metering of petroleum products

In this group we find NGL and condensate applications, which are characterised by low water content, low density, low viscosity, high vapour pressure and high thermal expansion. The water content will in many cases be very low due to use of process equipment like turbo-expanders and extraction column. Under these conditions it will be very difficult to maintain a homogenous liquid mixture, since the water is easily separated from the mixture.

Therefore, when utilising a WFM for fiscal / allocation purpose following key questions within flow regime and water distribution should be addressed:

1. For horizontal pipe: can the maximum content of free water, introduce stratified flow at the minimum velocity?
2. Does the actual water distribution fulfil the profile requirement for the WFM?
3. Is slip present?

Chapter 5 indicates a practical approach to quantify these effects (ISO 3171 [8] is relevant standard).

Purpose:
The applications discussed in Section 5.1 & 5.2 are typically those subject to NPD Regulation for fiscal measurement [13]. In addition, limits on allowable water fractions are normally stated in contracts between Seller, Pipeline operator or Buyer.

Online instruments will be superior in monitoring compliance with above requirements because they provide the information immediately, and the field operator or shipper can take immediate action in order to bring the process conditions back to normal.

Flow-proportional sampling and subsequent analysis will only provide the information retrospectively and will in many cases be available too late to make changes to the process conditions.

6.2 Test separator metering applications

In this group we find typical high vapour pressure liquids flowing from a separator outlet. Test separator, inlet separator (1st separation stage) or direct metering from production separators is relevant in this respect.

Presence of gas must be avoided in the oil leg of the separator. In most cases this is achieved by installing a pump to keep the pressure above the vapour pressure of the oil, however it is also possible to achieve an increase in pressure using gravitational methods. The water content in the oil or condensate stream will depend on separator internals & construction, liquid / gas retention time, proper level control, use of production chemicals etc.

The operating envelope could vary between:

1. Low water content (1 %< typical<5%) and water fully dispersed in the oil creating a homogenous mixture throughout the operating flow range.
2. High water content (typical > 5 %) may occur under these conditions i.e. water slugging on Separator input stream, poor level control, high load on the separator etc. Oil/water emulsions may also be present. However, these conditions could also be typical during the end of lifetime production from an oil field.

Normal operating conditions are: 50 – 100 °C at a pressure range of 40 - 100 barg.

Purpose:
It should be considered that installation of an online analyser could provide faster and more accurate well testing results. Taking manual samples during a well test will be time consuming and require use of trained personnel in order to obtain representative samples which can be used in the subsequent laboratory analysis.

Calculating flow weighted average value from continuous measurement will be both faster and has the potential to be equally accurate.

Water fraction meters can also be used favourably to obtain a better control of the process. Fast direct reading can be used to change the retention time of the separator. Manual operation using level glasses can provide wrong interpretations, particularly in cases where the thickness of the emulsion in the separator gives rise to misunderstandings.

7. PERFORMANCE SPECIFICATION

7.1 Recommended performance specification sheet for fiscal WFMs.

The purpose of this chapter is to propose an uncertainty specification format, which WFM manufacturers may use when quoting for a fiscal application.

Table 7.1 Recommended performance specification sheet for fiscal WFMs.

Uncertainty @ 95 % confidence level (k = 2)								
0 - *1*	% Water			±	*0.05*	% abs.		
1 - 10	% Water			±	*5*	% of reading		
Repeatability (assuming fixed **Typical process data** as suggested below)								
0.01 % abs.								
Resolution								
0.005 % abs.								
Sensitivity to errors in input parameters [1]								
Input parameter	**Input type** [2]	**Typical process data**		**Input error**	**0,10 %**	**1 %**	**10 %**	**Ref.**
Temperature	*Live*	*45*	deg. C	+/- 1 C	*-/+ 0.0055*	*-/+ 0.0054*	*-/+ 0.0065*	
Pressure	*Fixed*	*30*	BARG	+/- 10 BARG	*-/+ 0.000015*	*-/+ 0.00015*	*-/+ 0.0016*	
Dry oil density	*N/A*	*830*	kg/m3 @ 15 C	+/- 1 kg/m3	*N/A*	*N/A*	*N/A*	
Mixture density	*Live*	*810*	kg/m3 @ TP	+/- 1 kg/m3	*-/+ 0.034*	*-/+ 0.034*	*-/+ 0.035*	
Water density	*N/A*	*1025*	kg/m3 @ 15 C	+/- 10 %	*N/A*	*N/A*	*N/A*	
Water conductivity	*Fixed*	*50*	mS/cm @ 20 C	+/- 10 %	*-/+ 0.000039*	*-/+ 0.00048*	*-/+ 0.014*	
References (documentation of sensitivity to errors in input parameters)								
1								
2								
3								
4								
Available output parameters								
1								
2								
3								
4								
5								
6								
7								
Notes								
1) Effect of **Input error** on % Water value at 3 different ranges (enter *N/A* if **Input type** is *N/A*)								
2) **Input type** may be one of the following:								
Live - Continuous digital input signal								
Fixed - Values entered in menues								
N/A - Input parameter not used or calculated from other input parameter								

Table 7.1 refers to information about the uncertainty performance of a WFM, and may be included as part of the specification (e.g. Instrument Data Sheet) for the WFM. By following the format below, comparison of different WFMs quoting for the same application will be greatly simplified. (The values in *italic* are sample values).

7.2 Requirements for uncertainty evaluation of fiscal WFMs

In order to use a WFM in a fiscal application it is required that the meter has been evaluated with respect to combined uncertainty in measured water fraction.

Such an uncertainty evaluation must include the uncertainties of the quantities input to the WFM and the functional relationships used. This evaluation should also include the implementation of the models and measurement procedures in the WFM, in order to consider the meter as it really operates in a fiscal application. The uncertainty calculations must be performed according to the principles of the *ISO-Guide* [3].

In addition to the above-described quantitative evaluations, it is required to perform an evaluation (quantitative if possible, otherwise qualitative) of the suitability of the technology for use in fiscal applications, and to consider the influence on the WFM by different unwanted flow effects. Such unwanted effects may be:

- salinity variations
- free gas
- in-homogeneity of the flow
- chemicals
- scaling / wax
- pressure loss
- vibrations
- if intrusive parts: cavitation
- ambient temperature and pressure variations
- sand
- installation effects
- viscosity variations
- EMC noise

The evaluation should be properly documented and all information necessary for a re-evaluation of the work should be available to others who may need it. This requires references to sources and background material, and detailed outlining of the evaluations where engineering judgement has been utilised. For more details about documentation, please refer to the *Handbook of uncertainty calculations – fiscal metering stations* [7] or the *ISO-Guide* [3].

8. INSTALLATION

This chapter discusses different aspects to be considered when designing a WFM installation. It covers issues like sufficient mixing of water in oil, facilities for calibration, redundancy and manufacturer's installation recommendations, and also presentes several specific examples of installation, both in the main pipe, on the meter runs and in a sample loop.

8.1 General design considerations

8.1.1 Homogeneous mixture

The main consideration when designing the installation is to ensure that the WFM will measure a representative value for the water fraction in the main stream, at all relevant flow rates. Therefore it is important to ensure as homogeneous flow conditions as possible at the meter location (cf. Section 5).

There are many ways to enhance the mixing of water and oil through proper design of the installation [8]. The WFM may be installed downstream of a pump, a mixer or one or several blind T's to promote turbulent, well mixed flow. Although most WFMs will function properly in both horizontal and vertical installation, the fluid velocity required for adequate oil and water mixing is less with vertical installation than with horizontal (cf. Section 5).

8.1.2 Free gas

The presence of free gas in the liquid will affect the meter performance. A continuous liquid phase is recommended by keeping the line pressure minimum 2 bar over the boiling point.

8.1.3 Manufacturer's recommendations

The manufacturer of a particular WFM may have installation requirements that apply specifically for that make. Such requirements may relate to horizontal or vertical installation, upstream straight pipe or blind-T requirements, minimum and maximum fluid velocity etc. The pressure drop across the WFM may also be of relevance to the installation design, and should thus be noted. Manufacturer's specifications should be studied carefully during the design to esnsure compliant installation.

8.1.4 Maintenance and calibration

The installation shall always be designed in such a manner that maintenance, calibration and verification can be performed with a minimum of time and labour. This means that the method of calibration must be chosen before the installation is designed. Such methods may include the use of stabilised field oil samples, reference (repeatable) hydrocarbon liquids, air or inert gases etc. The installation shall also ensure comfortable access to both sensor part and electronics part for routine maintenance, repair etc. Locations where maintenance and calibration will take place shall be protected against environmental influences and vibration.

It shall be possible to perform reproducibility check with a repeatable fluid without removing the WFM sensor section from the piping (cf. Section 9.2). If a hydrocarbon liquid is used for reproducibility check, the design must allow the sensor section to be easily and completely filled with the fluid by means of a piping, valves and pumps etc. If air is used for reproducibility check, the design must facilitate proper draining and purging of the sensor section. For full bore WFMs installed on the main pipe, it should be possible to swing the WFM out of line position on the flange bolts for inspection and cleaning, without disconnecting any cables.

Optionally, the design may also allow for on-site primary calibration, by providing facilities for easy filling of sensor section with stabilised field oil sample.

8.1.5 Proximity to related instrumentation

The WFM should ideally be installed as close to and with the same line conditions as the temperature transmitter, densitometer, flow meter and other related instrumentation. This reduces the requirement for conversion of measurement values from e.g. densitometer conditions to WFM conditions, and thus reduces the amount of instrumentation required while also improving redundancy. Still, it may be required to convert water fraction measurements between different line conditions, and also between volume fraction and mass fraction, ref. Annex D to [14]. In this case, the installation must include all instrumentation required to perform such conversions at each of the different line locations.

8.1.6 Operator interface

It must be possible to configure, calibrate and troubleshoot the WFM through a digital link from a computer unit in safe area. The installation must also include data collection and back-up. Facilities to enable user verification when connecting to the WFM operator interface have to be considered.

8.2 Full bore or sample loop

When designing a WFM installation, the first and most fundamental decision to make is whether the water fraction shall be measured directly on the main pipe or in a sample loop. The considerations listed earlier in this chapter apply generally for all types of installations. This section discusses some specific installation considerations, governed by which one of these two basic design philosophies are selected.

8.2.1 Measuring on the main pipe

Measuring directly on the main pipe – or on each meter run – requires a full bore WFM, which will effectively measure all the water over the whole cross-section of the pipe. This type of installation will normally provide less measurement uncertainty than a sample loop, but will also allow for less flexibility with respect to horizontal or vertical installation, and less opportunity to use piping elements to enhance mixing of water and oil etc. Also, if the installation has to be designed such that it allows for removal of the WFM for maintenance or primary calibration outside of the planned shutdowns (i.e. without disrupting the flow), expensive and space consuming piping arangements and valves for bypassing the flow during such maintenance must be added.

8.2.2 Measuring in a sample loop

Measuring in a 1” or 2” sample loop offers the same advantages and drawbacks as with e.g. densitometers, automatic samplers etc. A sample loop provides much more opportunity to optimise the design with respect to serviceability, calibration and mixing of water in oil, but also introduces another challenge, i.e. how to ensure a representative tapping off of the main pipe. Basically the same considerations apply as when designing a bypass loop for automatic sampling, so ISO 3171 [8] may be used as a detailed guide to ensure that a representative portion of the main flow will circulate through the sample loop. Particular attention must be paid to ensure that the velocity of the fluid entering the sample loop is equal to or higher than that of the velocity of the fluid on the main pipe. The sample loop should be equipped with an alarm that will warn in case of a pump failure, or if the flow rate goes below a certain minimum value.

Also, the pipe diameter – including the WFM sensor section – must be uniform throughout the sample loop, to avoid cavities and pressure drops that may promote scaling and deposits. In addition, a 1” or 2” sensor section is much more sensitive to scaling than e.g. a 12” sensor section, and reproducibility check and adjustment may thus be required more frequently than for full bore meters. However, since the sample loop can be specifically designed for simple calibration and maintenance, and since the components involved are small and lightweight, frequent calibration does not necessarily require a lot of work.

8.3 Single or dual WFM

All meters – especially fiscal ones - must be taken out of operation for maintenance and calibration from time to time. The installation design, process fluid quality, company procedures etc. will determine how often and for how long the WFM will be inoperative. On a single meter installation, there will be no water fraction measurement whenever servicing, cleaning, verification or adjustment is performed. If downtime must be minimized, the need for a second WFM should be carefully considered. If two or more WFMs are installed, each meter may also be used to verify, correct or indicate problems with the other meter(s).

Different configurations may be considered if redundancy is required. The three most commonly encountered ones are described below.

8.3.1 Two meters in series

Two meters installed in series will provide redundancy, and with the proper piping and valve arrangement, close to 100 % operational time may be achieved. Also, by averaging the two measurements when both meters are operational, the uncertainty may be reduced. However, two meters in series will be equally exposed to deposits and corrosion, so any errors caused by such process related factors are also likely to develop equally on both meters. Thus, a series configuration will provide redundancy, but will not provide reliable warnings about potential errors, which could have been used to trigger condition based maintenance.

8.3.2 Two meters in Master-Duty

Another configuration – and probably the one that is best suited to provide reliable error indication – uses the Master-Duty concept. Commonly used with other types of fiscal instrumentation, this configuration normally has a duty meter continuously in service and a master meter normally out of service. The master meter is installed immediately upstream or downstream of the duty meter, on a valved bypass from the piping that carries the duty meter. Process fluid is only routed through the master meter as a reference during secondary calibration of the duty meter, or as a back-up reading when the duty meter is taken out of service for reproducibility check, repair or maintenance. Since the master meter is not expected to see process fluid other than during very short periods of time, it is highly unlikely that the master meter will develop the same amount of deposits as the duty meter. Thus, the master meter may provide clear indication about potential errors with the duty meter, and it may even be used as a reference for calibration of the duty meter (cf. 9.3). The master meter may also serve as a back-up in case the reading from the duty meter falls out for any reason. The Master-Duty configuration may thus be used both to achieve condition based maintenance and redundancy.

8.3.3 Installation in each meter run

A third option is to install one WFM on each meter run, e.g. downstream of each flow meter. Since fiscal metering stations already include a spare run by regulation [13], such configuration will provide the same kind of redundancy as the two types of installations mentioned above. There may be some uncertainty as to whether the water will be evenly distributed between all runs, but if measurements from all the meters are averaged, the result will represent the overall water fraction. However, this kind of configuration has the same weakness as two meters in series, in that the meters are likely to see the same build-up of deposits etc. Thus, one meter cannot easily be used to reveal a potential problem with another meter.

8.4 Installation examples

Considering the choice between full bore and sample loop installation as well as between single and dual meters, there is a wide range of possible installation variants, each one having specific advantages and drawbacks.

The table below summarizes the most relevant types of installation, and refers to typical sketches. Some theoretical installation variants are not discussed, either because they would be too impractical, big or complex, or they would not be fit for purpose.

The installation examples below are categorized by location:

1) WFM installed in the main pipe up-/downstream of the metering station
2) WFM installed up-/downstream of a flow meter in a meter run
3) WFM installed in a sample loop

Within each of these categories, the installation examples are subcategorized by configuration:

	Section	Stand-alone	Series	Master-Duty	Parallel
Main pipe	8.4.1	Figure 8.1	Figure 8.2	Figure 8.3	
Meter run	8.4.2				Figure 8.4
Sample loop	8.4.3	Figure 8.5	Figure 8.6	Figure 8.6	

All the installation examples proposed below are principle sketches, and may be employed equally well to horizontal and vertical installations, as long as the general installation considerations above (cf. 8.1) are taken care of.

All valves in conjunction with installation examples of this section shall be of DB&B[3] type.

8.4.1 Installation in the main pipe

The most basic configuration is that of a single, full bore WFM installed directly in the main pipe, either upstream of downstream of the metering station (cf. Figure 8.1). For non-ideal applications (high watercut and low velocity), a mixer may be installed immediately upstream of the WFM.
Several major advantages are obtained from a full bore WFM in the main pipe:

- It requires – in its simplest form – no additional piping or valves
- It provides the lowest level of uncertainty achievable, and thus the highest degree of accuracy, since all the water passing through the pipe is measured
- It is far less exposed to measurement error due to contamination, since the deposits constitute a much smaller part of the total measurement area than in a sample loop configuration

3 Two barriers with a bleed between the barriers. Typical arrangement is two block valves with a bleed valve in the middle. Double block and bleed as defined in ISO DIS-14313, and adopted by some valve manufacturers, is not according to the definition in this NORSOK standard. A single valve is acceptable as double block and bleed only if the force acting on the seal faces is independent of system pressure, and if a bleed connection is provided between the two seal faces (typically a double expanding gate valve). Furthermore, such a valve must be lockable in closed position to avoid malfunction or maloperation.

The major drawback is that – if cleaning, maintenance or calibration should become necessary – the sensor section cannot be removed from the piping without a shutdown. This may be solved by means of a full bore bypass arrangement with valves as indicated in Figure 8.1 below, although such solution would dramatically increase the space and capital expenditure required for the installation.

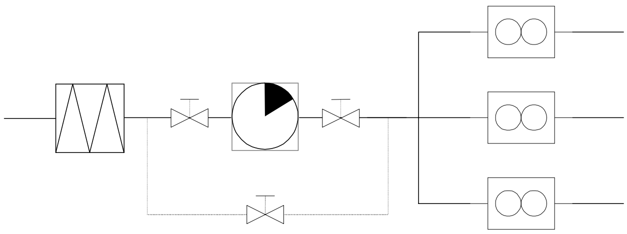


Figure 8.1: Single WFM installed in the main pipe upstream of the metering station

Figure 8.2 proposes a similar design, incorporating two WFMs in series and a bypass across the whole assembly. To avoid significant reduction in capacity during maintenance of the WFM, the piping and valves required for the bypass must be approximately the same size as the main pipe. This configuration provides both serviceability outside of shutdowns, as well as redundancy in case of any failure in electronics, software or communication with one of the WFMs. Also, the monitored data from both WFMs may be compared and used for quality checks, maintenance warnings etc. However, any deposits, contamination or corrosion inside the pipe is likely to develop identically on both meters, so this configuration is not very well suited for detecting measurement errors caused by such effects. Another disadvantage with this solution is that there will be no measurement of water fraction during maintenance, since both WFMs are always bypassed simultaneously.

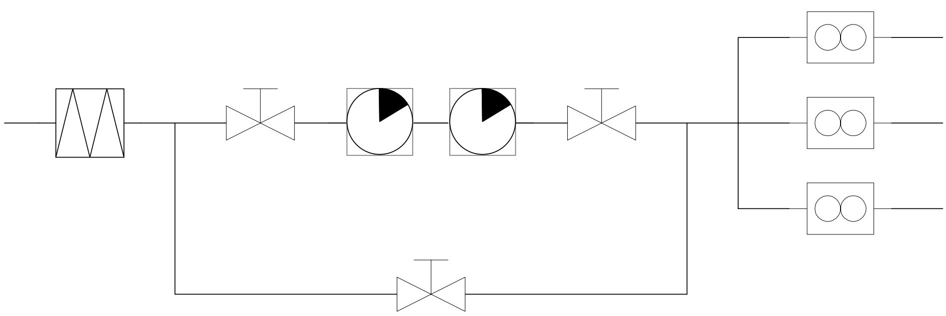


Figure 8.2: Dual WFM installed in series in the main pipe upstream of the metering station

The Master-Duty installation shown in Figure 8.3 will allow one of the WFMs (the master meter) to be taken out for cleaning, maintenance and calibration without a full shutdown. Also, any deposits, scaling, contamination or corrosion etc. inside the pipe will not develop identically on the two meters, since the actual operational hours will be different. The master meter may thus be used to verify – and possibly also to adjust – the duty meter at certain intervals (cf. Section 9.3). If the valves have automatic actuators, the comparison test can be done unmanned, although the capex for such full bore automatic actuators is high. By keeping the master meter as unaffected as possible by the product flow between each verification of the duty meter, the most recent traceable primary calibration (adjustment) of the master meter may be kept valid for a long time. It is even possible to perform a traceable primary calibration (adjustment) or reproducibility check (verification) of the master meter on site, either off-line or even in-line, as long as proper piping and valve arrangement for draining, purging and filling the master meter with reference liquid or gas is provided (cf. Section 9.2.1). However, the advantage of this configuration may diminish if the design is not made with great care. The two WFMs must be installed as close together as possible, to avoid that any rapid variations in the water fraction, along with the distance between the two meters, will render a comparison between the readings of the two meters difficult or irrelevant. Another drawback is that the Duty meter cannot be taken out for maintenance, cleaning or primary calibration without a shutdown. The ultimate installation would thus be to provide separate bypass arrangements across both master and duty WFM, as proposed for sample loop installation below (cf. Figure 8.6). However, such a grand arrangement will only be feasible for the very most high end applications, where accuracy, reliability and traceability is more critical than space and capital expenditure.

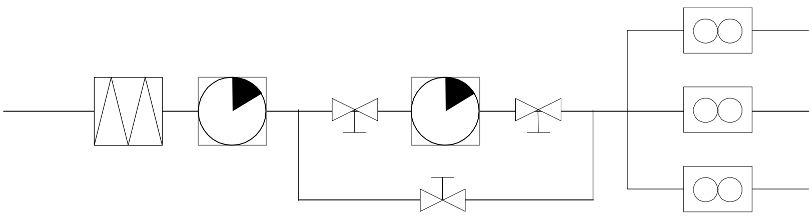


Figure 8.3: Dual WFM installed in Master-Duty configuration upstream of the metering station

8.4.2 Installation up- or downstream of a flow meter in a meter run

By installing the WFM up- or downstream of the flow meter in the meter runs, the stream is measured full bore (cf. Figure 8.4). By simply changing the meter run when service or maintenance is required, valves and piping for a WFM bypass loop are saved. However, if the metering station has more than two meter runs, more WFMs have to be installed than with series or Master–Duty installation.

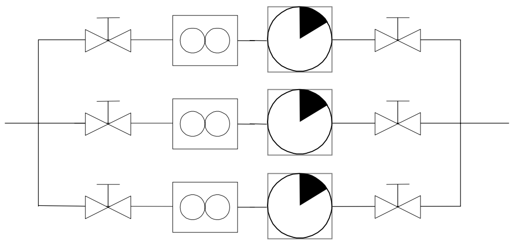


Figure 8.4: WFMs installed in each run on the metering station

8.4.3 Installation in a sample loop

The WFM may be installed in a sample loop, separately or together with density meters and sampling systems (cf. Figure 8.5). When designing a sample loop, special precaution must be taken to ensure that a representative portion of the total flow on the main pipe is circulated through the loop (cf. Section 8.2.2). Even if all possible recommendations are adhered to, it is not always easy to comply with this condition. Thus, measurements in a sample loop are often subject to greater uncertainty than measurements in the main pipe. One advantage, though, is that if density measurements are used to correct the WLR measurements, the densitometer is usually installed in the sample loop, so the WFM and densitometer can be installed in series, measuring on the same conditions. However, with this type of installation, there is no back-up meter, so measurements will be absent during maintenance and calibration. The advantage is smaller equipment size, which is thereby easier to handle during service.

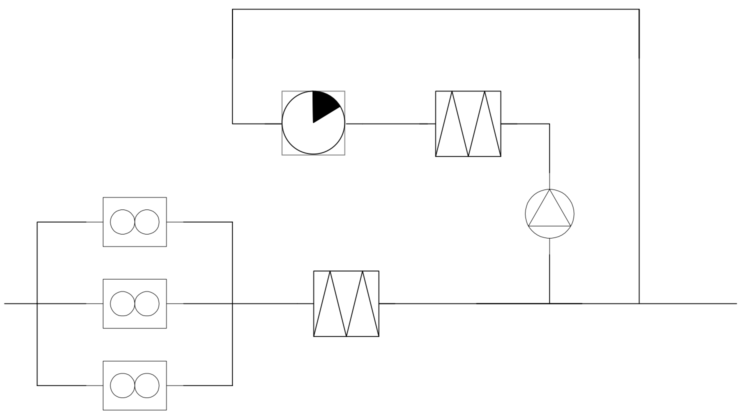


Figure 8.5: Single WFM installed in a sample loop downstream of the metering station

As with full bore installation, two WFMs installed in series in a sample loop may provide redundancy (cf. Figure 8.6). Since the piping and valves involved in a sample loop are much smaller, more easily handled and less expensive to install, a sample loop provides more freedom to optimise the installation for redundancy, maintenance and calibration etc. The configuration indicated below employs a total of 6 DB&B valves to ensure full bypass possibility for both WFMs. It is quite obvious that it would require a lot of space and capex to apply the same principle to a full bore pipe.

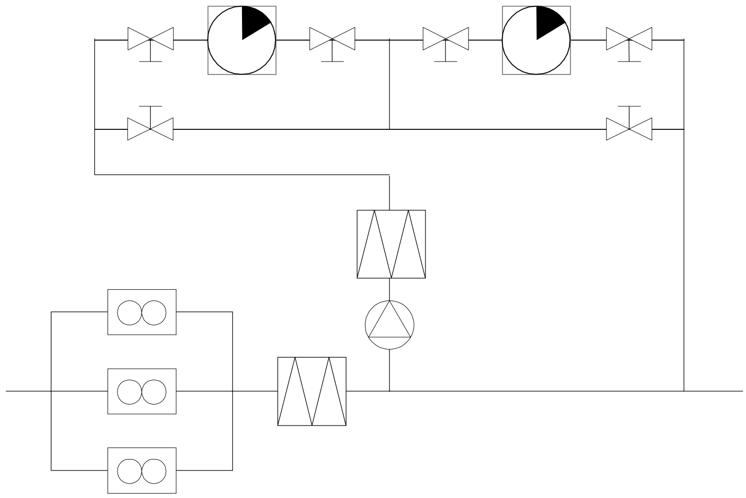


Figure 8.6: Dual WFMs installed in a sample loop in a series / Master-Duty configuration

The series configuration indicated above can – by simple valve operation – be made into a Master-Duty configuration, similar to the one described for full bore installation above (cf. Figure 8.3). If one of the WFMs (the master meter) is closed (bypassed) during normal operation, it can be opened for short periods whenever the operator wants to verify the other WFM (the duty meter). Since product flows through the master meter only for very short periods of time, it is highly unlikely that any long-term build-up of deposits in the duty meter will develop equally on the master meter. As for the full bore Master-Duty installation, this configuration is therefore very well suited for advanced monitoring of the measurement quality. The system may be designed to detect and warn about potential measurement error caused by contamination inside the WFM sensor section. This may in turn be used to develop condition based maintenance schemes.

9. CALIBRATION

This chapter discusses the calibration requirements for WFMs, including adjustment and in-situ verification of the WFM. Traceability is a fundamental requirement, especially for applications where the WFM is used in combination with flow meters for fiscal measurement of net crude oil.

Calibration may generally be required to determine (and – in the case of adjustment – to compensate for) the effect on the measured % Water of any of the following three main elements:

1. Mechanical wear and ageing of components
2. Contamination of sensor section by scaling, asphaltenes etc.
3. Changes in fluid composition due to non-hydrocarbon components

This chapter deals with the first two of these elements. As for changes in fluid composition, this handbook requires that a quantitative or at least a qualitative evaluation of the effects of different chemicals, sand and other non-hydrocarbon components is made for WFM candidates for fiscal applications (cf. 7.2). This handbook also seeks to make the calibration and adjustment of the WFM independent of conventional sampling and analysis (cf. Section 9.1.2). Since the amount of non-hydrocarbon components (apart from water) normally is in the ppm range, and since the only way to accurately determine the amount of such components at any given time is by spot sampling and analysis, this handbook assumes that the effect of changes in fluid composition due to non-hydrocarbon components will be part of the general uncertainty consideration for the application, and no adjustment will be performed to compensate for the effect of such changes.

This handbook covers calibration requirements in general terms. It is assumed that each manufacturer shall provide detailed calibration procedures specific for their WFM, based on the guidelines of this chapter.

Three types of calibration are presented in the following sections of this chapter:

- Primary calibration (performing adjustment and recording footprint)
- Reproducibility check (verifying meter against footprint)
- Secondary calibration (calibrating a duty meter against a master meter)

9.1 Primary calibration

The purpose of the primary calibration is to:

- Record the footprint of the WFM with a repeatable reference material
- Establish the error of the measured WLR on a stabilised field oil sample
- Perform adjustment of the WFM with a stabilised field oil sample

Since the purpose of establishing the error in the first place is to be able to perform an adjustment to compensate for the error, the cablibration and adjustment activities are described in the same section below.

The WFM sensor section should always be properly inspected and cleaned prior to primary calibration. Any scaling, asphaltenes or other contamination must be removed as fully as possible. For this reason, primary calibration is normally an off-line calibration (i.e. the meter has to be removed from its installation in the pipeline before calibration can be performed). Both calibration and recording of footprint require equipment, facilities and personnel that may not be available in the field. For the purpose of this section, it is therefore assumed that primary calibration is performed at factory, or other adequately equipped onshore facility, by manufacturer or his authorized representative. However, if the installation allows for it, primary calibration may also be performed in the field.

Primary calibration shall be performed as part of the factory acceptance testing (FAT) before delivery of the WFM, and a calibration certificate containing all relevant information and results shall be included along with the FAT report. After the WFM has been in operation for some amount of time, a primary calibration shall be performed again. The interval between each primary calibration will be determined based on the results of the reproducibility checks.

9.1.1 Recording the footprint

The footprint of a WFM is basically the raw response of the sensor with a repeatable reference material (hydrocarbon liquid or non-hazardous gas) in or around the sensor section. This raw response is normally a frequency, since most WFMs measure the permittivity of the mixture by either microwave or capacitance technology.

The purpose of the footprint is to serve as a reference for subsequent reproducibility checks, which means that it must be possible to reproduce the footprint in the field. This can only be accomplished if the content of the sensor section during the reproducibility check is exactly the same as when the footprint was first recorded.

Thus, the material inside or around the sensor section must be repeatable, and the sensor section must always be completely filled or surrounded by the material.

The footprint shall cover the complete measurement system of the WFM, i.e. sensor section, electronics, cables and any other elements that contribute to the response of the WFM. The footprint must also include additional information, e.g. how the raw frequency changes as a function of the temperature of the fluid (e.g. due to changes in fluid permittivity), the sensor section (due to thermal expansion) or the electronics (due to changes in component characteristics). The footprint shall be recorded and included in the calibration certificate as a single number (e.g. measured frequency), a set of numbers, a table, an equation or a curve.

Two methods for recording the footprint will be discussed, the difference between them basically determined by the type of reference material used for the footprint:

- Using a repeatable liquid (hydrocarbon or equivalent)
- Using air (or another non-hazardous gas, inert gas or even vacuum)

The principal difference between using gas and liquid for the footprint, is that with gas, the only significant effect of the line temperature is on the thermal expansion of the sensor spool piece material, and the effect that such expansion may have on the footprint of the meter. For liquids, however, the line temperature is also likely to have a significant effect on the measured property of the liquid (e.g. permittivity). The effect of thermal expansion can be predicted mathematically from the properties of the sensor spool piece material, so the method proposed below for recording the footprint with air requires measurement only at one (ambient) line temperature. The method proposed for generating the footprint with a liquid, however, requires several measurements over the expected ambient range for the installation.

9.1.1.1 Using a repeatable liquid

When considering which liquid to use for recording the footprint, one must bear in mind that most WFMs measure the permittivity (i.e the dielectric constant) of the water-in-oil mixture to determine the water fraction. Plain, single-molecule liquids like fresh water, alcohols etc. are not very well suited for recording the footprint, since the permittivity for these liquids is much higher than for the water-in-oil mixture, and the WFM may not even be able to generate a response with such liquids.

Dry hydrocarbons, or other liquids with dielectric constant between 2 – 3, lie within the operating range of the WFM, and can thus be used to generate a footprint that characterises the WFM as a complete system (sensor section and electronics). The challenge is to find a liquid that is sufficiently repeatable for this purpose.

Refined, “narrow” hydrocarbon liquids like Jetfuel A1 and Shellsol D70 have been considered for this purpose, but the specifications for these commercial products allow for a certain variation in the density (i.e. composition) of the finished product. If these are to be used to record the footprint, liquid from the same batch that was used for primary calibration must be used when the footprint is reproduced during subsequent reproducibility checks.

Ideally, a single-molecule hydrocarbon liquid should be used, since this would remove all uncertainty regarding the composition and thus the repeatability of the liquid. Although such liquids exist, they are either extremely expensive or extremely hazardous to health or safety, and are thus not very practical for this purpose.

When a liquid has been selected, the footprint shall be recorded while observing the instructions below. Whereever the instruction to “record” is mentioned, this implies that the information shall be noted and included in the final calibration certificate.

- Record all relevant information about the time and place of the calibration, e.g. location, WFM (make, model & serial no.), calibration date, calibration liquid (designation, manufacturer, supplier, batch no.), operator etc.
- Fill the sensor section completely with the liquid, making sure no pockets of air remain, and allow the temperature of the liquid and sensor section to stabilise
- Record the raw response of the WFM, the temperature of the liquid and – if relevant – the temperature of the electronics
- Establish and record – either by theoretical or experimental method – the correlation between raw response and liquid temperature and – if relevant – between the raw response and the electronics temperature, over the relevant ambient temperature range of the application
- Define and record the valid ambient temperature range for the footprint
- Establish and record the uncertainty of the footprint, and thus the acceptance criteria that will be applied when the footprint is used to verify the WFM response during subequent reproducibility checks

9.1.1.2 Using air

Instead of using a repeatable hydrocarbon liquid, the footprint may be recorded using air or another non-hazardous gas, or even vacuum, in the sensor section. Vacuum would be ideal for recording the footprint, since the permittivity for vacuum is 1 by definition. Repeatability would thus be guaranteed. However, the additional facilities required to generate vacuum in the sensor section, both at factory when recording the footprint and also in the field during reproducibility check, make this approach impractical.

For all practical purposes, air is also completely repeatable, as long as it is kept at atmoshperic pressure and ambient temperature. The temperature of the sensor section will only need to be considered for the purpose of thermal expansion of the sensor section, since changes in the air permittivity with temperature is negligible. Thus, it will be much easier to establish the correlation between raw response and sensor section temperature by theoretical rather than by experimental means. The following recommendations will only refer to air, although the principles may also be applied for other gases or vacuum.

The permittivity for air is lower than that of any dry oil, and the WFM as a complete system may thus not be able to provide a raw response with only air in the sensor section. However, if the empty sensor section itself is able to provide a unique response, which can be recorded with other, third party instrumentation, the footprint may be recorded separately for the sensor section and for the remaining system (electronics, cables etc.). This division of the footprint into a “sensor section” part and an “electronics” part is the basis for the method described in this chapter.

This approach requires some kind of reference sensor (i.e. a “dummy” sensor with a fixed response), which can be used to record the footprint of the remaining system, and the approach also assumes that the third party instrumentation for recording the footprint of the sensor section can be employed in the field during reproducibility checks.

When using air, the footprint shall be recorded while observing the instructions below. Whereever the instruction to “record” is mentioned, this implies that the information shall be noted and included in the final calibration certificate.

- Record all relevant information about the time and place of the calibration, e.g. location, WFM (make, model & serial no.), calibration date, calibration medium (air, nitrogen or other inert gas), operator etc.

- Make sure that the sensor section is completely clean and dry, and that the temperature of the sensor section has stabilised at ambient temperature
- Connect the third party instrument (e.g. a network analyser) to the sensor section and record the raw response as well as the temperature of the sensor section
- Establish and record – either by theoretical or experimental method – the correlation between raw response and sensor section temperature over the relevant ambient temperature range of the application
- Connect the reference sensor to the electronics, using all WFM cables, and record the raw response of the electronics with the reference sensor
- If relevant, record the temperature of the electronics and establish and record the correlation between raw response and electronics temperature over the relevant ambient temperature range of the application
- Define and record the valid ambient temperature range for the footprint
- Establish and record the uncertainty of both the sensor section part and the electronics part of the footprint. This will determine the acceptance criteria that will be applied when the footprint is used to verify the WFM response during subequent reproducibility checks

9.1.2 Performing calibration and adjustment

The second part of the primary calibration is performed with the purpose of establishing the error of the measured WLR on a stabilised field oil sample, and adjusting the WFM to measure according to a certificate from accredited laboratory, stating the water content of the sample of field oil by traceable Karl Fischer titration method.

The following requirements apply for the sample of field oil:

- The sample must be from the same field and reservoir that the WFM will be installed and measuring on
- The sample must be provided in sufficient amount so that it will completely fill the sensor section (including any temperature transmitter and/or densitometer that will be used to provide input to the WFM)
- The oil must be stabilised at atmospheric pressure and ambient temperature for as long as required prior to use for calibration and adjustment of the WFM
- If the sample was taken directly off of a pipeline, it may require decanting to remove the water that has separated into the bottom of the sample

- If the sample was taken off of a stock tank, the water content may already be sufficiently low to use for adjustment of the WFM
- The remaining sample (without the water that has separated during storage of the sample) must be carefully mixed, and a small sample must be taken with a syringe and analysed for reamining water at a certified laboratory by traceable Karl Fischer titration method.
- A certificate stating water content by weight or by volume, density of sample and corresponding temperature of the sample shall be issued by the laboratory
- The maximum remaining water content for a sample, which is to be used for adjustment of the WFM, is 0.1 % v/v. This limit has been defined to avoid any uncertainty as to the homogeneity of the sample during adjustment of the WFM

The calibration and adjustment shall be performed while observing the instructions below. Whereever the instruction to “record” is mentioned, this implies that the information shall be recorded in the calibration certificate.

- Record all relevant information about the time and place of the calibration, e.g. location, WFM (make, model & serial no.), calibration date, calibration medium (air, nitrogen or other inert gas), operator etc.
- Make sure the sensor section is clean and dry before filling it completely with the sample of field oil, making sure no pockets of air remain
- If the WFM is to be calibrated with a live density value, fill also the densitometer section with the sample of field oil
- Allow the temperature of the sample and sensor section to stabilise
- Configure the WFM with any temperature, pressure or density as may be required, in accordance with manufacturer’s instructions
- Record the (unadjusted) water fraction as measured by the WFM
- Record the reference water content as provided in the laboratory certificate
- Adjust the WFM to measure in accordance with the laboratory certificate for the sample, in accordance with manufacturer’s instructions, taking into account any differences in temperature between factory and laboratory conditions
- Record the (adjusted) water fraction as measured by the WFM
- Record the temperature of the sample as measured by the WFM
- If relevant, record the temperature of the electronics
- Specify the uncertainty of the calibration

9.2 Reproducibility check

The purpose of the reproducibility check is to verify that the most recent primary calibration (adjustment) of the WFM is still valid. Such verification is achieved through reproduction of the WFM footprint in the field, and comparing this with the footprint from the primary calibration certificate.

This type of calibration is not relevant for a duty WFM that is being subject to frequent secondary calibrations in a Master-Duty configuration. It is assumed that any shift in the duty meter readings between each secondary calibration is caused by inevitable build-up of deposits inside the duty meter, and thus the WFM will not be able to reproduce the footprint for the most recent primary calibration. The reproducibility check is however very relevant for the master WFM in the same configuration, since this will actually be used as a reference when calibrating the duty WFM.

The procedure for reproducibility check should be simple and straightforward, so that operator's personnel can do it, ideally without removing the meter from its location. There is no adjustment involved in connection with a reproducibility check.

It is the manufacturer's responsibility to define the procedures on how the most recent primary calibration may be verified with a minimum of manual labour and operator interference.

After the WFM has been put into operation, reproducibility check is initially performed at frequent intervals, e.g. weekly or monthly. The experience gained from these reproducibility checks will then determine how often operator has to continue to perform reproducibility checks to ensure the WFM is kept within its uncertainty specification. The acceptance criteria for reproducibility check shall be determined based on the sensitivity of the measured water to the parameter being verified. The deviation on the footprint from the most recent primary calibration should not produce an error in measured WLR that exceeds the uncertainty limits specified by the authorities ([13] and [14]).

The manufacturer's procedure for reproducibility check shall suggest the required actions if the deviation from the most recent primary calibration is not within the acceptance criteria. Such actions may include removing the WFM from the piping for inspection and cleaning, checking the sensor or electronics through third party instrumentation, performing a primary calibration etc. The procedure for reproducibility check shall also include a format (certificate), in which the data from the reproducibility check may be entered along with the data from the most recent primary calibration, and which then will automatically provide information about the acceptance criteria for relevant parameters (i.e. the primary variables, e.g. measured temperature, frequency, permittivity etc.) and the corresponding effect on the water fraction uncertainty.

9.2.1 Verifying the WFM response against the footprint

As with recording the footprint during primary calibration, the methods for reproducing and verifying the footprint in the field will be different depending on the material used to produce the footprint:

- Using a repeatable liquid (hydrocarbon or equivalent)
- Using air (or another non-hazardous gas or even vacuum)

9.2.1.1 Using a repeatable liquid

When using a repeatable liquid for the reproducibility check, the footprint shall be recorded and compared with the footprint from the most recent primary calibration while observing the instructions below. Whereever the instruction to “record” is mentioned, this implies that the information shall be noted and included in the format for reproducibility check as provided by the manufacturer.

- Record all relevant information about the time and place of the test, e.g. location, WFM (make, model & serial no.), calibration date, calibration liquid (designation, manufacturer, supplier, batch no.), operator etc.
- Retrieve the footprint as recorded in the certificate from the most recent primary calibration
- If the reproducibility check is performed without removing the sensor section from the piping, drain, flush and purge the sensor as applicable to remove remains of product from the line. If the sensor section is removed from the piping, clean and dry the sensor section and blind the bottom end.
- Fill the sensor section completely with the liquid, making sure no pockets of air remain, and allow the temperature of the liquid and sensor section to stabilise
- Record the raw response of the WFM, the temperature of the liquid and – if relevant – the temperature of the electronics
- Compare the measured raw response (footprint) of the WFM with the footprint from the most recent primary calibration. The format provided by the manufacturer for recording data from the reproducibility check should

automatically provide information on whether the footprint is within the acceptance criteria or not.

9.2.1.2 Using air

As when recording the footprint during primary calibration, this section assumes that when using air to characterise a meter, the footprint must be divided into a “sensor section” part and an “electronics” part.

When using air, the footprint shall be recorded and compared with the footprint from the most recent primary calibration while observing the instructions below. Whereever the instruction to “record” is mentioned, this implies that the information shall be noted and included in the format for reproducibility check as provided by the manufacturer.

- Record all relevant information about the time and place of the calibration, e.g. location, WFM (make, model & serial no.), calibration date, calibration medium (air, nitrogen or other inert gas), operator etc.
- Retrieve the footprint as recorded in the certificate from the most recent primary calibration
- If the reproducibility check is performed without removing the sensor section from the piping, drain, flush and purge the sensor to remove remains of product from the line. If the sensor section is removed from the piping, clean and dry the sensor section, and allow the temperature of the liquid and sensor section to stabilise.
- Connect the third party instrument (e.g. a network analyser) to the sensor section and record the raw response as well as the temperature of the sensor section
- Connect the reference sensor to the electronics, using all WFM cables, and record the raw response of the electronics with the reference sensor and – if relevant – the temperature of the electronics
- Compare the measured raw response (footprint) of the WFM with the footprint from the most recent primary calibration. The format provided by the manufacturer for recording data from the reproducibility check should automatically provide information on whether the footprint is within the acceptance criteria or not.

9.3 Secondary calibration

Secondary calibration of a WFM means that the reference value for the calibration is obtained from a master WFM, rather than directly from a certified primary reference (e.g. Karl Fischer titration analysis). If a master WFM is to be used as a reference for calibration of another WFM, it must have a valid calibration against a certified primary reference (primary calibration). Since the uncertainty of the master WFM is known, traceability to the certified primary reference is maintained also with secondary calibration, although with the added uncertainty of the master WFM. Secondary calibration may also include adjustment of the WFM to the master WFM reference.

Since secondary calibration requires a master WFM, it is only applicable for Master-Duty configurations (cf. 8.3.2). The secondary calibration method offers a greatly simplified procedure for calibration of a duty WFM, and would be one of the main motivations for designing the installation as a Master-Duty configuration.

In a Master-Duty configuration, the master WFM can be left unaffected by the process fluid between each calibration. Based on experience, the certificate that is issued following a primary calibration of the master WFM may be assigned an expiry date. Within the validity period for the most recent primary calibration, the master WFM may be used as a reference for a duty WFM calibration simply by operating the valves and routing the flow through both WFMs in series. If the validity of the most recent primary calibration has expired, a new primary calibration may be performed on the master WFM prior to using it for secondary calibration of the duty meter.

During all these operations, the duty meter will be in continuous operation. Any adjustment performed during secondary calibration will only be seen as a steep shift in the readings of the meter, possibly with a very short interruption during the actual adjustment.

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A APPENDIX - HOMOGENEOUS FLOW

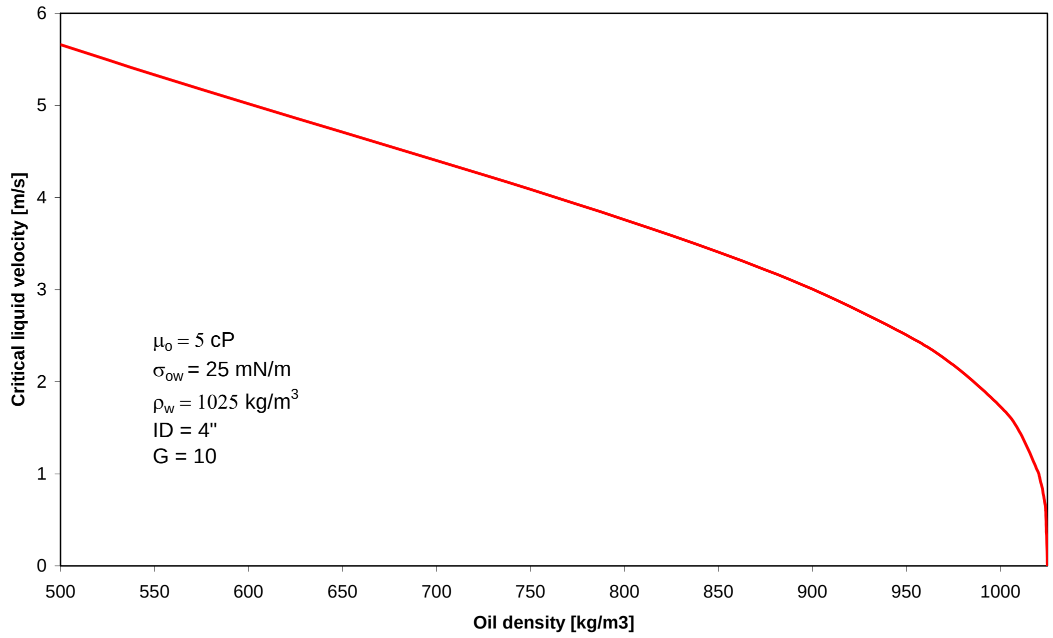

Figure 10.1 Critical liquid velocity as a function of the oil density in order to maintain a concentration ratio of 0.9 (G = 10) between the bottom and the top of a horizontal pipe. The flow will be homogeneous as long as the actual liquid velocity is greater than the critical velocity given by the diagram. The model is only expected to be valid for water fractions below 10-15 %.

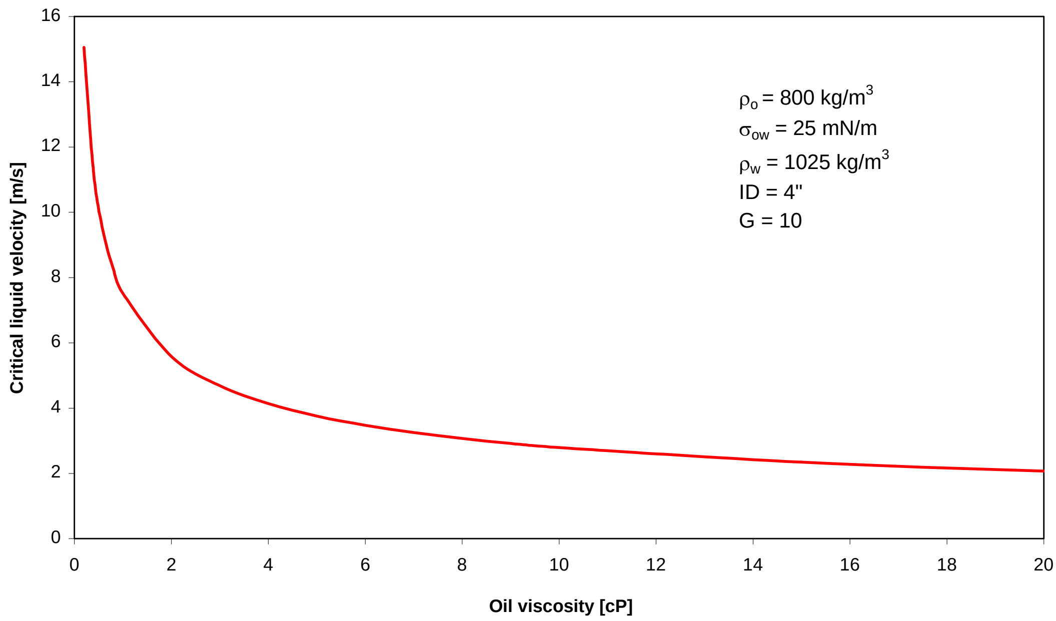

Figure 10.2 Critical liquid velocity as a function of the oil viscosity in order to maintain a concentration ratio of 0.9 (G = 10) between the bottom and the top of a horizontal pipe. . The flow will be homogeneous as long as the actual liquid velocity is greater than the critical velocity given by the diagram. The model is only expected to be valid for water fractions below 10 –15 %.

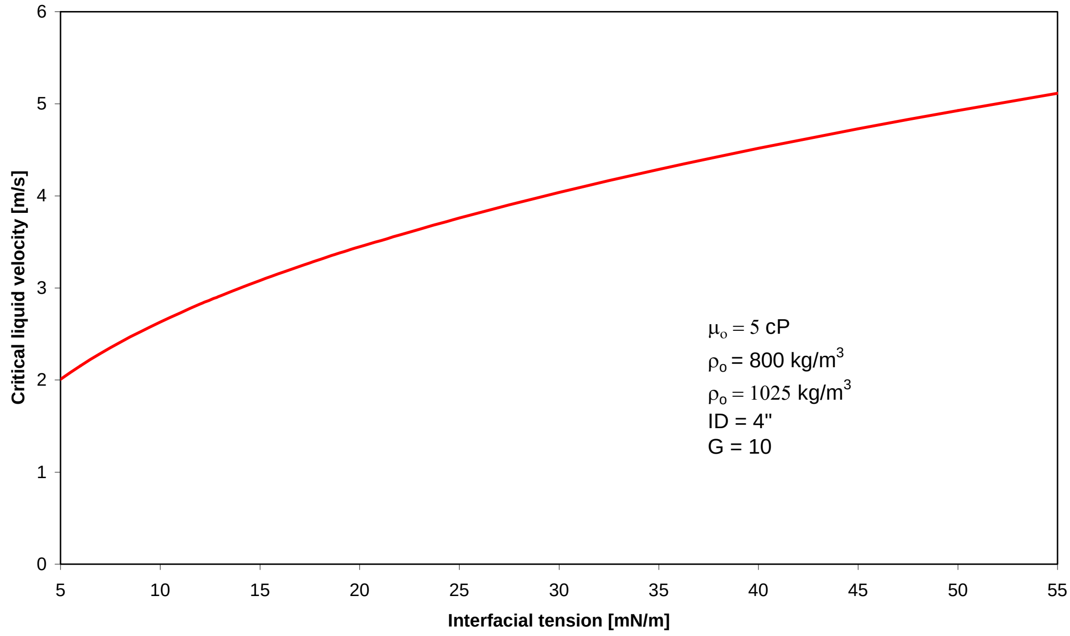

Figure 10.3 Critical liquid velocity as a function of the interfacial tension in order to maintain a concentration ratio of 0.9 (G = 10) between the bottom and the top of a horizontal pipe. . The flow will be homogeneous as long as the actual liquid velocity is greater than the critical velocity given by the diagram. The model is only expected to be valid for water fractions below 10-15 %.

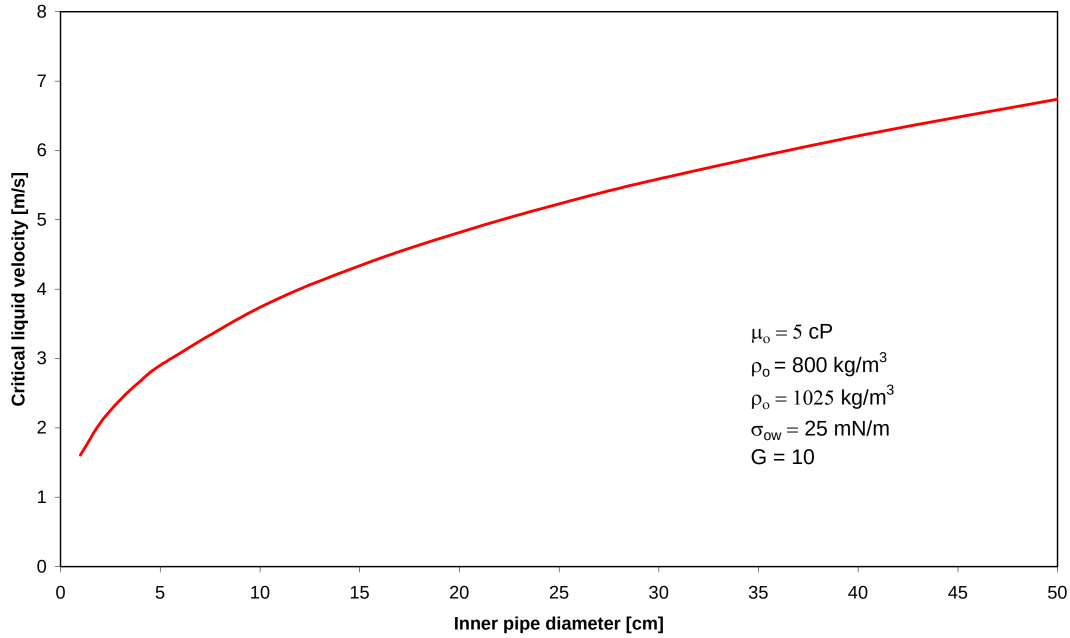

Figure 10.4 Critical liquid velocity as a function of the inner pipe diameter in order to maintain a concentration ratio of 0.9 (G = 10) between the bottom and the top of a horizontal pipe. . The flow will be homogeneous as long as the actual liquid velocity is greater than the critical velocity given by the diagram. The model is only expected to be valid for water fractions below 10-15 %.

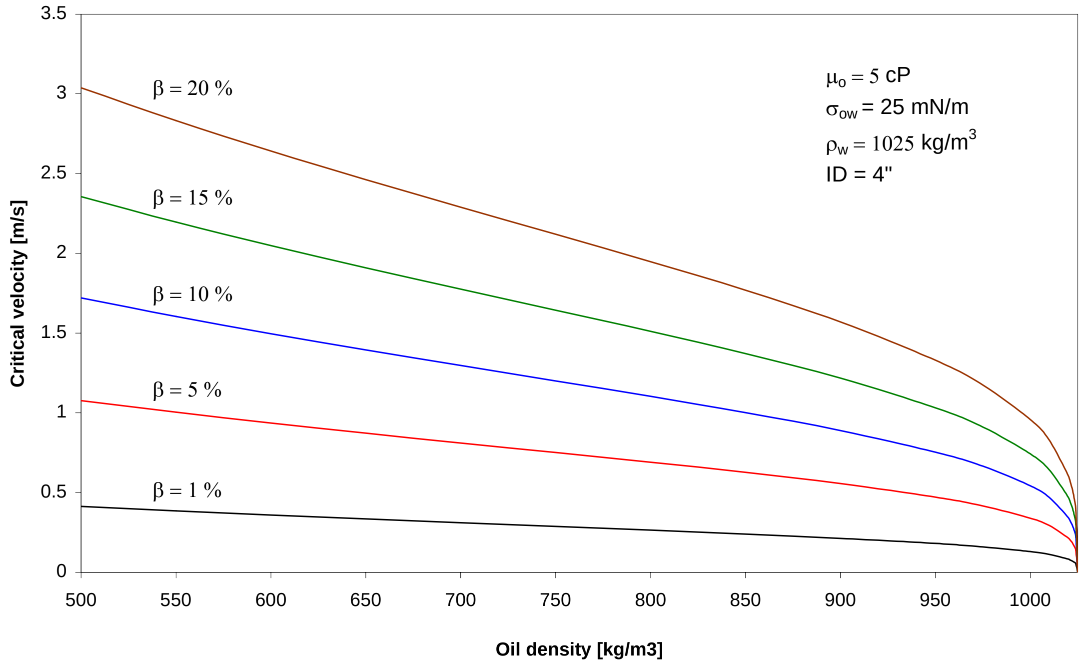

Figure 10.5 Critical liquid velocity for different water fractions β as a function of the oil density. For a given water fraction β, the flow will be homogeneous as long as the actual liquid velocity is greater than the critical velocity given by the diagram. The model is expected to be valid for water fractions below 20-25 %

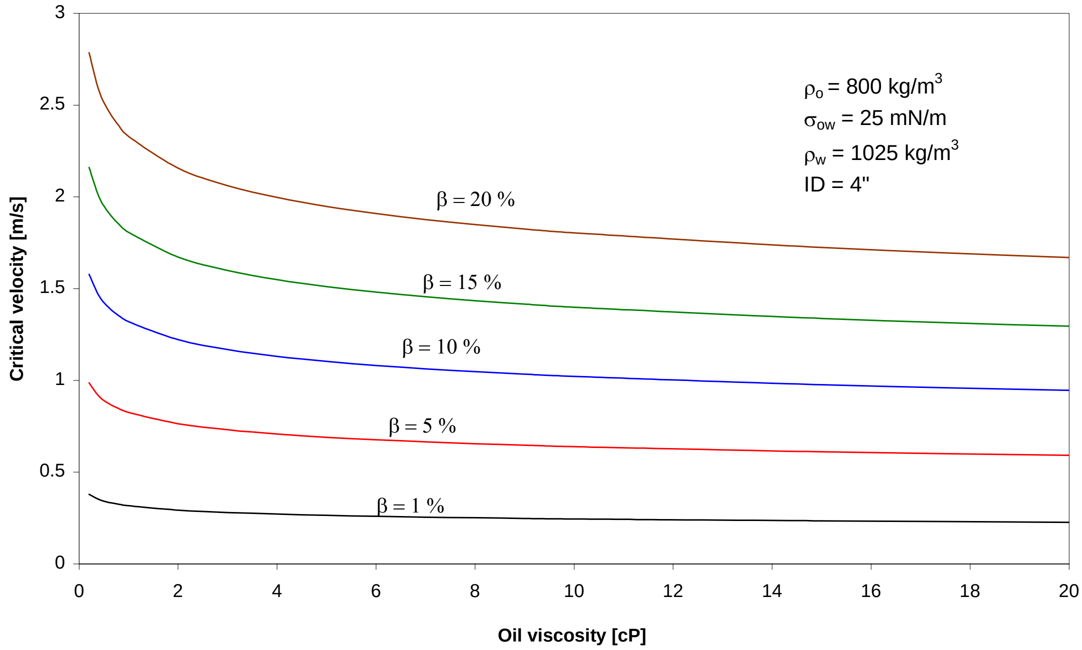

Figure 10.6 Critical liquid velocity for different water fractions β as a function of the oil viscosity. For a given water fraction β, the flow will be homogeneous as long as the actual liquid velocity is greater than the critical velocity given by the diagram. The model is expected to be valid for water fractions below 20-25 %

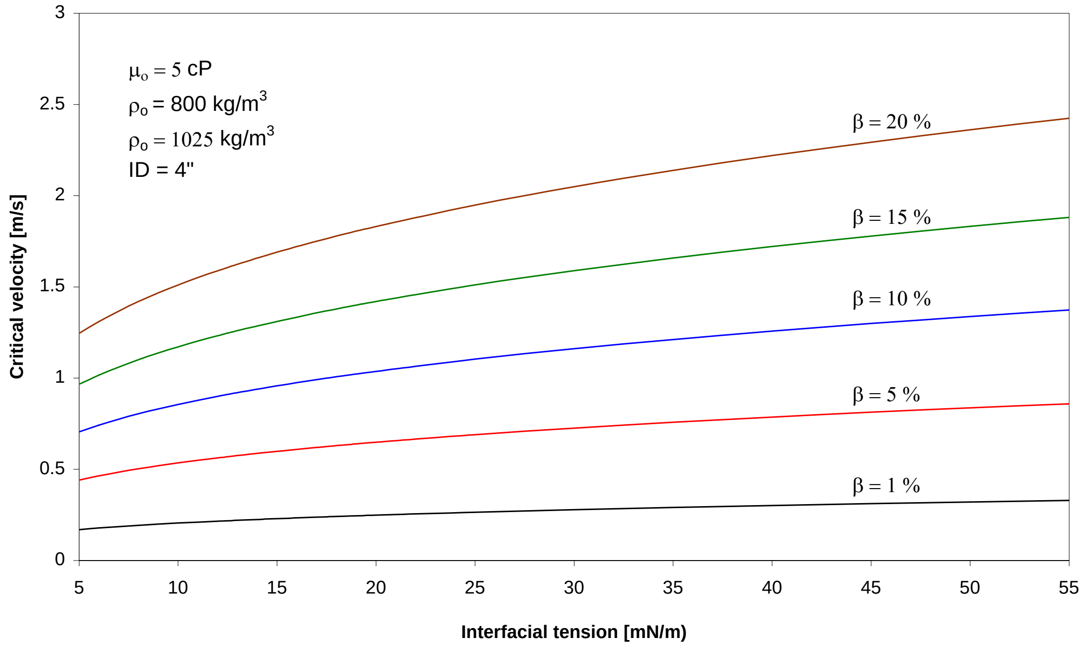

Figure 10.7 Critical liquid velocity for different water fractions β as a function of the oil interfacial tension between oil and water. For a given water fraction β, the flow will be homogeneous as long as the actual liquid velocity is greater than the critical velocity given by the diagram. The model is expected to be valid for water fractions below 20-25 %

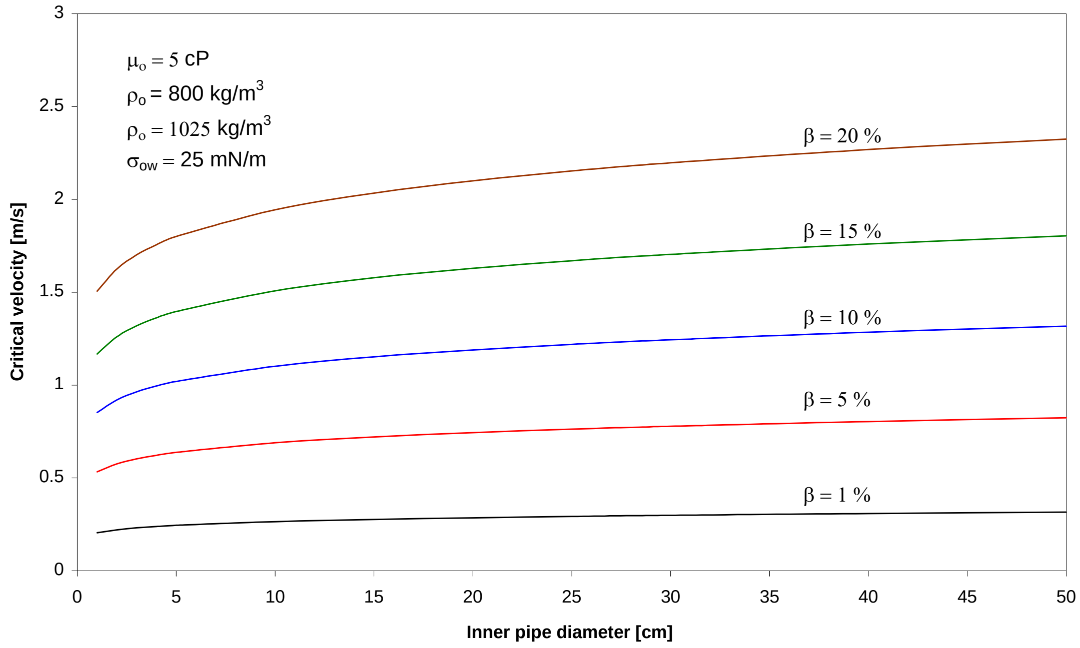

Figure 10.8 Critical liquid velocity for different water fractions β as a function of the oil inner pipe diameter. For a given water fraction β, the flow will be homogeneous as long as the actual liquid velocity is greater than the critical velocity given by the diagram. The model is expected to be valid for water fractions below 20-25 %

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