Fiscal metering of oil with high water fraction. Sensitivity study for a turbine meter - based metering station

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Contents

Introduction

Background

- Many oil fields in the North Sea are coming into their late production phase.
- Produced water is an increasing issue, and has increased focus by industry.
- Up to 20 % WIO (by volume) experienced in North Sea fiscal oil metering stations.
- Question: what are the most critical components of fiscal oil metering stations with respect to WIO?
- Phase 1:
  - NFOGM initiated project
  - Turbine meter based fiscal oil metering station
  - Sensitivity study
  - October 2006 – April 2007

Reference group

- Trond Folkestad,
- John Eide,
- Trond Hjorteland,
- Sidsel Corneliussen,
- Svein Neumann,
- Einar Halvorsen.

Objectives, phase 1

- Carry out a **sensitivity study** for a turbine meter based fiscal metering station for volumetric liquid rate, in order to
- **Identify** the parts of the metering station with **highest influence by high water content in the oil on the resulting liquid- and oil flow rate** (measurement uncertainty and systematic deviations).

Basis documents

- **NORSOK standard I-105:** Fiscal measurement systems for hydrocarbon liquids, Draft 2 for Edition 3, Standards Norway, Oslo, September 2006 (Draft).
- **ISO 3171**: “Petroleum liquids – Automatic pipeline sampling”. Second edition, 1988.
- Dahl et al.: “Handbook of water fraction metering, Rev. 2”, NFOGM Handbook 2004 [**WIO Handbook**].
- Dahl et al.: “Handbook of uncertainty calculations. Fiscal orifice gas and turbine oil metering stations”, NFOGM-NPD-NIF Handbook, Rev 2, 2003 [**Unc TM Handbook**].

Specifications

Specifications for sensitivity study – fiscal oil turbine metering station

-equipment

- Prover
- Turbine meter
- Densitometer
- Pressure transmitters
- Temperature transmitters

- Water-in-oil measurement:
  - Sampling devices

    or
  - Online water in oil meter

- Example considered here: 8” pipe
- Equipment scenario agreed on with reference group

Specifications for sensitivity study
-fluids

Calculation example agreed on with reference group

Oil density:	830 kg/m³	at 15 °C, 1 atm
Oil viscosity:	6 cSt	at 40 °C
Water density:	1020 kg/m³	at 15 °C, 1 atm
Operating flow rate:	1000 m³/h	at 15 °C, 1 atm
Volumetric fraction of water:	0 – 20 %	at line conditions

- Reynolds number range: 230 000 – 290 000

Specifications for sensitivity study
-Assumptions, liquids

- **No free gas (bubbles or layer) present in the liquids/pipe**
- **Homogeneously distributed water in oil.**

In conformity with

- **ISO 3171**: “Petroleum liquids – Automatic pipeline sampling”. Second edition, 1988.
- **WIO Handbook:** “Handbook of water fraction metering, Rev. 2”.
- As agreed on with **reference group**

Homogeneity:

- Water distributed as droplets throughout the oil phase
- Volumetric water fraction is equal throughout the pipe cross section (within ±5 % difference top-bottom – ISO 3171)
- The turbulence in the pipe will maintain the homogeneity of the water-oil mixture
- A lowest flow rate exists where this is valid – ISO 3171
- Vertical flow enhances homogeneity
- Use of mixing enhances homogeneity

Specifications for sensitivity study

-pressure and temperature

	Fram Vest	Ose-berg D	Ose-berg A	Unc TM Handbook
Operating (line) conditions				
Pressure	24.44	42.66	22.29	18 barg
Temperature	36.70	41.01	48.86	65 °C
Densitometer				
Pressure	24.66	43.12	17.76	17.5 barg
Temperature	36.60	38.68	48.93	63 °C
Prover (average at inlet and outlet)				
Pressure	1 bar less than operating line conditions			
Temperature	1 °C less than operating line conditions			
WIO-meter				
Pressure	as operating line conditions			
Temperature	as operating line conditions			

Pure oil – background info (functional relationship)

Turbine oil metering station – Pure oil

Functional relationship

NFOGM "Handbook of uncertainty calculations. Fiscal orifice gas and turbine oil metering stations", Rev. 2 (March 2003)

$$Q_V = \frac{MR_m}{K} \cdot \left[C_{tlm} \cdot C_{plm} \right]_{line} \cdot 3600$$

Q_V	standard oil volume flow rate	[Sm³/h]
MR_m	number of pulses counted by the turbine meter during the metering period	[1/s]
K	K-Factor	[1/Sm³]
C_{tlm}	volume correction factor for the effect of temperature on the liquid in the turbine meter	[-]
C_{plm}	volume correction factor for the effect of pressure on the liquid in the turbine meter	[-]

Turbine oil metering station – Pure oil

Functional relationship

NFOGM "Handbook of uncertainty calculations. Fiscal orifice gas and turbine oil metering stations", Rev. 2 (March 2003)

K-factor:

$$K = \frac{MR_p}{BV} \cdot \left[\frac{(C_{tlm} \cdot C_{plm})}{(C_{tlp} \cdot C_{plp}) \cdot (C_{tsp} \cdot C_{psp})} \right]_{proving}$$

MR_p	number of pulses counted by the turbine meter during the proving period	[-]
BV	base volume of prover	[m^3]
C_{tlp}	volume correction factor for the effect of temperature on the liquid in the prover	[-]
C_{plp}	volume correction factor for the effect of pressure on the liquid in the prover	[-]
C_{tsp}	volume correction factor for the effect of temperature on prover steel	[-]
C_{psp}	volume correction factor for the effect of pressure on prover steel	[-]

Turbine oil metering station – No treatment of WIO

Volume correction factors for temp. effects on the liquid: $C_{tlm}\ ,\ C_{tlp}\ ,\ C_{tld}$

$$C_{tl} = e^{-\alpha \cdot \Delta T - 0.8\alpha^2 \cdot \Delta T^2}, \qquad \alpha = \frac{K_0}{\rho_{ref}^2} + \frac{K_1}{\rho_{ref}}, \qquad \Delta T = T - 15$$

C_{tl}	volume correction factor, from temperature-in-question to std. ref. temp.	[-]
α	coefficient	[1/°C]
K_0	constant (API MPMS 11.1.54.7.1)	[kg/m³/°C]
K_1	constant (API MPMS 11.1.54.7.1)	[kg/m³/°C]
ρ_{ref}	density at standard reference conditions (15 °C and 101.325 kPa)	[kg/Sm³]
ΔT	difference between temperature-in-question and std. ref. temperature	[°C]
T	temperature-in-question (in meter, prover, or densitometer)	[°C]

The constants K_i depend on the oil. Given by:

- API-ATSM-IP Petroleum Measurement Tables, or
- Laboratory testing

Turbine oil metering station – No treatment of WIO

Volume correction factors for pressure effects on the liquid: $C_{plm}, \; C_{plp}, \; C_{pld}$

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

C_{pl}	volume correction factor, from pressure-in-question to std. ref. pressure		[-]
P	pressure-in-question (in meter, prover, or densitometer)		[kPa-g]
P_e	equilibrium vapour pressure		[kPa-a]
F	compressibility factor for the liquid		[1/kPa]
A	constant = -1.62080	(Cf. API MPMS 11.2.1M)	[-]
B	constant = 0.00021592	(Cf. API MPMS 11.2.1M)	[-]
C	constant = 0.87096	(Cf. API MPMS 11.2.1M)	[-]
D	constant = 0.0042092	(Cf. API MPMS 11.2.1M	[-]

Turbine oil metering station – Pure oil

NFOGM "Handbook of uncertainty calculations. Fiscal orifice gas and turbine oil metering stations", Rev. 2 (March 2003)

Calculation of density at standard reference conditions:

$$\rho_{ref} = \frac{\rho_{PT}}{C_{tld} \cdot C_{pld}}$$

ρ_{ref}	density standard reference conditions (15 °C and 101.325 kPa)	[kg/Sm^3]
ρ_{PT}	density at line conditions	[kg/m^3]
C_{tld}	volume correction factor for the effect of temperature on the liquid in the densitometer	[-]
C_{pld}	volume correction factor for the effect of pressure on the liquid in the densitometer	[-]

ρ_{ref} coupled with C_{tld} and C_{pld} => iteration necessary

Sampling based WIO treatment

Sampling-based WIO treatment
– functional relationship (agreed on with reference group)

Proving: $$K = \frac{MR_p}{BV} \frac{C_{tol} C_{pol}}{C_{top} C_{pop} C_{tsp} C_{psp}}$$

Turbine metering (line conditions): $$q_v^{mix} = 3600 \frac{MR_m}{K}$$

Density measurement: $$\rho_{line}^{mix} = \frac{\left(C_{tol} C_{pol}\right)_{line}}{\left(C_{tol} C_{pol}\right)_{dens}} \rho_{dens}^{mix}$$

Mass flow rate of mixture: $$q_m^{mix} = q_v^{mix} \rho_{line}^{mix}$$

Mass flow rate of oil: $$q_m^{net} = q_m^{mix} \left(1 - \phi_{m,line}^{water}\right)$$

Standard volumetric flow rate of oil: $$Q_{v,net} = \frac{q_m^{net}}{\rho_{ref-o-pure}}$$

Sampling-based WIO treatment

Uncertainty model for standard volumetric flow rate of oil:

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

Uncertainty for pure oil flow, considered in unc. TM Handbook, NOT CONSIDERED HERE

Excess uncertainty due to water in oil, CONSIDERED HERE

Sampling-based WIO treatment

Uncertainty model:

Turbine meter at metering — Turbine meter at proving — Prover

$$\left(\frac{u(Q_{v,net}^{water\,impact})}{Q_{v,net}}\right)^2 = \left(\frac{u(MR_m)}{MR_m}\right)^2 + \left(\frac{u(K_{MRp})}{K}\right)^2 + \left(\frac{u(K_{BV})}{K}\right)^2$$

Volume corrections:
-from prover to turbine meter conditions

-from densitometer
to turbine meter conditions

$$+\left(\frac{u(K_{corr})}{K}\right)^2 + \left(\frac{u\left(\frac{(C_{tol}C_{pol})_{line}}{(C_{tol}C_{pol})_{dens}}\right)}{\frac{(C_{tol}C_{pol})_{line}}{(C_{tol}C_{pol})_{dens}}}\right)^2$$

Measured density

$$+\left(\frac{u(\rho_{dens}^{mix})}{\rho_{dens}^{mix}}\right)^2 + \left(\frac{u(\phi_{m,line}^{water})}{1-\phi_{m,line}^{water}}\right)^2 + \left(\frac{u(\rho_{ref-o-pure})}{\rho_{ref-o-pure}}\right)^2$$

Volumetric water fraction

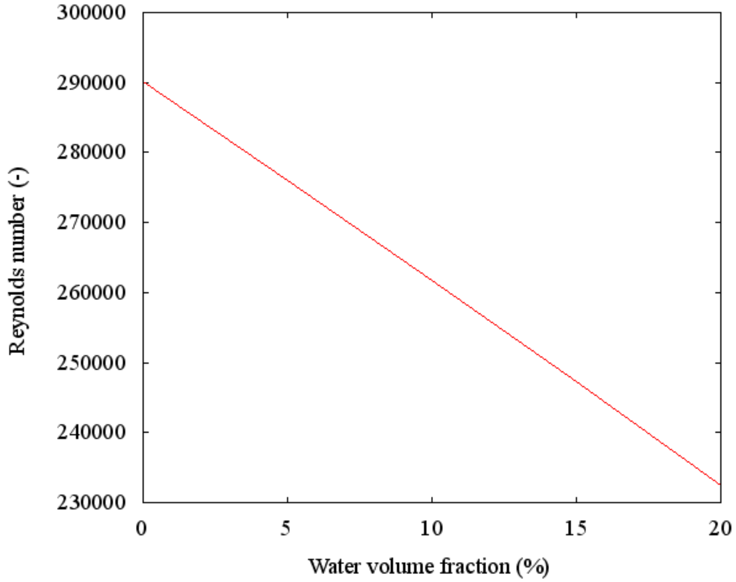
Oil density at standard
reference conditions

Sampling-based WIO treatment

Additional uncertainty contribution, turbine: $\left(\frac{u(K_{MRp})}{K}\right)^2 \left(\frac{u(MR_m)}{MR_m}\right)^2$

What is the **effect on the turbine meter itself** (pulse count pr volume) of water in the oil?

- Questionare to 3 vendors, 1 answer
  - Turbine meters not tested with water in oil
  - Assumed to influence mainly through Reynolds number (increased viscosity)
  - Conventional turbine meters expected to be more sensitive to water in oil than helical turbine meters
  - Linearity +/- 0.15 % for oil with Reynolds numbers from 50 000 to 500 000. Same with water in oil.
  - Linearity reasonable good down to 25 000.
  - For lower Reynolds numbers: modification of the turbine.
- Here: Re = 230 000 – 290 000.
- Conclusion: Influence typical less than 0.15 % (95 % conf. level).



Sampling-based WIO treatment

Additional uncertainty contribution, prover:

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

What is the **effect on the prover itself** (detection of base volume) of water in the oil?

- Questionare to 1 vendor, no answer
- The sensitivity study shows that if this uncertainty contribution is less than about 0.5 % for WIO = 20 %, it can be neglected.
- On basis of discussions in the reference group, this effect has been neglected in the sensitivity study.

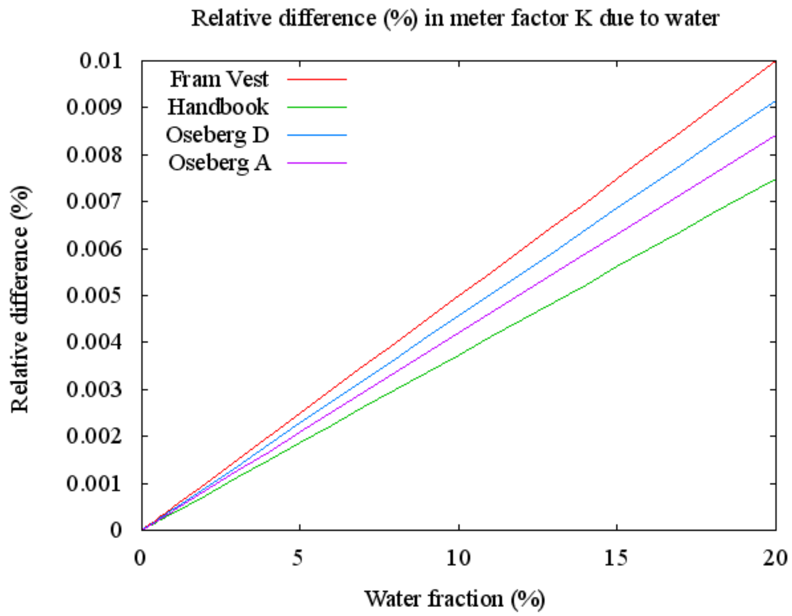
Sampling-based WIO treatment

Additional uncertainty contribution, vol. corr. from prover to turbine: $\left(\frac{u(K_{corr})}{K}\right)^2$

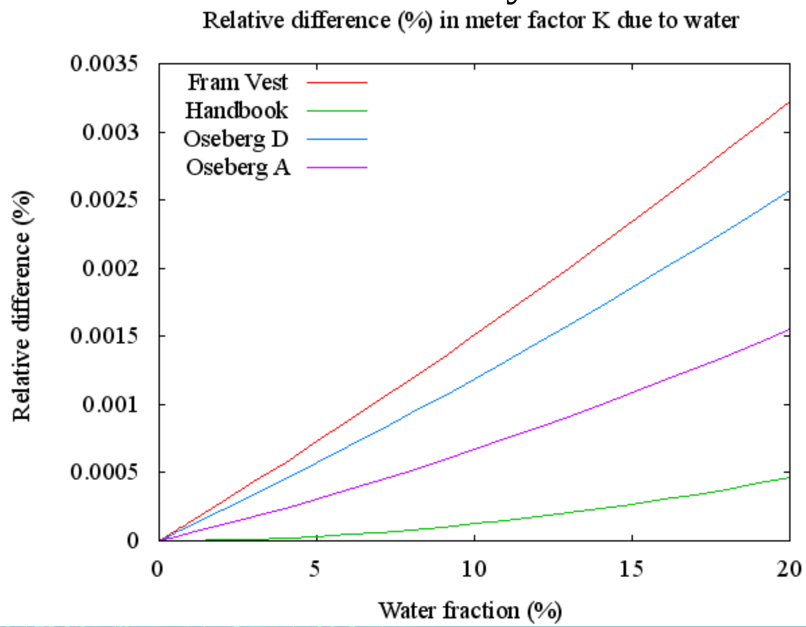
Effects:

- Using oil correction factors instead of water/oil mixture correction factors
- Possible effect of using mixture density instead of oil density
- Conclusion: Less than 0.01 % influence (100 % conf. level, rect. dist. func.)

Error when using correction factors based on pure oil density:



Error when using correction factors based on mixture density:



Sampling-based WIO treatment

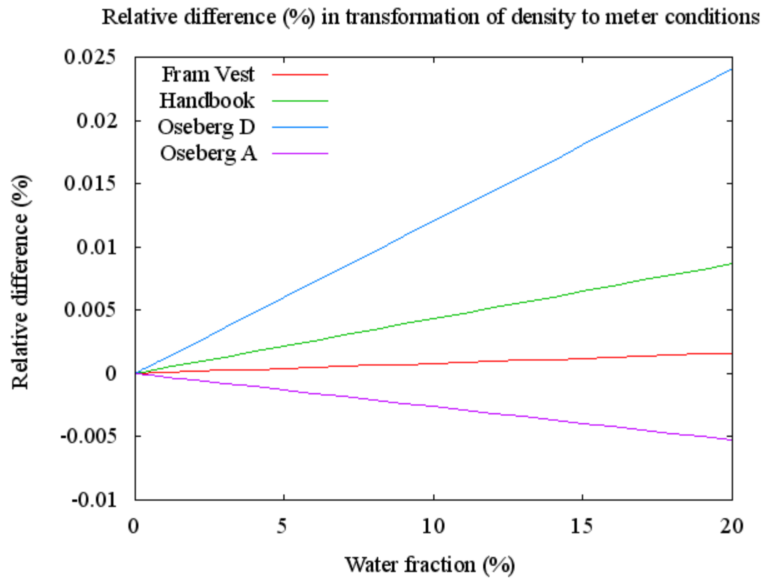
Additional uncertainty
contribution, vol. corr. from densitometer to turbine:

$$\left(\frac{u\left(\frac{(C_{tol}C_{pol})_{line}}{(C_{tol}C_{pol})_{dens}}\right)}{\frac{(C_{tol}C_{pol})_{line}}{(C_{tol}C_{pol})_{dens}}} \right)^2$$

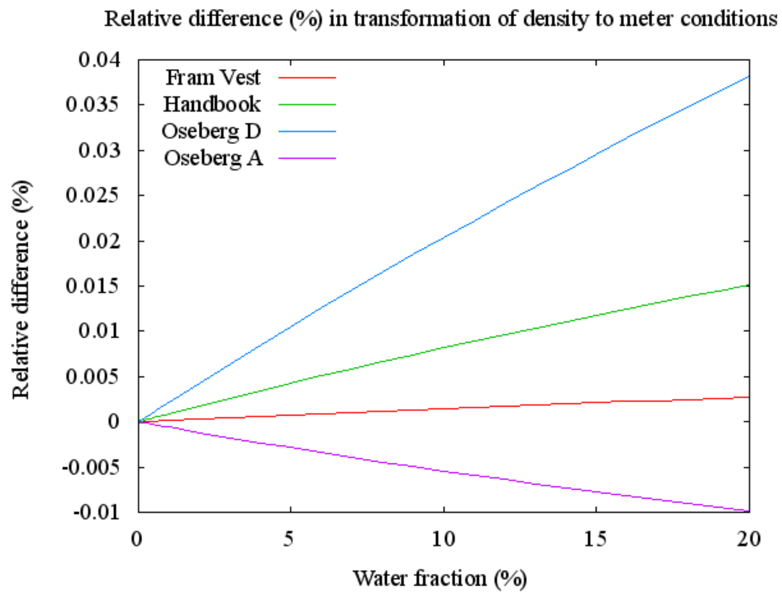
Effects:

- Using oil corr. factors instead of water/oil mixture corr. factors
- Possible effect of using mixture density instead of oil density
- Conclusion: Less than 0.04 % influence (100 % conf. level, rect. dist. func.)

Error when using correction factors based on pure oil density:



Error when using correction factors based on mixture density:



Sampling-based WIO treatment

Additional uncertainty contribution, density: $$\left(\frac{u(\rho_{dens}^{mix})}{\rho_{dens}^{mix}} \right)^2$$

What is the effect on the density meter itself (measured mixture density) of water in the oil?

- Questionare to 1 vendor, 1 answer
  - ”... any liquid ... is going to be measured, be it homogeneous or non-homogeneous.”
  - ”...we will measure the combined density of the water-in-oil mixture without any loss in density performance.”
- The sensitivity study shows that if this uncertainty contribution is less than about 0.5 % for WIO = 20 %, it can be neglected.
- In the sensitivity study, this effect has been neglected.

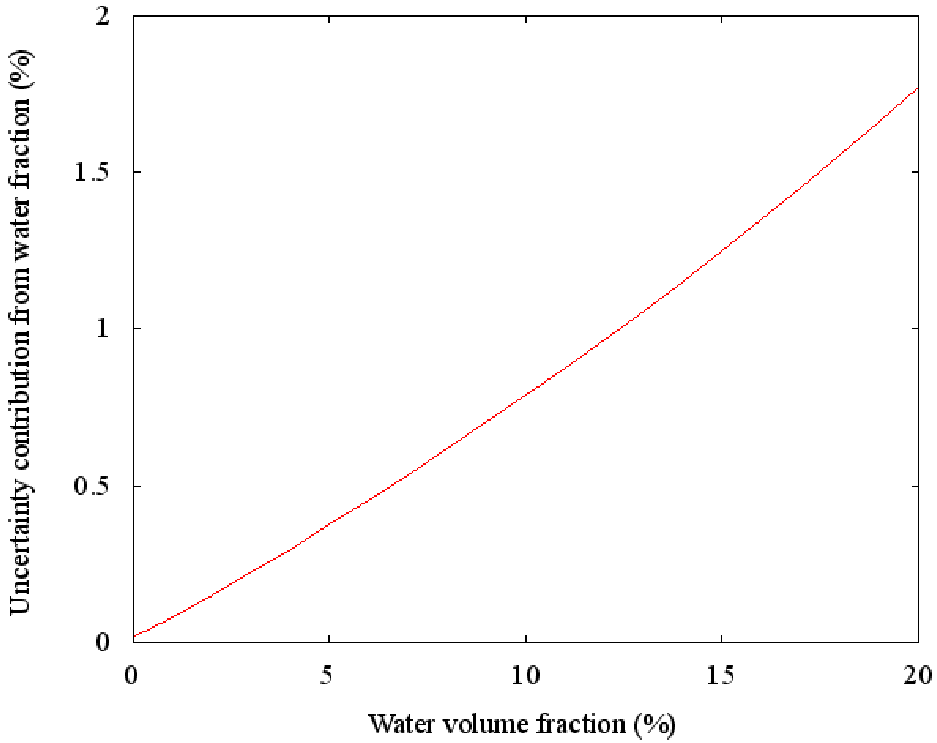
Sampling-based WIO treatment

Additional uncertainty contribution, water fraction, (sampling and analysis):

$$\left(\frac{u(\phi_{w,line}^{water})}{1-\phi_{w,line}^{water}} \right)^2$$

Uncertainty of the sample-based weight fraction of water at line conditions:

- ISO 3171 – Chapter 16.5.2, example 2
- Uncertainty due to random and systematic effects (95 % confidence interval)



Sampling-based WIO treatment

Additional uncertainty contribution, oil density at standard reference conditions:

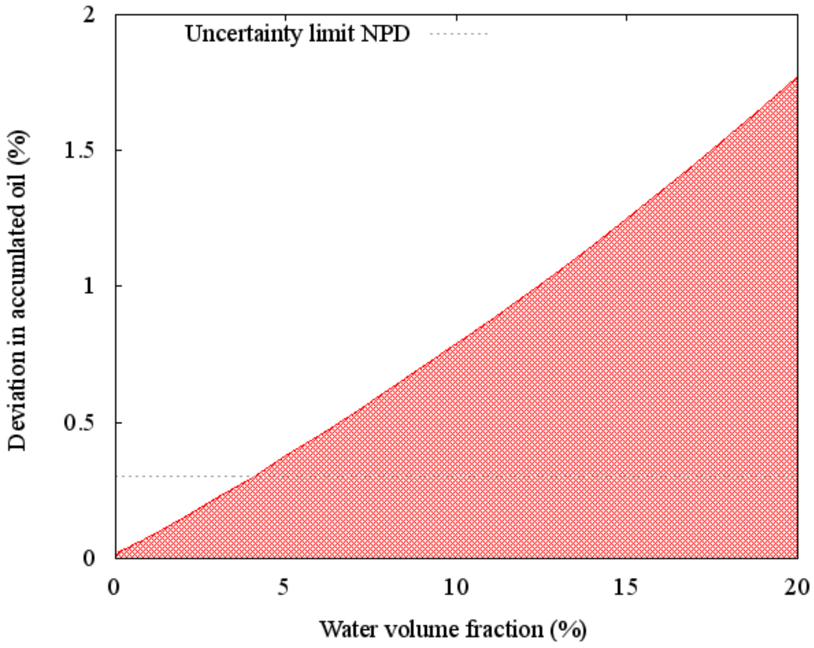
$$\left(\frac{u(\rho_{ref-o-pure})}{\rho_{ref-o-pure}}\right)^2$$

- From laboratory analyses.
- Assume complete separation.
- Measurement on pure oil.
- Water does not influence on the measurement
- Conclusion: 0 % influence

Sampling-based WIO treatment

Sensitivity summary for 20 % water in oil relative to pure oil:

Turbine:	0.15 %	(95 % c.l.)
K-factor, turbine:	0.15 %	(95 % c.l.)
K-factor, prover:	0 %	(95 % c.l.)
K-factor, volume correction:	0.01 %	(100 % c.l.)
Vol. correction densitometer to turbine:	0.04 %	(100 % c.l.)
Density measurement:	0 %	(95 % c.l.)
Water fraction:	1.77 %	(95 % c.l.)
Reference oil density:	0 %	(95 % c.l.)
TOTAL	**1.78 %**	**(95 % c.l.)**



Assumed ”linear” dependency of unc. contributions on WIO

Countinuous measurement of WIO

Continuous measurement of WIO

-functional relationship according to I-105

Proving:

$$K = \frac{MR_p}{BV}\frac{C_{tol}C_{pol}}{C_{top}C_{pop}C_{tsp}C_{psp}}$$

Water fraction at line conditions (similar for density conditions):

$$\phi_{line}^{water} = \left[1 + \frac{(1-\phi_{ref}^{water})C_{twl}C_{pwl}}{\phi_{ref}^{water}C_{tol}C_{pol}}\right]^{-1} \qquad \phi_{ref}^{water} = \left[1 + \frac{(1-\phi_{WIOmeter}^{water})C_{tow}C_{pow}}{\phi_{WIOmeter}^{water}C_{tww}C_{pww}}\right]^{-1}$$

Density at reference conditions:

$$\rho_{ref-o-pure} = \frac{\left(\rho_{dens}^{mix} - \phi_{dens}^{water}\rho_{dens}^{water}\right)}{\left(1-\phi_{dens}^{water}\right)C_{tod}C_{pod}}$$

Turbine metering:

$$q_v^{mix} = 3600\frac{MR_m}{K}$$

Volumetric flow rate of oil:

$$q_v^{net} = q_v^{mix}\left(1-\phi_{line}^{water}\right)$$

Standard volumetric flow rate of oil: $Q_{v,net} = q_v^{net}C_{tol}C_{pol}$

Continuous measurement of WIO

Uncertainty model:

$$\left(\frac{u(Q_{v,net}^{water\,impact})}{Q_{v,net}}\right)^2 = \left(\frac{u(MR_m)}{MR_m}\right)^2 + \left(\frac{u(K_{MRp})}{K}\right)^2 + \left(\frac{u(K_{BV})}{K}\right)^2 + \left(\frac{u(K_{corr})}{K}\right)^2 + \left(\frac{u(C_{tol}C_{pol})}{C_{tol}C_{pol}}\right)$$

$$+ \left(\frac{\partial Q_{v,net}}{\partial \rho_{dens}^{mix}} \frac{\rho_{dens}^{mix}}{Q_{v,net}} \frac{u(\rho_{dens}^{mix})}{\rho_{dens}^{mix}}\right)^2 + \left(\frac{\partial Q_{v,net}}{\partial \rho_{dens}^{water}} \frac{\rho_{dens}^{water}}{Q_{v,net}} \frac{u(\rho_{dens}^{water})}{\rho_{dens}^{water}}\right)^2 + \left(\frac{\partial Q_{v,net}}{\partial \phi_{line}^{water}} \frac{\phi_{line}^{water}}{Q_{v,net}} \frac{u(\phi_{line}^{water})}{\phi_{line}^{water}}\right)^2$$

Turbine meter at metering

Turbine meter at proving

Prover

As in sampling based WIO treatment

Volume corrections:
-from prover to turbine meter conditions

Volume corrections:
-from line to standard reference conditions

Measured density

Analysed water density

Volumetric water fraction at line conditions

NOT as in sampling based WIO treatment

Continuous measurement of WIO

Additional uncertainty contribution, volume correction from line to standard reference conditions:

$$\left(\frac{u(C_{tol}C_{pol})}{C_{tol}C_{pol}}\right)^2$$

This is due to uncertainty in oil density.

- Typical number for oil density uncertainty: less than 5 kg/m^3 (95 % c.l.) at WIO = 20 %.
- Influence on volume correction factor: 0.06 %

Continuous measurement of WIO

Additional uncertainty contribution, water density: $\left(\frac{u(\rho_{dens}^{water})}{\rho_{dens}^{water}} \right)^2$

This is based on laboratory analysis.

- Uncertainty contributions:
  - Degree of separation on laboratory
  - Analysis instrumentation
- Conclusions:
  - 1 % with 95 % confidence level chosen not to underestimate for measured water density.
  - Uncertainty contribution on vol. flow rate (95 % c.l.): 0 % (indirect through other contributions).

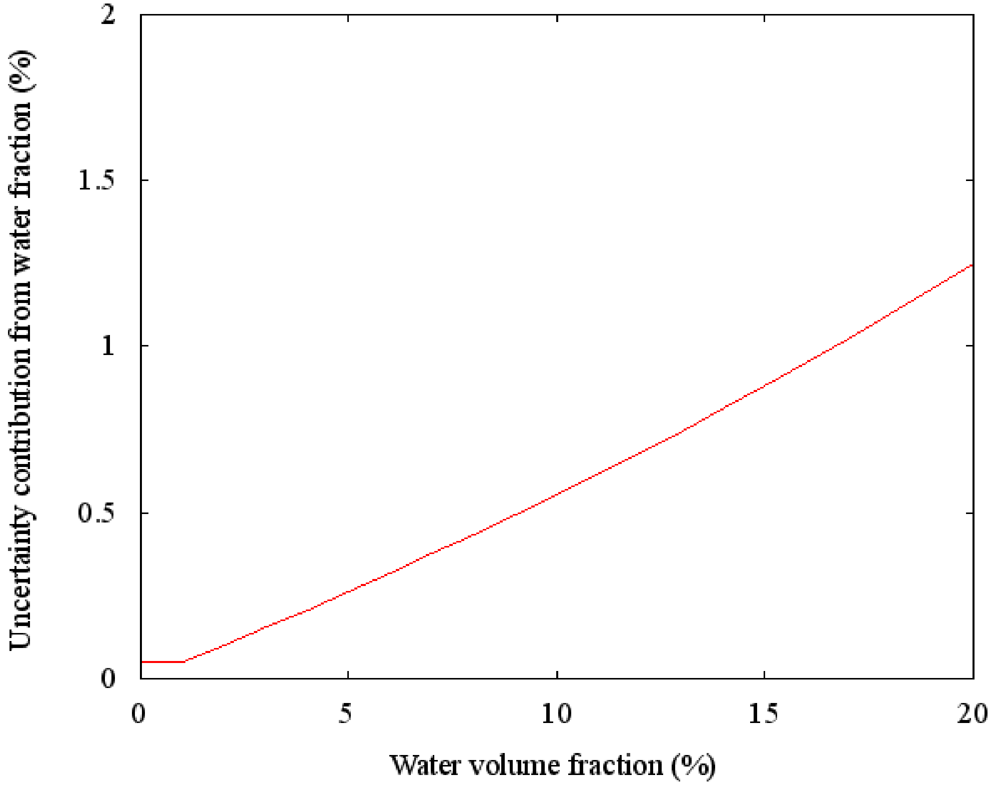
Continuous measurement of WIO

Additional uncertainty contribution, water density:

$$\left(\frac{\partial Q_{v,net}}{\partial \phi_{line}^{water}} \frac{\phi_{line}^{water}}{Q_{v,net}} \frac{u(\phi_{line}^{water})}{\phi_{line}^{water}} \right)^2$$

I-105: Uncertainty with 95 % conf. level (in agreement with Roxar WIOM specs. in the range 0-20 %):

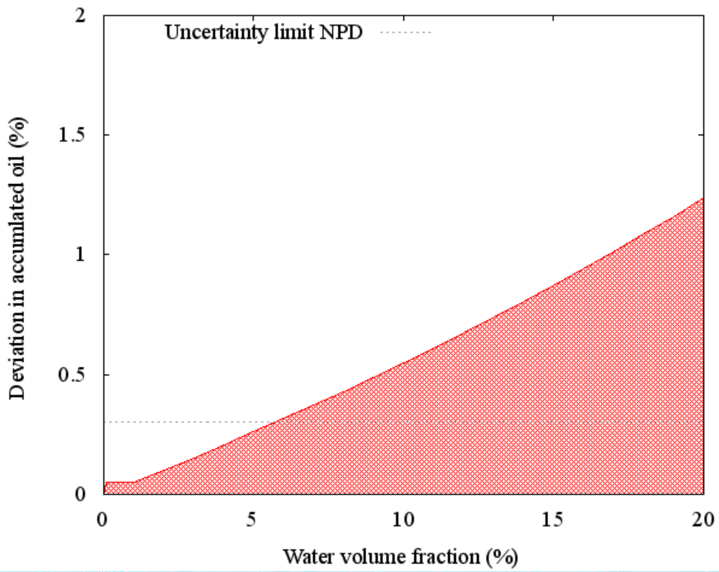
- 0.05 % abs volume fraction, for volume fractions 0 – 1 %.
- 5 % of reading, for volume fractions above 1 %



Continuous measurement of WIO

Sensitivity summary for 20 % water in oil relative to pure oil:

Turbine:	0.15 %	(95 % c.l.)
K-factor, turbine:	0.15 %	(95 % c.l.)
K-factor, prover:	0 %	(95 % c.l.)
K-factor, volume correction:	0.01 %	(100 % c.l.)
Vol. correction line to standard:	0.06 %	(100 % c.l.)
Mix. density measurement:	0 %	(95 % c.l.)
Water density:	0 %	(95 % c.l.)
Water fraction:	1.24 %	(95 % c.l.)
TOTAL	**1.26 %**	**(95 % c.l.)**



Assumed "linear" dependency of unc. contributions on WIO

Preliminary conclusions (study not fully completed)

- Fiscal turbine based oil metering station
- Volumetric flow rate of oil at standard reference conditions
- Cases studied:
  - Sampling based WIO treatment
  - Continuous measurement of WIO
- 0 – 20 % WIO
- Excess uncertainty due to the water in oil is studied
- Calculation examples from various North Sea fields
- The uncertainty in the WIO is the dominating term
- Results at 20 % WIO:
  - about 1.8 % uncertainty (95 % c.l.) for sampling based WIO treatment
  - about 1.2 % uncertainty (95 % c.l.) for continuous measurement of WIO