Challenges of ultrasonic quantum measurement of natural gas

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Introduction

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Fiscal gas flow measurement

"Measurement in connection with buying, selling and calculation of taxes" [a]:

• Sales measurement	Addressed here	(Class A)	(ISO: Class 1)
• Allocation measurement	Addressed here	(Class A)	(ISO: Class 2)
• Fuel gas measurement	Addressed here	(Class B)	
• Flare gas measurement		(Class C)	(ISO: Class 4)
• Simplified measurement system for gas		(Class D)	

[a] NPD Regulations (2001) ("Måleforskriften")

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USM fiscal gas flow measurement

- **Brief (and simplified) gas USM development history:**

  1985 - 1995: Development / testing of the first multipath fiscal ultrasonic meters (USMs) for natural gas

  1995 - 2000: Early industrialization

  2000 - 2010: Maturing of USM technology

- **Current situation (2010):**

  - The gross majority of new volumetric fiscal gas flow meters installed in the North Sea are USMs

  - USM technology has taken over for more traditional fiscal gas flow metering technologies, such as orifice and turbine meters

Examples of USM fiscal gas flow meters in the market

Emerson Daniel SeniorSonic

FMC Technologies MPU 1200

Elster Instromet Q-Sonic 5

Sick FLOWSIC600

Questions,
USM fiscal gas flow measurement

- Do the industry and national authorities (NPD) consider the present-day USM fiscal gas metering technology to be sufficient, with respect to
  - accuracy,
  - reliability,
  - robustness, etc.?

- Has the USM technology development reached its full potential with respect to
  - accuracy,
  - functionality,
  - measurement quantities?

Uncertainty requirements,
Fiscal measurement of natural gas

(flow laboratory calibrated)

	Gas metering station	USM Instrument
NPD (2001)	1 % of mass (95 % c.l.)	0.7 % of std. volume (95 % c.l.)
ISO/FDIS 17089-1 (2009) [a)]		Class 1 meters: 0.7 – 1.4 % of volume (large meters, ≥ 12") 1.0 – 1.4 % of volume (small meters, < 12") Class 2 meters: 1.0 – 2.0 % of volume (large meters, ≥ 12") 1.5 – 2.0 % of volume (small meters, < 12")
AGA-9 (2007) [a)]		0.7 – 1.4 % of volume (large meters, ≥ 12") 1.0 – 1.4 % of volume (small meters, < 12")

[a)] Confidence level not specified

Importance of accurate gas measurement
(Example: Ormen Lange gas, export station at Easington, UK)

Gas export Norway → UK:

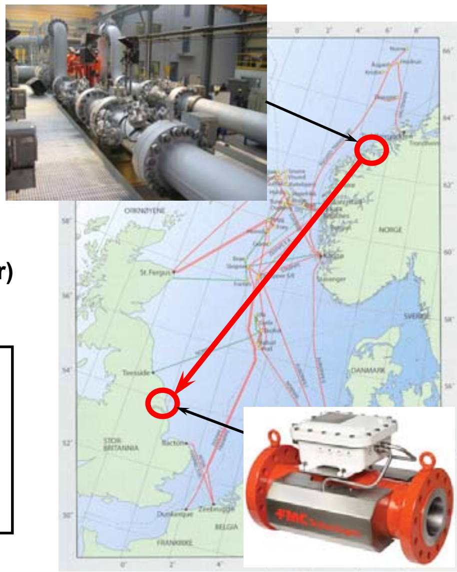
70 MSm³/day (≈ 25 billion Sm³/year)

20-25 % of Norway's gas export

20 % of UK's gas import

Assume sales price of 2 NOK/Sm³

=> 140 MNOK/day (≈ 50 billion NOK/year)



Importance of measurement error:

Example:	**0.5 % systematic error**
Represents:	**700 000 NOK/day**
	255 million NOK/year

The present talk

- **Addresses some of the important factors influencing on USM fiscal gas flow metering, with respect to**
  - **Recent developments**
  - **Challenges**
  - **Unexploited potentials**

- **Not intended to represent a complete overview of this topic**

Some developments 2000 - 2010

2000

Regulations and "standardization type" documents available in 2000:

- **NPD Regulations (1997),**
  "Forskrift om måling av petroleum for fiskale formål og for beregning av CO_2-avgift"
- **NORSOK Standard I-104, Rev. 2 (1998),**
  "Fiscal measurement systems for hydrocarbon gas"
- **ISO Technical Report ISO/TR 12765:1997,**
  "Measurement of fluid flow in closed cirquits - Methods using transit time ultrasonic flowmeters"
- **AGA Report No. 9 (1998),**
  "Measurement of gas by multipath ultrasonic meters"

2000

Some challenges pointed at [a]:

- **Need for accepted international standard on USM gas flow meters**
- **Need for improved control with systematic effects which are not necessarily eliminated by flow calibration:**
  - Installation effects, Wear, Deposits, PRV noise, Drift, P&T effects
- **Challenges with respect to achieving traceability (flow calibration → field operation)**
- **Need for uncertainty analysis of USM gas metering stations (aid to improve traceability)**

[a] *Lunde, Frøysa, Vestrheim: "Challenges for improved accuracy and traceability in ultrasonic fiscal flow metering", NSFMW 2000*

2010

Regulations and "standardization type" documents available in 2010:

- **NPD Regulations (2001) (updated 2006),**
  "Forskrift om måling av petroleum for fiskale formål og for beregning av CO_2-avgift"
- **NORSOK Standard I-104, Rev. 3 (2005),**
  "Fiscal measurement systems for hydrocarbon gas"
- **ISO/FDIS 17089-1 (2009),**
  "Measurement of fluid flow in closed conduits - Ultrasonic meters for gas - Part 1: Meters for custody transfer and allocation measurement"
- **AGA Report No. 9, Second ed. (2007),**
  "Measurement of gas by multipath ultrasonic meters"
- **NFOGM Handbook (2001),**
  "Handbook of uncertainty analysis. Ultrasonic fiscal gas metering stations"
- **Directive 2004/22/EC (2004),** "Measurement Instrument Directive (MID)"

Some other influencing factors, of increasing importance in recent years

- Increasing focus on "Integrated Operations" (IO):
  - Remote operation
  - Technical personnel on site covering a wider range of tasks
- Exchange of personnel connected to fiscal measurement of oil and gas (some operators)
- MID (EU Directive), in relation to NPD regulations
- Roles of NDP / Justervesenet / Klif (formerly SFT) in relation to regulation of fiscal measurements on the NCS

Factors influencing on accuracy, reliability and traceability

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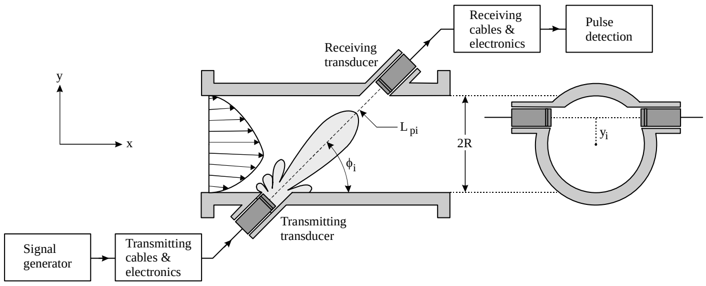
Factors influencing on measurement uncertainty, reliability, traceability, etc.



Discussed here:

- Transducers
- Factors influencing on transit time determination
- Installation effects (flow profiles)
- P & T effects (body, chords, angles, transducers, transit times)

Transducers

Transducer failure

- Seems to be less of a problem today than earlier
- Can still be experienced e.g. in connection with:
  - Steaming of the pipe / meter
  - Sudden and large pressure changes, e.g. in connection with "shut-down" (imposing "mechanical shock")
  - Exposure of transducer epoxy front to condensate (liquid "carry-over" at outlet of 1st and 2nd stage separators)
- Change of a single transducer instead of a transducer pair is desireable

Transducers

- In the North Sea: Several applications with gas metering at very high pressures (several hundred bars)
  - May impose severe challenges for the transducers

- Transducer properties:
  - Bandwidth (signal form), Transducer time delay, Diffraction correction, Directivity, Electrical impedance, ...
  - Change with P & T ("drift")
  - Ageing
  - May change if subject to
    - deposits (liquid film, grease)
    - wear (condensate, in case of epoxy front)
  - Changes increasingly important for small meters (3", 4", 6")

Factors influencing on Transit time determination

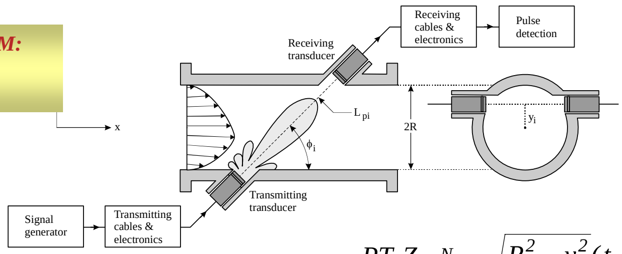
- "Dry calibration" parameters:
  - Cable / electronics / transducer time delay
  - Diffraction time shift
  - Δt-correction
- Variation of "Dry calibration" parameters with:
  - P & T, Path length, Time

Discussed here

- Transducer deposits / liquid film
- Transducer wear (exposure e.g. to condensate)
- Incoherent noise (PRV)
- Coherent noise (cross-talk, interference)
- Time detection (clock frequency, averaging)
- Turbulence
- Profile effects (refraction)

USM functional relationship (extract)

A single path in a USM: (ex.: downstream propagation)



$$Q \approx 7200\pi R^2 \frac{PT_0Z_0}{P_0TZ} \sum_{i=1}^{N} w_i \frac{\sqrt{R^2 - y_i^2}\,(t_{1i} - t_{2i})}{t_{1i}t_{2i}\,|\sin 2\phi_i|}$$

Transit time corrections

(possible formulation):

Cable / electronics / transducer / diffraction time delay

Upstream: $t_{1i} = t_{1i}^{measured} - t_{1i,0}^{eltr} - t_i^{cavity}$

Downstream: $t_{2i} = t_{2i}^{measured} - t_{1i,0}^{eltr} + \Delta t_{i,0}^{corr} - t_i^{cavity}$

Estimated in "dry calibration" procedure

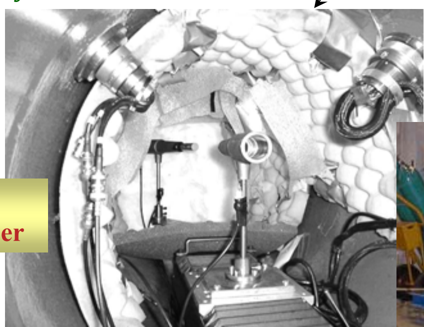
Δt-correction

Transit time corrections (1): Time delay

Cable / electronics delay **Transducer delay** **Diffraction time shift**

Upstream: $t_{1i} = t_{1i}^{measured} - \left(t_{1i,0}^{el,cab} + t_{1i,0}^{tr} + t_{1i,0}^{dif}\right) - t_i^{cavity}$

Transducer delay measurements:



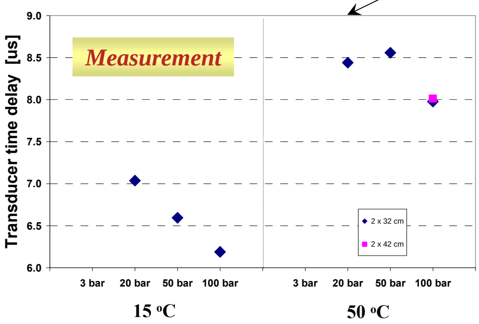
200 bar pressure chamber

[After: Lunde, Frøysa, Vestrheim, M. (eds.): "GERG project on ultrasonic gas flow meters, Phase II", GERG Technical Monograph 11, 2000]

Transit time corrections (1): Time delay

Transducer time delay (Systematic changes with *P & T*)

Upstream: $t_{1i} = t_{1i}^{measured} - \left(t_{1i,0}^{el,cab} + t_{1i,0}^{tr} + t_{1i,0}^{dif} \right) - t_i^{cavity}$



Consequences (example):

6” USM: If time delay deviates 1 µs from “dry calibration” value:

USM shift of 0.4 %

Control of systematic changes in transducer delay with *P & T* is very important …… and possible !

[After: Lunde, Frøysa, Vestrheim, M. (eds.): “GERG project on ultrasonic gas flow meters, Phase II”, GERG Technical Monograph 11, 2000]

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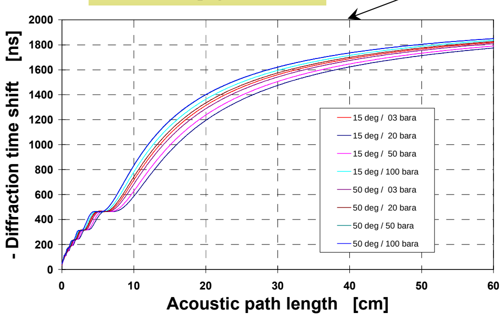
Transit time corrections (1): Time delay

Diffraction time shift (Systematic changes with *P, T & Path length*)

Upstream: $t_{1i} = t_{1i}^{measured} - \left(t_{1i,0}^{el,cab} + t_{1i,0}^{tr} + t_{1i,0}^{dif} \right) - t_i^{cavity}$

Measurement + calculation, simplified



Consequences (example):

If “dry calibration” time delay valid for 16” USM is used in 6” USM:

USM shift of 0.2 %

Control of systematic changes in diffraction time shift with *path length* is important …….. and possible !

[After: Lunde, Frøysa, Vestrheim, M. (eds.): “GERG project on ultrasonic gas flow meters, Phase II”, GERG Technical Monograph 11, 2000]

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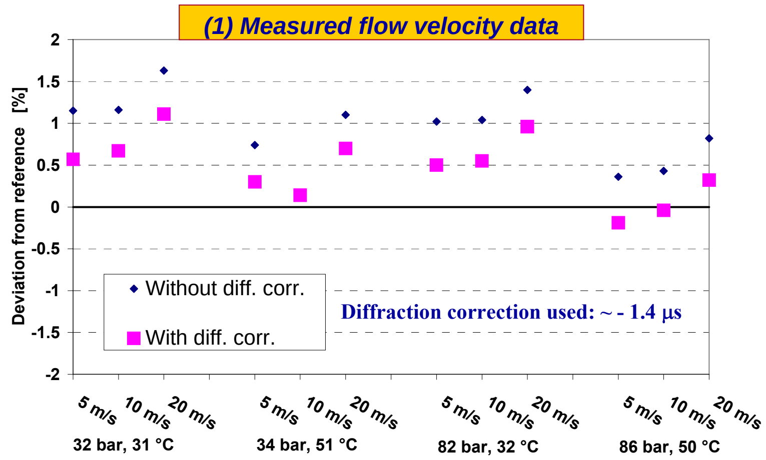
Flow testing (K-Lab), with and without diffraction correction

FMC Kongsberg Metering MPU 1200 ***6”, 5 – 20 m/s, 32 – 86 bar, 31 – 50 °C***



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[*After:* *Lunde, Frøysa, Kippersund, Vestrheim:* "*Transient diffraction effects in ultrasonic meters for volumetric, mass and energy flow measurement of natural gas*", *NSFMW 2003*]**

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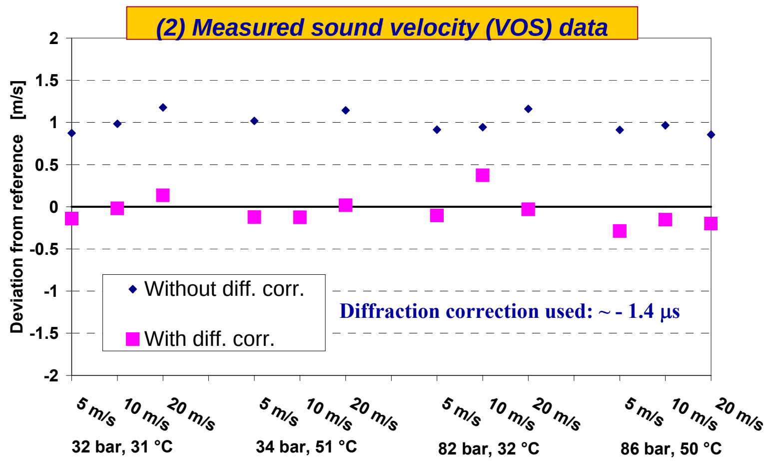

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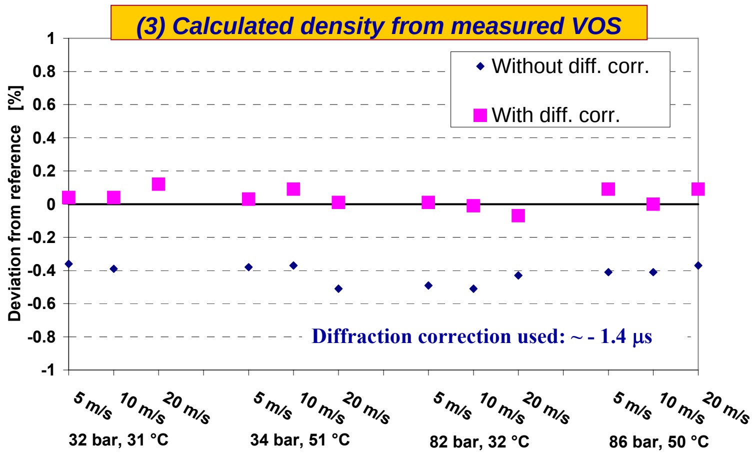
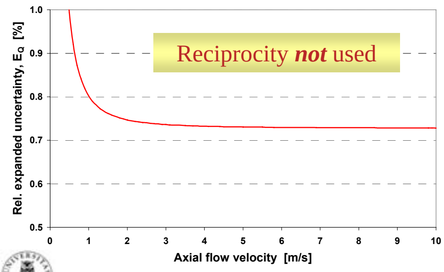


[*After:* **Lunde, Frøysa, Kippersund, Vestrheim:** *"Transient diffraction effects in ultrasonic meters for volumetric, mass and energy flow measurement of natural gas"*, **NSFMW 2003**]

Transit time corrections (2): Δt-correction

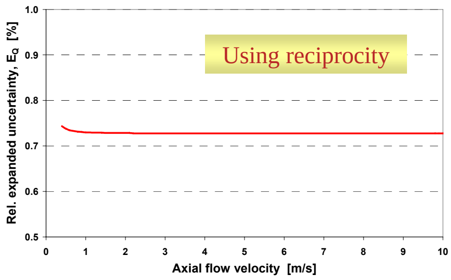
Reciprocal operation not realized

- "Dry calibration" / "Zero flow verification" (AGA-9, 2007)
- Active Δt-correction (AGA-9, 2007) (Manufacturer dependent procedure)
- Δt-correction may vary with P&T



Reciprocal operation realized

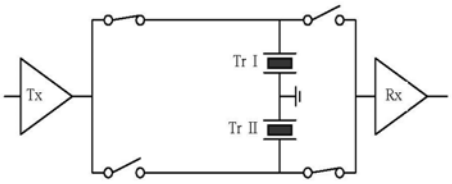
- Optimize electro-acoustic system with respect to reciprocity
- Reduced or no need for "dry calibration" (Δt-correction)
- Valid for all P, T & Path lengths



Reciprocal operation of USM gas flow meter

Realization of "sufficient reciprocal operation"

$$|Z_S - Z_L| < 0.6\Omega$$



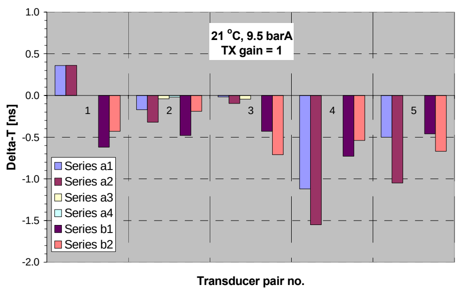
Transducer (Gas USM)

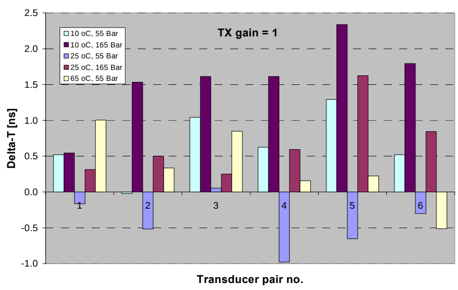
Electronics boards

[*After: Lunde, Vestrheim, Bø, Smørgrav, Abrahamsen: "Reciprocity and its utilization in ultrasonic flow meters", NSFMW 2005*]

Measurement results - Reciprocal operation

21 °C, 9.5 barA | **10 - 65 °C, 55 - 165 barA**





All results: Δt_i < 2.4 ns

"Sufficient reciprocal operation" achieved, over P-T range investigated

[*After: Lunde, Vestrheim, Bø, Smørgrav, Abrahamsen: "Reciprocity and its utilization in ultrasonic flow meters", NSFMW 2005*]

Reciprocal operation, - Consequences for USMs

If *“sufficient reciprocal operation”* is achieved for the USM measurement system:

- Eliminates the need for factory “dry calibration” of Δt_i
  - Cost reduction
  - Independent of gas used for “zero flow verification” (no gas properties needed)
- Eliminates the need for active Δt - correction in field operation
  - Independent of P & T, gas, etc.
- Reduces “false flow” reading at low flow velocities & Does not affect reading at higher flow velocities
  $\Rightarrow$ Improves linearity (low flow velocities)
- No need for transducers to be equal in their characteristics

Installation effects / USM integration methods

- **USM integration method influenced by:**
  - Axial and transversal flow profiles
  - Meter orientation rel. to flow profile
  - Pipe bends (single, double, upstream length, etc.)
  - Flow profile at bend inlet
  - Possible use of Flow conditioner (FC)
  - Pipe roughness (effects on flow profile)
  - Possible pipe deposits / wear (effects on flow profile)

- **Integration uncertainty:** One of the large and essentially un-known uncertainty contributors when going from flow calibration to field operation

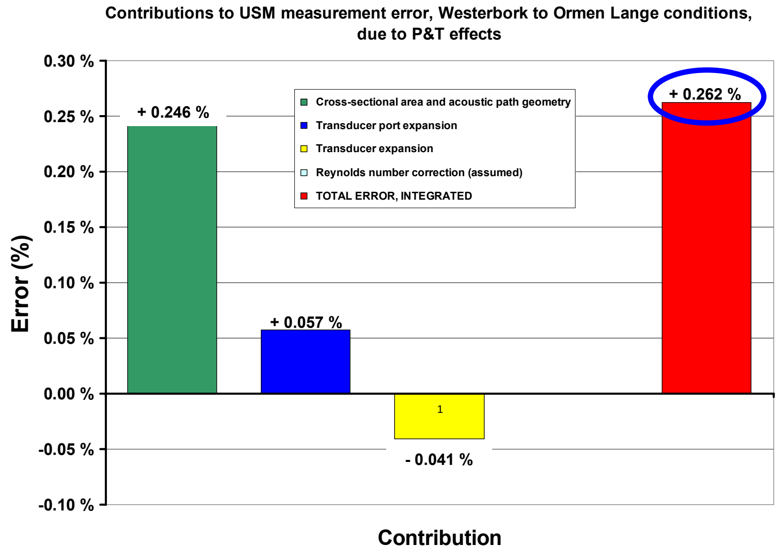
Pressure and temperature (P-T) effects

- **In the North Sea: Several applications with gas metering at very high pressures**
- **Flow calibration laboratories: Limited to 60 bar pressure**
- **Change of P-T conditions from flow calibration to field operation introduces systematic errors:**

	Direct P&T effect	Indirect P&T effect
A	Change of the meter body cross-sectional area	Affects amount of gas flowing through the flow meter
B	Change of the ultrasonic path geometry (changed inclination angles and lateral chord positions, caused by diameter change & changed transducer port orientation)	Affects acoustic path lengths and thus transit times. Influences on the numerical integration method.
C	Change of the length of the ultrasonic transducer ports	Affects acoustic path lengths and thus transit times.
D	Change of the length of the ultrasonic transducers	Affects acoustic path lengths and thus transit times.
E	Change of the Reynolds number	Influences on the numerical integration method.

- **Example: Ormen Lange (Nyhamna); extensive study indicated systematic error of the order of 0.26 % due to P&T effects, being corrected for**

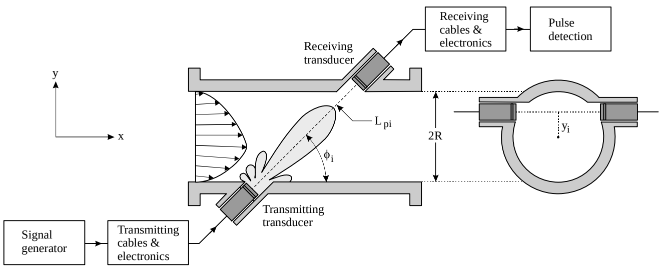
Contributions to measurement error – Ormen Lange



[*After: Lunde, Frøysa and Folkestad: "Pressure and temperature effects for Ormen Lange ultrasonic gas flow meters", NSFMW 2007*]

Possible approaches to improve on accuracy, reliability and traceability

Possible approaches to improve on accuracy, reliability, traceability, etc.



Discussed here:

- P & T correction (body, chords, angles, transd., transit times)
- Use of USM diagnostic tools, for condition based monitoring
- Use of USM "foot-print"
- Improved use of uncertainty modelling / evaluation, for fiscal gas metering systems

Pressure and temperature (P-T) effects

- Ormen Lange study initiated by NPD in cooperation with Norsk Hydro (now Statoil) and Norske Shell, and carried out by CMR in cooperation with UoB

- Ormen Lange study initiated important revised approach for P-T correction in ISO/FDIS 17089-1 (2009)

- The work is continued to investigate practical and still relatively accurate approaches for P-T correction, such as:
  - Accuracy of simplified correction approach (including use of thick-shell theory),

    relative to use of more accurate FEM (finite element modelling) based approach

Use of diagnostics tools, for Continuous condition based monitoring (1)

- Diagnostic tools (examples):
  - VOS, at every path
  - Gain, ------- " --------

- Key question from users:
  - What should the alarm limits be (e.g. for VOS and Gain)?

- AGA-9 (2007) recommendations:
  - VOS deviation re. calculation (AGA-10): $\pm$ 0.2 % $\approx$ 1 m/s
  - Max VOS path spread: 0.5 m/s $\approx$ 0.1 %

- NPD requirements (2001):
  - Shall use information available in the instrument
  - Condition based parameters shall be verified

Use of diagnostics tools, for Continuous condition based monitoring (2)

- **Possible additional approach (tentatively):**
  - **Gather long time operational information (history), to establish typical "standard deviation" limits, for given operational cond. (gas, P, T):** $\boxed{\sigma_{VOS}^{\lim},\ \sigma_{Gain}^{\lim}}$
  - **Continuously monitor "short-time standard deviations":** $\boxed{\sigma_{VOS},\ \sigma_{Gain}}$
  - **If** $\sigma_{VOS} > N \cdot \sigma_{VOS}^{\lim},\ \ \sigma_{Gain} > N \cdot \sigma_{Gain}^{\lim}$ $\Rightarrow$ **Alarm**

    N = 3, tentatively
  - **The potentials of such methods may be evaluated on current installations**
  - **Methods should be real-time, standardized, and preferably application independent (field and installation independent)**

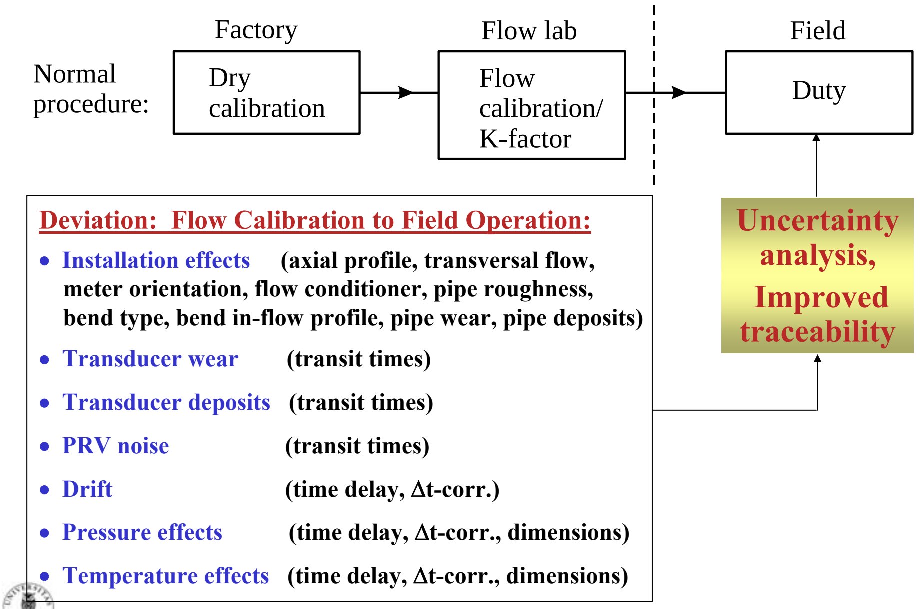
Use of USM "foot-print"

- **National regulations:**
  - **UK:** **Recalibration after a certain period of time**
  - **Norway:** **Recalibration when available information indicates need**
- **Recalibration in flow calibration lab. with full "installation piping": time consuming and expensive**
- **Possible alternative, use of USM "foot-print":**
  - **Check of meter characteristics in a standardized measurement set-up (with respect to installation and operational conditions), used before (or at) field installation, and after some time in duty**
  - **Serves to check to which extent the meter has changed over time (reproducability, long time drift, ageing)**
  - **Does *not* represent a flow calibration**
  - **Can indicate whether a new flow calibration is needed or not**
  - **May *not* indicate drift from flow calibration to field operation**

Uncertainty modelling and evaluation

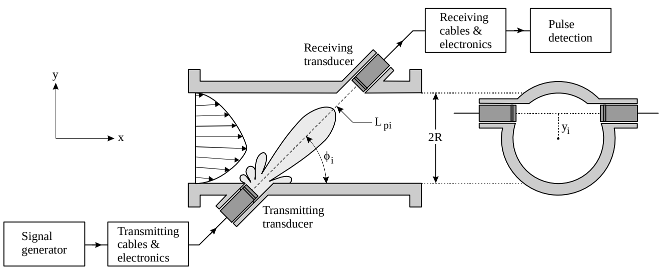
- Changes of the USM instrument from flow calibration to field operation may be treated using uncertainty models and evaluation
- An accepted uncertainty model and analysis of USM gas metering systems can be a valuable tool in the work to achieve improved traceability (flow calibration → field operation)
- An internationally accepted uncertainty description may eventually become an integrated part of international standards on fiscal measurement of natural gas
- Basis already available: NFOGM Handbook (2001), *"Handbook of uncertainty analysis. Ultrasonic fiscal gas metering stations"*
- For improved utility of the uncertainty Handbook:
  - Improved information on input uncertainties desirable, from manufactures, operators, empirical data, etc.

Uncertainty analysis of USM gas metering system



Extended measurement functions and applications

Extended measurement functions and applications



Discussed here:

- Mass and energy flow measurement using USMs
- Activity data and CO_2 emission factor
- Based on USM measurement of sound velocity (VOS)

Energy flow rate measurement – CMR method

Std. Volumetric Flow Rate (Sm^3/h) **x** Gross calorific value (GCV) **=** Energy Flow Rate (MJ/h)

Ultrasonic flow meter (USM)
(meter independent)

Pressure & Temperature
+
Velocity of sound (VOS)
+
Gas composition knowledge (optional)

Gas Analyzer
(connected to flow computer)

[*Ref.:* ***Frøysa, Lunde, Paulsen and Jacobsen:*** *"Density and calorific value measurement of natural gas using ultrasonic flow meters. Results from testing on various North Sea gas field data",* ***NSFMW 2006***]

Mass flow rate measurement – CMR method

Volumetric Flow Rate (m^3/h) **x** Density **=** Mass Flow Rate (kg/h)

Ultrasonic flow meter (USM)
(meter independent)

Pressure & Temperature
+
Velocity of sound (VOS)
+
Gas composition knowledge (optional)

Gas Analyzer
(connected to flow computer)

[*Ref.:* ***Frøysa, Lunde, Paulsen and Jacobsen:*** *"Density and calorific value measurement of natural gas using ultrasonic flow meters. Results from testing on various North Sea gas field data",* ***NSFMW 2006***]

Applications (examples)

- **Custody transfer USM gas metering stations:**
  - Backup for online GCs
  - Replacement for one GC in stations where two GCs are used
- **Allocation metering stations**
- **Metering stations without GC / densitometer (check metering)**
- **Fuel gas metering:**
  - Activity data (accumulated mass)
  - CO_2 emission factor

Conclusions

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Conclusions (1)

- USMs and USM fiscal gas metering systems are complex, high-tech instruments, requiring expertise for reliable and accurate operation

- A number of advances have been achieved in recent years, as a result of extensive R&D, e.g.:
  - National & international standardization and regulations,
  - Uncertainty modelling and evaluation,
  - Reduction of transducer failures,
  - Δt-correction / reciprocal operation,
  - Description and use of diffraction correction,
  - Pressure and temperature (P-T) correction,
  - Robustness vs. PRV noise

Conclusions (2)

- A number of topics still represent challenges, such as:
  - Change of conditions, flow calibration → field operation, influencing on traceability:
    - Installation effects, transducer drift with P&T, deposits, ...
  - Optimum use of uncertainty analysis, to improve traceability
  - Optimum and standardized use of USM diagnostic tools, e.g. real-time condition based monitoring / alarm (VOS, Gain, ...)
  - Methods for check of USM reproducibility and long-time drift

- An accepted uncertainty model can be a valuable tool in the work to achieve traceability, and should be an integrated part of the standards
  - Current international standards [ISO 17098-1 (2009), AGA-9 (2007)] are still insufficient on uncertainty modelling and evaluation of USM gas metering systems

Conclusions (3)

- There are clearly un-exploited potentials to further optimize USM technology to provide:
  - Technically improved meters
  - Improved operational cost/benefit ratio
  - Extended measurement functions and applications

- Further R&D is recommended, to better exploit the full potentials of USM technology. Potentials of improvement include:
  - Transit time corrections
    - P&T induced drift, Diffraction correction for real transd., etc.
  - Integration methods
  - Use of VOS for extended measurements
    - Energy measurement, Mass & CO_2 emission factor (fuel gas), ...
  - Improved use of USM diagnostics (condition based monitoring)

Conclusions (4)

Some important prerequisites for
(a) gradually closing the challenge gaps,
(b) further technology development,
to reach the full exploitation potential of the USM technology:

- Market driven development / manufacturer competition (*... we need to have what they have ...*)
- Focus from national authorities (NPD) to ensure safe, reliable and accurate fiscal measurement systems
- Expertise in user companies (oil and gas industry, pipeline operators) on USM technology, with capabilities of questioning the technology in their dialogue with manufacturers
- Independent organisations with high expertise on USM technology (universities / research institutes / service companies), with capabilities of questioning the technology, and further development of the technology
- Continuous development / upgrading of national and international standards, and other documents bringing the industry forward

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