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Fiscal measurement of oil with high water fraction

Phase 1: Sensitivity study for a turbine meter based fiscal metering station
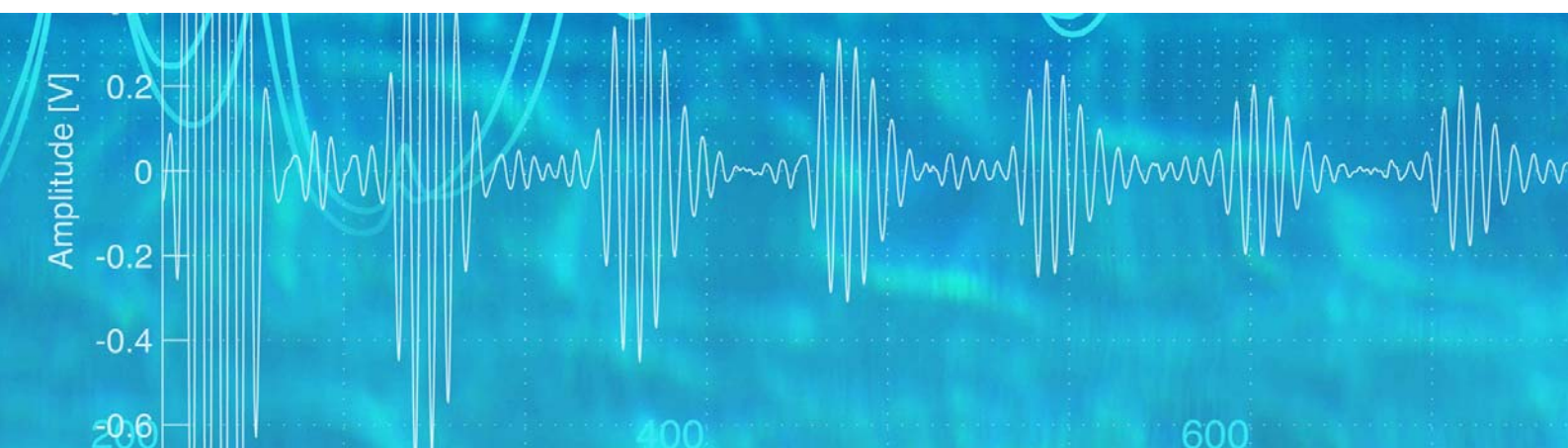
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Title

Fiscal measurement of oil with high water fraction.
Phase 1: Sensitivity study for a turbine meter based fiscal metering station

Extract

On behalf of the Norwegian Society for Oil and Gas Measurement (NFOGM) and in cooperation with Tekna, Christian Michelsen Research (CMR) has carried out a sensitivity study to evaluate the influence of high water-in-oil (WIO) contents on the accuracy of turbine meter based fiscal oil metering stations/systems. The fiscal metering stations in question for the study are normally allocation metering stations and not sales point metering stations. The objective has been to identify the parts of the metering system where a (high) water content in the oil will have a significant impact on the measured volumetric oil flow rate, in the form of increased measurement uncertainty, or as a systematic deviation (error). An uncertainty model for a turbine meter based fiscal oil metering station with high water fraction has been developed and used in the sensitivity analysis. Calculation results are given to illustrate the influence of various effects caused bu WIO contents.

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Fiskalmåling av olje med høyt vanninnhold, Fase 1: Sensitivitetsstudie for en turbinmeter-basert fiskal målestasjon

Revision

Rev.	Date	Author	Checked by	Approved by	Reason for revision
00	12.06.2007	Anders Hallanger Kjell-Eivind Frøysa Per Lunde	Kjell-Eivind Frøysa	Per Lunde	Draft for review by the project steering committee
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02	15.10.2007	Anders Hallanger Kjell-Eivind Frøysa Per Lunde	Kjell-Eivind Frøysa	Per Lunde	Final report, after second review by the project steering committee

SUMMARY

On behalf of the Norwegian Society for Oil and Gas Measurement (NFOGM) and in cooperation with Tekna, Christian Michelsen Research (CMR) has carried out a sensitivity study to evaluate the influence of high water-in-oil (WIO) contents on the accuracy of turbine meter based fiscal oil metering stations/systems. The fiscal metering stations in question for such a study are e.g. allocation metering stations, and normally not sales point metering stations.

The work has been carried out in the period October 2006 – September 2007 under the project "Fiscal measurement of oil with high water fraction. Phase 1: Sensitivity study for a turbine meter based fiscal metering station".

The work has been made in a close cooperation with a project reference group of experienced members from oil and gas companies, offshore service companies, and the Norwegian Petroleum Directorate (NPD).

The objective has been to identify the part(s) of the metering system where a (high) water content in the oil will have a significant impact on the measured volumetric oil flow rate, in the form of increased measurement uncertainty, or as a systematic deviation (error).

For this purpose, an uncertainty model for a turbine meter based fiscal oil metering station with high water fraction has been developed and used. The developments build on the results of the NFOGM "Handbook of uncertainty calculations. Fiscal orifice gas and turbine oil metering stations" (2003) and national and international regulations and standards in this area.

Two important pre-assumptions have been made for the present sensitivity study, in accordance with national and international regulations and standards in this area: (1) it is assumed that free gas is not present in the flow, neither as a separate phase nor as small bubbles dispersed in the liquid, and (2) the water is assumed to be dispersed homogeneously in the oil phase (i.e., the variation in water concentration is less than $\pm$ 5 % of the average water concentration over the pipe cross section).

Under these pre-assumptions, the excess uncertainty of the volumetric oil flow rate at standard reference conditions due to WIO contents has been studied and evaluated. Determination of water fraction by (a) sampling and laboratory analysis and (b) continuous measurement using a water fraction meter (WFM) are both covered. For the sampling/analysis approach, the discussion is based on the ISO 3171 standard. For the continuous water fraction measurement approach, the discussion is based on procedures prescribed in the NORSOK I-105 standard.

Calculations have been carried out based on field data from three fiscal metering stations at three different North Sea fields. Water fractions in the range 0 - 20 % are addressed. Three WIO scenarios, 2 %, 10 % and 20 % WIO, are addressed in some more detail.

In the calculation examples, chosen in a dialogue with the project reference group, the expanded uncertainty of the volumetric oil flow rate due to water, at 20 % water fraction, is estimated to be approximately:

- about 3.8 % uncertainty (95 % c.l.) for sampling/analysis based WIO treatment,
- about 1.3 % uncertainty (95 % c.l.) for continuous measurement of WIO (using a WFM).

It is emphasized that the "uncertainty estimates" given in the present report do not represent uncertainty estimates as such, due to the lack of sufficient information for a number of the input uncertainties. The "uncertainty estimates" given here are to be used for the sensitivity analysis only, to evaluate the relative importance of the various terms influencing on the volumetric oil flow rate, with emphasis on WIO contents.

In spite of that, the example calculations clearly indicate that the NPD requirement with respect to the uncertainty in measured volumetric oil flow rate of $\pm$ 0.3 % (at 95 % confidence level (c.l.)) is definitely not met at 20 % WIO, and also not met at significantly lower WIO scenarios. In the calculations, the combined expanded uncertainty (at 95 % c.l.) is above the NPD requirement at a water fraction of about 3.1 % for WIO determination using WFM, and at a water fraction of about 2.1 % for WIO determination using sampling/analysis.

The effect of systematic deviations from the use of pure oil volume correction factors (VCF) instead of oil-water mixture VCF, is shown to be small. For the WFM method, the pure-oil measurement uncertainty is the dominating contribution for 2 % WIO. For 10 % WIO the WFM measurement uncertainty dominates, and for 20 % the WFM measurement uncertainty is by far the largest.

For the sampling/analysis method, the uncertainty from pure oil measurement and water fraction analysis are approximately equal for 2 % WIO. For 10 % WIO, and even more for 20 % WIO, the water fraction measurement uncertainty due to sampling/analysis is dominating.

The individual instrument in the metering station that may be most susceptible to WIO is considered to be the turbine meter. If the turbine meter is operating near the lower operating range (low and moderate Reynolds numbers), changing Reynolds number due to increasing WIO (density, viscosity, etc.) may affect the linearity of the meter. It is also not clear how the turbine meter will work if the flow homogeneity is not uniform over the pipe cross section. Vertical differences in mixture densities and viscosities may then be present, which may affect the accuracy of the turbine.

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1   INTRODUCTION

On behalf of the Norwegian Society for Oil and Gas Measurement (NFOGM) and in cooperation with Tekna, Christian Michelsen Research (CMR) has carried out a sensitivity study to evaluate the influence of high water-in-oil (WIO) contents on the accuracy of turbine meter based fiscal oil metering stations. The work has been carried out under the project "Fiscal measurement of oil with high water fraction. Phase 1: Sensitivity study for a turbine meter based fiscal metering station", described in the project description [Dahl et al., 2006] and the project contract [Contract, 2006].

The results of this study are given in the present report.

1.1   Objectives

The objective in Phase 1 of the project is to carry out a sensitivity study for a turbine meter based fiscal oil metering station. The goal is to identify the part(s) in the metering station where a (high) water content in the oil will have an impact on the measured volumetric oil flow rate in form of increased measurement uncertainty or as systematic deviations.

In a longer term it may be of interest to propose a recommended practice for measurement of crude oil and condensate with water content in the range 0.5 – 20 % with the lowest possible uncertainty. This may be a more extensive task, containing several demanding challenges that must be addressed. This study represents a first step in such a direction.

1.2   Background

In the North Sea and elsewhere, produced water is becoming an increasing challenge, also for the fiscal oil metering systems used for allocation, custody transfer of oil (oil export, etc.). With increasing amount of fields with tail production from old wells, this challenge is expected to increase in the future. Imperfect separation of the produced 3-phase fluid results in water carry-over to the oil outlet of the separator process system, and as much as 20 % (or more) water in oil by volume (WIO) in the fluid measured by the fiscal metering station may be experienced in the North Sea. Such water contents may also represent a challenge with respect to integrated (e-field) operations related to governing the fiscal metering system.

In the North Sea, the majority of fiscal oil metering stations is based on turbine (TM) or ultrasonic (USM) meters. In some stations Coriolis meters are also used.

For a turbine meter based fiscal oil metering station, an uncertainty model has been given in the "Handbook of uncertainty calculations. Fiscal orifice gas and turbine oil metering stations" [Dahl et al, 2003], provided the fluid flow is pure oil. This handbook will here for convenience in notation be referred to as the "NFOGM TM Handbook". A similar handbook or uncertainty model for USM based fiscal oil metering stations is presently not available.

Situations when water is present in the oil flow are not addressed in the NFOGM TM Handbook [Dahl et al, 2003] and the uncertainty model described therein. The authors of the present document, in dialogue with the project reference group, are not aware of alternative uncertainty models covering such situations, nor any published sensitivity study addressing such situations in a systematic way.

On this background, NFOGM has initiated a study on the influence of water in oil (WIO) on the accuracy of fiscal oil metering stations. Phase 1 of the project addresses turbine meter based oil-

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metering stations, with objective to identify the most critical components of the fiscal metering system with respect to WIO influence on the measurement accuracy of the system.

1.3   Organization of the report

The national / international regulations, standards and documents used as basis for the present report are given in Chapter 2.

In Chapter 3 a brief overview of a typical turbine meter based fiscal oil metering station is given, as well as a list of the measurands and the terminology used in the different documents, including the present work. The functional relationships used in typical turbine meter based fiscal oil metering stations are given; both for single phase (oil) and two-phase (oil-water) flow. For two-phase flow, the functional relationships used with (a) sampling and laboratory analysis water treatment, and (b) continuous water fraction metering, to determine the water fraction, are both specified.

The influences of WIO contents on the different instruments of the fiscal metering station are discussed in Chapter 4. The operating conditions used in the calculations are given, and the effects of water on the flow mixture properties are outlined. Fundamental assumptions and limitations for the sensitivity study are discussed.

In Chapter 5 a sensitivity study is carried out with respect to the influence of WIO contents. An uncertainty model developed and used in the sensitivity study is described, accounting for the excess uncertainty contributions due to WIO contents. Calculations are given for the total uncertainty, due to WIO contents as well as other uncertainty contributions. Two scenarios are addressed with respect to water fraction determination: (a) sampling/laboratory analysis, and (b) water fraction metering.

A discussion of the results presented in Chapter 5 is given in Chapter 6.

Conclusions for the study are given in Chapter 7, and literature references at the end. In Appendix A a questionnaire sent to selected instrument makers is given, for reference.

1.4   Acknowledgements

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2   BASIS DOCUMENTS FOR THE STUDY

A number of national / international regulations, standards and basis documents have been used as a basis for the present work. The NPD "Regulations relating to measurement of petroleum for fiscal purposes and for calculation of CO_2 tax" [NPD, 2001] provides the basis for fiscal oil measurement at the Norwegian Continental Shelf, and also serves as the basis for other documents used in this region, such as the NORSOK Standard I-105 "Fiscal measurement systems for hydrocarbon liquid" [NORSOK, 2006].

Requirements for fiscal measurement systems for hydrocarbon liquid are described in I-105 [NORSOK, 2006][1], including determination of WIO contents.   Two different WIO determination scenarios are addressed: (a) systems using sampling and laboratory analysis to detect the water fraction, and (b) direct and continuous measurements using a water fraction meter (WFM). The calculation algorithm used with WFM as recommended by I-105, has been implemented and used for the calculations given in the present work.

Turbine meter measurements and the formulas for oil volume correction factors (VCF) are described in various API manuals for petroleum measurements [API, 1980, 1981, 1995]. These VCF formulas have been used for calculations in the present work. The formula for the accuracy of the Karl Fischer titration method for determination of the water in crude oil contents, is given in [API, 2002]. This expression is used in the present work.

In the NFOGM TM Handbook [Dahl et al, 2003], a turbine meter based fiscal metering station for pure oil (assuming no water contents) was addressed, including an uncertainty model (theoretical model and a calculation spreadsheet) and an uncertainty analysis example. In the present work the functional relationship for measurement of pure oil is taken from this document.

In the ISO 3171 standard [ISO, 1988], the requirements for automatic sampling and procedures to ensure that the sampling is satisfying such requirements, are described. For the calculations given in the present work, examples given in that standard are used.

In the "Handbook of water fraction metering" [Dahl et al, 2004], a discussion of oil-water flow regimes in vertical and horizontal lines are given, as well as a simplified formula for the calculations of critical (lower) velocity in flow lines. This simplified formula for the critical velocity in the calculations is used in the present work.

In ISO/DIS 12916 [ISO/DIS, 1995] and ISO 8222 [ISO, 2002], formulas of VCF for water and water density are given. These expressions are used in the calculations given in the present work.

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[1] The final version of I-105, Edition 3, was issued August 13, 2007

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3   TURBINE FISCAL OIL METERING STATION

The present chapter gives a description of a typical turbine meter based fiscal oil metering station, serving as a basis for the sensitivity analysis to analyze the influence of WIO contents on the accuracy of such a station. The measurands and terminology are presented, and the functional relationships used in the calculations are presented, for pure oil measurements and two-phase oil and water measurements, respectively.

3.1   Metering station instruments

A turbine meter consists of a turbine wheel rotating proportionally to the volumetric flow rate through the meter. By counting the number of revolutions the volumetric flow rate is determined. The turbine meter is normally flow calibrated *in situ*, using a prover and a known reference system. From this flow calibration, a K-factor ("meter factor") is determined, relating the rotation of the turbine wheel to a given liquid volume.

According to the NPD regulations [NPD, 2001], the pressure and temperature shall be measured in each of the metering tubes. The pressure and temperature shall also be measured at the inlet and outlet of the pipe prover. The density shall be measured in each of the metering pipes, or by two densitometers mounted at the inlet and the outlet of the metering station in such a manner that they provide representative density.

Pressure and temperature shall be measured as closely as possible to the densitometer. The densitometer is often mounted in a by-pass loop that is normally equipped with dedicated pressure and temperature transmitters for use with the density measurement. The complete set of density and dedicated temperature and pressure measurements then forms the basis for calculation of density at standard reference conditions (STP). In some cases, however, metering stations may not be equipped with dedicated pressure and/or temperature transmitters located close to the densitometer. This is normally based on an assumption of only small deviations between the conditions at the densitometer location (e.g. in a by-pass) and the meter run. One must then as an alternative use the line pressure and/or temperature measurements as estimations for the pressure and temperature at the densitometer location. The NORSOK I-105 standard [NORSOK, 2006] prescribes that the density shall be measured by the vibrating element technique. An example of a frequently used instrument of this type is the Solartron 7835 liquid densitometer [Solartron, 1994].

Automatic sampling equipment shall be installed [NORSOK, 2006]. For the determination of water content in oil, a WFM shall be considered as an alternative to automatic sampling and subsequent laboratory analysis. Sampling systems, however, may still be needed for other analyses such as density, salt, sediments etc.

If a WFM is used, the WFM instrument should be located as closely as possible to the fiscal measurement station. Alternatively the WFM may be installed in each meter run, downstream of the the primary measuring device. The WFM shall only be mounted in locations where there is a sufficiently well mixed flow-regime for the type of meter in use. The sampling system shall be designed in accordance with ISO 3171 [ISO, 1988]. Optionally the amendments and supplements to ISO 3171 as specified in Appendix E [NORSOK, 2006] shall be adhered to.

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3.2   Measurands and terminology

The standard reference conditions for pressure and temperature (STP) are 101.325 kPa and 15 $^{\circ}$C [NPD, 2001].

The measured quantities in a fiscal oil turbine metering station are:

- Pressure and temperature at the turbine meter (meter conditions),
- Pulses in the turbine meter during proving (proving conditions),
- Pressure and two temperatures at the prover (inlet & outlet),
- Pulses in the turbine meter (line conditions),
- Density in the densitometer (i.e. output pulses),
- Pressure and temperature at the densitometer,
- Water fraction measurement (sampling/analysis or online water fraction meter),
- Pressure and temperature at the water fraction measurement (this may be at line conditions, respectively laboratory conditions).

The terminology used in the API standards [API, 1980, 1981, 1995] and in the NFOGM TM Handbook [Dahl et al, 2003], differs from that used in the NORSOK I-105 standard [NORSOK, 2006]. In the present work the terminology used in [Dahl et al, 2003] will be used, with the necessary modifications and additions due to WIO contents. An overview of the terminology is given in Table 1.

Table 1.   Nomenclature for volume correction factors (VCF) and water fractions (ϕ) as used in API MPMS [API, 1980,1981,1995], NFOGM TM Handbook [Dahl et al, 2003], I-105 [NORSOK, 2006] and the present work. Cf. text for explanation of the various quantities.

	API MPMS Ch. 11 & 12, NFOGM Handbook (2003)			NORSOK I-105 (2006)			Present work			
Oil	C_{tlm}	C_{tlp}	C_{tld}	C_{tow}	C_{tol}	C_{tod}	C_{tow}	C_{tom}	C_{top}	C_{tod}
	C_{plm}	C_{plp}	C_{pld}	C_{pow}	C_{pol}	C_{pod}	C_{pow}	C_{pom}	C_{pop}	C_{pod}
Water	-			C_{tww}	C_{twl}	C_{twd}	C_{tww}	C_{twm}	C_{twp}	C_{twd}
	-			C_{pww}	C_{pwl}	C_{pwd}	C_{pww}	C_{pwm}	C_{pwp}	C_{pwd}
	-			W_{ref}	W_d	W_l	W_w	ϕ_{ref}	ϕ_d	ϕ_m	ϕ_w

The volume correction factors (VCF) terminology used in the API MPMS standards and the NFOGM TM Handbook is:

C_{tlm} VCF for the effect of temperature on the liquid in the turbine meter   [-]

C_{plm} VCF for the effect of pressure on the liquid in the turbine meter   [-]

C_{tlp} VCF for the effect of temperature on the liquid in the prover   [-]

C_{plp} VCF for the effect of pressure on the liquid in the prover   [-]

C_{tld} VCF for the effect of temperature on the liquid in the densitometer   [-]

C_{pld} VCF for the effect of pressure on the liquid in the densitometer   [-]

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The terminology for VCF and water fractions used in NORSOK I-105 is:

C_{tol} VCF for the effect of temperature on oil in the turbine meter   [-]

C_{pol} VCF for the effect of pressure on oil in the turbine meter   [-]

C_{twl} VCF for the effect of temperature on water in the turbine meter   [-]

C_{pwl} VCF for the effect of pressure on water in the turbine meter   [-]

C_{twd} VCF for the effect of temperature on water in the densitometer   [-]

C_{pwd} VCF for the effect of pressure on water at densitometer conditions   [-]

C_{tod} VCF for the effect of temperature on the oil at densitometer conditions   [-]

C_{pod} VCF for the effect of pressure on the oil at densitometer conditions   [-]

C_{tow} VCF for the effect of temperature on the oil at WIO measurement conditions   [-]

C_{pow} VCF for the effect of pressure on oil at WIO measurement conditions   [-]

C_{tww} VCF for the effect of temperature on water at WIO measurement conditions   [-]

C_{pww} VCF for the effect of pressure on water at WIO measurement conditions   [-]

W_{ref} Volumetric water fraction, at standard reference conditions   [-]

W_d Volumetric water fraction, at densitometer conditions   [-]

W_l Volumetric water fraction, at meter (line) conditions   [-]

W_w Volumetric water fraction, at WIO measurement conditions   [-]

The notation used in I-105 is followed in the present work, with two exceptions: (1) subscript m (meter) is used to denote turbine meter conditions, instead of the subscript l (line), and (2) the Greek symbol ϕ is used to denote water fraction, instead of W. This deviating terminology between I-105 and the present work is given below, together with the prover VCF terminology:

C_{tom} VCF for the effect of temperature on oil in the turbine meter   [-]

C_{pom} VCF for the effect of pressure on oil in the turbine meter   [-]

C_{twm} VCF for the effect of temperature on water in the turbine meter   [-]

C_{pwm} VCF for the effect of pressure on water in the turbine meter   [-]

C_{top} VCF for the effect of temperature on oil in the prover   [-]

C_{pop} VCF for the effect of pressure on oil in the prover   [-]

C_{twp} VCF for the effect of temperature on water in the prover   [-]

C_{pwp} VCF for the effect of pressure on water in the prover   [-]

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ϕ_{ref}	Volumetric water fraction, at standard reference conditions	[-]
ϕ_d	Volumetric water fraction, at densitometer conditions	[-]
ϕ_m	Volumetric water fraction, at meter conditions	[-]
ϕ_w	Volumetric water fraction, at WIO measurement conditions	[-]

3.3   Functional relationships

The functional relationships for turbine meter based fiscal metering stations used in the present work are described in the following, as a basis for the sensitivity study given in Chapter 5.

The functional relationship for pure (single phase) oil is given in Section 3.3.1, taken from the NFOGM TM Handbook [Dahl et al, 2003].

The functional relationship for metering situations with water present in the oil (two-phase flow) is given in Section 3.3.2, taken from the NORSOK I-105 standard [NORSOK, 2006].

3.3.1   Pure oil (single phase flow)

The basic equation for the turbine meter is given as [Dahl et al, 2003]

$$Q_V = \frac{MR_m}{K} \cdot \left[C_{tom} \cdot C_{pom} \cdot C_{tsm} \cdot C_{psm} \right]_{meter} \cdot 3600 , \tag{3.1}$$

where

Q_V	standard volumetric oil flow rate	[Sm^3/h]
MR_m	number of pulses counted by the turbine meter during the metering period	[1/s]
K	K-Factor	[1/m^3]
C_{tsm}	VCF for the effect of temperature on the turbine steel	[-]
C_{psm}	VCF for the effect of pressure on the turbine steel	[-]

The meter factor K is given as [Dahl et al, 2003]

$$K = \frac{MR_p}{BV} \cdot \left[\frac{(C_{tom} \cdot C_{pom}) \cdot (C_{tsm} \cdot C_{psm})}{(C_{top} \cdot C_{pop}) \cdot (C_{tsp} \cdot C_{psp})} \right]_{proving} , \tag{3.2}$$

where

MR_p	number of pulses counted by the turbine meter during the proving period	[-]
BV	base volume of the prover	[Sm^3]

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C_{tsp} VCF for the effect of temperature on the prover steel   [-]

C_{psp} VCF for the effect of pressure on the prover steel   [-]

In practice [Ref. group, 2006], the VCFs for the effect of temperature and pressure on the turbine steel are not used, and set to one. That is: $C_{tsm} = C_{psm} = 1$. The basic turbine meter equation (1.1) will then read

$$Q_V = \frac{MR_m}{K} \cdot \left[C_{tom} \cdot C_{pom} \right]_{meter} \cdot 3600 \,, \tag{3.3}$$

and the equation for the meter factor K simplifies to

$$K = \frac{MR_p}{BV} \cdot \left[\frac{C_{tom} \cdot C_{pom}}{C_{top} \cdot C_{pop} \cdot C_{tsp} \cdot C_{psp}} \right]_{proving} \,. \tag{3.4}$$

The volume correction factor (VCF) for the effect of temperature on pure oil is given as [Dahl et al, 2003]

$$C_{tox} = e^{-\alpha \cdot \Delta T - 0.8 \alpha^2 \cdot \Delta T^2}, \quad \alpha = \frac{K_0}{\left(\rho_{ref}^o \right)^2} + \frac{K_1}{\rho_{ref}^o}, \quad \Delta T = T - 15 \,, \tag{3.5}$$

where

ρ_{ref}^o oil density at standard reference conditions[2] (15 °C and 101.325 kPa),   [kg/Sm^3]

C_{tox} VCF for the effect of temperature on pure oil from condition x to std. ref. cond.,   [-]
          where the subscript x is short notation for m, p or d (denoting $meter$, $prover$ or
          $densitometer$ conditions, respectively),

α coefficient (calculated),   [1/°C]

K_0 constant,   [kg/m^3/°C]

K_1 constant,   [kg/m^3/°C]

ΔT difference between the actual temperature, T, and the std. ref. temperature   [°C]
          (15 °C),

T actual temperature in the turbine meter, the prover, or the densitometer,   [°C]
        depending on the subscript x in the correction factor C_{tox}.

The constants K_0 and K_1 are given in [API, 1980], or found in laboratory testing. For the calculations presented here, the values given in [API, 1980] for crude oil are used, as agreed on by the project reference group [Ref. group, 2006]. That is,

$K_0 = 613.97226,$ $K_1 = 0$.

The volume correction factor (VCF) for the effect of pressure on pure oil is given as [Dahl et al, 2003]

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[2] In the NORSOK I-105 standard, the notation $\rho_{ref-o-pure}$ is used to denote ρ_{ref}^o [NORSOK, 2006].

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$$C_{pox} = \frac{1}{1-(P-P_e)\cdot F}, \quad P_e \geq 0, \quad F = 10^{-6}\cdot e^{A+B\cdot T+10^6\cdot(\rho_{ref}^o)^{-2}\cdot(C+D\cdot T)}, \tag{3.6}$$

where

C_{pox}	VCF for the effect of pressure on pure oil from condition x to std. ref. cond., where the subscript x is short notation for m, p or d (denoting *meter*, *prover* or *densitometer* conditions, respectively),	[-]
P	actual pressure in the turbine meter, the prover, or the densitometer, depending on the subscript x in the correction factor C_{pox},	[kPa-a]
P_e	equilibrium vapour pressure,	[kPa-a]
F	compressibility factor for the liquid,	[1/kPa]
A	constant = -1.62080 [API, 1980]	[-]
B	constant = 0.00021592 [API, 1980]	[-]
C	constant = 0.87096 [API, 1980]	[-]
D	constant = 0.0042092 [API, 1980]	[-]

The volume correction factors (VCF) for the effects of temperature and pressure on the prover steel are given as [Dahl et al, 2003]

$$C_{tsp} = 1 + EM\,(T_{pa} - 15)$$

$$C_{psp} = 1 + \frac{P_{pa}\cdot DP}{EMP \cdot TP} \tag{3.7}$$

respectively, where

C_{tsp}	VCF for the effect of temperature on prover steel	[-]
EM	coefficient of cubical thermal expansion of prover steel	[1/°C]
T_{pa}	average of the two temperature measurements at the prover inlet and outlet	[°C]
C_{psp}	VCF for the effect of pressure on prover steel	[-]
P_{pa}	average of the two pressure measurements at the prover inlet and outlet	[bar-g]
DP	inner diameter of prover pipe	[m]
EMP	modulus of elasticity (or Young's modulus) of prover steel	[bar-g]
TP	wall thickness of prover pipe	[m]

Oil density at STP is calculated by [Dahl et al, 2003]

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$$\rho_{ref}^{o} = \frac{\rho_{d}^{o}}{C_{tod} \cdot C_{pod}} \tag{3.8}$$

where

ρ_{d}^{o} oil density at densitometer conditions.   [kg/m3]

Since the VCFs in Eq. (3.8), given by Eqs. (3.5) and (3.6) are functions of ρ_{ref}^{o}, ρ_{ref}^{o} must be calculated by numerical iteration.

3.3.2 Water in oil (two-phase flow)

The VCF for pure oil, C_{tox} and C_{pox}, are used as defined in Eqs. (3.5) and (3.6).

The VCF for the effect of pressure on the water phase is, after ISO/DIS 12916 [ISO,1995],

$$C_{pwx} = \frac{1}{1 - P \cdot F_w}, \quad F_w = \frac{1}{19690 + 141.8 \cdot T - 1.934 \cdot T^2 + 0.005866 \cdot T^3} \tag{3.10}$$

where

C_{pwx} VCF for the effect of pressure on water from condition x to STP,   [-]
where the subscript x is short notation for m, p or d (denoting $meter$, $prover$ or $densitometer$ conditions, respectively),

P actual pressure in the turbine meter, the prover, or the densitometer,   [kPa-g]
depending on the subscript x in the correction factor C_{pox},

The water density and VCF for the temperature effect on pure water is given by ISO 8222 [ISO, 2002]

$$\rho^{w} = 999.8395639 + 0.06798299989 \cdot T - 0.009106025564 \cdot T^2 +$$
$$1.005272999 \cdot 10^{-4} \cdot T^3 - 1.126713526 \cdot 10^{-6} \cdot T^4 + 6.5917956 \cdot 10^{-9} \cdot T^5 \tag{3.11}$$

$$C_{twx} = \frac{\rho^{w}(T)}{\rho^{w}(15)}. \tag{3.13}$$

where

C_{twx} VCF from actual pressure to standard reference pressure,   [-].
where the subscript x is short notation for m, p or d (denoting $meter$, $prover$ or $densitometer$ conditions, respectively).

According to ISO 8222, Eq. (3.11) can be used for temperatures between 1 to 100 ^{o}C.

A plot of the variation of the product of temperature and pressure volume correction factors (VCF) for crude oil (red) and water (green) is shown in Figure 1. The temperature is varied between 15 and 100 ^{o}C, the pressure from 10 to 90 bar-a. One can see that the sensitivity for the crude oil VCF to variations in pressure and temperature is larger than for the water VCF. Over the ranges in pressure

and temperature the variation in the oil VCF is 0.075, while the variation in the water VCF is 0.03. The VCF are also more sensitive to changes in temperature than to changes in pressure for both crude oil and water.
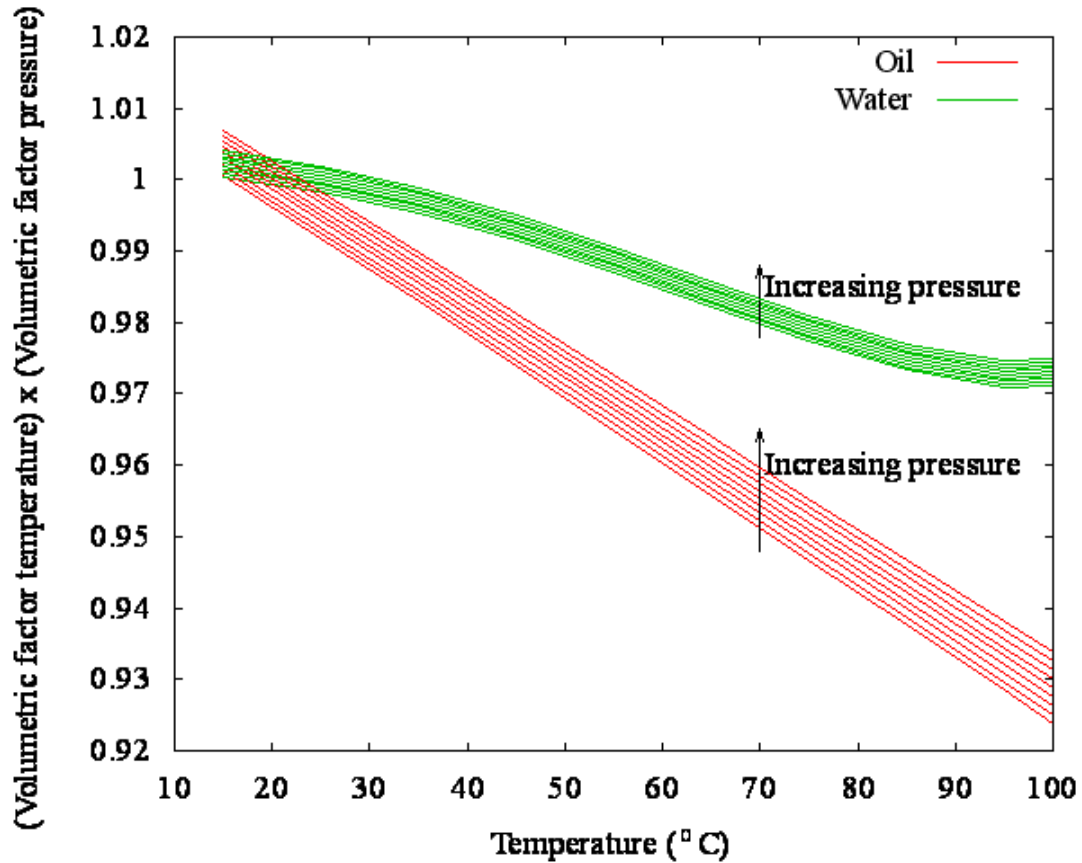

Figure 1.   Variation of the product of temperature and pressure volume correction factors (VCF) for crude oil (red) and water (green), as a function of (a) temperature (varied between 15 and 100 °C) and pressure (varied between 10 and 90 bar-a).

Case A: Sampling based WIO treatment

Consider the situation where the water fraction is determined by sampling and analysis. That is, the water fraction is found from samples taken at the specified flow rate during metering by separating oil and water in the laboratory. The density of pure oil can also be found in the laboratory. The quantities found in the laboratory at the prevailing pressure and temperature, must be transformed by use of the VCF for respectively water and oil to the values at STP and meter (line) conditions.

The industry practice [Ref. group, 2006] is to calculate the standard volumetric oil flow rate using the following functional relationship,

$$K = \frac{MR_p}{BV} \cdot \frac{C_{tom} \cdot C_{pom}}{C_{top} \cdot C_{pop} \cdot C_{tsp} \cdot C_{psp}}$$

$$q_V^{mix} = \frac{MR_m}{K} \cdot 3600$$

(3.14)

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$$\rho_m^{mix} = \frac{C_{tom} \cdot C_{pom}}{C_{tod} \cdot C_{pod}} \cdot \rho_d^{mix} \tag{3.15}$$

$$q_m^{net} = q_V^{mix} \cdot (1 - \phi_{mm}) \cdot \rho_m^{mix}$$

$$Q_V^{net} = \frac{q_m^{net}}{\rho_{ref}^o} \tag{3.16}$$

where

q_m^{net}	oil mass flow rate	[kg/h]
q_V^{mix}	volumetric flow rate of the oil-water mixture, at meter conditions	[m³/h]
Q_V^{net}	volumetric oil flow rate, at standard reference conditions (STP)	[Sm³/h]
ϕ_{mm}	mass water fraction, at meter conditions	[-]
ρ_d^{mix}	density of oil-water mixture, at densitometer conditions	[kg/m³]
ρ_m^{mix}	density of oil-water mixture, at meter conditions	[kg/m³]

Case B: Continuous measurement of WIO

Next, consider an alternative situation, for which the water fraction (WIO) is continuously measured using a water fraction meter (WFM). The pure oil density at STP can then be calculated from the WIO and densitometer measurements. The following equation is used [NORSOK, 2006]:

$$\rho_{ref}^o = \frac{(\rho_d^{mix} - \phi_d \cdot \rho_d^w) \cdot \dfrac{1}{1 - \phi_d}}{C_{tod} \cdot C_{pod}}, \tag{3.17}$$

where

ρ_d^w	water density, at densitometer conditions	[kg/m³]

The volumetric water fraction at densitometer conditions is calculated as

$$\phi_d \equiv \left(\frac{V_w}{V_w + V_o} \right)_d = \frac{1}{1 + \dfrac{(1 - \phi_{ref}) \cdot C_{twd} \cdot C_{pwd}}{\phi_{ref} \cdot C_{tod} \cdot C_{pod}}}, \tag{3.18}$$

where

V_w	partial volume containing water	[m³]
V_o	partial volume containing oil	[m³]

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The water fraction at standard reference conditions is calculated as

$$\phi_{ref} \equiv \left(\frac{V_w}{V_w + V_o} \right)_{ref} = \frac{1}{1 + \dfrac{(1 - \phi_w) \cdot C_{tow} \cdot C_{pow}}{\phi_w \cdot C_{tww} \cdot C_{pww}}} . \qquad (3.19)$$

The water fraction at meter condition follows the calculation of water fraction at densitometer conditions, by replacing the VCF for the densitometer with the VCF for the meter conditions, giving

$$\phi_m \equiv \left(\frac{V_w}{V_w + V_o} \right)_{meter} = \frac{1}{1 + \dfrac{(1 - \phi_{ref}) \cdot C_{twm} \cdot C_{pwm}}{\phi_{ref} \cdot C_{tom} \cdot C_{pom}}} . \qquad (3.20)$$

The volumetric flow rate of the oil-water mixture is given as

$$q_V^{mix} = 3600 \frac{MR_m}{K} . \qquad (3.21)$$

The net volumetric oil flow rate at meter conditions is given as

$$q_V^{net} = q_V^{mix} \cdot (1 - \phi_m) . \qquad (3.22)$$

The net volumetric oil flow rate at standard reference conditions is given as

$$Q_V^{net} = q_V^{net} \cdot C_{tom} \cdot C_{pom} . \qquad (3.23)$$

Since ρ_{ref}^o is used in the oil VCF, Eqs. (3.5) and (3.6), iteration is needed in the calculations between Eqs. (3.17), (3.18) and (3.19). The iterations process can stop when the difference between the old and new computed value of ρ_{ref}^o at two following iteration steps is less than $5 \cdot 10^{-6}$ [NORSOK, 2006].

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4   WATER-IN-OIL INFLUENCES

The present chapter addresses the influence of WIO on oil measurement. Results obtained on basis of a questionnaire sent to some instrument vendors on the influence of WIO on the various instruments in the turbine meter station are summarized in Section 4.1. Section 4.2 summarizes the operating conditions used in the sensitivity analysis calculations of Chapter 5. The influence of water on mixture properties such as fluid viscosity and density is discussed in Section 4.3. In Section 4.4 the fundamental assumptions underlying the sensitivity analysis with respect to flow conditions are discussed.

4.1   Influence of WIO on oil measurement

To collect information of the sensitivity to water in oil for the different types of instruments used in turbine meter based fiscal metering stations, a questionnaire (see Appendix A) has been sent to selected vendors. Regrettably, answers have been returned from only a minority of the vendors. Information was provided by one turbine meter vendor, FMC Smith Meters, and one densitometer vendor, Solartron Mobrey.

4.1.1   Turbine meter

FMC Smith Meters do not test their turbine meters with water in oil mixtures [FMC, 2007]. Instead they use a mixture of different oils in the test loop. In this way the oil viscosity can be varied significantly, from light up to heavy oil. As a consequence a large variation in Reynolds numbers (Re) can be investigated. FMC assume that WIO will influence the meter mainly through the Reynolds number due to the change in viscosity and density (see Figure 2). Other mechanism may also be possible. Conventional turbine meters are considered to be more sensitive to WIO than helical turbine meters. FMC claim that the meter linearity is within $\pm$ 0.15 % over a span in Reynolds numbers from 50000 to 500000. They also consider this to be true for WIO flow over the same range. The linearity will also be "reasonable" good down to about Re = 25000. For lower Reynolds numbers, modifications may be recommended for the turbine. This may involve adjustments of the blade angle, or modification of the tip clearance between the turbine and the pipe wall.

4.1.2   Densitometer

To the question of how the WIO influences the Solartron Mobrey 7835 Advanced Liquid Densitometer [Solartron, 1994], Solartron Mobrey responded as follows [Solartron, 2007]:

"The principle of operation of the 7835 is a vibrating tube. It is maintained at its natural frequency by the use of electromagnetic coils. The natural frequency changes as the density of the liquid inside the tube increases/decreases. Effectively, we are measuring the change in mass of the vibrating tube by detecting the change in its natural frequency.

As a consequence, any liquid inside the 7835 is going to be measured, be it homogeneous or non-homogeneous. Consequently we will measure the combined density of the water-in-oil mixture without any loss in density performance. Please note that it is not possible for the 7835 to distinguish between the oil and water densities."

To the question whether there is any upper limit of the densitometer with respect to the water cut, the answer was an explicit no.

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To the question of how the Solartron Mobrey 7835 Advanced Liquid Densitometer is affected by deviations from homogeneity, Solartron Mobrey gave the following answer [Solartron, 2007]:

"The recommended installation configuration for our 7835 densitometer is that it be mounted in vertical position, with flow coming from the bottom to the top. The reason for this is two fold. The first reason is that the 7835 is affected by air/gas bubbles. By installing the 7835 in a vertical plane, the bubbles with quickly pass through it thereby minimizing any error. The second reason is contamination from solids. If the 7835 is installed in a horizontal plane, and if the volumetric flow rate is too low, sediment could collect on the bottom of the vibrating tube. This will cause an error in density measurement. If the 7835 is in a vertical plane, the sediment will not collect on the vibrating tube.

The correct answer to the question is therefore probably is that we do not recommend that the 7835 be installed in a horizontal pipe. However if it is, there is no sediment in the liquid, and the sample flow rate is kept high, there will no effect on the performance of the 7835 if the water/oil mixture is homogeneous or non-homogeneous for the reasons given above."

4.2   Operating conditions

For the calculations presented in the present report, the flow and liquid data as given in Table 2 and Table 3 have been used. The data represent typical North Sea conditions, and have been agreed upon with the project reference group [Ref. group, 2006]. The field data from Fram Vest, Oseberg D, and Oseberg D have kindly been provided by Trond Folkestad, Norsk Hydro. It should be noted that the oil and water parameters given in Table 2 do not correspond directly to the oil and water parameters from the fields referred to in Table 3.

Table 2.   Physical parameters used in the sensitivity study calculations.

Oil density	830 kg/m^3 @ 15 ^{o}C, 1 atm
Oil viscosity	6 cS @ 40 ^{o}C
Water density	1020 kg/m^3 @ 15 ^{o}C, 1 atm
Inner diameter of pipeline, *D*	8 "
Maximum volumetric flow rate	1200 m^3/h @ 15 ^{o}C, 1 atm
Operating volumetric flow rate	1000 m^3/h @ 15 ^{o}C, 1 atm
Water fraction	0-20 % (by volume)
Prove volume	7 m^3
Inner diameter of prover, *DP*	20"

Table 3.   Meter, densitometer, prover and WFM conditions used in the sensitivity study calculations.

	Fram Vest	Oseberg D	Oseberg A	TM Handbook 2003
Meter (line) conditions				
Pressure (bar)	24.44	42.66	22.29	18
Temperature (^{o}C)	36.70	41.01	48.86	65
Densitometer conditions				
Pressure (bar)	24.66	43.12	17.76	17.5
Temperature (^{o}C)	36.60	38.68	48.93	63
Prover (average over inlet and outlet)				
Pressure (bar)		1 bar less than meter conditions		
Temperature (^{o}C)		1 ^{o}C less than meter conditions		
WFM-meter				
Pressure (bar)		As meter conditions		
Temperature (^{o}C)		As meter conditions		

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The difference between line and prover conditions is typically not larger than 1 bar and 1 ^{o}C [Ref. group, 2006]. In the calculations this offset is used. It is assumed that pressure and temperature are higher at the turbine meter than at the prover. The temperature and pressure at the WFM is set, when relevant, equal to the values at the meter (line) conditions.

4.3   Fluid properties

Water in oil will have an effect on the mixture flow velocity. When the water is dispersed as drops in the oil, the mixture will become effectively "stiffer". Ishii and Zuber [Ishii et al,1979] give a correlation for the mixture viscosity based on experimental data for different liquids and gases,

$$\mu^{mix} = \mu_c \cdot \left(1 - \phi\right)^{-2.5 \cdot \left(\mu_p + 0.4 \cdot \mu_c\right)/\left(\mu_P + \mu_c\right)} ,$$

where μ^{mix} is the effective mixture viscosity, μ_c the continuous (oil) phase viscosity, μ_p the particulate (water) viscosity and ϕ the volumetric water fraction.

For the value of the fluid properties used in Table 2, the effective mixture viscosity is shown in Figure 2 as a function of water fraction. According to this model, the mixture viscosity rises 30 % when the water fraction increases from 0 to 20 %.
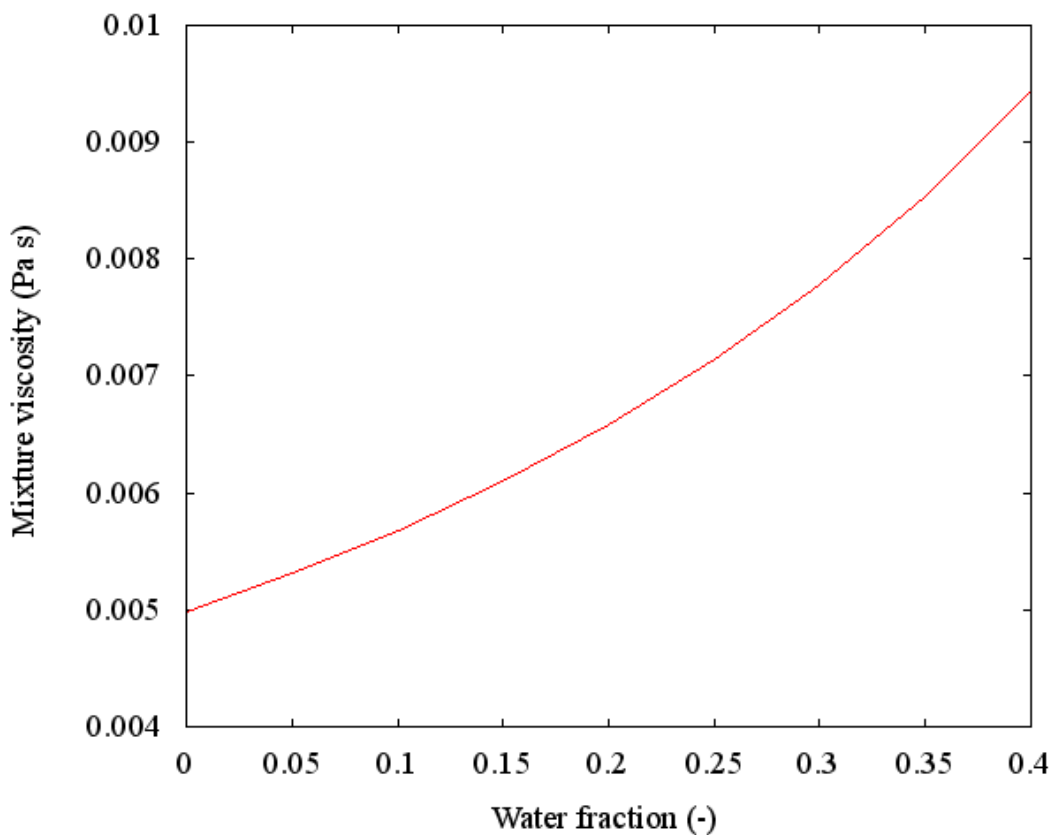

Figure 2.   Calculated mixture viscosity for water in oil, shown as a function of water fraction. The calculations are based on the formula given by [Ishii et al, 1979] and the fluid properties are given in Table 2.

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The increased mixture viscosity may have an effect on the turbine meter performance (see Section 4.2.1). The liquid mixture density will increase with water fraction,

$$\rho^{mix} = \rho^{o} \cdot (1 - \phi) + \rho^{w} \cdot \phi \ . \tag{4.1}$$

giving the pipe Reynolds number,

$$\mathrm{Re} = \rho^{mix} \cdot D \cdot U^{mix} / \mu^{mix} \ , \tag{4.2}$$

where U^{mix} is the average liquid mixture velocity. A plot of the Reynolds number based on the operating conditions given in Table 2 is shown in Figure 3. For this case the Reynolds number will vary between 230000 and 290000 for water fractions in the range 0 - 20 %.
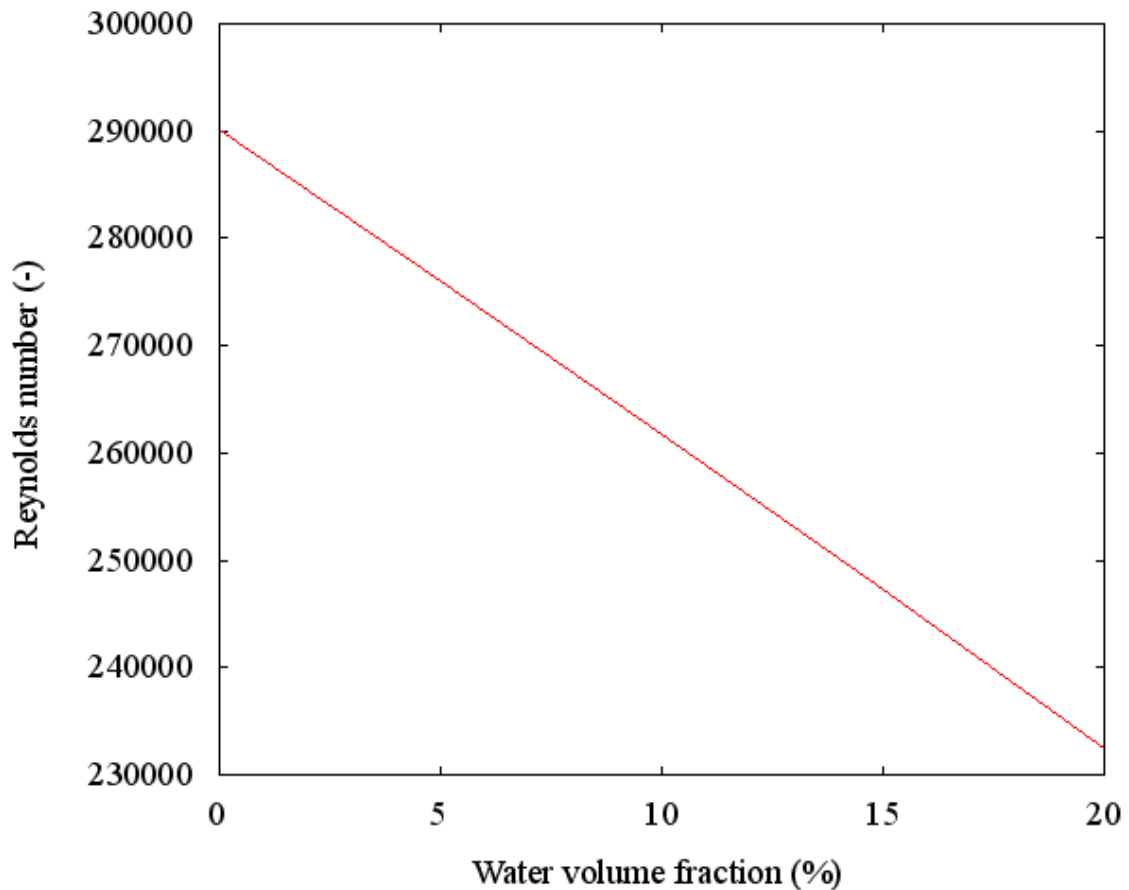

Figure 3.   *Calculated Reynolds number for the oil-water flow, shown as a function of water fraction, using the mixture density and the mixture viscosity. The flow data and pipe dimension are given in Table 2.*

4.4   Assumptions and limitations for the sensitivity study

Two fundamental assumptions are made for the sensitivity study.

The first assumption is that free gas is not present in the flow; neither as a separated phase nor as small bubbles dispersed in the liquid.

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The second assumption is that water, when present, is dispersed homogeneously in the oil phase. By homogeneously we here mean that the variation in water concentration is less than $\pm 5\%$ of the average water concentration over the pipe cross section [ISO, 1988].

The accuracy of the last assumption will depend on both fluid and flow properties. In the NFOGM "Handbook of water fraction metering" [Dahl et al, 2004], an equation is given which relates a critical flow velocity, V_C, to the fluid properties in a horizontal pipe. V_C represents a lower bound for the flow velocity in the pipe; below this critical velocity the two-phase mixture starts to separate due to gravity. The formula is based on the ISO 3171 standard [ISO, 1988], and V_C is given as

$$V_C = K \cdot G^{0.325} \cdot \sigma_{ow}^{0.39} \cdot \frac{\left(\rho^w - \rho^o\right)^{0.325}}{\rho^{0.283}} \cdot \frac{D^{0.366}}{\mu_o^{0.431}},$$

$$\phi < 10 - 15\%,$$

(4.3)

where

V_C	Critical (minimum) velocity for maintaining a dispersion of degree G	m/s
K	Constant = 2.02	-
G	Parameter defining the degree of dispersion	-
σ_{ow}	Interfacial (surface) tension between oil and water	N/m
D	Inner diameter of pipe	M
μ_o	Oil viscosity	Pa-s

The parameter G indicates the degree of dispersion. $G = 10$ corresponds to a ratio of 0.9 between the water concentration at the top to the water concentration at the bottom in the horizontal pipe. The dispersion will become perfectly homogeneous as G increases towards infinity. A ratio of 0.4 or smaller indicates poor dispersion with a high potential for water stratification.

The necessary mixing to avoid separation is provided by fluid turbulence. The formula, Eq. (4.3), is based on simplified semi-empirical correlations, and should be used with care.

For the parameter values used in this work (see Table 2), and with $G = 10$ and the oil-water surface tension σ_{ow} set to 0.025 N/m, the critical velocity V_C becomes 4.5 m/s. An operating volumetric flow rate of 1000 m³/h corresponds to a velocity of 8.5 m/s in a pipe with D equal to 8". For water volume fraction below 10% a water-in-oil dispersion should thus be maintainable, for water fractions in the range 10% to 20 %, mixing devices at suitable locations upstream of the measurement station is in any case necessary to meet the requirement of homogeneous flow. The distance between mixer and turbine meter should be as short as possible.

With the prover volume and D as given in Table 2, the average flow velocity in the prover is 1.4 m/s at the operating flow rate, and the critical velocity is 6.4 m/s. Using Eq. (4.3) for the prover may not be relevant due to the valves and short pipe distances between the turbine meter and the prover body. Among other factors, turbulence is also produced in the valves upstream of the prover. The low flow velocity in the prover still indicates that some separation between oil and water may take place during proving. The liquid residence time in the prover is 25 s, based on prover volume and operating flow rate for one run of the prove ball. The degree of stratification during this time interval will obviously depend on how the water is mixed in the inlet to the prover. At least for the high water fractions, 10-20 %, it is reasonable to assume that the mixture in the prover is on average less homogeneous than in the turbine meter. Whether this will have an influence on the accuracy of the proving is not known.

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5   SENSITIVITY STUDY

In the present chapter a sensitivity analysis for the excess measurement uncertainty due to effects of water in oil (WIO) is carried out. Possible systematic errors from the use of the equations are investigated, and the sensitivity of parameters in the formulas is addressed. Both sampling based WIO treatment as well as water fraction treatment using a water fraction meter (WFM) are covered.

5.1   Overall uncertainty model

Under certain assumptions, the standard uncertainty of a variable X_i in the functional relationship for the volumetric oil flow rate at standard reference conditions can be written as

$$u(X_i)^2 = u(X_i^{pure\ oil})^2 + u(X_i^{water\ impact})^2,$$
(5.1)

where $u(X_i)$ is the standard uncertainty of the variable X_i, and the superscripts *pure oil* and *water impact* refer to the measurement with pure oil and the excess effect of WIO, respectively. The fundamental assumption in setting up Eq. (5.1), is that the influence of WIO on the volumetric oil flow rate measurement is uncorrelated with the measurement uncertainty of the pure oil volume.

The total relative standard uncertainty of Q_V^{net} can then be written as

$$\left(\frac{u(Q_V^{net})}{Q_V^{net}}\right)^2 = \sum_{i=1}^{N}\left[\left(S_{x_i}^{pure\ oil} \cdot \frac{u(X_i^{pure\ oil})}{X_i^{pure\ oil}}\right)^2 + \left(S_{x_i}^{water\ impact} \cdot \frac{u(X_i^{water\ impact})}{X_i^{water\ impact}}\right)^2\right]$$
(5.2)

where *N* is the number of variables in the functional relationship for Q_V^{net}, and S_i is a relative sensitivity coefficient.

Eq. (5.2) is in the following written as

$$\left(\frac{u(Q_v^{net})}{Q_v^{net}}\right)^2 = \left(\frac{u(Q_v^{net,pure\ oil})}{Q_v^{net}}\right)^2 + \left(\frac{u(Q_v^{net,water\ impact})}{Q_v^{net}}\right)^2.$$
(5.3)

The first term on the right hand side of Eq (5.3) is the relative standard uncertainty of the pure oil volumetric flow rate measurement. This term is covered by the NFOGM TM Handbook [Dahl et al, 2003], and will not be further discussed here.

For simplicity, and as a tentative typical value for the sensitivity analysis, the relative expanded uncertainty of the pure oil volumetric flow rate measurement (at 95 % confidence level) is in the following taken to be 0.25 %, as an example. This example value may represent a typical uncertainty value for a turbine meter based fiscal oil metering station with pure oil and no water.   The corresponding relative standard uncertainty used in the sensitivity study calculations is thus

$$\left(\frac{u(Q_v^{net,pure\ oil})}{Q_v^{net}}\right) = \frac{0.25}{2}\% = 0.125\%.$$
(5.4)

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The second term on the right hand side of Eq (5.3) is the standard uncertainty associated with water in oil. This is the term addressed in the following.

5.2   Case A: Sampling based WIO treatment

The present section gives the sensitivity analysis of the volumetric oil flow rate measurement, for metering stations where WIO is measured using the sampling and laboratory analysis approach.

The functional relationship for the sampling based WIO treatment is given by Eqs. (3.14), (3.15) and (3.16). An uncertainty model for the sampling based method can then be given as

$$
\left(\frac{u(Q_v^{net,waterimpact})}{Q_v^{net}}\right)^2 = \left(\frac{u(MR_m)}{MR_m}\right)^2 + \left(\frac{u(K_{MRp})}{K}\right)^2 + \left(\frac{u(K_{BV})}{K}\right)^2
$$

$$
+ \left(\frac{u(K_{corr})}{K}\right)^2 + \left(\frac{u\left(\dfrac{C_{tom}C_{pom}}{C_{tod}C_{pod}}\right)}{\dfrac{C_{tom}C_{pom}}{C_{tod}C_{pod}}}\right)^2
$$

$$
+ \left(\frac{u(\rho_d^{mix})}{\rho_d^{mix}}\right)^2 + \left(\frac{\phi_{mm}}{1-\phi_{mm}}\right)^2 \cdot \left(\frac{u(\phi_{mm})}{\phi_{mm}}\right)^2 + \left(\frac{u(\rho_{ref}^o)}{\rho_{ref}^o}\right)^2
$$

(5.5)

Eq. (5.5) is formed by considering the terms where the WIO can have an impact, and expanding the total equation through the procedure given in GUM [ISO, 1995], see also ISO 5168 [ISO, 2005]. The excess uncertainty due to WIO can be found in the following variables

- pulses count and in the meter coefficient in the turbine equation,
- basic volume in proving,
- conversion factors from prover to turbine in the determination of the meter coefficient,
- conversion factors from densitometer to turbine,
- measurement of mixture density,
- sampling and analysis of water fraction,
- laboratory determination of oil density at reference conditions.

 The different terms in Eq. (5.5) are discussed and evaluated in the following.

5.2.1 Excess uncertainty due to the turbine meter

The uncertainty contributions to Eq. (5.5) due to WIO effects in the turbine meter are addressed in the following. The relevant terms in this context are the two variances

$$
\left(\frac{u(K_{MRp})}{K}\right)^2 \text{ and } \left(\frac{u(MR_m)}{MR_m}\right)^2,
$$

which represent the relative standard uncertainties associated with the pulse count per volume in the turbine meter, for proving and metering situations, respectively.

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Based on the information given by FMC [FMC, 2007], FMC turbine meters are claimed to have a linearity of ± 0.15% in the Reynolds number range 50,000 to 500,000. We assume in the following that water will influence the turbine meter only through changes in mixture density and mixture viscosity, i.e. through the Reynolds number only, as discussed in Section 4.3. For the flow conditions used in the calculations (given in Table 2), the Reynolds number will vary between 230,000 and 290,000 when the water fraction varies from 0 to 20 %. This is well within the Reynolds range where the linearity of the FMC meter is claimed to be ± 0.15 % [FMC, 2007].

Information from other turbine meter vendors has not been received. It is in the following assumed that the relative uncertainty due to water in the turbine meter is typically less than 0.15 % at a 95 % confidence level, for a water fraction of 20 %. The corresponding relative standard uncertainties used in the sensitivity analysis calculations then become

$$\left(\frac{u(K_{MRp})}{K}\right) = \frac{0.15}{2}\% = 0.075\%; \qquad \left(\frac{u(MR_m)}{MR_m}\right) = \frac{0.15}{2}\% = 0.075\% . \qquad (5.6)$$

For other water fractions, a linear dependency of the relative standard uncertainty with respect to water fractions is assumed and used.

5.2.2 Excess uncertainty due to the prover

The uncertainty contributions to Eq. (5.5) due to WIO effects in the prover are addressed in the following. The relevant term in this context is the variance

$$\left(\frac{u(K_{BV})}{K}\right)^2,$$

which represents the relative standard uncertainty of the prover base volume measurement due to WIO contents. Information provided by the project reference group [Ref. group, 2006] indicates that this uncertainty term may be relatively small. No response to the questionnaire has been received from the prover vendor, however.

For the purpose of the sensitivity analysis, and in order not to underestimate the uncertainty contribution, it is in the following assumed that the relative uncertainty contribution is 0.1 % for a water fraction of 20 %, at a 100 % confidence level and a rectangular probability distribution. The corresponding relative standard uncertainty used in the sensitivity analysis calculations then becomes

$$\left(\frac{u(K_{BV})}{K}\right) = \frac{0.1}{\sqrt{3}}\% \approx 0.06\% \qquad (5.7)$$

For other water fractions, a linear dependency of the relative standard uncertainty with respect to water fractions is assumed and used.

5.2.3 Excess uncertainty due to volume conversion from prover to meter conditions

The uncertainty contributions to Eq. (5.5) due to WIO effects in the volume conversion from prover to metering conditions, are addressed in the following. The relevant term in this context is the variance

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$$\left(\frac{u(K_{corr})}{K}\right)^2,$$

which represents the relative standard uncertainty due to the use of the pure oil volume correction factor (VCF) also when water is present in the oil.

In I-105 [NORSOK, 2006] no expression for the calculation of the meter factor K for an oil-water mixture by proving is given. Instead it is recommended to use the correction factors for pure oil, i.e. Eq (3.14).

If water fraction was accounted for in the meter factor K, the equation would read

$$K = \frac{MR_p}{BV} \cdot \left[\frac{C_{tom} \cdot C_{pom} \cdot (1-\phi_m) + C_{twm} \cdot C_{pwm} \cdot \phi_m}{\left\{C_{top} \cdot C_{pop} \cdot (1-\phi_p) + C_{twp} \cdot C_{pwp} \cdot \phi_p\right\} \cdot C_{tsp} \cdot C_{psp}}\right]_{proving}. \tag{5.8}$$

An example of the relative difference, $\left(K_{water-in-oil} - K_{pure-oil}\right)/K_{pure-oil}$, between the full formula, Eq. (5.8), and the formula for the meter factor for pure oil, Eq. (3.14), is shown in Figure 4. The difference is small, less than 0.01% for 20 % water fraction. The main reason for this is that pressure and temperature in the prover and in the meter usually are close, in the example set to 1 ^{o}C and 1 bar. The ratio of the VCF in the prover and in the meter will then be close to one, either with or without water in the meter formula. In Figure 5 the relative difference is shown when the mixture density is used in Eq (3.14) in the calculation of the oil VCF. The error is now reduced, and less than 0.0035 % at a water fraction of 20 %.

We can thus conclude that for 20 % water fraction the excess relative uncertainty is less than 0.01 % at 100 % confidence level and a rectangular probability distribution. The relative standard uncertainty used in the sensitivity analysis calculations then becomes

$$\left(\frac{u(K_{corr})}{K}\right) = \frac{0.01}{\sqrt{3}}\% \approx 0.006\% \tag{5.9}$$

For other water fractions, a linear dependency of the relative standard uncertainty with respect to water fractions is assumed and used.

5.2.4 Excess uncertainty due to volume correction from densitometer to meter conditions

The uncertainty contributions to Eq. (5.5) due to WIO effects in the volume correction from densitometer to metering conditions are addressed in the following. The relevant term in this context is the variance

$$\left(\frac{u\left(\frac{C_{tom}C_{pom}}{C_{tod}C_{pod}}\right)}{\frac{C_{tom}C_{pom}}{C_{tod}C_{pod}}}\right)^2,$$

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which represents the relative standard uncertainty due to the use of pure oil correction factors in the volume correction (VCF) from densitometer to turbine meter conditions, when water is present. According to the project reference group, use of pure oil VCF is industry practice today [Ref. group, 2006], with a density transformation factor given as

$$\rho_m^{mix} = \rho_d^{mix} \cdot \frac{C_{tom} \cdot C_{pom}}{C_{tod} \cdot C_{pod}} \ . \tag{5.10}$$

A transformation factor from densitometer to meter conditions where water *is* taken into account, can be written by using the identity

$$\rho_m^{mix} = \rho_d^{mix} \cdot \frac{\rho_m^{mix}}{\rho_d^{mix}} \ , \tag{5.11}$$

where

$$\rho_d^{mix} = \rho_d^o \cdot \left(1 - \phi_d\right) + \rho_d^w \cdot \phi_d$$
$$\rho_m^{mix} = \rho_m^o \cdot \left(1 - \phi_m\right) + \rho_m^w \cdot \phi_m \tag{5.12}$$

The relative difference between the transformation factors given by Eqs. (5.10) and (5.11) is shown in Figure 6 when the pure oil density is used for the oil VCF in Eq. (5.10), and in Figure 7 when the mixture oil density is used for the oil VCF in Eq. (5.10).

These calculations indicate that at a water fraction of 20 %, the excess relative uncertainty is less than 0.04 %, at 100 % confidence level with a rectangular distribution function. The relative standard uncertainty used in the sensitivity analysis calculations is thus taken as

$$\left(\frac{u\left(\dfrac{C_{tom} C_{pom}}{C_{tod} C_{pod}}\right)}{\dfrac{C_{tom} C_{pom}}{C_{tod} C_{pod}}} \right) = \frac{0.04}{\sqrt{3}} \% \approx 0.02\% \ . \tag{5.13}$$

For other water fractions, a linear dependency of the relative standard uncertainty with respect to water fraction is assumed and used.

5.2.5 Excess uncertainty due to the mixture density

The uncertainty contributions to Eq. (5.5) due to WIO effects on the mixture density are addressed in the following. The relevant term in this context is the variance

$$\left(\frac{u(\rho_d^{mix})}{\rho_d^{mix}} \right)^2 ,$$

which represents the relative standard uncertainty due to WIO effects on the density measurement when water is present. In response to the questionnaire, Solartron Mobrey very explicitly stated that there is not expected to be an excess contribution to the density measurement uncertainty from WIO contents, see Section 4.1.2. This was stated to be regardless of mixture homogeneity or water volume fraction.

In the sensitivity analysis calculations, the relative standard uncertainty for the measurement of mixture density is thus set to zero,

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$$\left(\frac{u(\rho_d^{mix})}{\rho_d^{mix}}\right) = 0\% \ .$$ (5.14)

5.2.6 Excess uncertainty due to the water fraction sampling and analysis

The uncertainty contributions to Eq. (5.5) due to WIO effects on water fraction measurement using sampling and analysis, are addressed in the following. The relevant term in this context is the variance

$$\left(\frac{u(\phi_{mm})}{\phi_{mm}}\right)^2 ,$$

which represents the relative standard uncertainty of the sampling/analysis - based water fraction determination at meter conditions.

For water fractions up to 5 % the standard laboratory test method is coulometric Karl Fischer titration.

For water fractions above 5 % other methods with higher uncertainty (i.e. the centrifuge method) is used [Ref. group, 2007]. A detailed study of these methods is not carried out here, but the work is based on API MPMS [API, 2002] for the Karl Fischer method, and ISO 3171 [ISO, 1988] for other methods. For the uncertainty connected with the sampling operation, results given in [ISO, 1988] are used here.

In industrial practice, the procedures used may deviate from the examples used in ISO 3171. The uncertainty estimates should then be adjusted for the actual case.

A water fraction uncertainty analysis is given in ISO 3171. In section 16 of that document, a formula for the estimation of the overall uncertainty of the sampling system is given as

$$U(\phi) = \frac{1}{N} + \phi \cdot (S + L) + 2\sqrt{\frac{1}{N}\left(0.012 + \sqrt{\phi R}\right)^2 + \phi^2 \cdot \left(\frac{h_t^2}{4} + P\right)}$$

$$S = a_s + b_s + h_s$$

$$R = \frac{1}{4} \cdot \left(a_t^2 + b_t^2 + c_t^2 + d_t^2\right)$$ (5.15)

$$L = f_s + g_s$$

$$P = \frac{1}{4} \cdot \left(f_t^2 + \frac{g_t^2}{n}\right)$$

where ϕ is the volumetric water fraction, $U(\phi)$ is the combined uncertainty associated with random and systematic errors in ϕ (95 % confidence level), n is the number of laboratory analyses, and N is the number of samples. The subscript s refers to relative systematic uncertainties, and subscript t refers to relative random uncertainties. The factor a refers to non-homogeneity of the water content, b to changes in the water content caused by the sampling system (non-isokinetic), d to uncertainty in the volume of each grab, c to uncertainty in the flow rate caused by flow meter (variations in meter factor), h to changes in water content during sampling (contamination or water vapour loss), f to changes in water content caused by sample handling and mixing (poor homogenization in laboratory) and g to

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changes in water content caused by transfer to laboratory glassware and analysis (centrifuge tube error).

Typical values for the factors in Eq.(5.15), taken from normal industry practices [ISO, 1988] are given in Table 4.

Table 4.   Parameters in Eq. (5.15) for the sampling system uncertainty. The data values are taken from Examples 1-3, ISO 3171, Section 16.5.1-3. Subscripts s and t denote systematic and random uncertainties, respectively.

Parameter	Description	Relative uncertainty		
		Ex. 1	Ex. 2	Ex. 3
a_s	Non-homogenity of water content in pipe	1 %	1 %	1 %
a_t		5 %	5 %	5 %
b_s	Changes in water content by sampling system (non-isokinetic)	1 %	1 %	1 %
b_t		2 %	4 %	2 %
c_s	Uncertainty of flow rate (variations in meter factor)	10 %	10 %	10 %
c_t		2 %	4 %	1 %
d_s	Uncertainty of sample volume	10 %	10 %	10 %
d_t		10 %	10 %	5 %
h_s	Changes in water content during sampling (water evaporation)	2 %	1 %	1 %
h_t		2 %	1 %	1 %
f_s	Changes in water homogenization in laboratory (poor homogenization)	1 %	0.5 %	0.5 %
f_t		1 %	1 %	1 %
g_s	Changes in water content by transfer to laboratory glassware and analysis	1 %	0.5 %	0.5 %
g_t		8 %	4 %	4 %
N	Number of samples	10000	20000	1000
n	Number of analyses	2	2	2

The reproducibility of the Karl Fischer method at 95 % confidence level is given as [API, 2002]

$$U(\phi_{mass}) = 0.105 \cdot \phi_{mass}^{2/3} . \tag{5.16}$$

ϕ_{mass} is here the water mass fraction. In the sensitivity analysis calculations, Eq. (5.16) is used for water fractions below 5 %. For the uncertainty due to sampling/analysis, Eq. (5.15) is used, but with the factors *f* and *g* as described in Table 4 set to zero. The sampling and analysis uncertainties are independent, and the combined uncertainty can be calculated by the "standard" approach ($u^2 = u_{sampling}^2 + u_{analysis}^2$).

For water fractions above 5 %, Eq. (5.15) is used with the factors *f* and *g* as given in Table 4.

In the following calculations, the result from Example 1 is used, which provides the largest uncertainty and represents the most conservative approach. The resulting uncertainty contribution is shown in Figure 8. The uncertainty drops significantly at a water fraction of 5 % and below, due to the use of the Karl Fischer method.

In the calculations it is also assumed that the uncertainty for water volume fraction is approximately equal to the uncertainty for water mass fraction.

At a volumetric water fraction of 20 %, the calculated relative expanded uncertainty of the volumetric water fraction is 2.42 % (2.93 % in mass fraction). The relative standard uncertainty at 20 % volumetric water fraction (23.5 % water mass fraction) is then taken to be

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$$\left(\frac{u(\phi_{mm})}{\phi_{mm}}\right) = \frac{100 \cdot 2.93}{23.5} \cdot \frac{1}{2}\% \approx 6.2\% \tag{5.17}$$

At a water mass fraction of 5 %, with Karl Fischer titration, the relative standard uncertainty is taken to be

$$\left(\frac{u(\phi_{mm})}{\phi_{mm}}\right) = \frac{100 \cdot 0.31}{5} \cdot \frac{1}{2}\% = 3.1\% \tag{5.18}$$

As seen from Figure 8, the uncertainty for Example 1 can be approximated by two straight lines. The relative standard uncertainty will then be given by two constants, one for each line. Between 5 and 20 % water fraction, the constant value for the standard relative uncertainty is taken from Eq. (5.17), between 0 and 5 % water fraction the constant value for the standard relative uncertainty is taken from Eq (5.18).

5.2.7 Excess uncertainty due to oil density at standard reference conditions

The uncertainty contributions to Eq. (5.5) due to WIO effects on the determination of oil density at standard reference conditions are addressed in the following. The relevant term in this context is the variance

$$\left(\frac{u(\rho_{ref}^{o})}{\rho_{ref}^{o}}\right)^2 ,$$

which represents the relative standard uncertainty due to possible influence of water in the sampling and laboratory analysis. If complete separation between oil and water in the laboratory is assumed, the influence from water on the pure oil density can be neglected. This term is in the following set to zero,

$$\left(\frac{u(\rho_{ref}^{o})}{\rho_{ref}^{o}}\right) = 0\% \tag{5.19}$$

5.2.8 Uncertainty calculation example for the volumetric oil flow rate due to WIO

The uncertainty contributions from the different terms in Eq. (5.5) as discussed above are given in Table 5, for a water fraction of 20 %. The uncertainty from the water fraction sampling and analysis is by far the dominant term. The second largest term is the influence of WIO on the uncertainty of the prover volume.

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Table 5.   Calculation example for the relative combined uncertainty of the volumetric oil flow rate due to WIO contents, at 20 % water fraction. In the estimation of the uncertainty of the water fraction determination due to the sampling and analysis method, the first example in ISO 3171, Section 16.5.1, is used.

Source	Input uncertainty	Relative combined uncertainty	
	Relative standard uncertainty (%)	Relative sensitivity coefficient (-)	Contribution to relative combined uncertainty (%)
Pure oil uncertainty	0.125	1	0.125
K-factor, turbine proving	0.075	1	0.075
K-factor, turbine metering	0.075	1	0.075
K-factor, prover volume	0.06	1	0.06
K-factor, VCF	0.006	1	0.006
VCF, densitometer to meter	0.02	1	0.02
Mixture density measurement	0	1	0
Water fraction	6.2	0.3	1.86
Reference oil density	0	1	0
Relative combined standard uncertainty			1.9
Relative expanded uncertainty (95 % c.l., coverage factor = 2)			3.8

A plot of the relative expanded uncertainty of the volumetric oil flow rate due to WIO as a function of water fraction is shown in Figure 9. Bar charts showing the individual contributions to the relative expanded uncertainty for 2 %, 10 % and 20 % WIO are shown in Figure 10, Figure 11 and Figure 12, respectively.
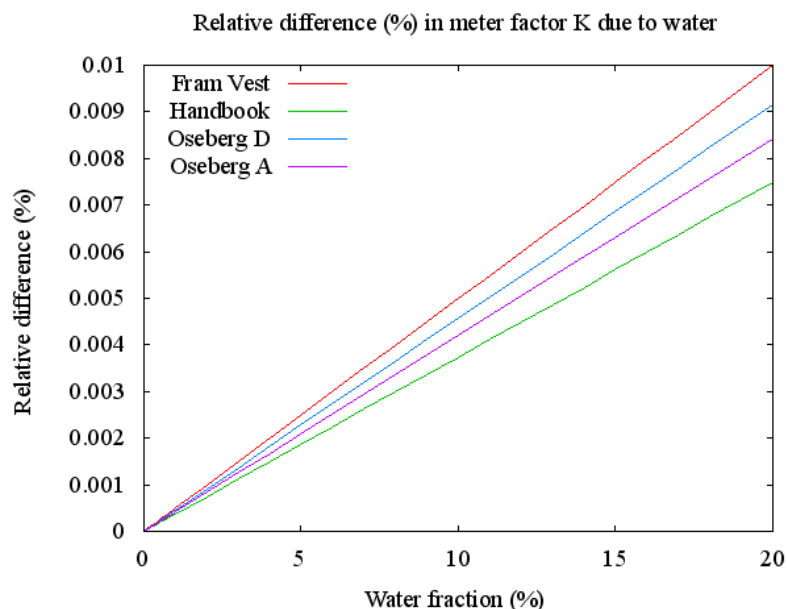

Figure 4.   Relative differences, $\left(K_{water-in-oil} - K_{pure-oil} \right) / K_{pure-oil}$ *, between a calculation using the VCF for both oil and water, and a calculation using only the VCF for pure oil. The pressures and temperatures used in the calculations are given in Table 3.*
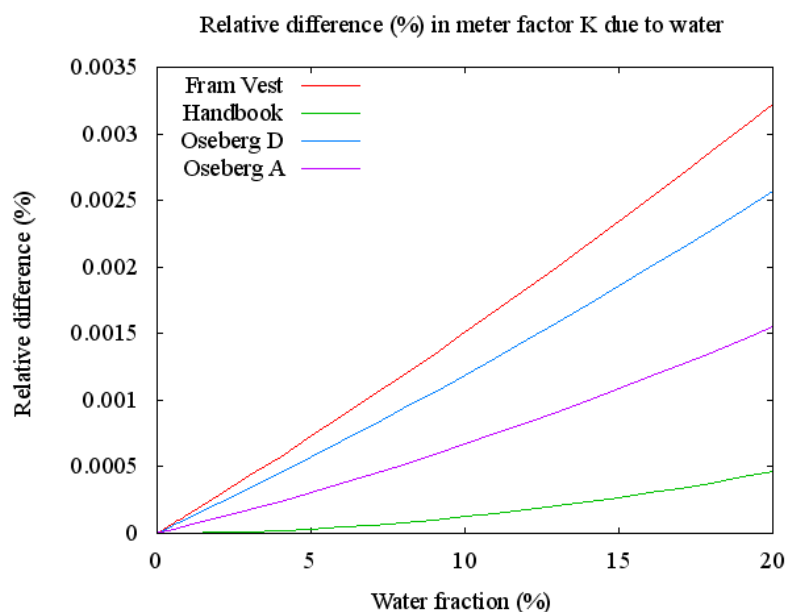
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Figure 5.   Relative differences, $\left(K_{water-in-oil} - K_{pure-oil} \right)/ K_{pure-oil}$, between a calculation using the VCF for both oil and water, and a calculation using only the VCF for pure oil. For the oil calculation the mixture densities at reference conditions are used as input in the VCF, replacing the reference value of pure oil. The pressures and temperatures used in the calculations are taken from Table 3.
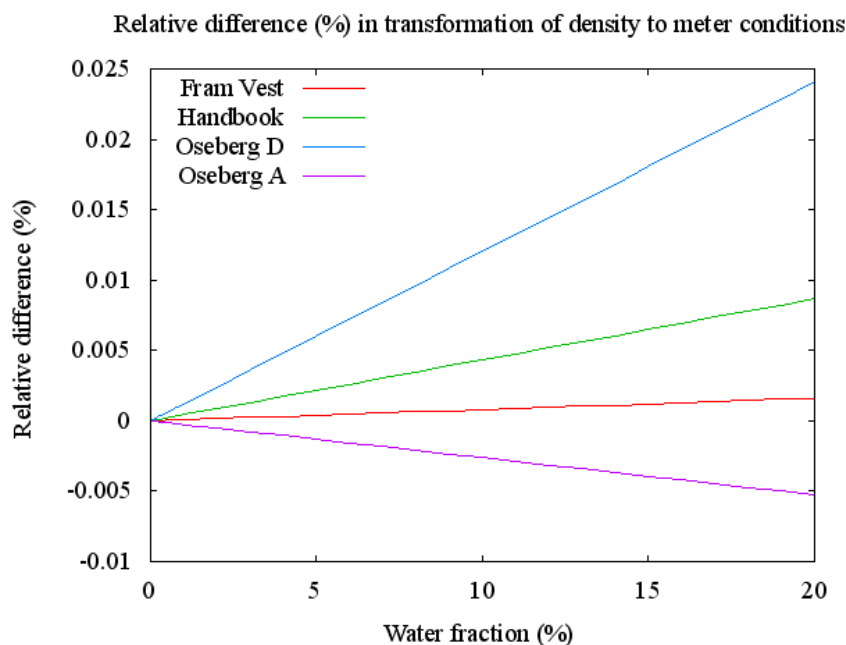

Figure 6.   Relative differences, $\left(\rho_{water-in-oil} - \rho_{pure-oil} \right)/ \rho_{pure-oil}$, between a mixture density calculation and a calculation using the formula for pure oil. The pressures and temperatures used in the calculations are taken from Table 3.
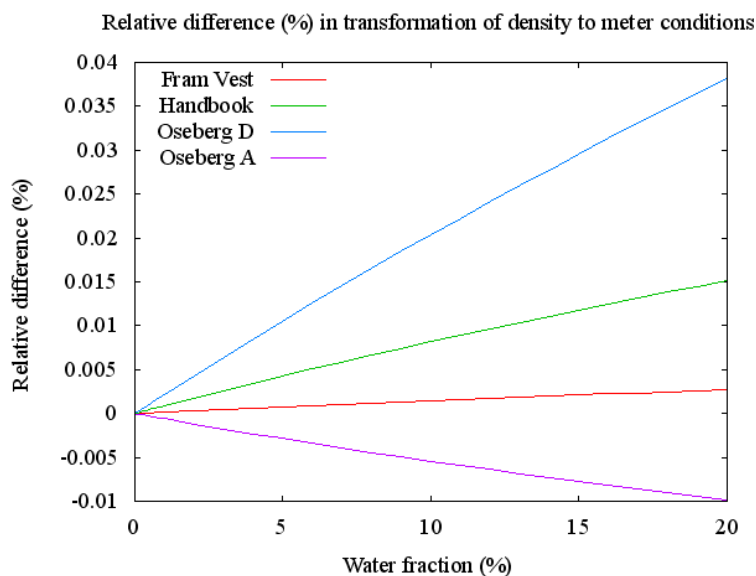
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Figure 7.   Relative differences, $\left(\rho_{water-in-oil} - \rho_{pure-oil} \right) / \rho_{pure-oil}$, between a mixture density calculation and a calculation using the formula for pure oil. The mixture densities at reference conditions are used as input in the VCF, replacing the reference value of pure oil. The pressures and temperatures used in the calculations are taken from Table 3.
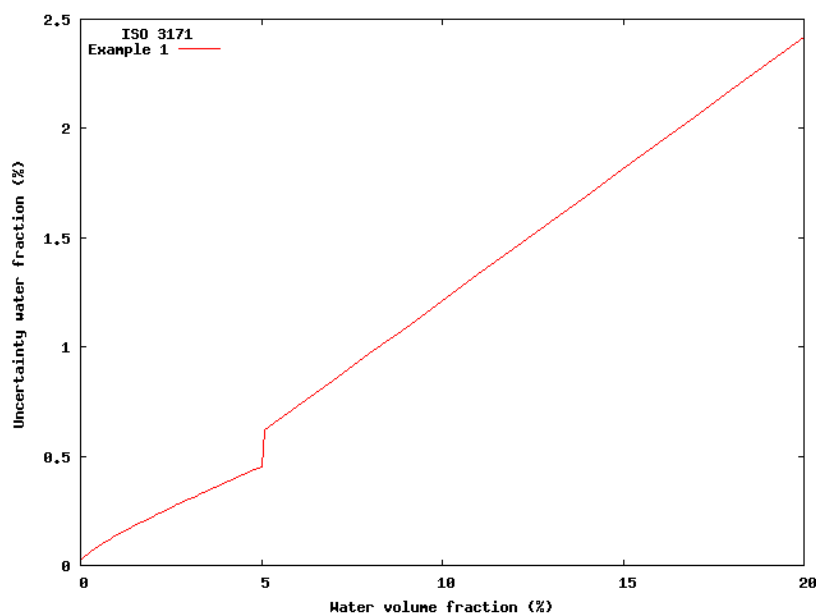

Figure 8.   Uncertainty in water fraction due to sampling and analysis (95 % confidence interval). The uncertainty in water volume fraction is calculated from Eq. (5.15) for water fractions above 5 %, using data set 1 in Table 4. For water fractions below 5 %, the uncertainty contribution from the laboratory analysis is taken from Eq. (5.16) and the uncertainty from the sampling is calculated from Eq. (5.15) with the factors f and g in Table 4 set to zero.

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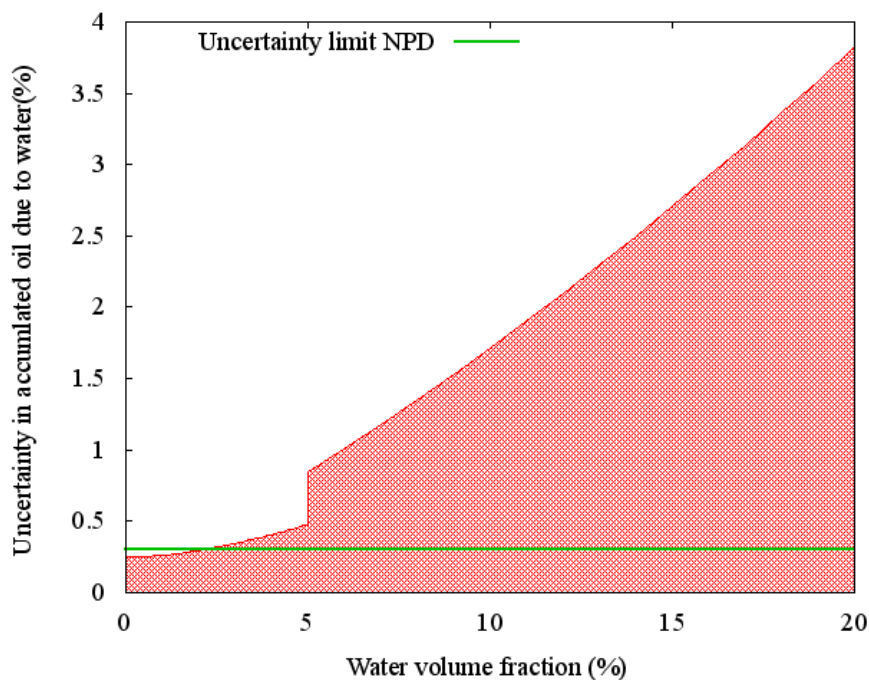Rev.: 02   Date: 15.10.2007
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Figure 9.   Example calculation of the relative expanded uncertainty (95 % confidence level) of the volumetric oil flow rate due to WIO as a function of water fraction for the sampling/laboratory analysis method. The different terms in Eqs. (5.3) and (5.5) are included as summarized in Table 5.
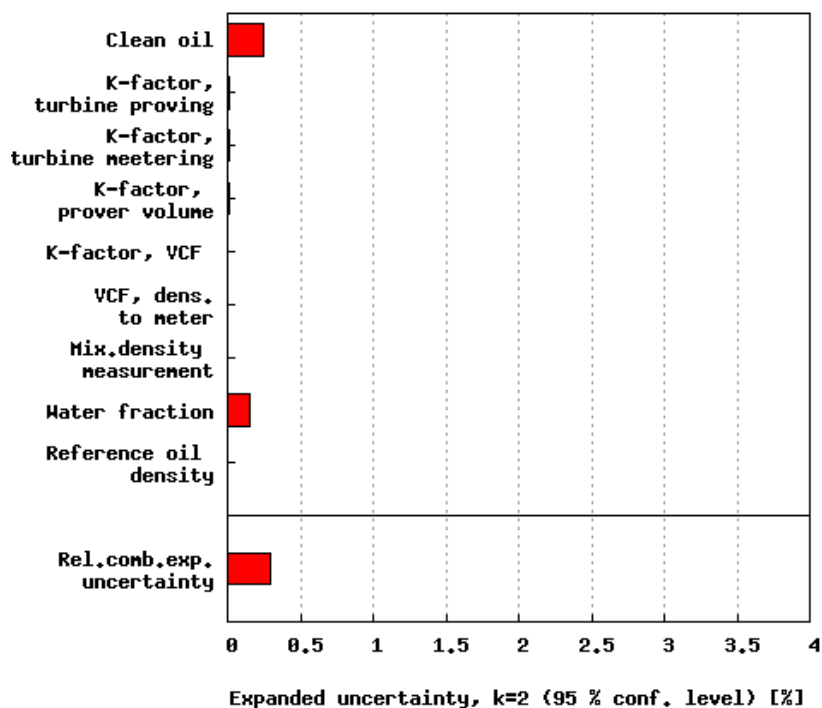

Figure 10. Example calculation bar chart showing the various contributions to the relative expanded uncertainty of the volumetric oil flow rate at standard reference conditions, for 2 % WIO, and for the sampling/analysis method.

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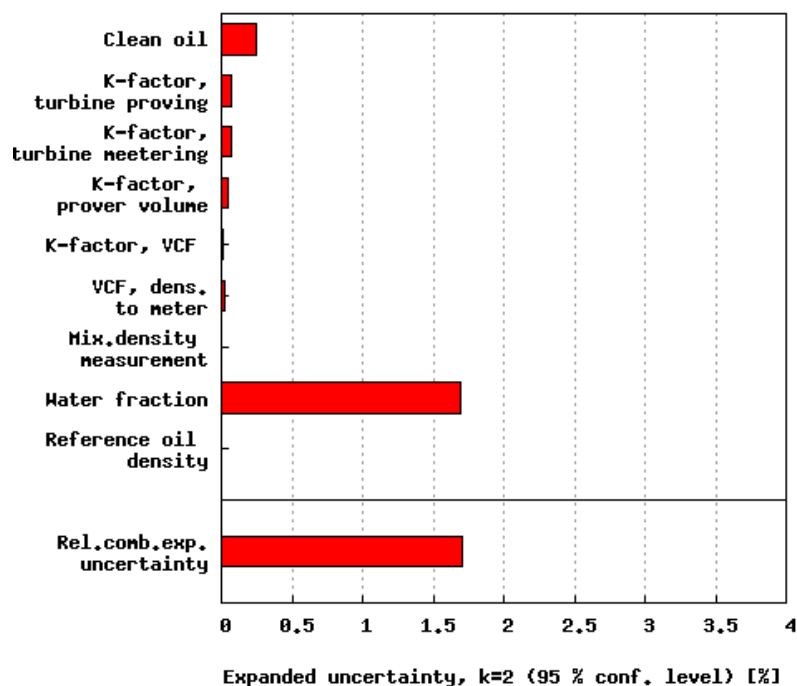Rev.: 02   Date: 15.10.2007
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Figure 11. Example calculation bar chart showing the various contributions to the relative expanded uncertainty of the volumetric oil flow rate at standard reference conditions, for 10 % WIO, and for the sampling/analysis method.
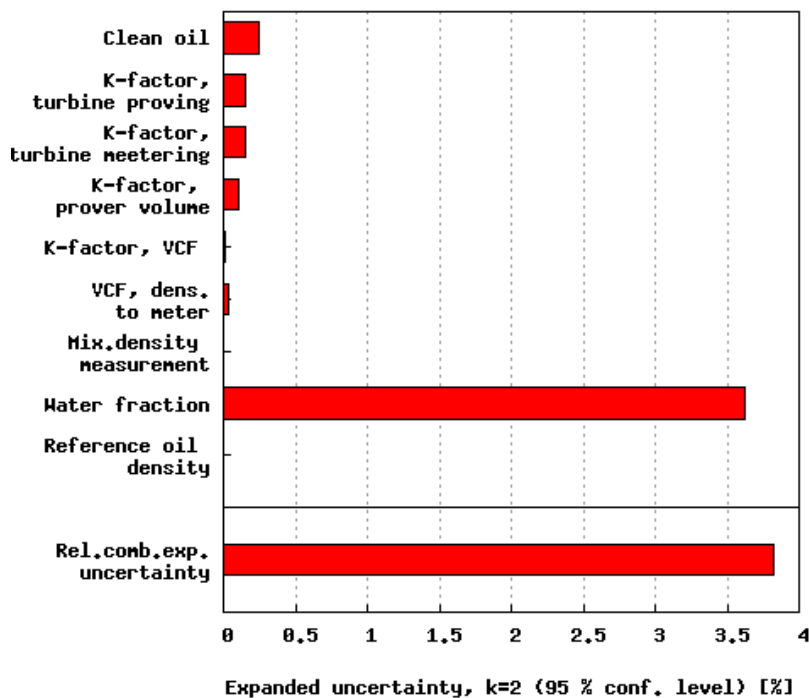

Figure 12. Example calculation bar chart showing the various contributions to the relative expanded uncertainty of the volumetric oil flow rate at standard reference conditions, for 20 % WIO, and for the sampling/analysis method.

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5.3   Case B: Continuous measurement of WIO

The present section gives the sensitivity analysis of the volumetric oil flow rate measurement, for metering stations where WIO is continuously measured using a water fraction meter (WFM).

The functional relationship for the WFM based WIO treatment is given by Eqs. (3.17) - (3.23). An uncertainty model for the I-105 method is given as

$$
\left(\frac{u(Q_v^{net,water\,impact})}{Q_v^{net}} \right)^2 = \left(\frac{u(MR_m)}{MR_m} \right)^2 + \left(\frac{u(K_{MRp})}{K} \right)^2 + \left(\frac{u(K_{BV})}{K} \right)^2
$$
$$
+ \left(\frac{u(K_{corr})}{K} \right)^2 + \left(\frac{u(C_{tom}C_{pom})}{C_{tom}C_{pom}} \right)^2 + \left(\frac{\phi_m}{1-\phi_m} \right)^2 \cdot \left(\frac{u(\phi_m)}{\phi_m} \right)^2
$$

(5.20)

Eq. (5.20) is formed by considering the terms where the WIO can have an impact, and expanding the total equation through the procedure given in the GUM [ISO, 1995] and ISO 5168 [ISO, 2005].

The uncertainty terms

$$
\left(\frac{u(MR_m)}{MR_m} \right)^2 + \left(\frac{u(K_{MRp})}{K} \right)^2 + \left(\frac{u(K_{BV})}{K} \right)^2 + \left(\frac{u(K_{corr})}{K} \right)^2
$$

have already been considered for the sampling and analysis based approach, cf. Section 5.2. The excess uncertainty from the other terms appearing in Eq. (5.20) is considered in the following.

5.3.1   Excess uncertainty contribution due to VCF from meter to standard reference conditions

The uncertainty contributions to Eq. (5.20) due to WIO effects on the volume correction from meter to standard reference conditions, are addressed in the following. The relevant term in this context is the variance

$$
\left(\frac{u(C_{tom}C_{pom})}{C_{tom}C_{pom}} \right)^2 ,
$$

which represents the relative standard uncertainty of the volume correction factors from meter conditions to standard reference conditions. The source for the uncertainty is the calculation of ρ_{ref}^o by the I-105 algorithm. ρ_{ref}^o depends on measured variables such as the mixture density, water density and the water volume fraction (Eq. (3.17)). A simplified relationship between ρ_{ref}^o and the measured variables can be written as

$$
\rho_{ref}^o \approx \frac{\rho_d^{mix} - \phi_d \rho_d^w}{1-\phi_d} .
$$

(5.21)

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In the derivation of Eq. (5.21), the VCF C_{tod} and C_{pod} in the denominator of Eq. (3.17) are set to one; if not the equation will be implicit in ρ_{ref}^o. An estimate of the standard uncertainty of ρ_{ref}^o can now be found by partial derivation,

$$
\begin{aligned}
u(\rho_{ref}^o)^2 &= \left(\frac{1}{1-\phi_d}\right)^2 u(\rho_d^{mix})^2 + \left(\frac{\phi_d}{1-\phi_d}\right)^2 u(\rho_d^w)^2 \\
&+ \left(\rho_d^{mix} - \rho_d^w\right)^2 \left(\frac{1}{1-\phi_d}\right)^4 u(\phi_d)^2
\end{aligned}
\tag{5.22}
$$

If the standard uncertainty of the water fraction is taken to be 5 % of reading (95 % c.l.), the standard uncertainty of ρ_{ref}^o is less than 5 kg/m^3 (95 % c.l.) at 20 % WIO.

The estimate for the standard uncertainty of ρ_{ref}^o can then be used to estimate the uncertainty of the VCF for pure oil. The resulting uncertainty of the VCF for oil is 0.1 % at 20 % water fraction.

It is concluded that at a water fraction of 20 %, the excess relative uncertainty is less than 0.1 %, at 100 % confidence level with a rectangular distribution function. The relative standard uncertainty used in the calculations is then taken to be

$$
\left(\frac{u(C_{tom}C_{pom})}{C_{tom}C_{pom}}\right) = \frac{0.1}{\sqrt{3}}\% \approx 0.06\%
\tag{5.23}
$$

For other water fractions, a linear dependency of the relative standard uncertainty with respect to water fractions is assumed and used.

5.3.2 Excess uncertainty due to water fraction measurement at meter conditions

The uncertainty contributions to Eq. (5.20) due to WIO effects on the continuous water fraction measurement are addressed in the following. The relevant term in this context is the variance

$$
\left(\frac{u(\phi_m)}{\phi_m}\right)^2,
$$

which represents the excess relative standard uncertainty due to continuous measurement of the water fraction using a water fraction meter (WFM). The allowable uncertainty limits are specified in I-105 [NORSOK, 2006], and are (at a 95 % confidence level) given as

± 0.05 % of volume absolute, for 0 - 1 % water volume fraction (WIO),
± 5 % of reading above 1 % water volume fraction (WIO).

The relative standard uncertainty for water fractions in the range 1 - 20 % is thus taken to be

$$
\left(\frac{u(\phi_m)}{\phi_m}\right) = \frac{5}{2}\% = 2.5\%
\tag{5.24}
$$

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In the sensitivity analysis calculations this value is used for water fractions in the range 1 - 20 %. In the water fraction range 0 - 1 % the relative standard uncertainty multiplied with the sensitivity coefficient will read

(5.25)

$$\left(\frac{\phi_m}{1-\phi_m}\right)\left(\frac{u(\phi_m)}{\phi_m}\right)=\left(\frac{1}{1-\phi_m}\right)u(\phi_m)=\left(\frac{1}{1-\phi_m}\right)\frac{0.0005}{2}$$

In the limit $\phi_m = 0$ the relative standard uncertainty contribution from the WFM will then be 0.025 %.

5.3.3 Estimation of excess uncertainty of the volumetric oil flow rate due to WIO

The different uncertainty terms appearing in Eq. (5.20) are here combined. Results for 20 % WIO are shown in Table 6. The excess uncertainty due to the WFM measurement is clearly the dominant term. The second largest term is the excess uncertainty of the prover volume measurement.

In these example calculations, the relative combined standard uncertainty is 0.72 %, and the expanded uncertainty at a 95 % confidence level is 1.43 %. A plot of the combined relative uncertainty (at a 95 % confidence level) is shown in Figure 13. Bar charts showing the individual contributions to the relative expanded uncertainty for 2, 10 and 20 % WIO are shown in Figure 14, Figure 15 and Figure 16, respectively.

Table 6.   Estimation of the combined uncertainty of the volumetric oil flow rate due to WIO contents, at 20 % water fraction, using a water fraction meter (WFM) and the calculation algorithm given in the NORSOK standard I-105.

Source	Input uncertainty	Relative combined uncertainty	
	Relative standard uncertainty (%)	Relative sensitivity coefficient (-)	Contribution to the relative combined uncertainty (%)
Pure oil uncertainty	0.125	1	0.125
K-factor, turbine proving	0.075	1	0.075
K-factor, turbine metering	0.075	1	0.075
K-factor, prover volume	0.06	1	0.06
K-factor, VCF	0.006	1	0.006
VCF, meter to standard conditions	0.06	1	0.06
Water fraction	2.5	0.25	0.625
Relative combined standard uncertainty			0.65
Relative expanded uncertainty (95 % c.l., coverage factor = 2)			1.30

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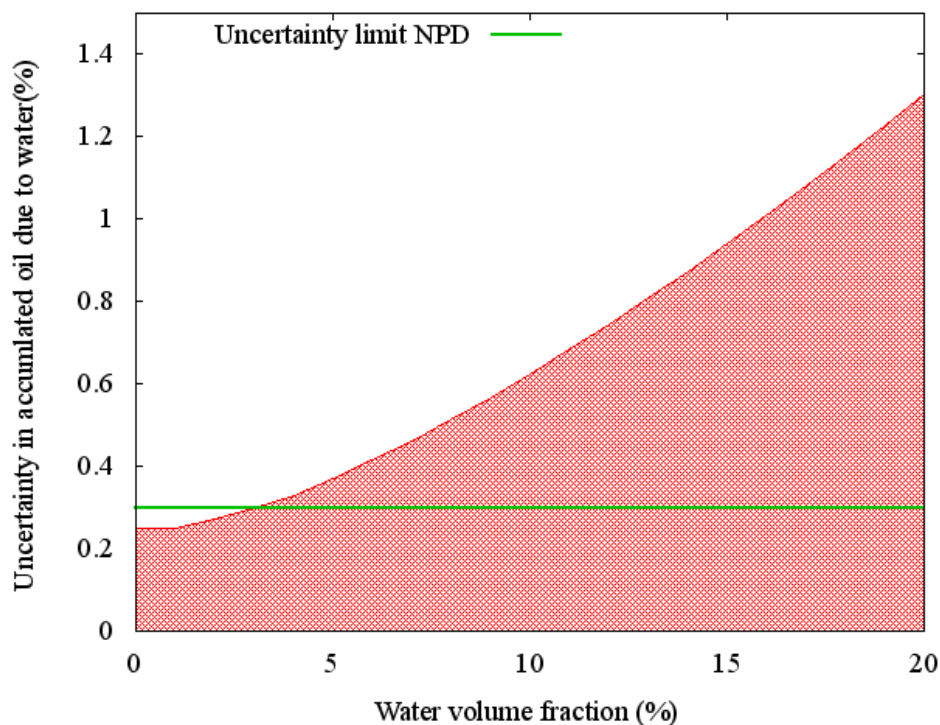Rev.: 02   Date: 15.10.2007
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Figure 13. Example calculation of the relative expanded uncertainty (at 95 % confidence level) of the volumetric oil flow rate due to WIO as a function of water fraction, for the WFM water measurement method. The different terms in Eq. (5.20) are included as summarized in Table 6.
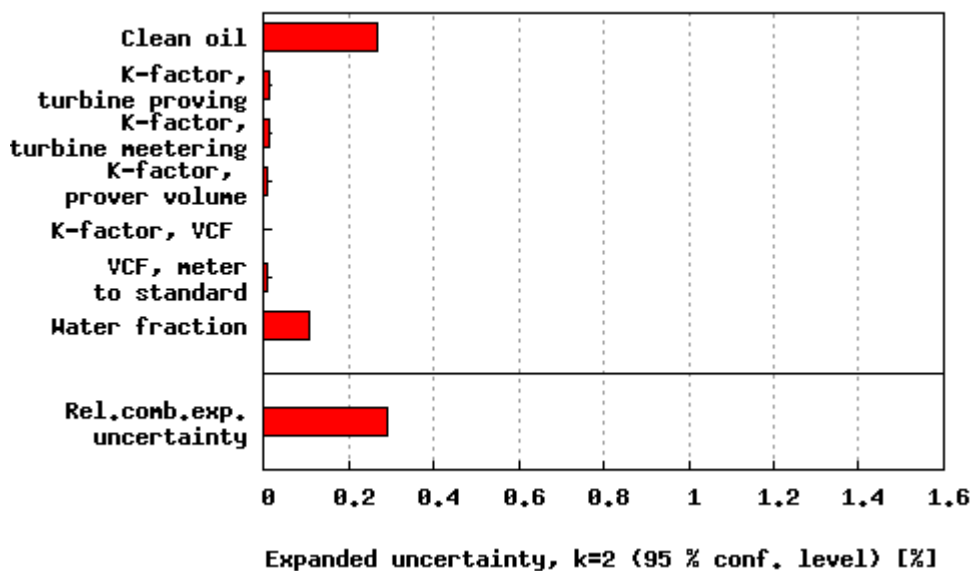

Figure 14.   Example calculation bar chart showing the contributions to the relative expanded uncertainty of the volumetric oil flow rate at standard reference conditions, for 2 % WIO, using WFM water fraction measurement.

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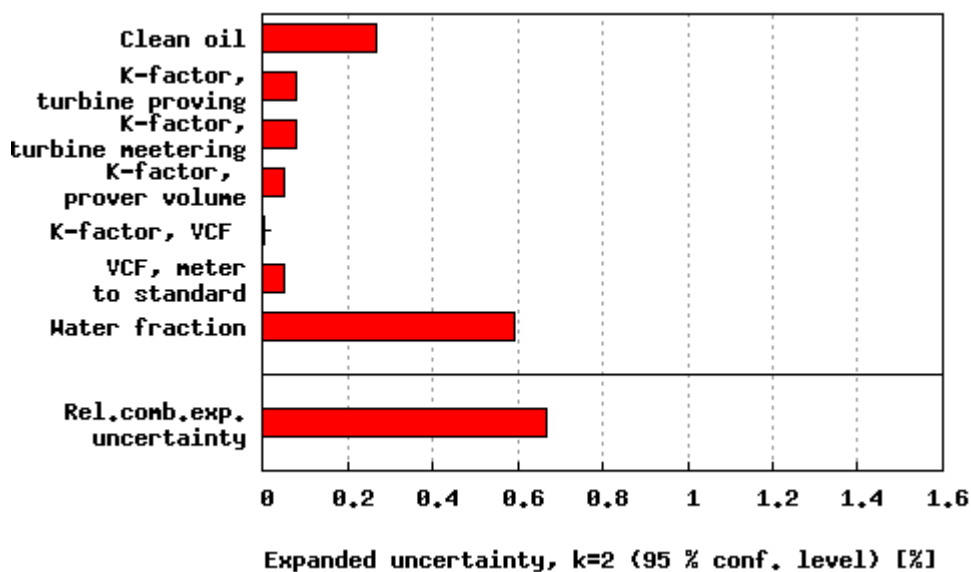Rev.: 02   Date: 15.10.2007
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Figure 15.   Example calculation bar chart showing the contributions to the relative expanded uncertainty of the volumetric oil flow rate at standard reference conditions, for 10 % WIO, using WFM water fraction measurement.
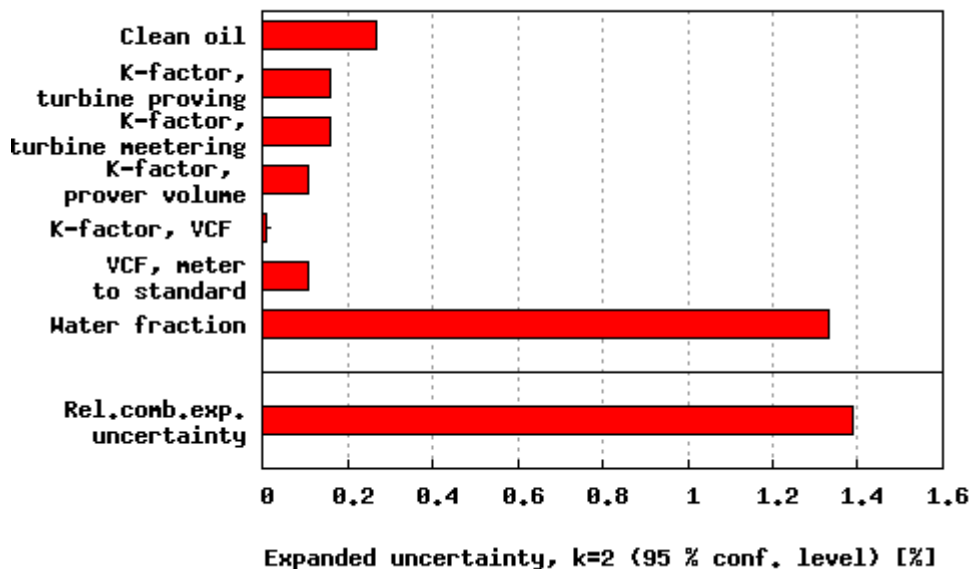

Figure 16.   Example calculation bar chart showing the contributions to the relative expanded uncertainty of the volumetric oil flow rate at standard reference conditions, for 20 % WIO, using WFM water fraction measurement.

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6   DISCUSSION

It is emphasized that the "uncertainty estimates" given in the present report (Chapter 5) do not represent uncertainty estimates as such, due to the lack of sufficient information for a number of the input uncertainties. The "uncertainty estimates" given here are to be used for the sensitivity analysis only, to evaluate the relative importance of the various terms influencing on the volumetric oil flow rate, with emphasis on WIO contents.

In spite of that, the calculation examples given in Chapter 5 strongly indicate that the NPD requirement with respect to the relative expanded uncertainty of the measured oil flow rate ($\pm$ 0.3 % at a 95 % confidence interval) may not be met over the complete 0 - 20 % water fraction range. In the sensitivity analysis calculations, the NPD requirement could be met for water fractions below 2.1 % (tentatively) with sampling/analysis based WIO treatment, and below 3.1 % (tentatively) for continuous water fraction measurement using a WFM. In these calculations the relative expanded uncertainty of the pure oil volumetric flow rate measurement is set to 0.25 % as a typical example (at a 95 % confidence level). The uncertainty of the pure oil flow rate measurement is covered in detail elsewhere, cf. the NFOGM TM Handbook [Dahl et al., 2003].

The sensitivity analysis calculations indicate that for high water fractions, the most important contribution to the volumetric oil flow rate measurement uncertainty is by far the measurement uncertainty of the water fraction. The other factors like oil and water VCF are relatively smaller. For low water fractions (WIO < 2 %), the uncertainty of the pure oil measurement starts to dominate as the water fraction is reduced. With the data used in the calculation examples, the relative expanded uncertainty by using the sampling/analysis method is clearly larger than by using the WFM based method. The differences between the two methods increases with increasing water fraction.

In the calculations for the sampling/analysis based WIO treatment, the sampling and analysis accuracy is taken from examples given in ISO 3171 [ISO, 1988] and in AIP MPMS [API, 2002] for the Karl Fischer measurement. The accuracy may perhaps be better in a well-designed sampling system, but to meet the NPD requirements, the accuracy would have to be substantially improved. For Case B using continuous water fraction measurement, the WFM accuracy would have to be less than 0.1 % of reading in the range 1 - 20 % WIO, in addition to a reduction in the uncertainty due to water in the other terms (turbine-meter etc). This would necessitate a 50 times more accurate measurement of water fraction than the requirement given in I-105 [NORSOK, 2006].

Two important pre-assumptions have been made for the present sensitivity study, in accordance with national and international regulations and standards in this area: (1) free gas is not present in the flow, neither as a separated phase nor as small bubbles dispersed in the liquid, and (2) the water is dispersed homogeneously in the oil phase (i.e. the variation in water concentration is less than $\pm$ 5 % of the average water concentration over the pipe cross section). The second assumption may be difficult to realize for horizontal pipes under actual conditions for water fractions above 10 %. For water fractions below 10 % correlations based on theory exists which will give an estimate of the minimum flow velocity needed to maintain a homogeneous mixture.

Given that there is no free gas and a homogeneous WIO mixture, it is assumed for the calculations that the instruments in the metering station are functioning with WIO in the range 0 - 20 % WIO, and that the individual relative standard uncertainties were varying linearly with the water fraction. The individual meter that may be most susceptible to WIO is considered to be the turbine meter. In the calculations the mixture Reynolds number varied from 230,000 and 290,000 at an operating flow rate of 1000 m^3/h. If for some reason the flow rate was reduced, the Reynolds number could come close to or below the lower operating range for the meter. This could have an effect on the linearity of the meter. It is also not clear how the turbine meter will work if the flow homogeneity is not uniform over the pipe cross section, but still is within the definition of homogeneous flow given in ISO 3171 [ISO, 1988]. If the difference in water concentration between the top and bottom in a horizontal pipe is 10 % relative to the average water concentration, vertical differences in mixture densities and viscosities exists. This may, to some degree, affect the accuracy of the turbine.

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7   CONCLUSIONS

A sensitivity study has been carried out to evaluate the influence of high water-in-oil (WIO) contents on the accuracy of turbine meter based fiscal oil metering stations/systems. The fiscal metering stations in question for such a study are e.g. allocation metering stations, and normally not sales point metering stations.

The objective or the work has been to identify the part(s) of the metering station where a (high) water content in the oil will have a significant impact on the measured volumetric flow rate, in form of increased measurement uncertainty or as systematic deviation (error).

For this purpose an uncertainty model for a turbine meter based fiscal oil metering station with high water fraction has been developed and used. The developments build on the results of the NFOGM TM Handbook [Dahl et al, 2003], and national and international regulations and standards in this area.

The work has been made in close cooperation with a project reference group with experienced members from oil and gas companies, offshore service companies and the Norwegian Petroleum Directorate (NPD).

Two important pre-assumptions have been made for the present sensitivity study, in accordance with national and international regulations and standards in this area: (1) free gas is not present in the flow, neither as a separated phase nor as small bubbles dispersed in the liquid, and (2) the water is dispersed homogeneously in the oil phase (i.e. the variation in water concentration is less than $\pm 5\%$ of the average water concentration over the pipe cross section).

Under these pre-assumptions, the excess uncertainty of the volumetric oil flow rate at standard reference conditions due to WIO contents has been studied and evaluated. Determination of water fraction by (a) sampling/analysis and (b) continuous measurement (using a water fraction meter, WFM) are covered. For the sampling/analysis approach, the discussion is based on the ISO 3171 standard [ISO, 1988]. For the continuous water fraction measurement approach, the I-105 standard [NORSOK, 2006] is used.

Calculations have been carried out based on field data from three North Sea fields / metering stations. Water fractions in the range 0-20 % are addressed. Three WIO scenarios, 2 %, 10 % and 20 % WIO, are addressed in some more detail.

In the calculation examples chosen in a dialogue with the project reference group, the estimated uncertainty in the volumetric oil flow rate due to water at 20 % water fraction has been found to be:

- about 3.8 % uncertainty (95 % c.l.) for sampling/analysis based WIO treatment,
- about 1.3 % uncertainty (95 % c.l.) for continuous measurement of WIO (using a WFM).

It is emphasized that the example "uncertainty estimates" given in the present report do not represent uncertainty estimates as such, due to the lack of sufficient information for a number of the input uncertainties. The "uncertainty estimates" given here are to be used for the sensitivity analysis only, to evaluate the relative importance of the various terms influencing on the volumetric oil flow rate, with emphasis on WIO contents.

In spite of that, the example calculations clearly indicate that the NPD requirement [NPD, 2001] with respect to the uncertainty of the measured oil flow rate ($\pm$ 0.3 % at 95 % confidence level) is definitely not met at 20 % WIO, and also not met at significantly lower WIO scenarios. In the calculations, the relative expanded uncertainty (at 95 % confidence level) is above the NPD requirement at a water fraction of about 3.1 % for WIO determination using WFM, and at a water fraction of about 2.1 % for WIO determination using sampling/analysis.

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The effect of systematic deviations from the use of pure oil volume correction factors (VCF) instead of oil-water mixture VCF, is relatively small. For the WFM method, the pure-oil measurement uncertainty is the dominating contribution for 2 % WIO. For 10 % WIO the WFM measurement uncertainty dominates, and for 20 % the WFM measurement uncertainty is by far the largest.

For the sampling/analysis method, the uncertainty of the pure oil volumetric flow rate measurement and water fraction analysis are approximately equal for 2 % WIO. For 10 % WIO, and even more for 20 % WIO, the water fraction measurement uncertainty due to sampling/analysis is dominating.

The individual instrument in the metering station that may be most susceptible to WIO is considered to be the turbine meter. If the turbine meter is operating near the lower operating range (low and moderate Reynolds numbers), changing Reynolds number due to increasing WIO (density, viscosity, etc.) may affect the linearity of the meter. It is also not clear how the turbine meter will work if the flow homogeneity is not uniform over the pipe cross section. Vertical differences in mixture densities and viscosities may then be present, which may affect the accuracy of the turbine.

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8   REFERENCES

API: "Manual of Petroleum Measurements Standards, Chapter 11 – Physical Properties Data, Chapter 1 Volume Correction Factors". American Petroleum Institute, Washington D.C., U.S.A. (1980).

API: "Manual of Petroleum Measurements Standards, Chapter 12 – Calculation of petroleum quantities. Section 2 – Calculation of liquid petroleum quantities measured by turbine or displacement meters". First edition, American Petroleum Institute, Washington D.C., U.S.A. (Paragraphs 12.2.5.1 and 12.2.5.2) (September 1981).

API: "Manual of Petroleum Measurements Standards, Chapter 12 – Calculation of petroleum quantities. Section 2 – Calculation of liquid petroleum quantities measured using dynamic measurement methods and volumetric correction factors Part 1 - Introduction". Second edition, American Petroleum Institute, Washington D.C., U.S.A. (Paragraphs 1.11.2.1 and 1.11.2.2) (May 1995).

API: "Manual of Petroleum Measurements Standards, Chapter 10 – Sediment and Water. Section 9 – Standard Test Method far Water in Crude Oils by Coulometric Karl Fischer Titration". Second edition, American Petroleum Institute, Washington D.C., U.S.A.) (December 2002).

Contract for the project "Fiskalmåling av olje med høyt vanninnhold, Fase 1: Sensitivitetsstudie for en turbinmeterbasert fiskal målestasjon"; between the Norwegian Society for Oil and Gas Measurement (NFOGM) and Christian Michelsen Research (CMR), dated June 29 and July 3, 2006.

Dahl, E.O., Lunde, P., Frøysa, K.-E. and Hallanger, A., "Fiskalmåling av olje med høyt vanninnhold, Fase 1: Sensitivitetsstudie for en turbinmeterbasert fiskal målestasjon"; CMR project proposal CMR-M-10-05/21, Christian Michelsen Research AS, Bergen, Norway (June 29, 2006).

Dahl, E.O., Dykesteen, E., Jacobsen, E., Malde, M., Flåten, F., Tunheim, H., Brandt, M., Albrechtsen, R., Vikingstad, O., Corneliussen, S.E., Hjorteland, T., "Handbook of water fraction metering, Rev. 2", Handbook prepared on behalf of the Norwegian Society of Oil and Gas Measurement (NFOGM) (December 2004) (ISBN 82-91341-86-9).

Dahl, E. O., Frøysa, K.-E. and Lunde, P.: "Handbook of uncertainty calculations. Fiscal orifice gas and turbine oil metering stations". Handbook prepared on behalf of the Norwegian Society for Oil and Gas Measurement (NFOGM), Norwegian Petroleum Directorate (NPD) and the Norwegian Society of Chartered Engineers (NIF), 220 p. (ISBN 82-91341-62-1) (Revision 2, May 2003).

FMC: Private communication with Ray Kalivoda, FMC Smith Meters, USA, February 1, 2007.

Ishii, M., Zuber, N.: "Drag Coefficient and Relative Velocity in Bubbly, Droplet or Particulate Flows", AIChE Journal Vol. 25, No. 5, 843-855 (1979).

ISO 3171: "Petroleum liquids – Automatic pipeline sampling", ISO Standard, Second edition (1988-12-01).

ISO/DIS 12916: "Liquid hydrocarbons - Dynamic measurement - Volumetric proving tanks or measures" (1995).

ISO 5158: "Measurement of fluid flow – Procedures for the evaluation of uncertainties", ISO standard (2005).

ISO 8222: "Petroleum measurement systems - Calibration - Temperature corrections for use when calibrating volumetric proving tanks", ISO Standard (2002).

ISO: "Guide to the expression of uncertainty in measurement" (GUM). First edition, 1993, corrected and reprinted 1995. ISO, Geneva, Switzerland (1995).

NORSOK standard I-105: "Fiscal measurement systems for hydrocarbon liquid", Draft 2 for Edition 3, Standards Norway, Oslo, Draft (September 2006).

NPD: "Regulations relating to measurement of petroleum for fiscal purposes and for calculation of CO_2 tax", Norwegian Petroleum Directorate, Stavanger, Norway (November 1, 2001).

Ref. group: Meeting in the Technical Reference Group of the project "Fiscal measurement of oil with high water fraction. Phase 1: Sensitivity study for a turbine meter based fiscal metering station" (October 19, 2006).

Ref. group: Meeting in the Technical Reference Group of the project "Fiscal measurement of oil with high water fraction. Phase 1: Sensitivity study for a turbine meter based fiscal metering station" (May 9, 2007).

Solartron: Solartron 7835 Technical Manual, Solartron Mobrey Ltd, Slough Berks, UK, 2000, Part No. 7835 5001 (October 1994).

Solartron: Information from Solartron Mobrey supplied by Morten Kirkhus, Sigurd Sørum AS, February 1, 2007.

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Appendix A: Questionnaire sent to instrument vendors

The questionnaire given below was sent to selected vendors of individual instruments (here the letter sendt to Solartron Mobrey) used in a typical fiscal turbine based oil metering station.

Emerson Process Management

Att.:
Solartron Mobrey 7835 Advanced Liquid Densitometer

| **Your ref.** | **Our ref.**
CMR-07-10050BR-01 | **Date**
January 17, 2007 |

NFOGM study on the effect of water-in-oil on the accuracy of a turbine fiscal oil metering station.

The Norwegian Society for Oil and Gas Measurement (NFOGM) has initiated a study on the accuracy of a turbine fiscal oil metering station when water is dispersed in the oil. Christian Michelsen Research AS (CMR) is carrying out the investigation on behalf of NFOGM. The results from this work will be available in an open report during the spring of 2007, and some results will also be presented at the "NFOGM Temadag" in Oslo on March 16, 2007.

The investigation is restricted to a "standard" measurement station with a turbine meter, densitometer, temperature transmitters, pressure transmitters, prover and the other necessary equipment and software needed to have an operating unit.

The physical parameters used as an example in this study are given in the table below.

Variable	*Value*
Oil density	830 kg/m^3 @15 ^{o}C, 1 atm.
Oil viscosity	6 cS @ 40 ^{o}C
Water density	1020 kg/m^3 @15 ^{o}C, 1 atm
ID pipe line	8 "
Maximum flow rate	1200 m^3/h
Operating flow rate	1000 m^3/h
Operating pressure & temperature	30 bar g, 40 ^{o}C
Water cut	0-20 % (volume)

When water is dispersed in the oil, the effective liquid viscosity will increase above the 6 cS given above.

We would like to receive information on how the *Solartron Mobrey 7835 Advanced Liquid Densitometer* is influenced when operating on a mixture of water and oil, and, if possible, on any concequences on the accuracy of the *Solartron Mobrey 7835 Advanced Liquid Densitometer* under such conditions.

Questions:

1. How is Solartron Mobrey 7835 Advanced Liquid Densitometer influenced by the water in oil when we assume that the water-in oil mixture is homogeneous?

2. Is there any upper limit of the water cut?

3. How is Solartron Mobrey 7835 Advanced Liquid Densitometer affected by deviations from homogeneity (the definition of homogeneity in ISO 3171 allows for a 5% vertical gradient in water concentration in a horizontal pipe)?

If you have operational experience from measurements on water-in-oil mixtures, we would appreciate receiving such information.

If you are able to reply within February 9, 2007, that would be highly appreciated. We apologize for this relatively short "deadline". Thank you for the time you take to reply to these questions!

Yours sincerely
for CMR Instrumentation

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Senior Scientist

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