Pressure and temperature effects for Ormen Lange ultrasonic gas flow meters

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Introduction

Ormen lange ultrasonic fiscal gas metering station

Gas at 230 bar pressure, 18" pipe

Gas export Norway → UK:

70 MSm^3/day (≈ 25 billion Sm^3/year)

20-25 % of Norway's gas export

20 % of UK's gas import

Assume sales price of 2 NOK/Sm^3

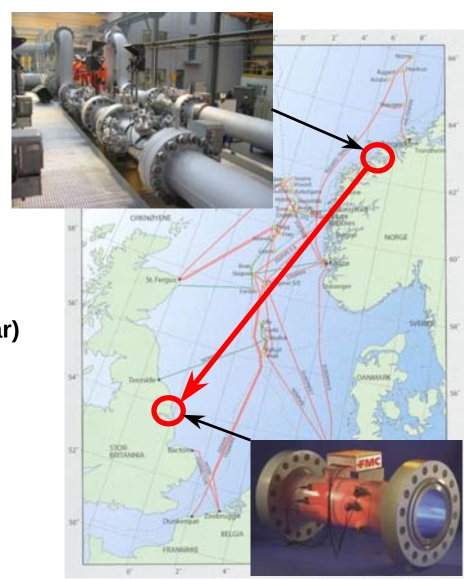
=> 140 MNOK/day (≈ 50 billion NOK/year)

Importance of measurement error:

0.3 % (example)

Represents: 420 000 NOK/day loss

150 million NOK/year loss

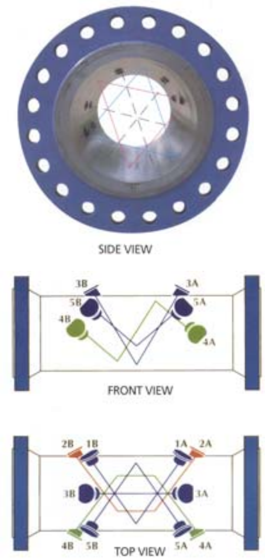


Ormen lange ultrasonic fiscal gas metering station

Ormen lange ultrasonic fiscal gas metering station

- **Location: Nyhamna, Møre and Romsdal, Norway**
- **3 parallel runs, with 5 ultrasonic gas flow meters (USMs):**
  - **2 parallel runs with 2 18" USMs in series (ID = 366.5 mm)**
  - **1 parallel run with 1 18" USM, for measurement at maintenance (ID = 366.5 mm)**
- **Flow conditioner: K-Lab / Laws type**
- **USM: Elster Instromet Ultrasonics Q-Sonic 5**

Elster-Instromet Q-sonic 5 path configuration



Specifications

	Westerbork flow calibration conditions	Ormen Lange line conditions (metering station) (nominal)
Gas	Dry natural gas	Dry natural gas
Pressure	63 barg	230 barg
Temperature	7 ºC	40 ºC
Viscosity	$1.30 \cdot 10^{-5}$ Pa-s	$2.28 \cdot 10^{-5}$ Pa-s
Density	57.36 kg/m^3	186.6 kg/m^3
Flow velocity	1.5 – 19 m/s	15 - 16 m/s
Reynolds number	$2.4 \cdot 10^6 – 3.0 \cdot 10^7$	$4.5 \cdot 10^7$

Objective

On behalf of Hydro, on a request from NPD, and in a close dialogue with Shell, CMR has undertaken a study with objective to:

Establish correction factor(s) for pressure and temperature effects on the 18" Q-Sonic 5 ultrasonic flow meters, from Westerbork flow calibration conditions, to Ormen Lange line conditions.

The correction factor is to account for:

	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.

The correction factor is to be implemented in the flow computer, not in the ultrasonic flow meter

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Analysis of

P&T effects on:

Cross-sectional area &

ultrasonic path geometry

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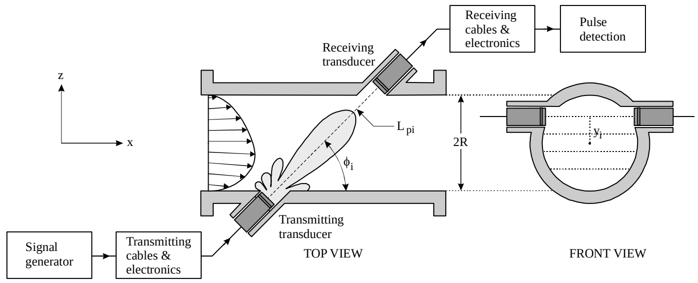
USM functional relationship

Volumetric flow rate (at line conditions):



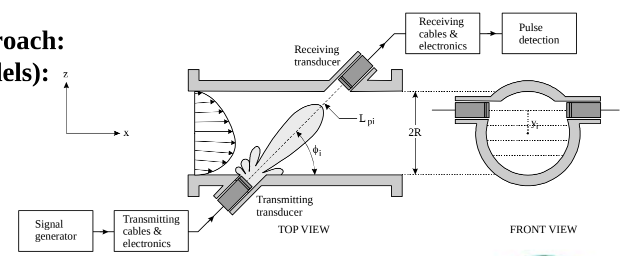
$$q_{USM} = 2\pi R^2 \sum_{i=1}^{N} w_i \frac{(N_{refl,i}+1)\sqrt{R^2 - y_i^2}\,(t_{1i} - t_{2i})}{t_{1i} t_{2i} \,|\sin 2\phi_i\,|}$$

Instromet Q-Sonic 5: $N_{refl,i}$ = 1 (3 center paths) and

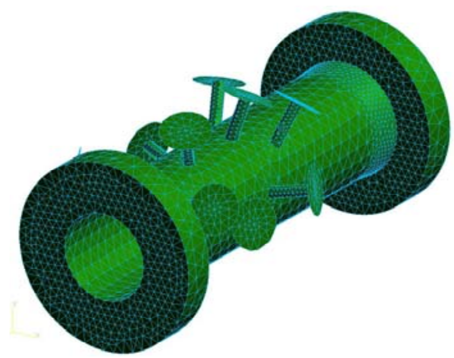
2 (2 paths)

Analysis methods: P & T effects on USM meter body

(1) Analytical approach: (simplified models):

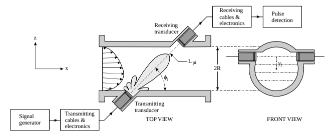


(2) Numerical approach: Finite element modelling (FEM):



P & T effects on USM meter body: Analytical model A

$$q_{USM} = 2\pi R^2 \sum_{i=1}^{N} w_i \frac{(N_{refl,i}+1)\sqrt{R^2 - y_i^2}\,(t_{1i} - t_{2i})}{t_{1i}t_{2i}\,|\sin 2\phi_i|}$$



where

$$R \approx K_T K_P R_0$$

$$y_i \approx K_T K_P y_{i0}$$

$$\phi_i \approx \tan^{-1}\left(\frac{\tan(\phi_{i0})}{1-(1-\frac{\beta^*}{\beta})(K_P - 1)} \right)$$

$$K_T \equiv 1 + \alpha \Delta T_{dry} \qquad \Delta T_{dry} = T - T_0$$

$$K_P \equiv 1 + \beta \Delta P_{dry} \qquad \Delta P_{dry} = P - P_0$$

α = thermal expansion coefficient of meter body material

β = radial pressure expansion coefficient of meter body material

β^* = axial pressure expansion coefficient of meter body material

K_T = *radial* temperature correction factor of meter body material

K_P = *radial* pressure correction factor of meter body

R_0 = meter body radius at dry calibration conditions

y_{i0} = lateral chord position at dry calibration conditions

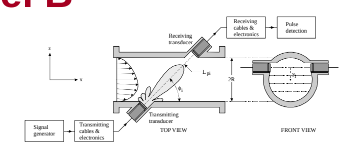
ϕ_{i0} = inclination angle at dry calibration conditions

T_0 = gas temperature at dry calibration conditions

P_0 = gas pressure at dry calibration conditions

Ref.: *Handbook of uncertainty calculations, Ultrasonic fiscal gas metering stations*, NFOGM, NPD, CMR (2001)

P & T effects on USM meter body: Analytical model B



Less accurate model (OK for angles ϕ_i = ±45º):

$$q_{USM} \approx q_{USM,0} C_{tsm} C_{psm}$$

where

$$C_{tsm} = K_T^3 = (1 + \alpha \Delta T)^3 \approx 1 + 3\alpha \Delta T$$

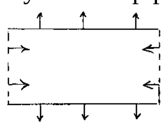
$$C_{psm} = K_P^3 = (1 + \beta \Delta P)^3 \approx 1 + 3\beta \Delta P$$

Ref.: *Handbook of uncertainty calculations, Ultrasonic fiscal gas metering stations*, NFOGM, NPD, CMR (2001)

Radial and axial pressure expansion coefficients

Various analytical models for meter body pressure expansion
(for thin wall, $w/R_0 < 0.1$)

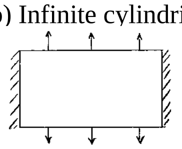
(a) Cylindrical pipe section model (ends free):



$$\beta = \frac{R_0}{wY} \qquad \beta^* = -\frac{R_0\sigma}{Yw} \qquad \frac{\beta^*}{\beta} = -\sigma$$

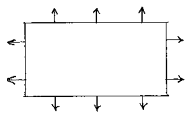
← Used for Ormen Lange

(b) Infinite cylindrical pipe model (ends clamped) :



$$\beta = \frac{R_0}{wY}\left(1-\frac{\sigma}{2}\right) \qquad \beta^* = 0 \qquad \frac{\beta^*}{\beta} = 0$$

(c) Cylindrical tank model (ends capped) :



$$\beta = \frac{R_0}{wY}\left(1-\frac{\sigma}{2}\right) \qquad \beta^* = \frac{R_0}{Yw}\left(\tfrac{1}{2}-\sigma\right) \qquad \frac{\beta^*}{\beta} = \frac{1-2\sigma}{2-\sigma}$$

w = average wall thickness of meter body
Y = Young's modulus (modulus of elasticity) of meter body material
σ = Poisson's ratio of meter body material

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Radial and axial pressure expansion coefficients

Various analytical models for meter body pressure expansion
(for thin wall, $w/R_0 < 0.1$)

Model (a): Relevant for thin-walled spoolpiece mounted in pipe section where ends can move relatively freely (displacement ~ sub-mm), e.g. with U-bend as part of the pipe section
➔ Most relevant here, of these three

Model (b): Relevant for thin-walled spoolpiece mounted in pipe section where ends can not move (clamped), such as straight and very long ("infinite") pipe sections
➔ Not relevant here

Model (c): Pressure tank model, relevant for thin-walled spoolpiece with blind flanges
➔ Not relevant here

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Radial and axial pressure expansion coefficients

Models in use for β and β^* by Standards & gas USM manufacturers:

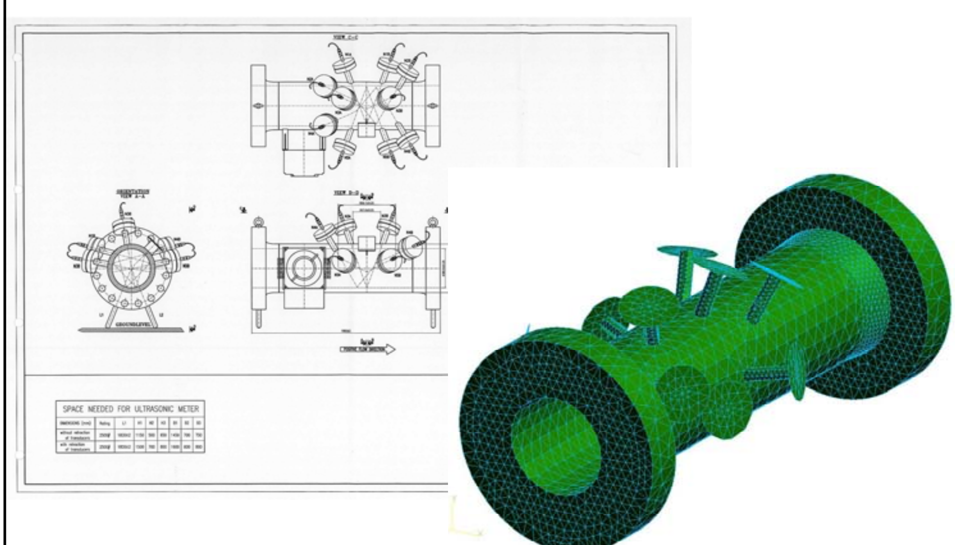
Reference / USM manufacturer	Models for the coefficient of linear radial pressure expansion, β	USM meter body assumptions
[AGA-9, 1998], [Roark, 2001, p. 592]	$\beta = \frac{R_0}{wY}$	• Cylindrical pipe section model (ends free) • Thin wall, $w < R_0/10$
Daniel Industries [Daniel, 1996, 2001]	$\beta = \frac{1}{Y}\frac{1.3(R_0+w)^2+0.4R_0^2}{(R_0+w)^2-R_0^2}$ ($\beta \approx 0.85\frac{R_0}{wY}$ for $w << R_0$)	• Cylindrical tank model (pipe with ends capped) • Thick wall • Steel material ($\sigma = 0.3$)
FMC Kongsberg Metering [Kongsberg, 2001], [Roark, 2001, p. 593]	$\beta = \frac{R_0}{wY}\left(1-\frac{\sigma}{2}\right)$ ($\beta = 0.85\frac{R_0}{wY}$ for $\sigma = 0.3$ (steel))	• Cylindrical tank model (pipe with ends capped) [1] • Thin wall, $w < R_0/10$
Instromet [Autek, 2001]	No P or T correction used. Pressure expansion analysis based on: $\beta = 0.5\frac{R_0}{wY}$	• Infinitely long pipe model (ends clamped, no axial displacement) • Radial expansion assumed to be = 0.5 · radial expansion for ends-free model • Thin wall, $w < R_0/10$
ISO/CD 17089 [Draft V15, April 2006]	$\beta = \frac{1}{3}\frac{3D_0}{4wY} = 0.5\frac{R_0}{wY}$	• Flanged-in meter body • Thin wall, $w < R_0/10$ (?)
ISO/CD 17089 [Draft V15, April 2006]	$\beta = \frac{1}{3}\frac{7D_0}{4wY} = \frac{7}{6}\frac{R_0}{wY} = 1.17\frac{R_0}{wY}$	• Welded-in meter body • Thin wall, $w < R_0/10$ (?)

Not relevant (Daniel Industries; FMC Kongsberg Metering)

Not documented, no traceability (Instromet; ISO/CD 17089)

Finite element (FEM) analysis of P & T effects:

Spoolpiece, Inclination angles & Lateral chord positions



FEM analysis of P & T expansion; – Results (volumetric flow rate)

Flow calibration cond. (Westerbork) → Operation (Ormen Lange)

7 ˚C / 63 barg → 40 ˚C / 230 barg
Difference: -33 ˚C / 167 bar

$$q_{USM} = \pi R^2 \sum_{i=1}^{N} w_i \frac{L_i^2 (t_{1i} - t_{2i})}{2 x_i t_{1i} t_{2i}}$$

7 °C, 63 barg (Westerbork) → 40 °C, 230 barg (Ormen Lange)

Path no.	Rel. diff R²L²/X [%]
1	0.2722
2	0.2420
3	0.2640
4	0.2410
5	0.2698
Integrated	**0.2457**

Pressure change: 7 °C, 63 barg (Westerbork) → 7 °C, 230 barg

Path no.	Rel. diff R²L²/X [%]
1	0.1473
2	0.1171
3	0.1391
4	0.1161
5	0.1449
Integrated	**0.1208**

Temperature change: 7 °C, 230 barg → 40 °C, 230 barg (Ormen Lange)

Path no.	Rel. diff R²L²/X [%]
1	0.1247
2	0.1247
3	0.1247
4	0.1247
5	0.1247
Integrated	**0.1247**

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Analysis of

P&T effects on:

Transducer ports

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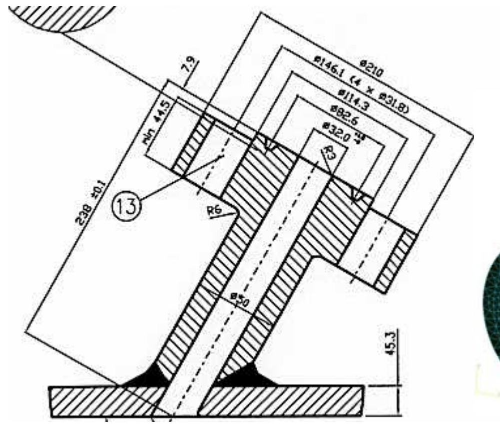
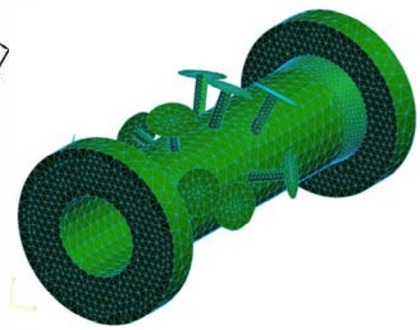
Finite element (FEM) analysis of P & T effects: Transducer port lengths



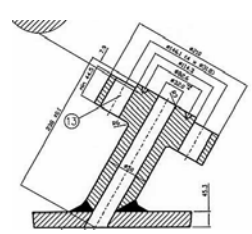


Transducer ports, FEM analysis of P & T expansion

Flow calibration (Westerbork) → Operation (Ormen Lange)
7 ˚C / 63 barg → 40 ˚C / 230 barg
Difference: 33 ˚C / 167 bar

FEM analysis: Expansion transducer port:

	Westerbork [mm]	Ormen Lange [mm]	Differanse [mm]
1A	237.9642	238.0722	0.1080
1B	237.9641	238.0717	0.1076
2A	237.9821	238.1364	0.1543
2B	237.9864	238.1522	0.1658
3A	237.9677	238.0849	0.1172
3B	237.9685	238.0877	0.1192
4A	237.9809	238.1320	0.1511
4B	237.9848	238.1462	0.1614
5A	237.9627	238.0665	0.1038
5B	237.9634	238.0691	0.1057



Analysis of

P&T effects on:

Ultrasonic transducers

Instromet Q-sonic 5 transducers for Ormen Lange

Ultrasonic transducer, FEM-analysis of P & T expansion/contraction

		Change	Effect
Factory → Westerbork:	Pressure increase, 0 – 63 barg	-0.0336 mm	Compression
	Temperature decrease, 20 - 7 ºC	-0.0766 mm	Compression
Factory → Ormen Lange:	Pressure increase, 0 – 230 barg	-0.1225 mm	Compression
	Temperature decrease, 20 – 40 ºC	+0.1179 mm	Expansion
Westerbork → Ormen Lange:	Pressure increase, 63 – 230 barg	-0.0889 mm	Compression
	Temperature decrease, 7 – 40 ºC	+0.1945 mm	Expansion
	Total PT effect:	+0.1056 mm	Expansion

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Analysis of P&T effects on:

Reynolds number correction

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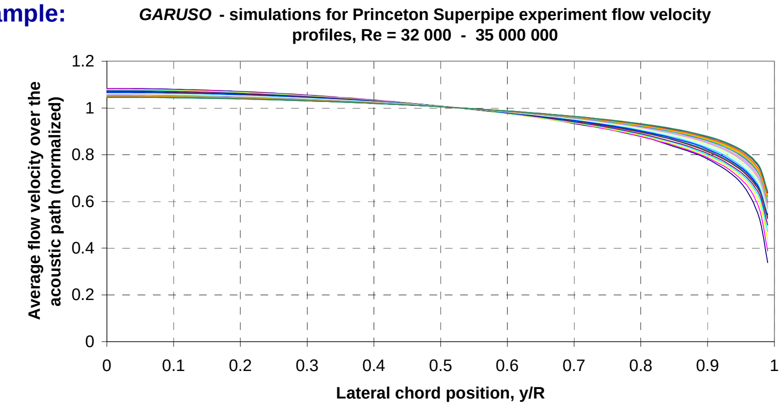
Reynolds number correction analysis

Based on measured axially symmetric flow profiles:

(Re = 7000 - 35·10⁶)

- **Princeton**
- **Melbourne (rough and smooth)**
- **Delft**
- **Erlangen-Nürnberg**
- **Laufer**

Example:



Actual Reynolds numbers, Westerbork and Ormen Lange

$$\mathrm{Re} = \frac{vD\rho}{\mu}$$

WESTERBORK

- Flow velocity: 1.5 – 19 m/s
- Viscosity: 1.30 · 10^{-5} Pa s
- Density: 57.36 kg/m³
- ID: 366.5 mm

- **Re = $2.4 \cdot 10^{6}$ – $3.0 \cdot 10^{7}$**

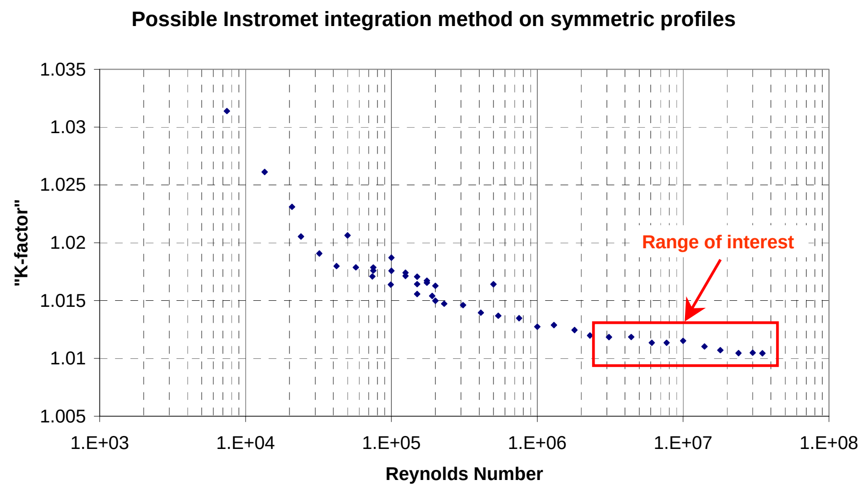
ORMEN LANGE

- Flow velocity: 15 m/s
- Viscosity: 2.28 · 10^{-5} Pa s
- Density: 186.60 kg/m³
- ID: 366.5 mm

- **Re = $4.5 \cdot 10^{7}$**

Reynolds number correction analysis

Based on tentative (assumed) Q-Sonic 5 integration weights



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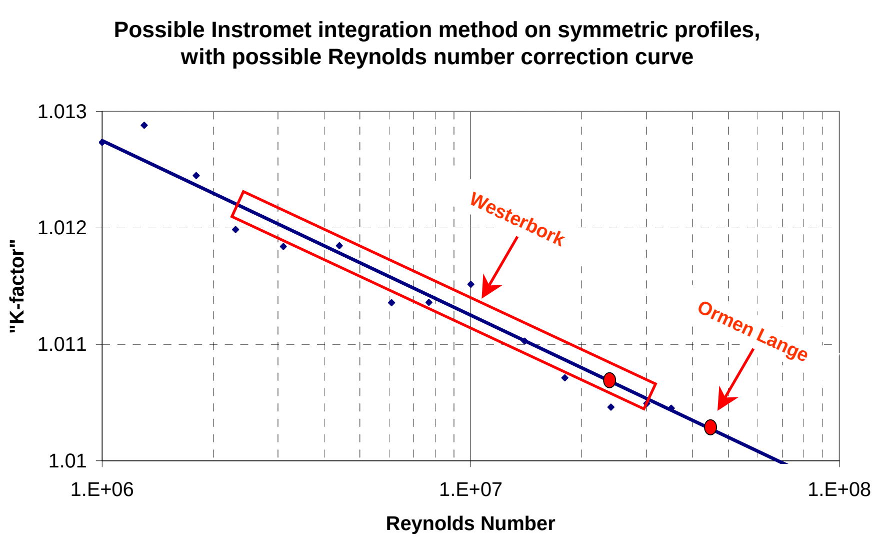
Reynolds number correction analysis

Based on tentative (assumed) Q-Sonic 5 integration weights



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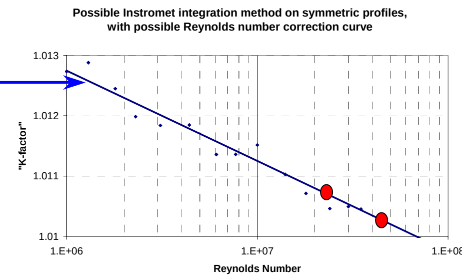
Example of possible Reynolds number correction

$$RC = 1.01275 - \frac{\ln(10^{-6}\,\mathrm{Re})}{\ln 10} 0.0015$$



$$\boxed{q = q_{USM} C_{W-OL}^{RE-Number}}$$

$$C_{W-OL}^{RE-Number} = \left.\frac{RC_{Westerbork}}{RC_{Ormen\ Lange}}\right|_{v=15\ m/s} \approx \frac{1.01067}{1.01027} \approx 1.00040$$

Reynolds number correction, Westerbork to Ormen Lange: +0.040 %

…. valid for all flow velocities in question here, 1-19 m/s

Assembley of Results

P&T effects on USM

from
Westerbork (flow calibration, 63 barg, 7 °C)
to
Ormen Lange (field operation, 230 barg, 40 °C):

Spoolpiece radius:	**0.14 mm**	**(expansion)**
Inclination angles:	**0.01°**	
Interrogation length:	**0.6 mm**	**(expansion)**
Axial distance:	**0.07 – 0.17 mm**	**(expansion)**
Transducer ports:	**0.10 – 0.17 mm**	**(expansion)**
Ultrasonic transducers:	**0.10 mm**	**(expansion)**

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Contributions to measurement error – Ormen Lange

Contributing factor to measurement error, due to pressure and temperature changes	Path no.	Contribution to error	Integrated contribution to error (all 5 paths)	Combined contribution to error
Cross-sectional area and acoustic path geometry (inclination angles & lateral chord positions), effect on paths 1-5:	1	+ 0.272 %	+ 0.246 %	+ 0.246 %
	2	+ 0.242 %		
	3	+ 0.264 %		
	4	+ 0.241 %		
	5	+ 0.270 %		
Expansion transducer ports, effect on paths 1-5:	1	+ 0.055 %	+ 0.057 %	
	2	+ 0.058 %		
	3	+ 0.061 %		
	4	+ 0.057 %		
	5	+ 0.054 %		
Expansion transducers, effect on paths 1-5:	1	- 0.054 %	- 0.041 %	
	2	- 0.038 %		
	3	- 0.047 %		
	4	- 0.033 %		
	5	- 0.047 %		
Combined integrated effect, expansion transducer ports & expansion transducers, all 5 paths:				+ 0.017 %
Reynolds number correction (assumed deviation from Instromet Reynolds number correction):				0 %
Combined effect, total (%)				**+0.262 %**

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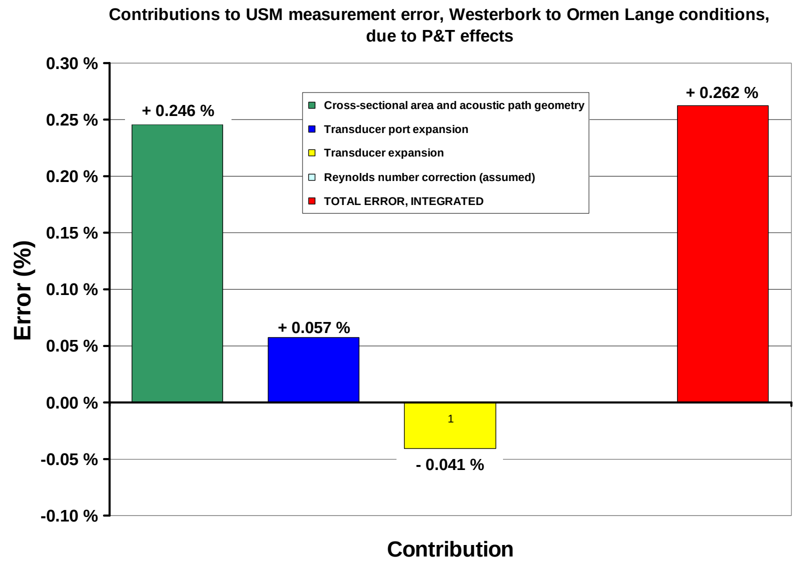
Contributions to measurement error – Ormen Lange



Recommended P&T correction factor for Ormen Lange metering station

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Correction model for P&T effects – Ormen Lange

Proposed correction:

Measured volumetric flow rate at Ormen Lange line conditions → q

Output volumetric flow rate from USM → q_{USM}

Correction factor established under flow calibration at Westerbork (flow dependent) → $K^{Flow}_{Westerbork}$

$$q = q_{USM} \cdot K^{Flow}_{Westerbork} \cdot C^{PT-nom}_{W-OL} \cdot C^{PT-inst}_{OL}$$

Nominal PT correction factor, for change from Westerbork to Ormen Lange conditions (nominal):

- Changed cross-section (FEM)
- Changed acoustic path geometry (FEM)
- Expansion transducer ports (FEM)
- Expansion transducers (FEM)
- Reynolds number correction

Instantaneous PT correction factor, for instantaneous (small) changes of Ormen Lange line conditions (re. nominal):

- Changed cross-section,
- Changed acoustic path geometry,

using the simplified analytical model B

Correction model for P&T effects – Ormen Lange

Nominal PT correction factor:

$$C^{PT-nom}_{W-OL} = 1 + 0.262\% = 1.00262$$

Instantaneous PT correction factor:

$$C^{PT-inst}_{OL} = (1 + 3\alpha\Delta T)(1 + 3\beta\Delta P)$$

Analytical model B

where

$$\Delta T = \left(T^{inst}_{OL} - T^{nom}_{OL}\right) - \left(T^{new}_{cal} - T^{old}_{cal}\right)$$

$$\Delta P = \left(P^{inst}_{OL} - P^{nom}_{OL}\right) - \left(P^{new}_{cal} - P^{old}_{cal}\right)$$

Line conditions (first terms) — **Flow calibration conditions** (second terms)

and

$$\beta = \frac{R_0}{wY}$$

Radial pressure expansion coefficient (meter body, ends free)

Correction model for P&T effects – Ormen Lange

(A)	**Nominal P&T correction factor:**					
	Nominal correction factor:	$C_{W\text{-}OL}^{PT\_nom}$	=	**1.00262**		
(B)	**Instantaneous P&T correction factor:**					
	Fixed quantities:	R_0	=	0.183250	m	
		w	=	0.045350	m	
		Y	=	2.0E+11	Pa	
		α	=	1.260E-05	1/K	
		T_{OL}^{nom}	=	40.0	°C	
		T_{cal}^{new}	=	7.0	°C	
		T_{cal}^{old}	=	7.0	°C	
		P_{OL}^{nom}	=	23000000.0	Pa-g	(= 230 barg)
		P_{cal}^{new}	=	6300000.0	Pa-g	(= 63 barg)
		P_{cal}^{old}	=	6300000.0	Pa-g	(= 63 barg)
	Input from instruments:	T_{OL}^{inst}	=	45.0	°C	
		P_{OL}^{inst}	=	24000000.0	Pa-g	(= 240 barg)
	Calculations:	ΔT	=	5.0	K	
		ΔP	=	1000000.0	Pa	
		β	=	2.02040E-11	1/Pa	
		$1+3{*}\alpha{*}\Delta T$	=	1.00018900		
		$1+3{*}\beta{*}\Delta P$	=	1.00006061		
	Instantaneous correction factor:	$C_{OL}^{PT\_inst}$	=	**1.00025**		
(C)	**Total P&T correction factor:**	$C_{W\text{-}OL}^{PT\_nom} * C_{OL}^{PT\_inst}$	=	**1.00287**		

⇨ **Corrected volumetric flow rate:** $q = q_{USM} * K_{Westerbork}^{Flow} * 1.00262 * 1.00025 = q_{USM} * K_{Westerbork}^{Flow} * 1.00287$

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……. what if

transducer expansion

was neglected?

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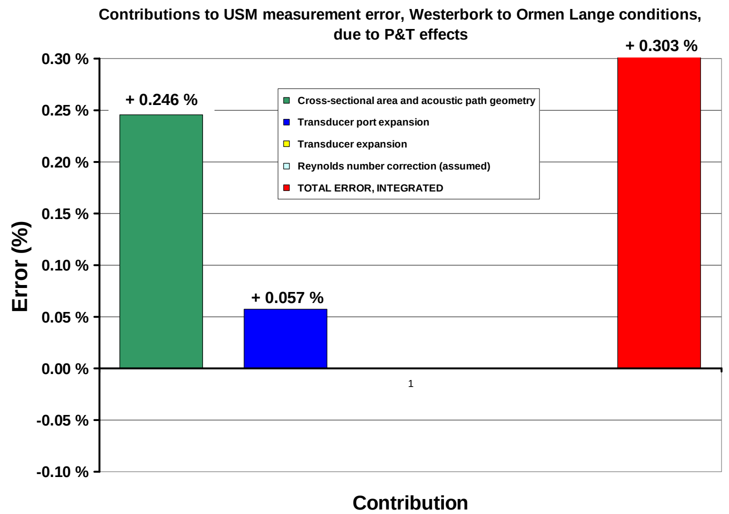
If transducer expansion of ≈ 0.1 mm was neglected in study



Difference in error ≈ 0.04 %: Represents 20 million NOK/year

Conclusions

Conclusions (1)

- Correction factors are established for P & T effects on the 18” Q-Sonic 5 ultrasonic flow meters, from Westerbork flow calibration conditions, to Ormen Lange line conditions.

- The correction factors account for several P & T effects:

  A. Change of the meter's cross-sectional area,
  B. Change of the ultrasonic path geometry (inclination angles and lateral chord positions),
  C. Change of the length of the ultrasonic transducer ports,
  D. Change of the length of the ultrasonic transducers,
  E. Change of the Reynolds number.

- For the Ormen Lange application, evaluation of all of the effects A-E have been necessary.

Conclusions (2)

- 2 correction factors are proposed for implementation in the flow computer:
  (1) A “nominal PT correction factor” = 1.00262 (main correction)
  (2) An “instantaneous PT correction factor”, typically an order of magnitude smaller (“living” correction, based on analytical model B)

- If the correction factors are not used, the Q-Sonic 5 will underestimate the volumetric flow rate by the same amount (≈ 0.26 %)

- The conclusion is based on a theoretical analysis (using analytical and finite element numerical modelling)

- Experimental validation of the theoretical results has been investigated, but not found feasible today, on basis of:
  - Screening of available flow calibration laboratories (dynamic)
  - Evaluation of possible static (no-flow) measurements

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