PRESSURE AND TEMPERATURE EFFECTS FOR ORMEN LANGE ULTRASONIC GAS FLOW METERS

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ABSTRACT

Ultrasonic gas flow meters (USMs) may be influenced by pressure and temperature in several ways. Change of the meter body's cross-sectional area (the "pipe bore") influences directly on the amount of gas flowing through the meter. Change of the ultrasonic path geometry (i.e. change of the inclination angles and lateral chord positions, caused by e.g. meter body diameter change and change of the orientation of the ultrasonic transducer ports) influences on the transit times and the numerical integration method of the meter. Change of the Reynolds number influences on the integration method. Change of the length of the ultrasonic transducer ports influences on the acoustic path lengths, and thus on the transit times. Likewise, change of the length of the ultrasonic transducers influences on the acoustic path lengths, and thus on the transit times. In addition, changes of the transducer properties such as the directivity, influences on the diffraction correction, and thus on the transit times.

Some of these issues are addressed to some extent in current draft standards for such meters, such as the AGA-9 (1998) report, and the ISO/CD 17089-1 (August 2007). Other of these effects have not been described or treated in the literature.

In the present paper, pressure and temperature effects have been investigated for 18" Elster-Instromet Q-Sonic 5 ultrasonic flow meters (USMs) to be operated in the Ormen Lange fiscal metering system at Nyhamna in Møre and Romsdal, Norway, from October 2007. Pressure and temperature changes from flow calibration (Westerbork, at 63 barg and 7 ^{o}C) to field operation (Ormen Lange, nominally at 230 barg and 40 ^{o}C) conditions are evaluated. The effects addressed are changes related to (a) the meter's cross-sectional area, (b) the ultrasonic path geometry (inclination angles and lateral chord positions), (c) length expansion of the ultrasonic transducer ports, (d) length expansion/compression of the ultrasonic transducers, and (e) Reynolds number correction.

The various effects (a)-(e) contributing to the measurement error are discussed and quantified. Investigations are made using a combination of analytical modeling and finite element numerical modeling of the meter body and the ultrasonic transducers, combined with a model for USM numerical integration relevant for the Q-Sonic 5 multipath ultrasonic flow meter in question.

It is shown that for the Ormen Lange application, investigation and evaluation of all of the factors (a)-(e) mentioned above have been necessary to evaluate the effect of pressure and temperature on the meter. Expressions for pressure and temperature effects on ultrasonic flow meters proposed in ISO/CD 17089-1 do not appear to be preferred for the Ormen Lange fiscal metering system.

The study shows that pressure and temperature affects the Q-Sonic 5 by about 0.26 % in the Ormen Lange application. If this systematic measurement error is not corrected for, the Q-Sonic 5 will underestimate the volumetric flow rate by the same amount. Significant economic values are involved.

Two correction factors are thus proposed for the Q-Sonic 5 in this application: (1) one "nominal P&T correction factor" (accounting for by far the largest part of the correction, about 0.26 %), and (2) an "instantaneous P&T correction factor" (accounting for small deviations in pressure and temperature from nominal to actual Ormen Lange conditions), which is typically an order of magnitude smaller than the nominal P&T correction factor. The correction factors and the individual contributors to these are discussed and quantified.

1. INTRODUCTION

From October 2007 five 18" Elster-Instromet Q-Sonic ultrasonic gas flow meters will be operated at a land based fiscal gas metering station at Nyhamna, Møre and Romsdal, Norway, for export of gas through the 1200 km Langeled pipeline, to an import metering station in Easington, UK, built by Statoil, cf. Fig.1. The Ormen Lange export station at Nyhamna was constructed and built by Norsk Hydro, and will be operated by Shell. The production life of Ormen Lange is estimated to 50 years.

The nominal flow rate of the Ormen Lange export metering station is 70 million Sm^3/day, or 25 billion Sm^3/year. At an assumed sales price of 2 NOK/Sm^3 this corresponds tentatively to 140 million NOK/day, or 50 billion NOK/year. An assumed systematic measurement error of only 0.3 % (as an example), would correspond to about 420 000 NOK/day, or about 153 million NOK/year, for such a tentative sales price.

Flow calibration of the flow meters have been made at the Westerbork laboratory in the Netherlands, at temperature and pressure conditions of 7 ^{o}C og 63 barg, respectively, with two meters in series installed in a "long pipe", and with flow conditioner upstream of the meters.

The high pressures in question at the Ormen Lange metering station, 230 barg nominal, have raised the question whether correction for pressure and temperature effects on the ultrasonic meters will be needed, relative to the 63 barg pressure used under flow calibration at Westerbork.

Pressure and temperature effects on the ultrasonic meters relates to factors such as e.g[1].

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

The influence of these factors are addressed here, on basis of the results given in [1].

2. SPECIFICATIONS

The Ormen Lange metering station consists of 3 parallel meter runs, with in total 5 ultrasonic flow meters, cf. Fig. 1:

- 2 parallel runs, each with two 18" ultrasonic flow meters in series,
- 1 parallel run with one 18" ultrasonic flow meter, for backup measurement,
- Flow conditioner will be used (DN450 Laws type 316SS or Duplex Material),
- Elster-Instromet Q-Sonic 5 ultrasonic gas flow meters [2].

Table 1 gives various parameters of the USM, and Table 2 other specifications for the study.

[1] In general, the properties of an ultrasonic flow meter will also depend on the pressure and temperature properties of the ultrasonic transducers used in the meter that is, the electrical and acoustical properties of the transducers, which for a large part determine the signal form, etc.). These are factors which relate to the time detection of the meter (the signal processing). There is no evaluation of *such* factors in the present study, since these types of effects – if the transducers function as they should – are not considered to be very significant (several decades smaller than the other effects) in a 18" meter with reflecting paths. (However, if pressure and temperature cause effects such as period error, transducer error or defect, etc., that would of course be serious and significant.) Pressure test certificates for the K10 transducers used in Q-Sonic 5 given in [19] show that the transducers have survived pressure testing to 620 bar, in water at room temperature.

Table 1. Specifications of the ultrasonic flow meters used in the Ormen Lange metering station.

Parameter	**Property**	**Conditions**
Material type	Steel (Duplex)	
Length	1800 mm	(at assumed 20 ^{o}C, 1 atm.)
Outer diameter, *OD*	457.2 mm	(at assumed 20 ^{o}C, 1 atm.)
Inner diameter, *ID*	(366.5 ± 0.25) mm	(at assumed 20 ^{o}C, 1 atm.)
Inner radius, R_0	183.25 mm	(at assumed 20 ^{o}C, 1 atm.)
Wall thickness, *w*	45.35 mm	(at assumed 20 ^{o}C, 1 atm.)
w/R_0	0.25	(at assumed 20 ^{o}C, 1 atm.)
Young's modulus, *Y*	$2.0 \cdot 10^5$ MPa	
Poisson's ratio, σ	0.3	
Coeff. of linear thermal expansion, α	$12.6 \cdot 10^{-6}$ K^{-1} (ASME)	

Table 2. Specifications for the study.

Parameter	**Westerbork flow calibration conditions**	**Ormen Lange metering station (line conditions, nominal)**
Gas	Dry natural gas	Dried natural gas[a)]
Pressurel *P*	63 barg	230 barg (design)
Temperature	7 ^{o}C	40 ^{o}C (design)
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
Metering configuration	2 USMs in series, with upstream flow conditioner	2 USMs in series, with upstream flow conditioner
Flow velocity	1.5 – 19 m/s	Volumetric flow rate 70 MSm^3/d (=> flow velocity = 15-16 m/s per run)
Reynolds number, *Re*	$2.4 \cdot 10^6$ – $3.0 \cdot 10^7$	$4.5 \cdot 10^7$

a) The gas composition is known, but has not been necessary to specify for the present study.

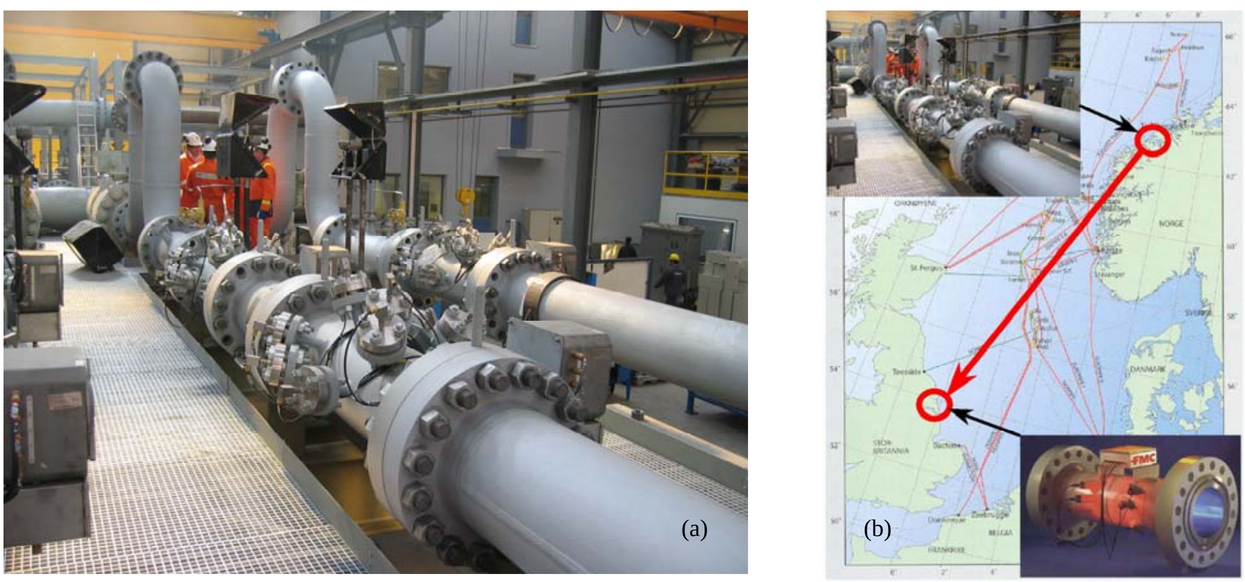


Fig. 1. (a) Photograph of the Ormen Lange fiscal gas metering station, under factory acceptance test (FAT) in Athens, Greece, 2005.
(b) Sketch of the Ormen Lange transport system, with fiscal metering stations at Nyhamna (Norway) and Easington (UK).

3. MULTIPATH ULTRASONIC GAS FLOW METERS

3.1 USM functional relationship

In ultrasonic transit time flow meters with reflecting and/or non-reflecting paths, the volumetric flow rate (at line conditions) is given as [3-5]

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

where (cf. Fig. 2), R is the inner radius of the USM meter body; $\bar{v}_A$ is the axial volume flow velocity (at line conditions); N *is* the number of acoustic paths; i is the path number; w_i is the integration weight factor for path no. i; $\bar{v}_i$ is the average axial flow velocity along path no. i (i.e. the line integral along the path); y_i is the lateral distance from the pipe center (lateral chord position) for path no. i; L_i is the interrogation length for path no. i; ϕ_i is the inclination angle (relative to the pipe axis) of path no. i; t_{1i} and t_{2i} are the measured transit times for upstream and downstream sound propagation of path no. i; and $N_{refl,i}$ is the number of wall reflections for path no. i ($N_{refl,i}$ = 0, 1 or 2 in current USMs), i = 1, …, N.

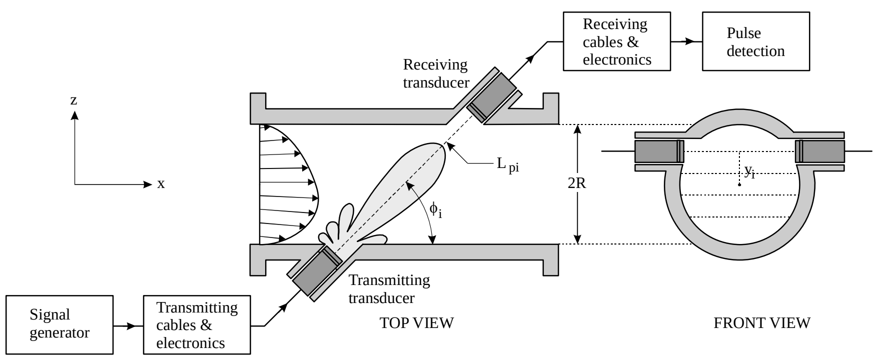


Fig. 2. Schematic illustration of a single path in a multipath ultrasonic transit time flow meter with non-reflecting paths (for downstream sound propagation). (Left: centre path example (y_i = 0); Right: path at lateral chord position y_i.)

3.2 Pressure and temperature influences on USMs

Ultrasonic gas flow meters may be influenced by pressure and temperature in several ways, cf. Table 3. Change of the meter body's cross-sectional area (the "pipe bore") influences directly on the amount of gas flowing through the meter. Change of the ultrasonic path geometry (i.e. change of the inclination angles and lateral chord positions, caused by e.g. meter body diameter change and change of the orientation of the ultrasonic transducer ports) influences on the transit times and the numerical integration method of the meter. Change of the Reynolds number influences on the integration method. Change of the length of the ultrasonic transducer ports influences on the acoustic path lengths, and thus on the transit times. Likewise, change of the length of the ultrasonic transducers influences on the acoustic path lengths, and thus on the transit times.

Table 3. Direct and indirect pressure and temperature influences on USMs.

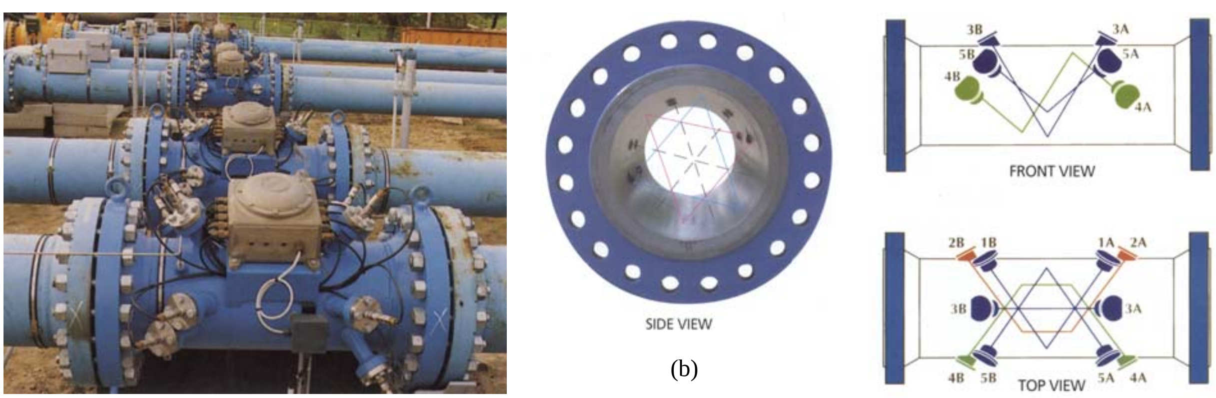
	Direct P&T effect	Indirect P&T effect
A	Change of the meter body cross-sectional area	Affects amount of gas flowing through the flow meter
B	Change of the ultrasonic path geometry (changed inclination angles and lateral chord positions, caused by diameter change & changed transducer port orientation)	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.

3.3 Elster-Instromet Q-Sonic 5

The Q-Sonic 5 ultrasonic meter employs 5 acoustic paths. Three of these paths are single reflection paths. These paths are denoted path 1, 3 and 5, cf. Fig. 3. These paths are centre paths. This means that in the side view of Fig. 3, these 3 paths are represented by the three straight lines going through the centre of the pipe ($y_i = 0$). The inclination angle of these paths is typically 70° for the meters in question at Ormen Lange.

The two remaining paths are double reflecting paths. These paths are denoted path 2 and 4, cf. Fig. 3. These paths propagate at a lateral distance, y_i, of 0.5·R. In the side view of Fig. 3b, each of these paths is represented as a triangle. The inclination angle of these paths is typically 60° for the meters in question at Ormen Lange.

(a)



(c)

Fig. 3. Meter body and path geometry of the Elster-Instromet Q-Sonic 5 ultrasonic gas flow meter (after [2].)

In the present work, pressure and temperature effects for each of the five acoustic paths are first analyzed individually. Thereafter, values for the pressure and temperature effect on the volumetric flow rate are found through integration over the five acoustic paths, using the integration weight factors, w_i, $i = 1, \ldots, 5$, cf. Eq. (1) and e.g. [22]. The integration weights of the Q-Sonic 5 have not been available for the present study. A tentative set of integration weight factors, w_i, $i = 1, \ldots, 5$, has thus been worked out for the Q-Sonic 5. This gives one integration weight factor for each of the three single-bouncing paths (centre paths), and a second one for each of the two double-bouncing paths (swirl paths). This set is the best estimate that has been possible to obtain for the present work, and has been used in the analysis presented here [1].

4. PRESSURE AND TEMPERATURE INFLUENCES ON THE METER CROSS-SECTIONAL AREA AND ULTRASONIC PATH GEOMETRY

The present section addresses changes in the USM's cross-sectional area (diameter) and ultrasonic path geometry (inclination angles and lateral chord positions) caused by changes in pressure and temperature, and the consequences of such changes for the measurement accuracy. In particular, this relates to

(a) changes in the Q-Sonic 5 ultrasonic meter's cross-sectional area and its path geometry, from factory ("dry calibration") to Westerbork (flow calibration) conditions,
(b) changes in the Q-Sonic 5 cross-sectional area and its path geometry, from Westerbork (flow calibration) to Ormen Lange (operating) conditions,
(c) the effect of these changes on the Q-Sonic 5 measurement uncertainty at Ormen Lange (operating) conditions.

In Section 4.1, simplified analytical models for pressure and temperature expansion / contraction are discussed and used for describing (a) - (c). In Section 4.2, finite element numerical modelling (FEM) is used, as a more accurate approach. Calculation results are given in Section 4.3.

4.1 Simplified analysis

Analytical models generally represent simplified descriptions of pressure and temperature effects on USM cross-sectional area and ultrasonic path geometry, both with respect to meter geometry and validity ranges, but may be useful for certain purposes, depending on their accuracy. Various models used in the literature and international standards to correct for pressure and temperature expansion of USMs are discussed.

4.1.1 Analytical Model A

At a temperature T and pressure P, the meter body radius (R), the lateral chord positions (y_i), and the inclination angles (ϕ_i), can be shown to be approximately given by [5,1]

$$R \approx K_T K_P R_0 , \quad y_i \approx K_T K_P y_{i0} , \quad \phi_i \approx \tan^{-1}\left(\frac{\tan(\phi_{i0})}{1-(1-\beta^*/\beta)(K_P-1)} \right), \quad i = 1, \ldots, N \qquad (2)$$

where subscript "0" is used to denote the respective geometrical quantity at "dry calibration" conditions, i.e. R_0, y_{i0} and ϕ_{i0}. The correction factors for the inner radius of the meter body due to dimensional changes caused by temperature and pressure changes relative to "dry calibration" conditions, are given as (cf. e.g. [6,7,8,10])

$$K_T \equiv 1+\alpha\Delta T_{dry} , \qquad \Delta T_{dry} \equiv T - T_{dry} , \qquad (3)$$

$$K_P \equiv 1+\beta\Delta P_{dry} , \qquad \Delta P_{dry} \equiv P - P_{dry} , \qquad (4)$$

respectively, where P_{dry} and T_{dry} are the pressure and temperature at "dry calibration" conditions, e.g. P_{dry} = 1 atm. and T_{dry} = 20 ^{o}C. α is the coefficient of linear thermal expansion of the meter body material. β and β* are the *radial* and *axial* linear pressure expansion coefficients for the meter body, respectively (cf. Section 4.1.3). K_P and K_T are here referred to as the *radial* pressure and temperature correction factors for the USM meter body, respectively[2]. Eqs. (2)-(4) are referred to as the "analytical model A", and applies to all inclination angles.

4.1.2 Analytical Model B

For USMs where all inclination angles are equal to ±45°, i.e, $\phi_{i0} = \pm 45^o$, $i = 1, \ldots, N$, q_{USM} can - from Eqs. (1)-(4) - be written as [5,1]

$$q_{USM} \approx q_{USM,0} \cdot C_{tsm} \cdot C_{psm} \quad , \tag{5}$$

where

$$C_{tsm} = K_T^3 = (1 + \alpha \Delta T_{dry})^3 \approx 1 + 3\alpha \Delta T_{dry} , \quad C_{psm} = K_P^3 = (1 + \beta \Delta P_{dry})^3 \approx 1 + 3\beta \Delta P_{dry} , \tag{6}$$

are the *volumetric* thermal and pressure correction factors of the USM meter body[3], and $q_{USM,0}$ is given by Eqs. (1)-(2), with the "dry calibration" quantities R_0, y_{i0}, L_{i0}, x_{i0} and ϕ_{i0} inserted instead of the quantities R, y_i, L_i, x_i and ϕ_i, $i = 1, \ldots, N$. Eqs. (5)-(6) are referred to as the "analytical model B".

For USMs with inclination angles equal to ±45°, thus, the analytical model B is equivalent to the analytical model A. For other inclination angles it represents an approximation to the more accurate analytical model A [5]. This is the case for Q-Sonic 5, which employ inclination angles of 60° and 70°. Eq. (D.28) in [5] gives the relative error by using this approximation. It turns out that for moderate pressure deviations ΔP_{dry} (a few tens of bars), the errors made by using analytical model B may be neglected, and that this model may be used for inclination angles in the range of relevance for current USMs, 40° to 60°. However, for larger pressure deviations, and especially for inclination angles approaching 60°, the error introduced by using Eqs. (5)-(6) increases.

The main advantage of analytical model B over A lays in the fact that in model B, the *P* and *T* corrections of the geometrical quantities of the meter body can be separated from the basic USM functional relationship and put outside of the summing over paths, as illustrated by Eq. (6). Consequently, since the analytical model A is not easily applicable for use in the "instantaneous correction factor" to be implemented at the flow computer level, Eqs. (5)-(6) is the model proposed for the "instantaneous correction factor" described in Section 7.2, used for relatively small pressure changes only (a few bar).

4.1.3 Coefficients of linear pressure expansion

The radial and axial linear pressure expansion coefficients β and β^* involved in the analytical models A and B depend on the type of support provided for the meter body installation (i.e. the

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[2] The *radial* pressure and temperature correction factors for the USM meter body, K_P and K_T, should not be confused with the corresponding *volumetric* pressure and temperature correction factors of the meter body, C_{psm} and C_{tsm}, cf. e.g. Eqs. (6).

[3] For the correction factor of the *meter body*, a notation is used according to "common" flow metering terminology, where subsripts *t*, *p*, *s* and *m* refer to "temperature", "pressure", "steel" and "meter", respectively, cf. e.g. [6-8].

model used for the meter body pressure expansion / contraction). For thin-walled cylindrical and isotropic elastic meter bodys, β and β* are related by [1]

$$\frac{\beta^*}{\beta} \approx \begin{cases} -\sigma = -0.3 & \text{for the cylindrical pipe section model (ends free),} \\ 0 & \text{for the infinite-length cylindrical pipe model (ends clamped),} \\ \dfrac{1-2\sigma}{2-\sigma} = 0.235 & \text{for the cylindrical tank model (ends capped),} \end{cases} \qquad (7)$$

where the values given for β^*/β apply to steel (σ = 0.3).

With respect to K_T and K_P, there seems to be general agreement in the literature that temperature and pressure expansion/contraction can be described by expressions such as Eqs. (3)-(4). However, there is widely varied practice with respect to which model is used for the coefficient of linear radial pressure expansion, β. Table 4 gives different models in use for β, and a discussion of these is given in [1]. Note that all models in use represent simplifications.

Table 4. Models used by USM manufacturers, standards, etc. for linear pressure expansion of the inner radius of the USM meter body (isotropic material assumed), under uniform internal pressure.

Reference / USM manufacturer	Models for the coefficient of linear radial pressure expansion, β	USM meter body assumptions
AGA-9 (1998) [10], Roark (2001), p. 592 [11]	$\beta = \frac{R_0}{wY}$	• Cylindrical pipe section model (ends free) • Thin wall, $w < R_0/10$
Daniel Industries (2001) [20,5]	$\beta = \frac{1}{Y}\frac{1.3(R_0+w)^2+0.4R_0^{\,2}}{(R_0+w)^2-R_0^{\,2}}$ ($\beta \approx 0.85\frac{R_0}{wY}$ for $w << R_0$)	• Cylindrical tank model (pipe with ends capped) • Thick wall • Steel material (σ = 0.3)
FMC Technologies (2001) [21], [5], Roark (2001), p. 593 [11]	$\beta = \frac{R_0}{wY}\left(1-\frac{\sigma}{2}\right)$ ($\beta = 0.85\frac{R_0}{wY}$ for σ = 0.3 (steel))	• Cylindrical tank model (pipe with ends capped) • Thin wall, $w < R_0/10$
Instromet (2001) [12], [5]	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 taken to be = 0.5 · radial expansion for ends-free model • Thin wall, $w < R_0/10$
ISO/CD 17089-1 (2007) [3]	$\beta = \frac{1}{3}\frac{3D_0}{4wY} = 0.5\frac{R_0}{wY}$	• Flanged-in meter body • Thin wall, $w < R_0/10$ (?)
ISO/CD 17089-1 (2007) [3]	$\beta = \frac{1}{3}\frac{7D_0}{4wY} = \frac{7}{6}\frac{R_0}{wY} = 1.17\frac{R_0}{wY}$	• Welded-in meter body • Thin wall, $w < R_0/10$ (?)

The "cylindrical pipe section model (ends free)" [11] (1st row of Table 4) applies to a finite-length pipe section with free ends and does not account for flanges, bends, etc. It is considered to be relevant for thin-walled meter bodies mounted in pipe sections where ends can move relatively freely (note that according to the FEM analysis of Section 4.2, axial displacements are in the sub-mm range), e.g. with U-bend as part of the pipe section. Calculations using this model are confirmed relatively well by the FEM calculations described in Section 4.2 (which do account for flanged meter bodies), cf. Section 4.3. For the Ormen Lange metering station, this model for β is considered to be the most relevant of the analytical models given in Table 4, and consequently used here (cf. Section 7.2).

The two expressions proposed in ISO/CD 17089-1 [3], given in the latter two rows of Table 4, and claimed to cover "flanged-in meter body" (5th row) and "welded-in meter body" (6th row), respectively, give 50 % smaller and 17 % higher radial displacement than the ends-free model (1st row). These models are not found to be very relevant for use in correction factors for the Ormen Lange fiscal metering station, basically for two reasons: (a) no documentation or references for the β expressions has been given in ISO/CD 17089-1 (i.e. no traceability), and (b) the expressions given in ISO/CD 17089-1 are not confirmed by the FEM calculations, cf. Section 4.3.

4.2 Finite element modelling (FEM) analysis

The analytical models A and B described in Section 4.1 represent simplified descriptions, accounting for "average" effects only, and are in general not able to account very precisely for the effects of P&T on the meter body. To analyze such effects in more detail and more accurately (including effects of flange thickness, wall thickness, the resulting form of the meter body (e.g. pipe bulging), influence of the transducer ports and their location, displacement of the transducer ports, precise calculation of the ultrasonic path lengths, etc.), a numerical finite element model (FEM) is needed.

Thus, as a second and considerably more accurate step to analyze pressure and temperature effects on the Q-Sonic 5 ultrasonic meter, a FEM approach was used. The finite element mesh used for FEM calculations of the Q-Sonic 5 meter body is shown in Fig. 4a. Dimensional changes caused by temperature and pressure changes, at any position of the meter body, are calculated using FEM. Details are given in [1].

With respect to boundary conditions, the model of the meter body is fixed as follows, cf. Fig. 4:

- In vertical direction (x-direction) in two points corresponding to bolts in 3 o’clock and 9 o’clock positions.
- In axial direction (y-direction) in the bolt's circle diameter.
- In transveral direction (z-direction) in one point corresponding to a bolt in 6 o’clock position.

This means that the centre of the pipe in principle does not move in vertical and transversal direction, and that no constraint loads will appear.

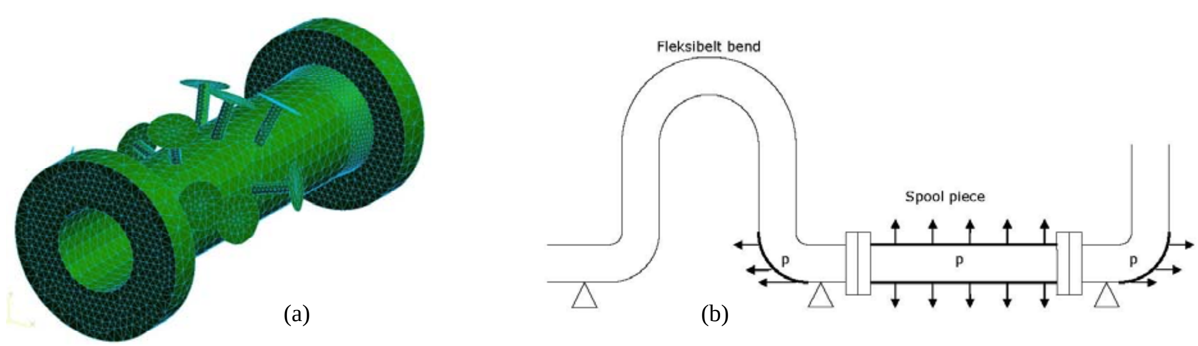


Fig. 4. (a) Finite element grid used for FEM analysis of P & T effects on the meter body (spoolpiece) of the Q-Sonic 5 ultrasonic gas flow meter. (b) Sketch of pipe section accounted for in the FEM analysis.

Due to the U-bend and the header at the opposite side of the USM in the Ormen Lange metering station (cf. Fig.1), it is assumed that the meter body can expand freely in the axial direction (as for the ends-free analytical model for β chosen in Section 4.1.3) (note that axial displacements are in the sub-mm range). Flanges and the 10 transducer mounting ports of the Q-Sonic 5 meter body are all accounted for, as well as axial forces on the meter body flanges caused by the associated 18" pipe section in which the Q-Sonic 5 is mounted, cf. Fig. 4 [1]. The material data used for the calculations are given in Section 2.

The FEM calculations give the change of position for every point of the meter body. Thus, the change of diameter in the horizontal and vertical directions and changes with respect to the transducer ports (i.e. inclination angles and directional orientation of the port (rotation, etc.)), are calculated. This includes the rotation around the vertical, axial and transversal axes, of the back plane of the transducer ports.

The results of the FEM calculations are used as input data to calculation of the pressure and temperature effects on the individual acoustic paths, and the pressure and temperature effects on the USM volumetric flow rate measurement, through integration over the 5 acoustic paths of the USM, using the tentative Q-Sonic 5 weight factors discussed in Section 3.3 [1].

4.3 Calculation results

First, consider the accuracy of the different models for radial linear pressure expansion coefficient β given in Table 4. Table 5 provides a comparison of 4 of the different β models given in Table 4, compared to the results of the FEM analysis[4]. It appears from the pressure effect results given in the table that the cylindrical pipe section model (ends free) (1st row of Table 4) gives the best approximation to the FEM results. A relatively good agreement is found between the FEM calculations and this β model, for both cases. The flanged-in and welded-in models proposed in ISO/CD 17089-1 [3] represent another type of correction than found to be recommended here, and is not used for the Ormen Lange fiscal metering station,

Table 5. Calculated change in USM meter body radius, ΔR [mm], due to pressure and temperature expansion/contraction, for 4 different models for β given in Table 4, compared to the results of the FEM analysis. Two cases are considered: (a) "dry calibration" to flow calibration (Westerbork) conditions, and (b) flow calibration (Westerbork) to operating (Ormen Lange) conditions.

	Flow calibration (Westerbork) **7 °C, 63 barg**			**Operation (Ormen Lange)** **40 °C, 230 barg**		
	Temperature effect ΔT = -13 °C ΔP = 0 bar	Pressure effect ΔT = 0 °C ΔP = 63 bar	**P & T effect ΔT = -13 °C ΔP = 63 bar**	Temperature effect ΔT = 33 °C ΔP = 0 bar	Pressure effect ΔT = 0 °C ΔP = 167 bar	**P & T effect ΔT = 33 °C ΔP = 167 bar**
Cylindrical pipe section β model (ends free) [AGA-9, 1998] [Roark, 2001, p.592]	-0.03002	**0.02332**	-0.00670	0.07619	**0.06183**	0.13804
Cylindrical tank β model (ends capped) [Roark, 2001, p.593]	-0.03002	**0.01983**	-0.01019	0.07619	**0.05255**	0.12877
Flanged-in meter body β model [ISO 17089]	-0.03002	**0.01166**	-0.01836	0.07619	**0.03091**	0.10711
Welded-in meter body β model [ISO 17089]	-0.03002	**0.02729**	-0.00273	0.07619	**0.07234**	0.14856
FEM	-0.03002	**0.02388**	-0.00614	0.07665	**0.06329**	0.13994

4 In the FEM analysis of pressure effects, the calculated diameter change is different in the vertical and horizontal directions, due to the asymmetric distribution of the transducer ports (all located at the upper half of the meter body, cf. Fig. 4a). In the FEM results of Table 5, the vertical and horizontal diameter changes have been averaged.

Next, consider the error in the volumetric flow rate as measured by the USM caused by pressure and temperature effects on the meter diameter and the ultrasonic path geometry.

For the change from flow calibration (Westerbork) to field operation (Ormen Lange) conditions, there is a significant systematic shift in the volumetric flow rate due to pressure and temperature effects, ranging approximately from about 0.24 (double reflecting paths) to about 0.27 % (single reflection paths) for the various acoustic paths [1]. Integrated over the 5 acoustic paths the effect is calculated to 0.2457 %, cf. Fig. 5. It is also seen from Fig. 5 that the effect of the pressure effect isolated is calculated to 0.1208 % and the temperature effect isolated is calculated to 0.1247 %, which act in the same direction since both the temperature and the pressure increases from Westerbork to Ormen Lange conditions. If not corrected for, the Q-Sonic 5 will thus underestimate the volumetric flow rate.

For the analytical model approaches, the corresponding results become 0.250 % for the analytical model A (0.125 % both for temperature and pressure effects isolated), and 0.226 % for the more simplified analytical model B, valid at inclination angles of 45° (0.10 % for the pressure effect isolated and 0.126 % for the temperature effect isolated) [1]. The difference between the results from the analytical model A and the FEM results are therefore only 0.0043 %, and the difference between the FEM results and the results from the simplified analytical model B is 0.0207 %.

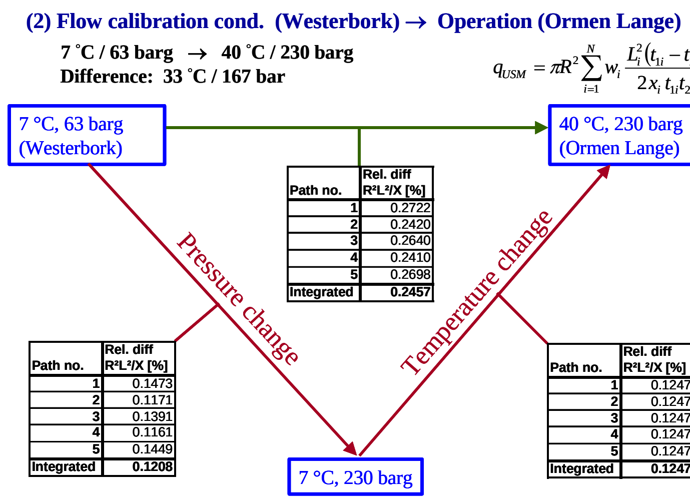


Fig. 5. Effect of pressure and temperature on the measured volumetric flow rate for the Elster-Instromet Q-Sonic 5 ultrasonic gas flow meter, calculated from the FEM analysis results, for Westerbork (flow calibration) to Ormen Lange (operational). conditions (After [1].)

This result is of high interest in the sense that the FEM results may be used for the correction from Westerbork conditions to nominal Ormen Lange conditions (the "nominal PT correction factor"), and the analytical model B may be used for the remaining correction from nominal to the actual Ormen Lange line conditions (the "instantaneous PT correction factor"), cf. Section 7.2.

5. PRESSURE AND TEMPERATURE INFLUENCES ON TRANSDUCER PORTS, TRANSDUCER LENGTH AND ACOUSTIC PATH LENGTH

Changes in pressure and temperature influence on the length of the transducer ports in which the ultrasonic transducers are mounted, the length of the ultrasonic transducers themselves, and consequently on the length of the acoustic paths, and thus the measured transit times. The present section addresses these length changes, and the consequences for the measurement error. In particular, this relates to

(a) length changes from Westerbork (flow calibration) to Ormen Lange (operating) conditions,
(b) the effect of these changes on the Q-Sonic 5 measurement uncertainty at Ormen Lange (operating) conditions.

5.1 Expansion / compression of the transducer ports

Changes in pressure and temperature will induce expansion/compression of the transducer ports and thus changes in the length of the ports, which influences on the acoustic path lengths, and thus on the transit time measurements. A detail study of the pressure and temperature induced expansion / compression of the transducer ports of the Q-Sonic 5 ultrasonic meter is given in the following, for the Ormen Lange application. The analysis is based on the finite element modelling (FEM) numerical calculations described in Section 4.2.

Fig. 4a gives the finite element mesh used for modeling of the Q-Sonic 5 meter body with transducer ports, and Fig. 6 a detail drawing of a transducer port of this meter. In the FEM calculations, each transducer port is assumed to be covered with a pressure tight and rigid plate (instead of the transducer flange), so that pressure-induced length changes of the port can be described, from Westerbork (flow calibration) to Ormen Lange (operating) conditions. Actual and realistic length changes are calculated for each of the 10 ports in the 5 acoustic paths.

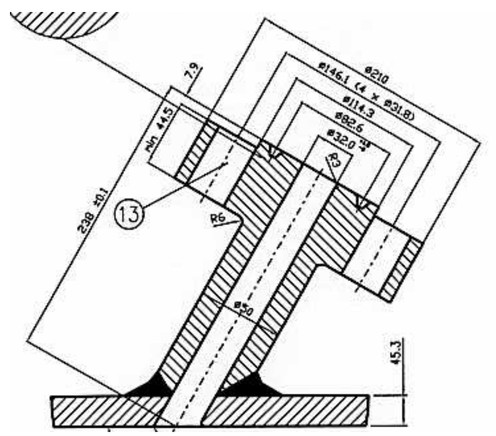


Fig. 6. Detail drawing of a transducer port of the Q-Sonic 5 meter body, as accounted for in the FEM analysis of the meter body.

The calculated length changes of the transducer ports range from 0.1038 mm to 0.1658 mm, depending on the path no., cf. Table 6 [1]. To illustrate the basic analysis and indicate the level of significance, consider an average length change of about, say, 0.12 mm, as a simplified and preliminary approach. If the length change is not corrected for, the (isolated) measurement error due to port length changes becomes, approximately [1],

$$\frac{\Delta \bar{v}_i}{\bar{v}_i} \approx -2\frac{\Delta L_i}{L_i} = -2\frac{2 \cdot 0.12\,mm}{780\,mm} \approx -0.0006 = -0.06\,\%\,, \qquad (8)$$

where L_i is the interrogation length of path no. i, $i = 1, \ldots, N$, and ΔL_i is the change of L_i due to pressure and temperature effects.

However, note that when the two effects of the changed transducer ports and the changed transducer length are combined, the influence on the Q-Sonic 5 volumetric flow rate measurement in the Ormen Lange application becomes different from Eq. (8), cf. Section 5.3.

5.2 Expansion / compression of the ultrasonic transducers

Fig. 7 shows photographs of an Q-Sonic 5 ultrasonic transducer of the K2 type used in the Ormen Lange application. Changes in pressure and temperature will induce expansion/compression of the transducers, which influences on the acoustic path lengths, and thus on the transit time measurements.

An extract of a detail study of the expansion / compression of the Q-Sonic 5 ultrasonic transducer in the Ormen Lange application is given in the following. The analysis is based on finite element (FEM) numerical calculations of pressure and temperature induced length changes of the transducer [1]. In particular, this relates to

(a) changes of the transducer length, from Westerbork (flow calibration) to Ormen Lange (operating) conditions, and
(b) the effect of these changes on the Q-Sonic 5 measurement uncertainty at Ormen Lange (operating) conditions.


(a)

(b)

Fig. 7. Photographs of an Elster-Instromet Q-Sonic 5 ultrasonic transducer of the K2 type used in the Ormen Lange application. Left: side view; Right: front view. (After [1].)

The FEM analysis is based on information provided by Elster-Instromet [12], in addition to "qualified guess" on some of the construction details of the transducer. It is known that the active acoustic part of the transducer (the piezoelectric element, etc., in the front of the transducer) is pressure equalized, that the pressure barrier is located behind this region, and that important parts of the transducer interior are made up of epoxy [12]. However, the information provided on the construction details of the transducer was in general insufficient to do a precise FEM analysis of the pressure and temperature expansion/compression of the transducer. Thus, some assumptions had to be made in relation to constructional details, materials used, and material properties. The calculations given below are based on the best possible "qualified guess" of the constructional details of the transducer one could establish. A finite element model mesh of the transducer was thus developed, and finite element calculations made, in two steps:

(i) changes of the transducer length, from factory ("dry calibration") to Westerbork (flow calibration) conditions, and
(ii) changes of the transducer length, from factory ("dry calibration") to Ormen Lange (operating) conditions.

These are then combined to evaluate the changes of the transducer length, from Westerbork (flow calibration) to Ormen Lange (operating) conditions.

In short, the FEM calculations indicate that a pressure increase from 63 to 230 barg leads to a change in the transducer length of –0.0889 mm (compression) [1]. A temperature increase from 7 to 40 ^{o}C leads to a calculated change in the transducer length of +0.1945 mm (expansion) [1]. Some further details are given in [1]. The combined effect of the calculated pressure induced compression of –0.0889 mm and the calculated temperature induced expansion of +0.1945 mm becomes [+0.1945 – 0.0889] mm = +0.1056 mm (expansion). Thus, the FEM results indicate that the temperature effect dominates and that the transducer increases in length by 0.1056 mm from Westerbork to Ormen Lange conditions.

It should be emphasized that, from the above discussion on the FEM analysis of the transducer, it is evident that due to the uncertainties in relation to some of the constructional details and the materials used, the calculated change in transducer length (0.1056 mm) is associated with some uncertainty (which is difficult to estimate, however).

If this length change is not corrected for, the measurement error due to transducer expansion becomes, approximately [1] (by noting that a transducer expansion corresponds to negative ΔL_i),

$$\frac{\Delta \bar{v}_i}{\bar{v}_i} \approx -2\frac{\Delta L_i}{L_i} = -2\frac{2\cdot(-0.1056)\,mm}{780\,mm} \approx +0.00054 = +0.054\,\%\,. \qquad (9)$$

However, note that when the two effects of the changed transducer ports and the changed transducer length are combined, the influence on the Q-Sonic 5 volumetric flow rate measurement in the Ormen Lange application becomes different than predicted by Eq. (9), cf. Section 5.3.

5.3 Combined effect, in relation to change of acoustic path length

The results of Sections 5.1 indicate that pressure and temperature effects on the transducer ports will lead to increased acoustic path length, in the range from 2 · 0.1038 mm to 2 · 0.1658 mm, depending on the path no. On the other hand, the results of Sections 5.2 indicate that pressure and temperature effects on the transducers themselves will lead to a decreased acoustic path length, by about 2 · 0.1056 mm.

Consequently, in the Ormen Lange application the effect of changed transducer port length and changed transducer length partly cancel each other, and by combining them, one finds an increased acoustic path length, in the range from 0.0017 mm to 0.1089 mm, depending on the path no., cf. Table 6 [1].

First, consider a simplified analysis of the effect of the increased acoustic path length, to illustrate the basic analysis. The average calculated length change for the five acoustic paths is about, say, 0.04 mm, as a very rough figure. If this average length change is not corrected for, the measurement error (misreading) due to transducer port and transducer length changes becomes, approximately [1],

$$\frac{\Delta \bar{v}_i}{\bar{v}_i} \approx -2\frac{\Delta L_i}{L_i} = -2\frac{2\cdot 0.04\,mm}{780\,mm} \approx -0.000205 \approx -0.021\%\,. \qquad (10)$$

If this error is not corrected for, the ultrasonic flow meter thus underestimates the volumetric flow rate. Consequently, the effect of this average acoustic path length change on the USM is positive, +0.021 %.

The above simplified analysis effectively illustrates the basic idea of the analysis, but does not account for changes in the acoustic path lengths of the individual paths. A more thorough analysis has thus been made, where calculated changes in the individual acoustic path lengths are accounted for. This analysis - given in the following - reveals that the tentative figure given by Eq. (10) may represent a rough but still reasonable estimate. Table 6 gives the calculated change in acoustic path length based on the calculated change in transducer port length and the calculated change in transducer length, calculated using FEM in Sections 5.1 and 5.2, respectively.

Table 6. Combined effect of (a) calculated transducer port length change and (b) calculated transducer length change, due to pressure and temperature effects, from flow calibration (Westerbork) to field operation (Ormen Lange) conditions, for each of the 5 paths of the Q-Sonic 5. Results both for individual paths and for the integrated effect are given. (After [1].)

Path no.	Port no.	Change in port length [mm]	Change in transducer length [mm]	Change in acoustic path length [mm]	Interrogation length [mm]	Effect on acoustic path [%]
1	1A	0.1080	0.1056	+0.0044	780	+0.0011
	1B	0.1076	0.1056			
2	2A	0.1543	0.1056	+0.1089	1100	+0.0198
	2B	0.1658	0.1056			
3	3A	0.1172	0.1056	+0.0252	780	+0.0065
	3B	0.1192	0.1056			
4	4A	0.1511	0.1056	+0.1013	1100	+0.0184
	4B	0.1614	0.1056			
5	5A	0.1038	0.1056	-0.0017	780	-0.0004
	5B	0.1057	0.1056			
Integrated effect, using the assumed USM integration weight factors:						**+0.0165**

Based on these numbers, the effect on the velocity measured on each acoustic path can be calculated similar to Eqs. (8)-(10), for each of the 5 paths of the Q-Sonic 5. The integrated value is then found based on the tentative Q-Sonic 5 integration weights discussed in Section 3.3. The integrated value (typical value for the effect on the flow meter in total) is found to be about +0.0165 % ≈ +0.017 %. The positive sign is an effect of increased transit times, meaning that the USM is underestimating the volumetric flow rate if this acoustic path length effect is not corrected for.

6. PRESSURE AND TEMPERATURE INFLUENCES ON THE REYNOLDS NUMBER CORRECTION

The Reynolds number used at the Westerbork flow calibration is lower than at Ormen Lange operating conditions, cf. Table 2. At Westerbork, the Reynolds number was in the range $2.4 \cdot 10^6$ - $3.0 \cdot 10^7$, and at Ormen Lange, it is about $4.5 \cdot 10^7$. For constant flow velocity, the Reynolds number is about a factor 2 larger at Ormen Lange than at Westerbork conditions.

This means that the flow profile is different at Westerbork conditions than at Ormen Lange conditions, for the same flow velocity. In the Q-Sonic 5 software, a Reynolds number correction is made by Elster-Instromet, with intention to account for this difference [12]. The Reynolds number correction for the Ormen Lange metering station is discussed in the following.

The effect of the change in Reynolds number from Westerbork to Ormen Lange conditions is here studied by a set of measured axially symmetric flow profiles, reported by a series of laboratories [13-17]. In one laboratory, both smooth and rough pipe walls were used. In the other laboratories smooth pipes were used. The Reynolds number range covered by these experiments is about $7{\cdot}10^3$ - $35{\cdot}10^6$. For each Reynolds number (flow velocity profile), the deviation from reference is calculated using the tentative Q-Sonic 5 integration weights discussed in Section 3.3. The results are shown in Fig. 8a over a wide Reynolds number region.

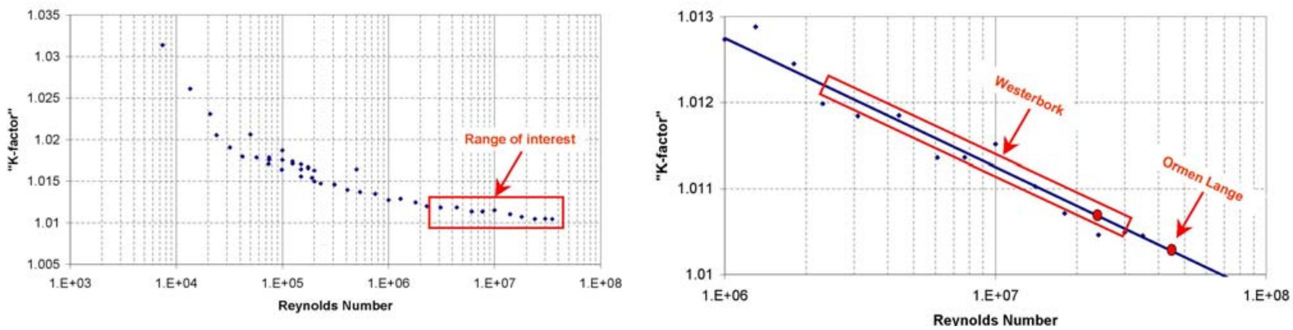
(a)  (b)

Fig. 8. Tentative Q-Sonic 5 USM integration method used on a set of measured symmetric flow profiles taken from the literature, over (a) a wide Reynolds number range, and (b) the Reynolds number range of interest here. The Q-Sonic 5 results are shown with blue dot markers. In (b), the Reynolds number correction curve proposed by Eq. (11) is shown using the blue line. The Westerbork and Ormen Lange Reynolds number ranges are indicated with a red rectangular box and a red marker, respectively. Corresponding Reynolds numbers at Westerbork and Ormen Lange for constant flow velocity of 15 m/s are shown with red markers.

In Fig. 8b, the same results are shown over the Reynolds number region of interest here. In addition, a fitted straight line is added, given as

$$RC = 1.01275 - \frac{\ln(10^{-6}\,\mathrm{Re})}{\ln 10} 0.0015 , \tag{11}$$

where *RC* is the Reynolds number correction, and *Re* is the Reynolds number. Fig. 8b may be interpreted as follows:

At Westerbork, the flow calibration is intended to ensure that at 15 m/s, the USM gives 15 m/s as output value, at the Reynolds number $2.43{\cdot}10^7$. At Ormen Lange conditions, however, use of the USM at 15 m/s gives (erroneously) a lower output flow velocity value than 15 m/s, since the Reynolds number corresponding to 15 m/s is $4.5{\cdot}10^7$, and the curve in Fig. 8b decreases by increasing Reynolds number. At Ormen Lange conditions, thus, the USM underestimates the flow velocity. This is a property of the integration method of the USM (i.e. the integration weigth factors).

The underestimation made by the USM can be corrected using a Reynolds number correction factor for the Q-Sonic 5 flow meter, from Westerbork to Ormen Lange conditions,

$$q = q_{USM} C_{W-OL}^{RE-Number} , \tag{12}$$

where

$$C_{W-OL}^{RE-Number} = \left. \frac{RC_{Westerbork}}{RC_{OrmenLange}} \right|_{v=15\ m/s} \approx \frac{1.01067}{1.01027} \approx 1.00040 \tag{13}$$

is the Reynolds number correction factor from Westerbork to Ormen Lange conditions, evaluated at 15 m/s flow velocity at both locations (Re = $2.4 \cdot 10^7$ and $4.5 \cdot 10^7$, respectively). The Reynolds number correction from Westerbork to Ormen Lange conditions is thus about +0.040 %. It can be shown that this Reynolds number correction of about +0.04 % applies to all flow velocities of relevance here, 1 – 19 m/s.

The actual Reynolds number correction carried out in the Q-Sonic 5 has not been available for the present work. However, Elster-Instromet claims that the Reynolds number correction they use is 90 % correct [12]. Now, assume that the magnitude of the correction is about 0.04 %, as argued above, and assume that the Reynolds number correction made in the Q-Sonic 5 is at least 50 % correct. Then the error of the Q-Sonic 5 Reynolds number correction will be less than 0.02 %. Consequently, the Reynolds number correction already carried out in the Q-Sonic 5 is assumed to be sufficient, and no further correction is introduced here. (It would also be difficult to device any additional Reynolds correction.)

7. CORRECTION MODEL FOR PRESSURE - TEMPERATURE EFFECTS

Correction models for pressure and temperature effects are proposed on basis of the calculation results given in Sections 3-6. Correction factors have been designed to be implemented at the flow computer level, and not at the USM level (i.e. not in the Q-Sonic 5 software).

7.1 Combined measurement error

Table 7 gives an overview of the calculated contributions, and their combined effect on the USM [1].

Table 7. Various contributions to the measurement error, and their combined effect, caused by pressure and temperature changes, from flow calibration (Westerbork) to field operation (Ormen Lange) conditions, for the Q-Sonic 5 ultrasonic flow meter. (Cf. also Table 8, which is an extract of Table 7.) (After [1].)

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	Source (further details)
Cross-sectional area and acoustic path geometry (inclination angles & lateral chord positions), effect on paths 1-5:	1	+ 0.272 %	+ 0.246 %	+ 0.246 %	Fig. 5
	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 %		Table 6
	2	+ 0.058 %			
	3	+ 0.061 %			
	4	+ 0.057 %			
	5	+ 0.054 %			
Expansion transducers, effect on paths 1-5:	1	- 0.054 %	- 0.041 %		Table 6
	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 %	Table 6
Reynolds number correction (assumed deviation from Elster-Instromet Reynolds number correction):				0 %	Sect. 6
Combined effect, total (%)				**+ 0.262 %**	

The contribution to the measurement error from the cross-sectional area and the acoustic path geometry (the inclination angles and the lateral chord positions), integrated over all 5 paths, is calculated to be +0.246 %, cf. Fig. 5. The contribution from expansion of the transducer ports, integrated over all 5 paths, is calculated to be +0.057 %. The contribution from expansion of the transducers themselves, integrated over all 5 paths, is calculated to be +0.041 %. The contribution from Reynolds number correction (assumed deviation from the Elster-Instromet Reynolds number correction), is taken to be 0 %, cf. Section 6.

Thus, according to the models used, the combined effect accumulates to +0.262 %. If effects caused by pressure and temperature changes are not corrected for, the Q-Sonic 5 will underestimate the volumetric flow rate by the same amount. A graphical visualization of the same data is given in Fig. 9.

The estimates of the various contributions are obtained by calculations, and are of course associated with uncertainties. The estimates used here are considered to be the best possible on basis of the information at hand.

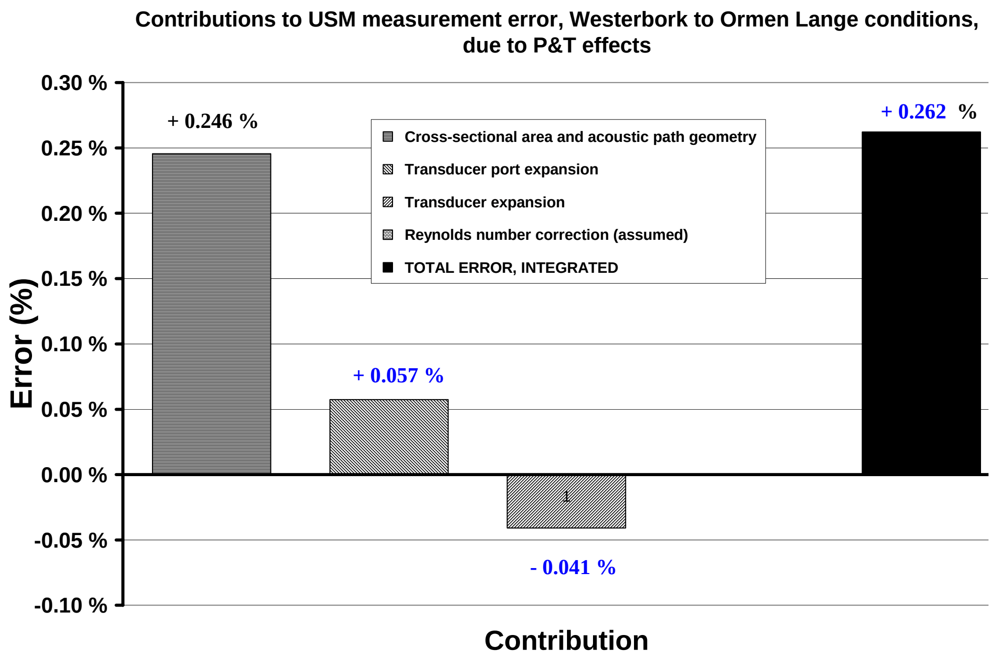


Fig. 9. Various contributions to the measurement error, and their combined total effect, caused by pressure and temperature changes, from flow calibration (Westerbork) to field operation (Ormen Lange) conditions, for the Elster-Instromet Q-Sonic 5 ultrasonic flow meter. (After [1].)

7.2 Correction factors

Correction of the volumetric flow rate for the effects of pressure and temperature changes from flow calibration (Westerbork) to field operation (Ormen Lange) conditions, as discussed in Chapters 4-6 and summarized in Section 7.1, is proposed to be done by multiplication of the measured volumetric flow rate with two correction factors, as outlined in the following:

(1) A "nominal P&T correction factor", C_{W-OL}^{PT-nom}, representing the main correction:

- Westerbork (63 barg, 7 ^{o}C) → Ormen Lange (nominal P&T, 230 barg, 40 ^{o}C),

- Fixed correction factor, based on the FEM calculations.
- Accounts for the effects A - E in Table 3.
- Implemented in the flow computer (not in the USM software).

(2) An "instantaneous P&T correction factor", $C_{OL}^{PT-inst}$, representing an adjustment for smaller P&T changes:
- Ormen Lange (nominal P&T, 230 barg, 40 ^{o}C) → Ormen Lange (actual P&T),
- Westerbork (63 barg, 7 ^{o}C) → Possible new flow calibration (new P&T conditions).
- Online "living" correction factor, based on the (simplified) analytical model B.
- Accounts for the effects A and B in Table 3.2.
- Implemented in the flow computer (not in the USM software).

The following correction model is thus proposed for the Ormen Lange application,

$$q = q_{USM} \cdot K_{Westerbork}^{Flow} \cdot C_{W-OL}^{PT-nom} \cdot C_{OL}^{PT-inst} , \qquad (14)$$

where

q : Corrected volumetric flow rate at Ormen Lange line conditions [m^3/s].

q_{USM} : Output volumetric flow rate of the Q-Sonic 5 at Ormen Lange line conditions [m^3/s].

$K_{Westerbork}^{Flow}$: Flow calibration correction factor [dimensionless], established under flow calibration at Westerbork. Flow dependent. Not addressed here.

C_{W-OL}^{PT-nom} : "Nominal P&T correction factor" [dimensionless], for pressure and temperature changes from flow calibration (Westerbork) to field operation (Ormen Lange) conditions (nominal), accounting for:
- Changes of cross-sectional area (diameter) (based on FEM)
- Changes of acoustic path geometry (inclination angles and lateral chord positions) (based on FEM)
- Expansion / contraction of transducer ports (based on FEM)
- Expansion / contraction of transducers (based on FEM)
- Changes of the Reynolds number.

$C_{OL}^{PT-inst}$: "Instantaneous P&T correction factor" [dimensionless], for

(a) instantaneous (small) changes of Ormen Lange pressure and temperature conditions, i.e. deviation between actual and nominal Ormen Lange P&T conditions, and

(b) in case of a future recalibration at Westerbork or another flow calibration lab, pressure and temperature changes from "old" to "new" flow calibration, both accounting for
- Changes of cross-sectional area (diameter)
- Changes of acoustic path geometry (inclination angles and lateral chord positions), both based on the analytical model B.

The two proposed correction factors are given as (from Table 7 and Eqs. (6))

$$C_{W-OL}^{PT-nom} = 1 + 0.262\ \% = 1.00262, \qquad C_{OL}^{PT-inst} = (1+3\alpha\Delta T)(1+3\beta\Delta P), \qquad (15)$$

respectively, where

ΔT = the temperature deviation between the nominal (40 ^oC) and the actual line temperature at Ormen Lange [^oC],
ΔP = the pressure deviation between the nominal (230 barg = $230\cdot10^5$ Pa-g)[5] and the actual line pressure at Ormen Lange [Pa],
β = the radial linear pressure expansion coefficient of the meter body [Pa^{-1}],

given as (cf. Section 4.1)

$$\Delta T = (T_{OL}^{inst} - T_{OL}^{nom}) - (T_{cal}^{new} - T_{cal}^{old}), \qquad \Delta P = (P_{OL}^{inst} - P_{OL}^{nom}) - (P_{cal}^{new} - P_{cal}^{old}), \qquad \beta = \frac{R_0}{wY}, \qquad (16)$$

where

T_{OL}^{inst} = the instantaneous (actual measured) line temperature at the Ormen Lange metering station [^oC],
T_{OL}^{nom} = the nominal line temperature at the Ormen Lange metering station [^oC] = 40 ^oC,
T_{cal}^{new} = the line temperature in the USM at a possible (future) new flow calibration [^oC]. As long as a new flow calibration has not been made, T_{cal}^{new} is set equal to T_{cal}^{old},
T_{cal}^{old} = the line temperature in the USM at the initial Westerbork flow calibration of the USM [^oC] = 7 ^oC,
P_{OL}^{inst} = the instantaneous (actual measured) line pressure at the Ormen Lange metering station [Pa-g],
P_{OL}^{nom} = the nominal line pressure at the Ormen Lange metering station [Pa-g] = 230 barg = $230\cdot10^5$ Pa-g,
P_{cal}^{new} = the line pressure in the USM at a possible (future) new flow calibration [Pa-g]. As long as a new flow calibration has not been made, P_{cal}^{new} is set equal to P_{cal}^{old}.
P_{cal}^{old} = the line pressure in the USM at the initial Westerbork flow calibration of the USM [Pa-g] = 63 barg = $63\cdot10^5$ Pa-g,

7.3 Correction factor calculation example

Fig. 10 shows an example of calculation of the corrected volumetric flow rate, q, including calculation of the instantaneous P&T correction factor, $C_{OL}^{PT-inst}$, and the total P&T correction factor, $C_{OL}^{PT-inst}\cdot C_{W-OL}^{PT-nom}$.

[5] Here, for brevity, the unit notation "Pa-g" is used for the gauge pressure (the excess pressure in Pascal relative to 1 atm.), i.e. in the meaning "Pa gauge" normally used in the SI unit system, analogous to the notation "barg" used for the excess pressure in bar relative to 1 atm.

In the example the following quantities are used: T_{OL}^{inst} = 45 °C and P_{OL}^{inst} = 240 barg, i.e. ΔT = (45-40) °C = 5 °C and ΔP = (240-230) bar = 10 bar = $10 \cdot 10^5$ Pa. The nominal P&T correction factor is $C_{W-OL}^{PT-nom} \approx$ 1.00262 (fixed), the instantaneous P&T correction factor becomes $C_{OL}^{PT-inst} \approx$ 1.00025 (calculated), and the total P&T correction factor thus becomes $C_{OL}^{PT-inst} \cdot C_{W-OL}^{PT-nom} \approx$ 1.00287 (calculated).

Due to the simplifications and approximations on which the calculations are based, at maximum four significant digits are considered to be valid for the present analysis. The total P&T correction factor for this example is thus rounded to $C_{OL}^{PT-inst} \cdot C_{W-OL}^{PT-nom} \approx$ 1.0029, corresponding to correcting for an error of +0.29 % (underreading).

Fig 10. Example of calculation of the corrected volumetric flow rate, including calculation of the instantaneous P&T correction factor and the total P&T correction factor.

(A)	**Nominal P&T correction factor:**					
	Nominal correction factor:	$C_{W-OL}^{PT\_nom}$	=	**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:**	$C_{W-OL}^{PT\_nom} * C_{OL}^{PT\_inst}$	=	**1.00287**		

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

8. CONCLUSIONS

Ultrasonic gas flow meters may be affected by pressure and temperature changes in several ways, such as (cf. Table 3)

- (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.

In the present work, pressure and temperature effects have been evaluated for the Elster-Instromet Q-Sonic 5 ultrasonic flow meter for operation in the Ormen Lange metering station at Nyhamna in Norway. The study addresses pressure and temperature changes from flow calibration (Westerbork, at 63 barg and 7 ^oC) to field operation (Ormen Lange, nominally at 230 barg and 40 ^oC) conditions.

The study shows that for the Ormen Lange application, investigation and evaluation of all of the factors (A)-(E) mentioned above have been necessary to evaluate the effect of pressure and temperature on the meter.

A theoretical approach has been chosen to establish such pressure and temperature corrections, since a screening of available flow laboratories in Europe and elsewhere has shown that currently no flow calibration laboratory can offer calibration or flow testing under process conditions which are relevant for Ormen Lange. This is particularly so with respect to the high pressure in question, 230 barg. Most flow calibration laboratories can not operate above about 60 barg with such large piping.

Investigation and evaluation of the pressure and temperature effects have been made by theoretical calculations, using various types of numerical and analytical models. Effects (A)-(D) have been evaluated very accurately using finite element modeling (FEM), in combination with a CMR model for USM numerical integration. In addition, effects (A)-(B) have been evaluated using two analytical models, as a simplified approach, for comparison. Effect (E) has been evaluated using a CMR model for USM numerical integration.

Accurate FEM calculations show that the combined effect of (a) change of the meter's cross-sectional area (diameter change) and (b) change of the ultrasonic path geometry (inclination angles and lateral chord positions) is by far the largest and most dominant effect, amounting to about 0.246 %. For this effect, a fair agreement has been obtained between FEM and the analytical models A and B, for the P&T conditions considered here. This indicates that the analytical model B may be used for the instantaneous correction factor in the Ormen Lange application, see below. How general this fair agreement is, however, and whether it can be extrapolated to other conditions, has not been investigated here.

With respect to the combined effects of (a) transducer port length changes and (b) transducer length change, accurate FEM calculations show that the two individual contributions are both significant for the Ormen Lange application, but effectively cancel each other to a large extent when combined, so that an error of about 0.017 % remains, cf. Table 8. This is an effect of the P&T conditions in question at Westerbork and Ormen Lange. In general (at other P&T conditions), such cancellation might not be the case, and a "reinforcement" effect may be experienced instead of cancellation. It is thus in general recommended to calculate or by other means investigate both the change of the transducer port length and the change of the transducer length.

The effect of Reynolds number change from Westerbork to Ormen Lange is relatively small (about 0.04 %), but still significant if Reynolds number correction were not used in the USM. For the Q-Sonic 5 flow meter a Reynolds number correction from Westerbork to Ormen Lange conditions is used by the manufacturer [12], but the actual magnitude of the manufacturer's correction has not been available for the present study. In a dialogue with Autek, Elster-Instromet and the Ormen Lange project, it has been assumed here that the manufacturer's Reynolds number correction is sufficiently close to the Reynolds number correction calculated here (0.04 %), so that an additional Reynolds number correction is not devised.

When combining the above mentioned contributions, the pressure and temperature effect on the Q-Sonic 5 in the Ormen Lange application is estimated to +0.262 %, cf. Table 8. Several factors contribute to this number: (a) cross-sectional area and acoustic path geometry (inclination angles and lateral chord positions) +0.246 %, (b) expansion of transducer ports +0.057 %, (c) expansion of the transducer -0.041 %, (d) Reynolds number correction 0 % (cf. Table 7 and Fig. 9).

Table 8. Extract of Table 7: Various contributions to the measurement error, and their combined effect, caused by pressure and temperature changes, from flow calibration (Westerbork) to field operation (Ormen Lange) conditions, for the Elster-Instromet Q-Sonic 5 ultrasonic flow meter. (After [1].)

Contributing factor to measurement error, due to pressure and temperature changes	**Integrated contribution to error (all 5 paths)**	**Combined contribution to error**
Cross-sectional area and acoustic path geometry	+ 0.246 %	+ 0.246 %
Expansion transducer ports, effect on paths 1-5:	+ 0.057 %	
Expansion transducers, effect on paths 1-5:	- 0.041 %	
Combined effect, expansion transducer ports & expansion transducers, all 5 paths:		+ 0.017 %
Reynolds number correction (assumed deviation from Elster-Instromet Re no. correction):		0 %
Combined effect, total (%)		**+ 0.262 %**

If the effects caused by pressure and temperature changes are not corrected for, the Q-Sonic 5 will underestimate the volumetric flow rate by the same amount.

Consequently, 2 correction factors are proposed for implementation in the flow computer, to account for pressure and temperature effects from flow calibration (Westerbork, 63 barg, 7 ^{o}C) to field operation (Ormen Lange, nominal P&T = 230 barg, 40 ^{o}C) conditions:

(1) A "nominal P&T correction factor", C_{W-OL}^{PT-nom}, representing the main correction, as a fixed number, equal to 0.262 %.

(2) An "instantaneous P&T correction factor", $C_{OL}^{PT-inst}$, representing an adjustment for smaller P&T changes at Ormen Lange (nominal P&T = 230 barg & 40 ^{o}C to actual P&T). This is an online "living" correction factor, based on the (simplified) analytical model B described in Section 4.1.

In case of a future flow calibration at possibly another pressure and temperature condition than the Westerbork condtions (63 barg, 7 ^{o}C), the P&T effects of that possible change of calibration conditions may also be accounted for in the "instantaneous P&T correction factor", cf. Eqs. (14)-(16).

A closer discussion of the two correction factors C_{W-OL}^{PT-nom} and $C_{OL}^{PT-inst}$ is given in Section 7. Note that $C_{OL}^{PT-inst}$ is calculated using the approximate analytical model B, strictly valid for inclination angles equal to ±45° only. Although an alternative and more accurate model is available (analytical model A), this model B has been chosen since the correction factor needs to be implemented at flow computer level, and not in the USM software.

The results and proposed correction factors are based on calculations, using theoretical models (analytical and numerical models). The question was therefore raised at an early stage in the project whether the calculations could by some means be verified experimentally, such as e.g. by doing static measurements with an 18" Q-Sonic 5. The purpose would be to supply or verify parts of the theoretical calculations. However, an analysis has indicated [1] that with the dimensional changes in question here, the effects on the transit times will be so small that control with time delay correction (transducer, electronics and diffraction correction delay, etc.) will be required beyond what is considered to be realistic today. Until such challenges are solved, it seems like one has to rely on theoretical models and calculations when pressure and temperature corrections of ultrasonic flow meters are required.

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REFERENCES

[1] **Lunde, P. and Frøysa, K.-E.:** "Ormen Lange ultrasonic gas flow meters. A study for establishment of corrections for pressure and temperature effects", CMR report no. CMR-06-A10048-RA-01, Christian Michelsen Research AS, Bergen, Norway (March 2007).

[2] Elster-Instromet Q-Sonic 5 ultrasonic flow meter web site, Elster-Instromet NV, Rijkmakerlaan 9, B-2910 Essen, Belgium (2006); http://www.elster-instromet.com/en/ultrasonic_flow_metering.html

[3] "Measurement of flow in closed conduits – ultrasonic meters for gas – Part 1: meters for custody transfer and allocation measurement", ISO/CD 17089-1, August 31, 2007, International Organization for Standardization, Genéve, Switzerland. (Committee Draft.) (Reference number ISO/TC 30/SC 05 N210.)

[4] **Lunde, P., Frøysa, K.-E. and Vestrheim, M. (eds.):** "GERG project on ultrasonic gas flow meters, Phase II", GERG TM11 2000, Groupe Européen de Recherches Gazières (VDI Verlag, Düsseldorf, 2000).

[5] **Lunde, P. and Frøysa, K.-E.:** "Handbook of uncertainty calculations. Ultrasonic fiscal gas metering stations". Handbook prepared on behalf of the Norwegian Society of Oil and Gas Measurement (NFOGM) and the Norwegian Petroleum Directorate (NPD) (December 2001), 279 p. (ISBN 82-566-1009-3). (Free download available from www.nfogm.no.)

[6] “Manual of petroleum measurement standards. Chapter 12 - Calculation of petroleum quantities. Section 2 - Calculation of liquid petroleum quantites measured by turbine or displacement meters”, First edition. American Petroleum Institute, U.S.A. (September 1981). (Paragraphs 12.2.5.1 and 12.2.5.2.)

[7] “Manual of petroleum measurement standards. Chapter 12 - Calculation of petroleum quantities. Section 2 - Calculation of liquid petroleum quantites using dynamic measurement methods and volumetric correction factors. Part 1 - Introduction”, Second edition. American Petroleum Institute, Washington D.C., U.S.A. (May 1995). (Paragraphs 1.11.2.1 and 1.11.2.2.)

[8] **"**Institute of Petroleum. Petroleum Measurement Manual. Part X - Meter Proving. Section 3 - Code of practice for the design, installation and calibration of pipe provers", Published on behalf of The Institute of Petroleum, London (J. Wiley & Sons, Chichester, 1989), Section 10.7, p. 31 (ISBN 0 471 92231 5).

[10] “Measurement of gas by ultrasonic meters”, A.G.A. Report no. 9, American Gas Association, Transmission Measurement Committee (June 1998). (Presently under revision.)

[11] **Young, W. C. and Budynas, W. C.,** *Roark’s formulas for stress and strain*, 7th edition (McGraw-Hill, New York, 2001).

[12] Personal communication between Per Lunde, CMR, and Per Salvesen, Autek, Norway (Elster-Instromet’s Norwegian sales representative) (2001, 2006 and 2007), including communication with Timo Smits, Elster-Instromet NV, Holland (2006 and 2007).

[13] **Zagarola, M. V. and Smits, A. J.**, ”Experiments in high Reynolds number turbulent pipe flow". *Phys. Rev. Lett.* 78, (1997).

[14] **Perry, A. E., Henbest, S. M. and Chong, M. S.**, ”A theoretical and experimental study of wall turbulence ". *J. Fluid Mech.* 165, 163-199 (1986).

[15] **den Toonder, J. M. J.,** ”Drag reduction by polymer additives in a turbulent pipe flow". Ph. D. thesis, Delft University of Technology (1995).

[16] **Durst, F., Jovanovic, J. and Sender, J.,** ”LDA measurements in the near-wall region of a turbulent pipe flow". *J. Fluid Mech.* 295, 305-335 (1995).

[17] **Laufer, J.,** “The structure of turbulence in fully developed pipe flow.” Report 1174, National Bureau of Standards, 1952.

[18] “Regulations relating to measurement of petroleum for fiscal purposes and for calculation of CO_2 tax”, Norwegian Petroleum Directorate, Stavanger, Norway (November 1, 2001).

[19] Test reports for K10 ultrasonic transducers, 44005-R114 to -R119, dated December 2004, and 54012-5005, -5008 and -5009, dated January 2005. Elster-Instromet NV, Rijkmakerlaan 9, B-2910 Essen, Belgium (2004).

[20] Personal communication between Per Lunde, CMR, and Klaus Zanker, Daniel Industries, Houston, USA (2001).

[21] Personal communication between Per Lunde, CMR, and Skule Smørgrav, FMC Kongsberg Metering, Kongsberg, Norway (2001).

[22] **Hallanger, A., Frøysa, K.-E. and Lunde, P.:** “CFD simulation and installation effects for ultrasonic flow meters in pipes with bends”, International Journal of Applied Mechanics and Engineering, **7(**1), 33-64 (2002).