How Accurate are Ultrasonic Flowmeters in Practical Conditions; Beyond the Calibration

Jankees Hogendoorn, Herman Hofstede,
Peter van Brakel and André Boer.

1. Introduction

In the Oil and Gas industry, tens of thousands Custody Transfer Flowmeters are in operation for many decades. These flowmeters have been carefully calibrated on-site or in accredited laboratories. Furthermore, they are verified on a regular basis.

However, the majority of these flowmeters are working at other conditions than they have been calibrated at. The flow, and thus the flowmeters are subject to change in temperature, pressure, viscosity, environmental conditions, etc.. Very often the upstream piping configuration is different from the configuration during calibration or verification in the laboratory as well.
It is very important to know what is left from the custody transfer accuracy the user is looking for. The real performance of the flowmeter can differ significantly from the accuracy that is expected.

This paper gives an overview of the major parameters that affect the performance of these flowmeters for liquids. A sensitivity analysis shall be presented quantifying the effects of changing flow and environmental conditions. This analysis shall cover a wide range of changing conditions.

The paper concludes with some practical directions how to reduce the uncertainty in performance with immediate effect and over its life time. This includes a design-, diagnostics- and calibration-based approach.

A very clear methodology for the calculation of the uncertainty of a fiscal oil measurement system is given in [1]. In the present paper the focus is on the ultrasonic flowmeter and ALTOSONIC V in particular. An overview of other measuring principles is given in [2]. It should be noted, that the present paper doesn't has the intention to provide the reader with a complete and extensive overview on this topic. However, as far as we can see, most relevant sources have been addressed.

Sources of additional measuring uncertainty
There are several sources that lead to additional measuring uncertainty. One could distinguish the sources in several categories as depicted in Figure 1.

The first category is related to the initial performance of the installed flowmeter, which comprises e.g. linearity, repeatability and reproducibility. This category will be addressed in section 2.

The second category (described in section 3) is related to the process itself, e.g. process temperature and pressure. But also the fluid properties and flow pattern are significant influencing parameters having an effect on the performance of the flowmeter. An important question is what the flowmeter sensitivity is to these parameters. Therefore a sensitivity analysis is mandatory.

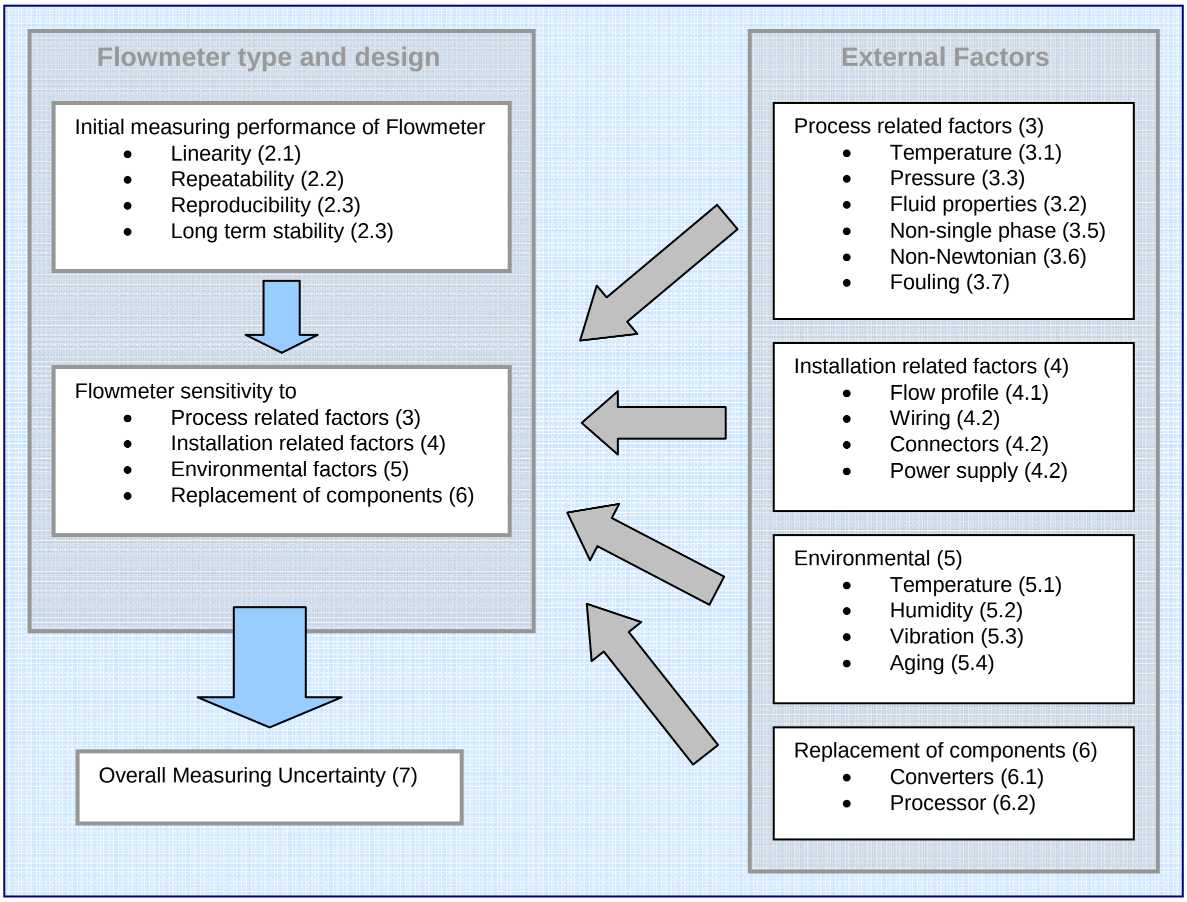

Figure 1 Schematic overview of different categories of parameters that affect the flowmeter uncertainty. The number behind the items refer to the paragraph in which this specific item is addressed.

A third category is the installation conditions. Upstream piping will affect the flow profile. Important is to know what the effect is on the flowmeter reading. An uncertainty analysis is valuable here as well. In addition the condition of the cabling, connectors, power supply is important also. This category is discussed in section 4.

A fourth category should be considered as environment related issues like ambient temperature, humidity, vibrations, etc. This shall be addressed in section 5.

A fifth category (described in section 6) is related to the exchange of critical components having an impact on the flow meter uncertainty.

All factors mentioned above will be systematically addressed in this paper. Where possible, an estimation of the sensitivity to that specific parameter shall be made supported by measuring data.
By doing this, an overall figure is being created of the total uncertainty of the flowmeter. It becomes clear which parameters are dominant and how the total uncertainty could be minimized.

2. Initial Measuring Performance of the Flowmeter

2.1 Linearity

The linearity of a flowmeter indicates the relation between the flow rate measured by the flow meter and the reference flow rate. During calibration, the error is determined between the reference and measured flow rate for specified range of flow rates.

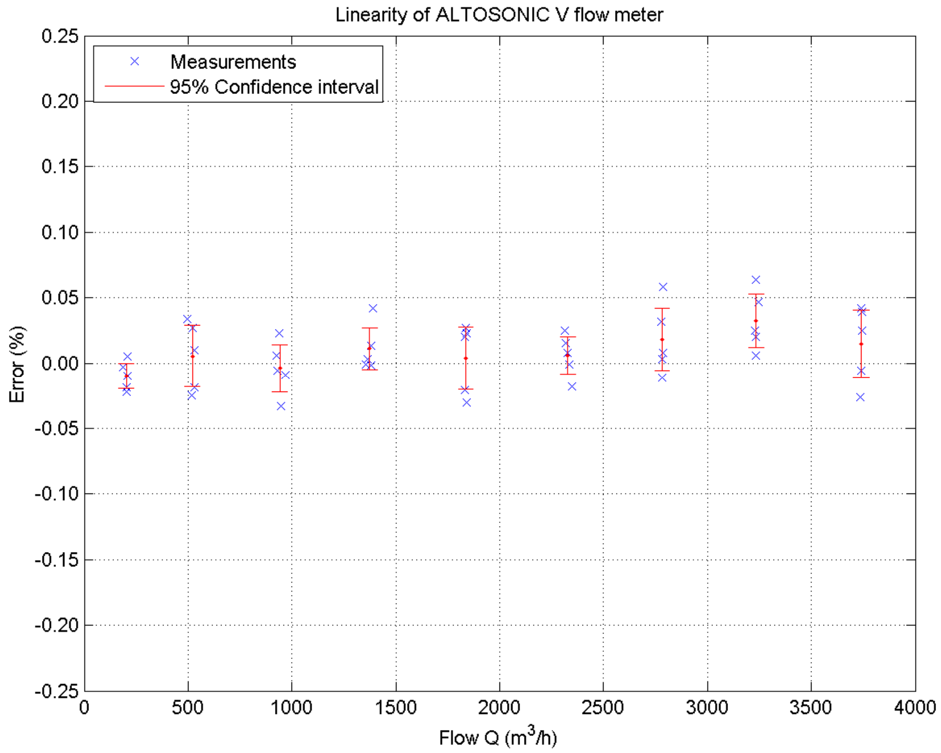

Figure 2 : Calibration data of a 16" ALTOSONIC V flowmeter with water at T=18 ºC for a flow range of 200...3700 m^3/h. The crosses indicate the individual measurements. The red bar indicates the uncertainty on the average value per flow rate. This graph shows that the uncertainty of the flow meter reading including non-linearity stays within 0.05 %.

The 95% confidence interval is calculated based on the average (=mean) error at specific flow rates plus or minus the estimated accuracy in the mean error.

As depicted in Figure 2, the uncertainty for the whole flow range is investigated and calculated as maximum 0.05%. The reported deviations from the reference meter are random effects and not systematically.

A few remarks need to be made on the results shown in Figure 2. The measurement at each flow rate was repeated 5 times, with more measurements, thus when measuring for a longer time, the value of n will increase, so the uncertainty $\Delta\bar{x}$ decreases.

Important is to recognise that the linearity in the previous graph is shown as a function of volume flow. Especially for hydrocarbon applications it makes sense to plot the linearity as function of Reynolds number, since the viscosity of the application might vary significantly. By plotting the linearity as a function of Reynolds, both flow and viscosity effects are taken into account. An example is given in Figure 3.

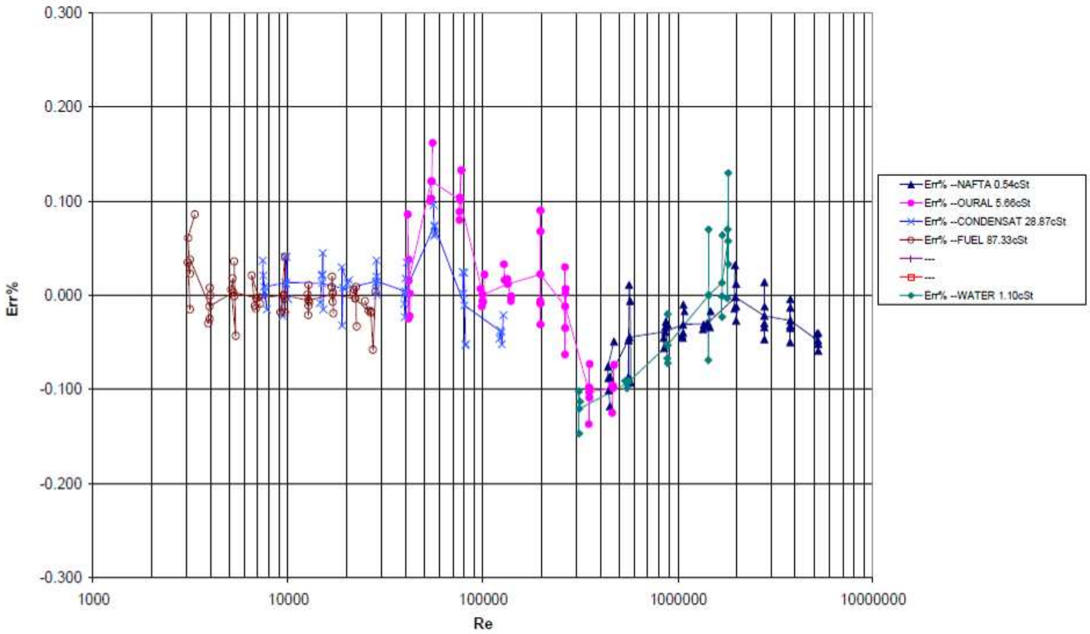

Figure 3 Linearity curve of a 20"ALTOSONIC V as function of Reynolds, calibrated at different products with different viscosities. A clear correlation and overlap between the individual linearity curves for different products is observed.

Typically, the linearity plotted as a function of volume flow is just a small fraction of the scale that is covered by the linearity plotted as a function of Reynolds number. This is clearly illustrated in Figure 3. Each colour indicates an individual calibration curve per liquid (viscosity).

Since the flow range which has to be covered is much larger, a wider variety of flow profile shapes have to be covered (laminar, transitional and turbulent). This leads typically to an additional error in linearity when compared to a tailor made calibration at one specific viscosity (as shown in Figure 2).

It is important that the end user provides all process data to calculate the operating Reynolds range. Based on the Reynolds range the appropriate calibration products can be selected to cover this range. If this is not the case, errors in flow reading easily can go up to 0.5% or more!

<u>Based on the experimental data as shown in Figure 3, the uncertainty for the ALTOSONICV due to non-linearity over a wide Reynolds number range is calculated as 0.10 %.</u>

2.2 Repeatability

The repeatability of a flowmeter indicates the spread which is observed when multiple measurements at the same flow conditions are performed. Referring to Figure 2, it is clear that the spread between different measurements at the same flow conditions is limited to about ± 0.03% variation. The spread in error values when measuring five times at the same flow rate is shown in Figure 4.

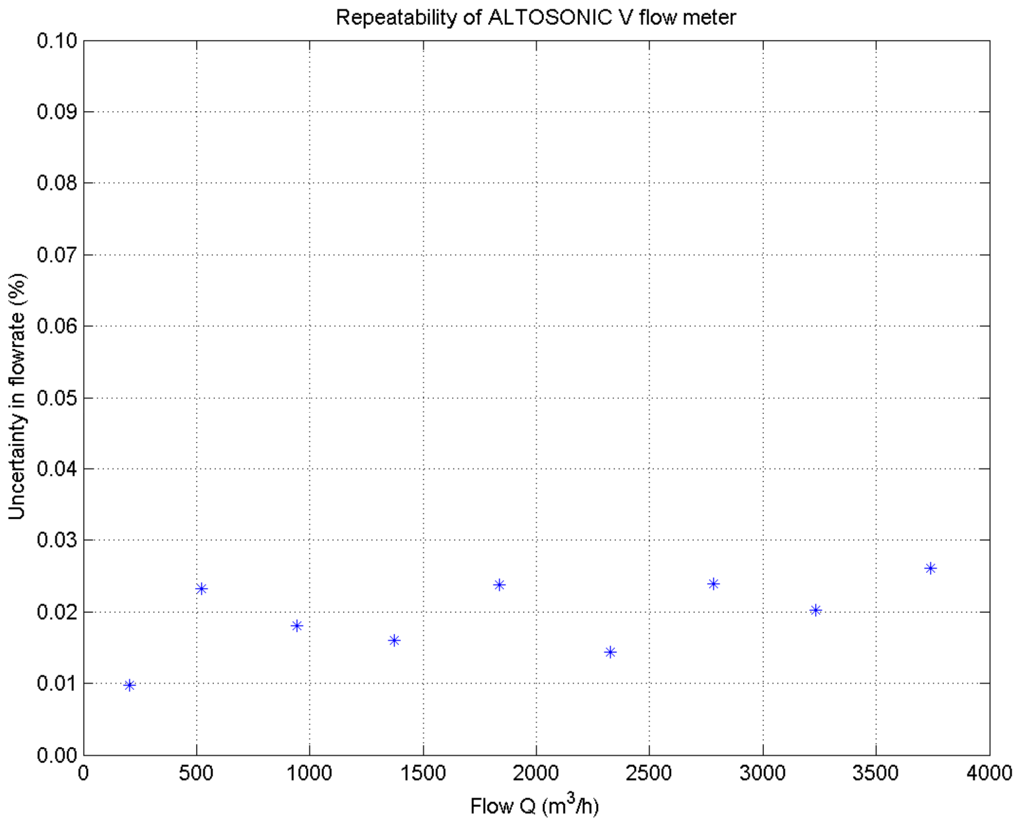

Figure 4 : Calibration data of a 16" ALTOSONIC flowmeter with water at T=18 ºC for a flow range of 200..3700 m³/h. The uncertainty in flow rate $\Delta\bar{x}$ of the measurements performed at the same flow rate is determined.

<u>The uncertainty in the flow meter reading due to the repeatability of the flowmeter equals 0.03 % as indicated in the figure above.</u>

2.3 Reproducibility and long term stability

According to the API MPMS Ch. 1 Reproducibility is defined as:

> *The closeness of the agreement between the results of measurements of the same quantity, where the individual measurements are made by different methods, with different measuring instruments, by different observers, at different locations after a long period of time: or where only some of the factors listed are different. More specifically, the ability of a meter and prover system to reproduce over a long period of time in service where the range of variations of pressure, temperature, flow rate and physical properties of the metered liquid is negligible small. Reproducibility is expressed as :*

$$R\ (absolute) = \ Max - Min$$

The reproducibility of ultrasonic flowmeters is calculated based on calibrations performed on the ALTOSONIC V over a long period of time. The stability is obvious while no component are used which can drift neither are any moving parts used in this flowmeter.

In Figure 5 the calibration results are shown for a 24” ALTOSONIC V calibrated over a period of 6 years.

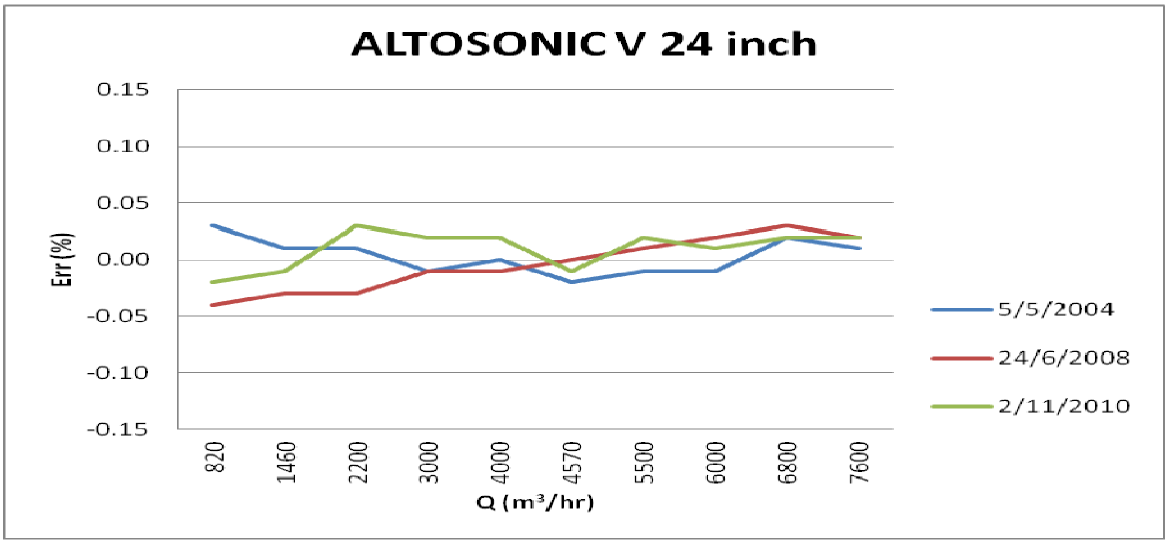

Figure 5 : Over a period of 6 years an ALTOSONIC V 24” was calibrated showing excellent reproducibility results.

Long term reliability has been proven with the ALTOSONIC V, of which the first meters are in use since 1997. Test results obtained from these very first flowmeters demonstrate stable verification data. No systematic shift or drift has been observed.

Figure 6 demonstrates another set of calibration data of a 20” ALTOSONIC V. It concerns data over a time interval of 10 years. The flowmeter has been initially calibrated in France in 1999 and verified at the same calibration installation in 2009. During the operational lifetime of 10 years, no maintenance have been carried out. Based on the results the conclusion can be drawn that the flow meter shows no systematic shift over these years. The average variation lies between 0.08%. The 0.08% uncertainty is not only caused due to long term effects, but also includes the uncertainty of the used test rig.
In another example where the meter was calibrated and tested in-situ (so the meter did not move between the tests), there were no installation effects which resulted in a long term stability effect of 0.05% uncertainty. This includes also the 0.02% uncertainty of the small volume prover (SVP) which has been used for in-situ verification.
A last example, which illustrates the long term stability at high viscosity applications, is given in [3].

<u>The total uncertainty due to long term stability effects is calculated as maximum 0.08%.</u>

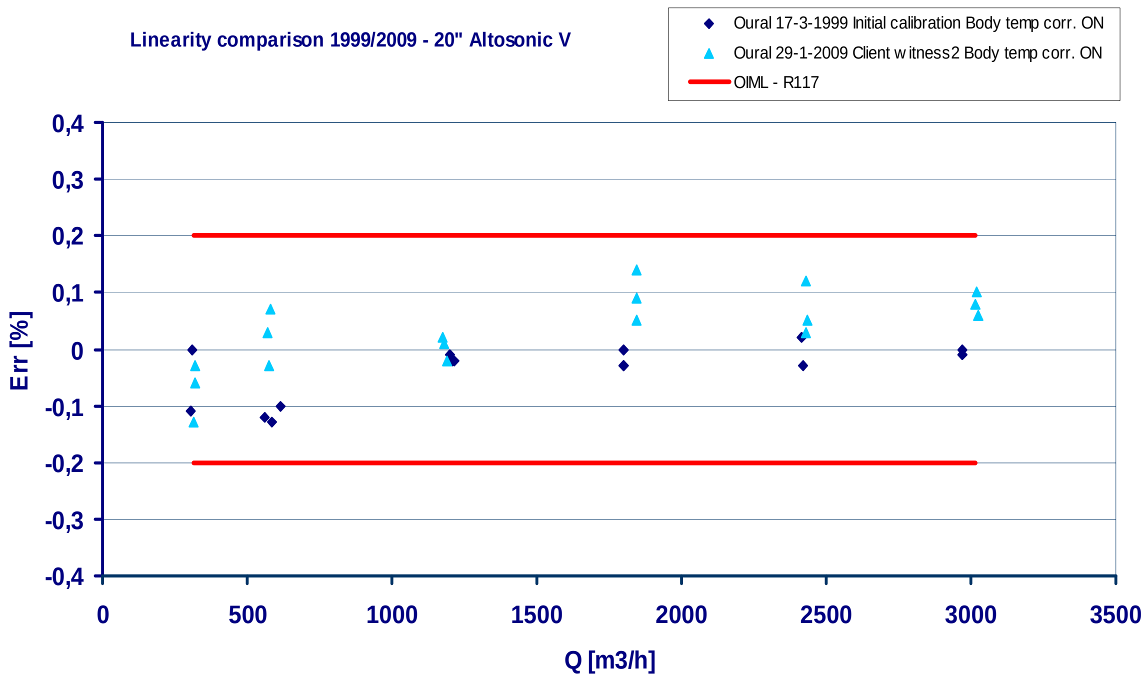

Figure 6 *: After a period of 10 years, an 20" ALTOSONIC V was tested on Crude Oil (5 cSt). During the operation life time of 10 years, no maintenance was performed. The test resulted in a 0.08% difference over the timeframe 1999 – 2009.*

3. Process Related Factors

There are a number of process related parameters that affect the performance of the flowmeter. The most well known parameters are the temperature and pressure. In this section the sensitivity of the flowmeter to temperature and pressure is quantified.

The sensitivity of the measured flow rate to e.g. pressure and temperature variations can be written as:

$$Q = Q(T, P)$$

$$\Delta Q = \left.\frac{\partial Q}{\partial T}\right|_{P=const} \Delta T + \left.\frac{\partial Q}{\partial P}\right|_{T=const} \Delta P$$

$$\frac{\Delta Q}{Q} = \sqrt{\left(\frac{T}{Q}\left.\frac{\partial Q}{\partial T}\right|_{P=const}\right)^2 \left(\frac{\Delta T}{T}\right)^2 + \left(\frac{Q}{Q}\left.\frac{\partial Q}{\partial P}\right|_{T=const}\right)^2 \left(\frac{\Delta P}{P}\right)^2}$$

The flow Q is given by

$$Q = Mc \cdot A \sum_{n=1}^{5} w_n \frac{Lp_n}{2\cos\phi_n}\left(\frac{t_{BA,n} - t_{AB,n} - t_{zero,n}}{t_{AB,n} \cdot t_{BA,n}}\right)$$

With:

- meter constant (Mc),
- cross sectional area of the flowmeter (A),
- weighting factors of the individual paths (w_n)
- path lengths (Lp_n)
- corresponding transit times ($t_{AB,n}$, $t_{BA,n}$).

The ALTOSONIC V is equipped with a Reynolds correction function, which corrects for errors due to changing velocity profiles based on the Reynolds number. This results in an extra term.

$$Q = \left\{ Mc \cdot A \sum_{n=1}^{5} \left(w_n \frac{Lp_n}{2\cos\phi_n} \frac{t_{BA,n} - t_{AB,n} - t_{zero,n}}{t_{AB,n} \cdot t_{BA,n}} \right) \right\} \times [1 - \varepsilon(\mathrm{Re})]$$

Using partial derivatives as mentioned before, the effect of temperature and pressure variations on the measured flow rate can be determined. When speaking of flow rate, the actual volume flow rate is meant. In the following paragraphs, the various contributions are summarised.

3.1 Temperature

Process temperature change has two major effects:

- affecting the geometry of the flowmeter
- influences the fluid properties.

<u>3.1.1. Flowmeter geometry</u>

It is well known that the geometry of each flowmeter is affected by temperature. However, the effect of temperature on the flowmeter reading can be quantified and corrected for [4] [5] [6]. The sensitivity analysis is shown in this paragraph and supported by experimental data.

The expression for the flow is given by

$$Q = \left\{ Mc \cdot A \sum_{n=1}^{5} \left(w_n \frac{Lp_n}{2\cos\phi_n} \frac{t_{BA,n} - t_{AB,n} - t_{zero,n}}{t_{AB,n} \cdot t_{BA,n}} \right) \right\} \times [1 - \varepsilon(\mathrm{Re})]$$

Several terms can be combined and the expression is rewritten as

$$Q = \left\{ Mc^{*} \cdot D^{3} \sum_{n=1}^{5} \left(w_n^{*} \times \frac{t_{BA,n} - t_{AB,n} - t_{zero,n}}{t_{AB,n} \cdot t_{BA,n}} \right) \right\} \times [1 - \varepsilon(\mathrm{Re})]$$

Variables indicated with * are constants, not changing the temperature behavior of the expression. Since temperature behavior is isotropic, axial and radial effects can be combined in a single variable D.

The partial derivative $\left.\frac{\partial Q}{\partial T}\right|_{p=const}$ is determined. In this expression different terms can be indicated.

a) Meter constant Mc (or Mc^{*})
b) Diameter D
c) Weighing factor w_n (or w_n^{*})
d) The transit times t_{AB}, t_{BA}.
e) Zero drift t_{zero}
f) Reynolds correction term.
g) The effect of t_{zero} drift in the denominator is treated separately.

These terms a) - g) are treated one by one below.

a) Meter constant Mc (or Mc*) is a constant, so not temperature dependent.

b) The diameter D changes with temperature as $D=D_{cal}*[1+\alpha(T_{oper}-T_{cal})]$, with α as the thermal expansion coefficient. The temperature dependency of the diameter is calculated as

$$\left.\frac{\partial}{\partial T}\left\{D_{cal}^{\ 3}\left[1+\alpha\underbrace{\left(T_{oper}-T_{cal}\right)}_{\Delta T}\right]^3\right\}\right|_{p=const} = 3\alpha D_{cal}^{\ 3}$$

Which indicates the temperature sensitivity of the flow rate Q. The introduced uncertainty in the flow rate is given by

$$\frac{\Delta Q}{Q} = \frac{1}{Q}\frac{\partial Q}{\partial T}\Delta T = 3\alpha\Delta T$$

Since the D_{cal}^3 cancels with the D^3 term in the expression for Q. The other terms in Q (like w_n and t_A etc) are assumed constant, and thus cancel out when dividing by Q.

Besides this analytical derivation, PTB in Berlin has done measurements which confirms the $3\alpha\Delta T$ behavior of the ALTOSONIC V. Extensive tests at PTB demonstrate that the flowmeter thermal expansion can be corrected for using the $3\alpha\Delta T$ relation (see Figure 7 and Figure 8).

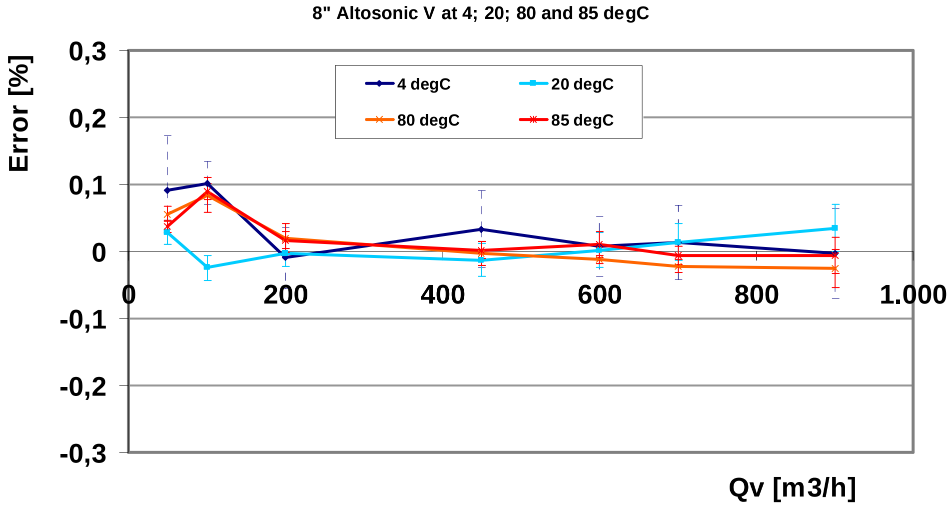

Figure 7 : Linearity curves obtained with an 8"ALTOSONICV at PTB in Berlin. Calibration liquid: water at 4, 20, 80 and 85°C. The flowmeter applies the $3\alpha\Delta T$ *correction. It is clearly demonstrated that the effect of thermal expansion is effectively eliminated. The additional measuring error at low flow rates is caused by buoyancy effects.*

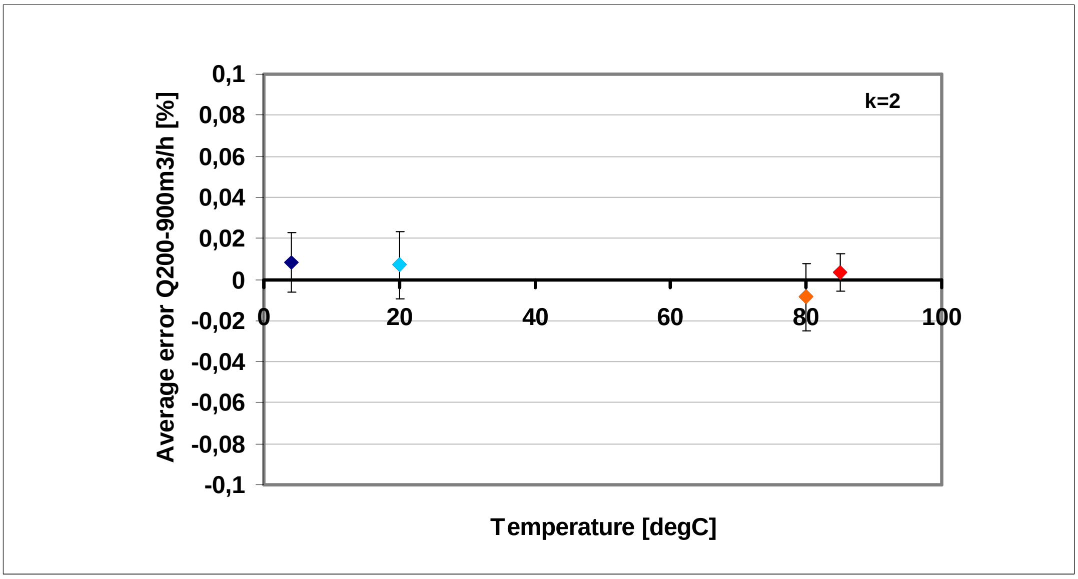

Figure 8 : The same test results as shown in Figure 7 but now averaged on flow and plotted as function of process temperature. These results clearly illustrates that the measurement points coincide with the $3\alpha\Delta T$ *theory, and can thus be corrected for. On the vertical axis, the deviation is shown in %.*

<u>The resulting residual uncertainty (remaining after correction) is estimated at 0.025 %.</u> This includes the effect of uncertainties in the temperature measurement.

c) Weighing factors w_n (or w_n^*) are constants, so not temperature dependent.

d) The next temperature dependent term is the difference in transit times, t_{AB}-$t_{BA,}$ which depend on the flow velocity profile via the Reynolds number. For the transit time sensitivity to temperature, the temperature dependence of the Reynolds number is calculated. The Reynolds number is defined as.

$$\mathrm{Re} = \frac{VD}{\nu}$$

with

V = flow velocity [m/s]
D = Diameter of the flowmeter [m]
ν = Kinematic viscosity of the fluid [m^2/s]

The effect of a changing Reynolds number as a function of temperature is addressed in section 3.2.2.

e) The next temperature dependence term in the flow rate expression is the t_{zero} ,which drifts slightly with temperature. This contribution has an electronic component and a sensor hardware component.
Assuming 20 ºC±10 ºC temperature variation in the environment of the converter, the zero point might change ±16 psec at maximum over this temperature span. For a 10" pipe, at a flow velocity of v=1 m/s and c=1280 m/s, the time difference t_{BA}-t_{AB} equals $\Delta t = 0.30\ 10^{-6}$ sec. Based on these results, the error made due to zero point drift is calculated as

$$\frac{16\cdot 10^{-12}}{0.30\cdot 10^{-6}} = 5.4\cdot 10^{-5} = 0.0054\ \%.$$

For higher flow velocities and bigger diameters, this value will decrease since the transit time in the denominator increases linear with flow speed and flow meter size. The same calculation can also be done for larger ambient temperature variations.

f) The last contribution is the Reynolds correction term which has been discussed under item d.

g) The used expression with $t_{AB,n}\cdot t_{BA,n}$ in the denominator is not completely correct since both t_{AB} and t_{BA} should be corrected for the delay times, such that the expression for Q should read as

$$Q \propto \frac{1}{\left(t_{AB,n}+t_{del,AB}\right)\cdot\left(t_{BA,n}+t_{del,BA}\right)}$$

The effect of the delay time in the value of Q is calibrated for. When the meter is used under conditions different than the calibration conditions (i.e. other speed of sound), the t_{AB} and t_{BA} values change, and the delay times will affect the measured flow.

This uncertainty can be quantified as

$$\frac{\Delta Q}{Q} = -\underbrace{\frac{2(\beta-1)}{\beta}}_{const}\times\frac{\Delta t_{del}}{t_{AB}} \quad \text{with} \quad \beta = \frac{C_{cal}}{C_{meas}}$$

Indicating the ratio of the speed of sound during initial calibration situation over the operational situation. The delay time uncertainty is divided by the transit time.

<u>The flow measurement uncertainty due to change in speed of sound equals 0.0052 %</u>.

This is calculated for the 20” ALTOSONIC V example as used before.

Summarizing the terms a) – g) above, the total uncertainty made in the flow measurement caused by temperature deviations can be quantified as

Contribution	***Value***	***Remarks***
a) Meter constant Mc	0	Mc is constant
b) Diameter D	0.025 %	Residual after correction for systematic part
c) Weighing factor w_n	0	w_n are constant
d) Transit time t_{AB},t_{BA} → Re	0	Systematic error, compensates with f)
e) Zero drift t_{zero} – Electronics	0.0054 %	Systematic
e) Zero drift t_{zero} – Sensor drift	0	Included in b)
f) Reynolds correction	0	Systematic error, compensates with d)
g) Delay time effect	0.0052%	Systematic
Total error due to temperature variations	**0.03 %**	

<u>3.1.2 Fluid properties</u>

Due to changing process temperature the fluid viscosity and vapour pressure is affected. The vapour pressure could be affected in such a way that it runs beyond the (local) process pressure, leading to cavitation. This could be detected by the ultrasonic flowmeter by increasing standard deviation on the velocity measurement per path. At higher gas fractions measuring paths will start to fall out, resulting in alarms.

Chemical reactions due to changing process temperature leading to significant changing fluid properties is outside the scope of this paper.
This paper focuses on hydrocarbons. The hydrocarbon viscosity as a function of temperature is fairly well predictable. Especially the combination of high viscosities (e.g. > 100 cSt) and decreasing temperature could easily lead to rapidly increasing viscosities [7].
The viscosity of highly viscous oil is strongly dependent on temperature. The higher the viscosity, the stronger the dependency. This is clearly illustrated in Figure 9 where the kinematic viscosity is shown as a function of temperature.

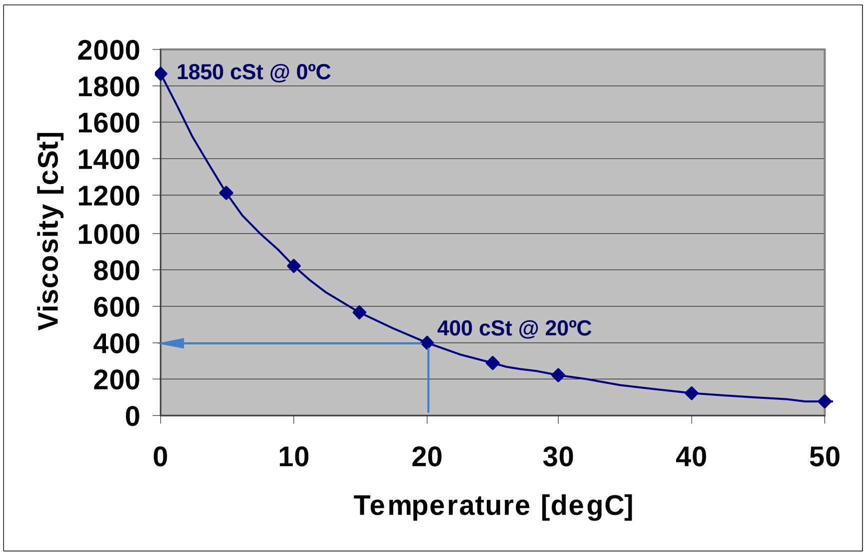

Figure 9 Relationship between viscosity and temperature of an extra-heavy-oil sample.

This temperature dependency has implications for practice. First of all, it is essential to demonstrate that the flow meter linearity is a function of Reynolds only. If this is the case, the variations in viscosity can be handled by the flowmeter and will not lead to additional reading error. A clear illustration has been given in Figure 3. Especially at high viscosity applications, the end user has to verify the maximum allowable viscosity which can be handled by the flowmeter. This has to be studied in conjunction with the Reynolds range expected in practice.
Besides the viscosity, also the density will be influenced by the process temperature. However, the density has a negligible effect on the flowmeter reading.

3.2 Pressure

In addition to the process temperature the process pressure is important too. Due to a decreasing pressure the local process pressure can get below the vapour pressure leading to (local) cavitation. For this situation the same approach can be followed as described in section 3.1.2.
The density of the liquid is hardly affected by process pressure and will not influence the flowmeter performance significantly.
If the flowmeter is properly constructed, the flowmeter geometry is very weakly dependent on pressure. Dependent on the flowmeter construction, either analytical formulas can be used or Finite Element calculations are required.

For the pressure sensitivity analysis in this paper, two approaches were used. First, the analytical model is described. The second part deals with the numerical model.

3.2.1. Analytical approach

What is done for the temperature sensitivity can be done for the pressure sensitivity in a similar way. Again the basic flow equation is used as a start.

$$Q = \left\{ Mc \cdot A \sum_{n=1}^{5} \left(w_n \frac{Lp_n}{2\cos\phi_n} \frac{t_{BA,n} - t_{AB,n} - t_{zero,n}}{t_{AB,n} \cdot t_{BA,n}} \right) \right\} \times [1 - \varepsilon(\mathrm{Re})]$$

In the previous (temperature) calculations, length (X) and diameter (D) were treated similar. For pressure load this assumption can not be made since the mechanical behaviour is non-isotropic.

From detailed analysis applied to the ALTOSONIC V geometry, it turns out that the only relevant parameter for pressure effects is the diameter D. The relative error in flow rate Q is expressed by

$$\frac{\partial Q}{Q} = 3\frac{\partial D}{D}$$

Assuming capped ends and a thick wall approximation, the deformation of the tube and the effect on the flow rate is given by the Roark expressions [5]. Below the deformation is shown for a calculation example.

$$\frac{\Delta Q}{Q} = 3\frac{\Delta D}{D}$$

$$\frac{\Delta D}{D} = \frac{\Delta P}{E}\left[\frac{\xi^2(1+\sigma)+(1-2\sigma)}{\xi^2-1}\right]$$

$$\frac{\Delta Q}{Q} = \frac{3\Delta P}{E}\left[\frac{\xi^2(1+\sigma)+(1-2\sigma)}{\xi^2-1}\right]$$

$$\frac{\Delta Q}{Q} = 0.057\%$$

in which

$$\left\{ \begin{array}{l} \xi = \dfrac{D_{outer}}{D_{inner}} = \dfrac{600 \cdot 10^{-3}}{500 \cdot 10^{-3}} = 1.2 \\ \sigma = 0.3 \\ E = 1.9 \cdot 10^{11}\ \mathrm{N/m^2} \\ \Delta P = 70 \cdot 10^{5}\ \mathrm{N/m^2} \end{array} \right.$$

This effect of 0.057% can be corrected for since this is a systematic effect of pressure. Assume that the correction is not exact, but can differ by 10%. This results in a remaining random uncertainty in the flow rate of 0.0057%. When the pressure is assumed to be known within 1% accuracy, this 1% in pressure (or ΔP in the equations) results in an extra 1% of 0.057% = 0.00057% in the flow rate, which is again random.

<u>The total flow rate uncertainty due to pressure effects :</u> $\sqrt{0.0057^2 + 0.00057^2}$ = <u>0.00573 %</u>

3.2.2 Numerical approach

In addition to the analytical analysis, Finite elements method calculations (FEM) have been performed for more complex geometries to determine the effect of pressure on the sensor meter body, and the corresponding flow inaccuracy. The calculations, done within the computational package “ANSYS”, give almost exact the same results as the Roark equations used in the analytical model when using the same geometry. In the FEM calculations, axial and radial deformation haven been treated individually.
For comparison, here also the analytical model with decoupled X and D (or R) is shown. For the thick wall / capped ends situation, the deformations are determined using FEM and compared against the analytical Roark expressions.

Radial $$\frac{\Delta R/R_{\text{ansys}}}{\Delta R/R_{\text{roark}}} = \frac{1.86316788 \cdot 10^{-4}}{1.86316776 \cdot 10^{-4}} = 1.000000064 \qquad (0.0000064\%)$$

Axial $$\frac{\Delta X/X_{\text{ansys}}}{\Delta X/X_{\text{roark}}} = \frac{3.28022502 \cdot 10^{-5}}{3.28022493 \cdot 10^{-5}} = 1.000000027 \qquad (0.0000027\%)$$

3.3 Fluid properties e.g. viscosity

Fluid properties may vary with temperature. The temperature dependency for the viscosity has been discussed in section 3.1.2.
Due to a change in the process, another liquid can be offered to the flowmeter. In upstream applications the composition of the oil might gradually change. All these changes can be treated as a liquid with changing viscosity and is addressed in section 2.1.

3.4 Non-single phase flow

The flowmeter is working in a non-ideal world. This can lead to applications where the flowmeter has to deal with vapour bubbles, oil-in-water or solid particles.
Important is to know how much the flowmeter reading is affected by these imperfections in the process.

3.4.1 Vapour bubbles

Flowmeter accuracy will be affected by content of gas/air in the liquid. As a rule of thumb a one-to-one relationship is used. This implies that ~0.1 Vol.% of vapour bubbles give rise to ~0.1% over reading in the volume flow measurement. In practise a couple of percent of gas can be handled by the ultrasonic flowmeter. A precise limit is hard to indicate since this is strongly affected by the flow pattern of the ‘two-phase flow’.
The diagnostics module in the ALTOSONIC V shall create an alarm as soon as the fraction of path failures exceeds a predefined threshold.
A significant advantage of ultrasonic flowmeters compared to mechanical flow meters is that air/gas will be detected and an alarm will be raised. Mechanical flow meters will register the gas/air content as liquid and consequently introduces significant errors.

3.4.2 Water-in-oil

The sensitivity of Water-in-oil is much less that the sensitivity to gas. The physical explanation is that the difference in acoustical impedance between oil and water is much less than between oil and gas. In practise a couple of a percent of water-in-oil can be handled up to about 10%. The upper limit also depends on a number of parameters like droplet size, flow speed, Reynolds number, difference in density, surface tension, droplet distribution, free or dissolved water etc.

An experiment focussing on the effect of water-in-oil has been carried out. Three different water fractions have been tested: 0%, 4% and 6%.
The result is shown in Figure 10. It can be observed that the 4% water-in-oil fraction doesn't affect the flowmeter reading above 0.75 m/s. At 6% the meter shows a very little effect of about 0.05%. Below the 0.75 m/s buoyancy and coagulation effects starts to play a role, leading to larger deviations. It is obvious that the flowmeter doesn't correct for the water fraction. The overall volumetric flow is being measured.
Analogue to the situation with too much gas in the system, the diagnostics module in the ALTOSONIC V shall create an alarm as soon as the time fraction of path failures exceeds a predefined threshold.

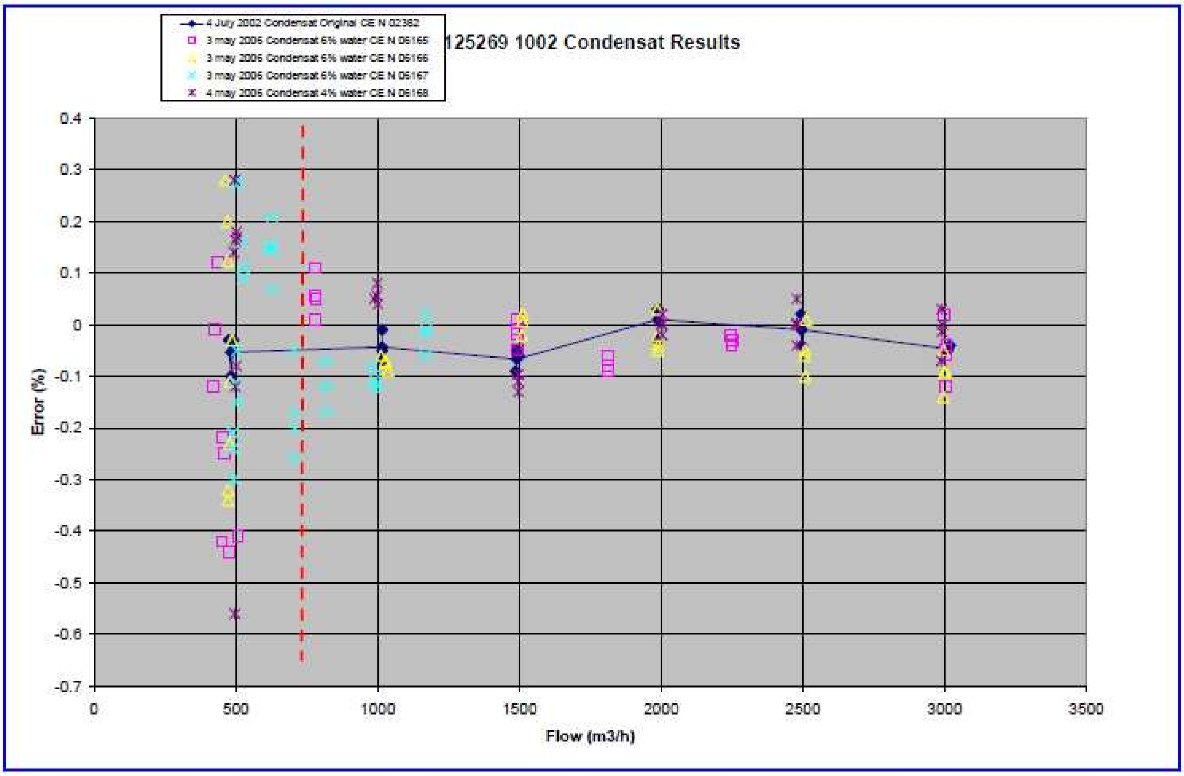

Figure 10 Error versus flow rate for an 24"ALTOSONICV at pure oil (blue diamonds), 4% water in oil (purple crosses) and 6% water in oil (yellow triangles and pink squares).

3.4.3 Solid particles
The ultrasonic flow measuring principle is not very sensitive to solids in the liquid. As a rule of thumb, the upper limit is taken at ~10 Vol.-%. The flowmeter considers the solid particles as part of the volumetric flow. Consequently, a proportional over reading is obtained. Therefore , 0.1% Vol.-% leads to a ~0.1% over reading in the volumetric flow.

3.5 Non-Newtonian behaviour

The experience with hydrocarbon applications is that in basis all hydrocarbon liquids behave as Newtonian liquids. This even holds for very viscous crudes at e.g. > 1000 cSt. A clear illustration is given in Figure 3. From this figure one could observe that at different flow speeds but equal Reynolds number the same error is obtained. In case the liquid had a non-Newtonian behavior, the flow would have been influences by e.g. the shear stress as well, leading to a different flow profile and consequently leading to a different error.

However, there are applications where this assumption is not valid anymore. As soon as drag-reducing-agents (DRA's) are used the Newtonian behavior disappears. Due to the small amount of long polymer chains, the velocity profile will not show the classical shapes anymore (like a turbulent, parabolic or transitional shape) which can be characterized by Reynolds number and eventually wall roughness. By using DRA's, the flow profile shape will be completely different and is hard to describe and predict. In these specific applications the user is advised to contact the manufacturer.

3.6 Fouling

Dependent on the process and type of fluid, fouling might occur. The type of fouling can vary from scaling to wax formation. Fouling most likely will occur in the entire system or part of the system (dependent on the conditions) and consequently in the flowmeter as well.
In case of wax formation, often heat tracing is applied, keeping the surface temperature of the measuring system at a higher temperature, which prevents wax formation.
In case fouling does occur, the acoustical properties (density, speed of sound, attenuation) of the fouling layer will differ from the properties of the liquid. By means of a very precise measurement of speed of sound at 5 different horizontal positions and considering acoustic attenuation, very thin layers of fouling can be detected and an alarm is created.
In addition, a check on this potential source of additional uncertainty has been taken into account in the procedure as described in chapter 8.

4. Installation

4.1 Flow Profile and Installation Effects

The sensitivity to flow profile distortion has not yet been addressed. The meters are calibrated with a fully developed flow profile. When the meter is installed in the application, the local upstream piping geometry might cause a change in the flow profile in the meter, causing an error in the flow measurement. An extensive set of flow profile disturbance tests, using water a calibrating medium, have been carried out. Multiple tests have been performed on the effects of flow profile disturbances on the performance of ultrasonic flow meters. Different types of disturbances have been created in order to investigate the corresponding errors. In all cases, a 10 D inlet spool piece with an ISO tube bundle straightener was used. Upstream of the inlet spool piece, the disturbances were installed. The upstream disturbance distance was measured from the beginning of the inlet spool piece.

The errors as a result of these disturbance tests are shown Figure 11 for a 180º bend at various upstream locations of 0D, 3D and 6D. As expected, a steady decreasing effect could be observed with increasing distance between the disturbance and inlet run of the flowmeter. The most left data point is obtained with a header installed at 0D, so directly connected to the 10D straightener.

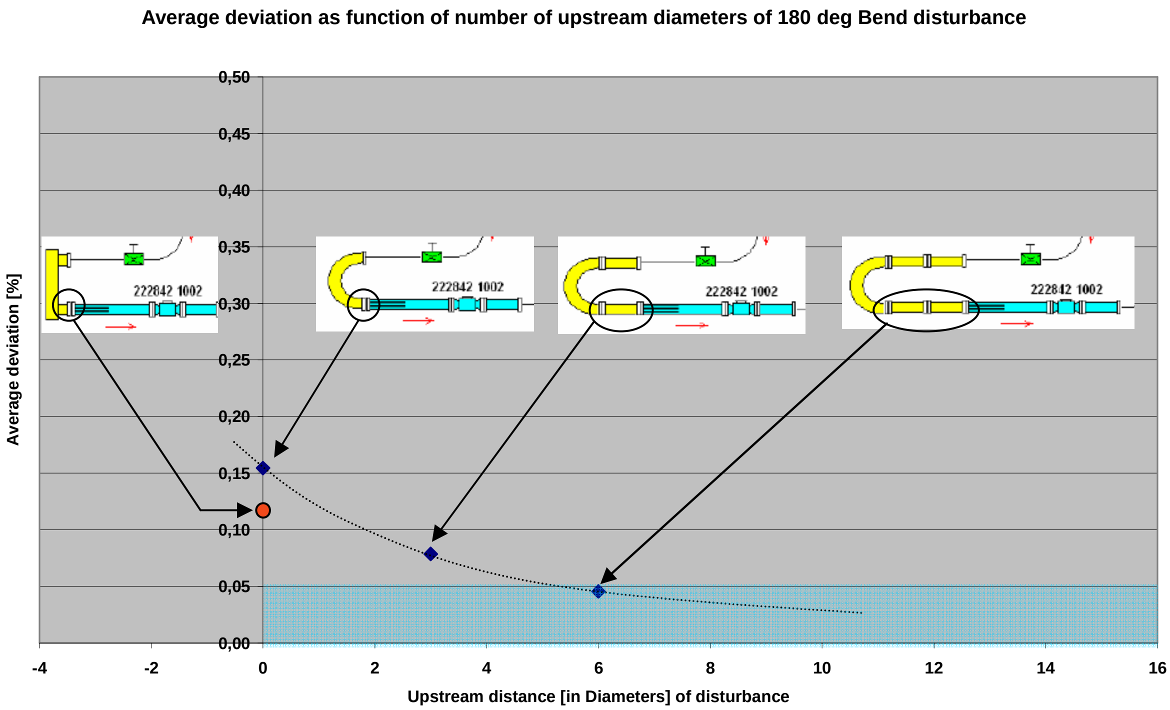

Figure 11 : Average deviation of the ALTOSONIC V as a function of upstream diameters for the various types of disturbances.

According to these results it might be assumed that the additional error as a result of these types of flow profile distortions is smaller than 0.05% when the distance between disturbance and inlet run of the ALTOSONIC V is larger than 10D.

The experiments presented above were carried out at high Reynolds numbers and using a conical section, which suppresses flow profile effects. This makes that the results indicated in the graph are better than would be obtained using a full bore situation. Since not all possible upstream piping configurations can be tested, one could take a factor of two as a margin to cover the effect of all possible piping configurations. It should be noted that the sensitivity of a multi-beam ultrasonic flowmeter is very much dependent on the design and algorithms that have been used. A conical section seems to be very effective. The number of paths, the path position and additional algorithms behind are very important as well. On basis of experimental data, supported with simulations we assume an uncertainty of the ALTOSONIC V for installation effects of 0.10 %.

The flow profile effects that occur in the application caused by the upstream piping configuration can be taken into account in the calibration. Therefore a copy of the upstream piping configuration could be installed in the calibration facility to resemble the in-situ situation similar as in the application. This reduces the uncertainty due to installation effects. Another possibility is an in-situ calibration (with all pro’s and con’s).

4.2. Connectors, wiring and Power supply

A proper transfer of measuring signals and measuring data is of vital importance. In this respect a sound electrical contact and electrical shielding is required.
Due to vibration, corrosion and mechanical damage the connectors and wiring could easily be damaged, leading to bad signal transfer, and consequently worse performance of the flowmeter or even loss of measuring data.

In order to prevent this kind of mal performance, dedicated diagnostic features have been developed continuously monitoring the quality of data transfer.
In addition, a systematic procedure has been developed checking this item. In this procedure also a check is incorporated on the power supply voltages to verify whether or not they are within the specified limits.

5. Environmental

5.1 Temperature

The ambient temperature usually has a limited effect on the performance of the flowmeter. The effect is specified by the manufacturer. In paragraph 3.1.1. under sub-item e) this dependency has been addressed.

5.2. Humidity and salty environment

The effect of humidity has been specified by the manufacturer also. Usually the effect is negligible as long as the flowmeter is operated within the specified range.
Special attention must be paid to off-shore applications or applications near the coast. Due to the salty environment corrosion might easily occur especially in cable connections.

5.3. Vibration/Mechanical damage

Due to continuous vibrations mechanical damage might occur in connectors, cabling or electronics. Mechanical damage could also be caused by labour or uncontrolled actions in the vicinity of the flowmeter. This damage could lead to deteriorated electrical connection which might lead to a non proper working flowmeter. Using a verification procedure as described in section 8 the functionality of the flowmeter could be demonstrated by applying a systematic check and using the diagnostic features of the flowmeter.

5.4. Aging

As long as the flowmeter is being used within its specification, aging effects can be considered as long term stability which is described in section 2.3.

6.Effects from repair actions

6.1 Replacement converters

Both the converter effects and the effect of UFP replacement have been tested. The effects of drift in the converters on the flow rate were calculated and tested, and showed to be smaller than 0.01%, provided that a proper zero flow calibration can be carried out. This result includes the replacement of the UFP.

6.2 Replacement Ultrasonic Flow Processor (UFP)

The effect of UFP replacement is discussed in the previous section, combined with converter replacement.

<u>The total uncertainty due to repair / replacement of components is less than 0.01%</u>

7.Total Uncertainty Calculation

In the sections above, all parameters or actions that might affect the flow meter uncertainty have been discussed and quantified. It is important to note that the uncertainty caused by individual sources can depend on diameter and flow speed. The dependency is given in previous paragraphs.

In this section, all contributions are summed in order to obtain the total meter uncertainty under operational conditions. For systematic uncertainties, the individual contributions are summed. The random effects are taken root-mean-square.

$$\Delta Q_{total} = \sqrt{\left(\Delta Q_{sys,1} + \Delta Q_{sys,2} + \ldots\right)^2 + \Delta Q_{rand,1}{}^2 + \Delta Q_{rand,2}{}^2 + \Delta Q_{rand,3}{}^2 + (\ldots.)^2}$$

When all uncertainties that have been discussed before, are added, a total uncertainty of 0.17% is obtained. This is shown in Figure 12.

Contribution	***Value***	***Remarks***
Linearity	0.10 %	Random
Repeatability	0.03 %	Random
Long term stability	0.08 %	Random
Temperature effects	0.03 %	Random (after correction for systematic part)
Pressure effects	0.006 %	Random (after correction for systematic part)
Installation effects	0.10 %	Random
Calibration facilities	0.04 %	Random
Replacement	0.01 %	Random
TOTAL	**0.17** %	Total uncertainty in volumetric flow rate

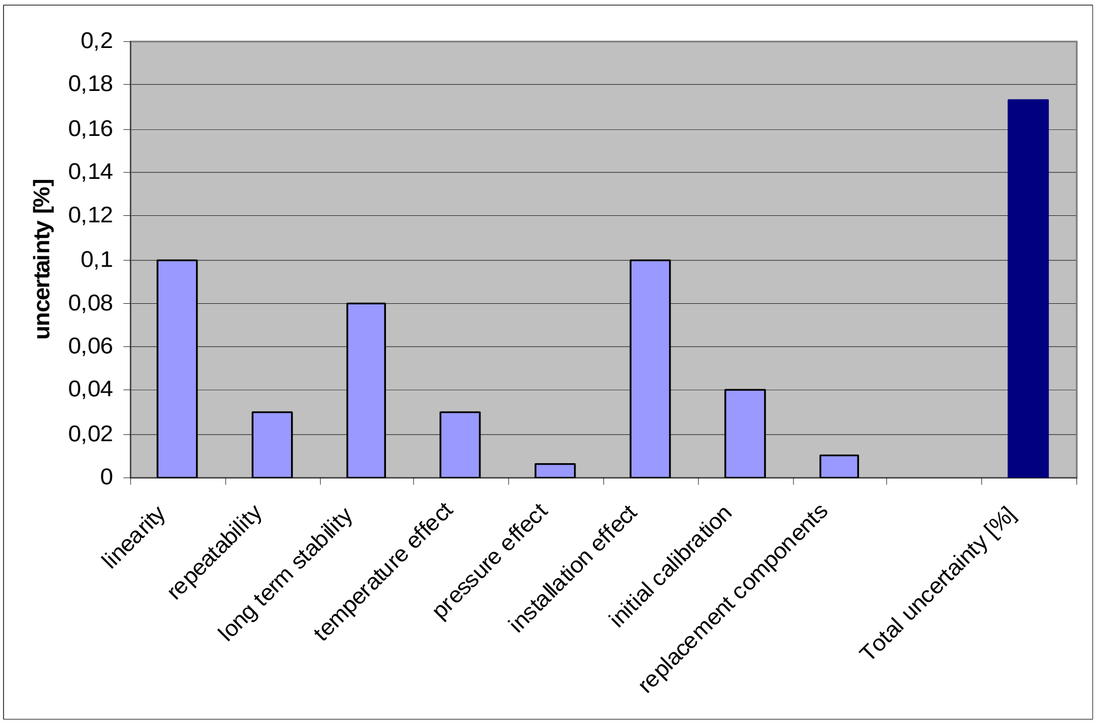

Figure 12 : Total uncertainty as result of all individual sources of uncertainty as described in this paper.

When studying Figure 12 it becomes clear that the total uncertainty is dominated by three sources: linearity, long term stability and installation effects.

There are possibilities to reduce the uncertainty of these sources by using dedicated actions. The uncertainty due to linearity is a result of taking the entire Reynolds range into account. Figure 2 shows clearly that it is possible to further improve the linearity with a factor of two when a tailor made Reynolds range calibration is performed in the more limited range of application. A further improvement in performance of the flowmeter regarding linearity would contribute here as well.
The long term stability number as described before is a result of using the flowmeter without any verification during a time interval of e.g. 10 years. By using the verification procedure as described in section 8, the long term stability can be monitored in-situ and will result in reducing the long term stability significantly.
By paying attention to upstream piping configuration or by taking proper flow conditioning measures, the result of installation effects could be significantly reduced too. In-situ calibration could reduce the installation effects also [8], but requires an expensive on-site prover system or mobile prover which are expensive and requires a lot of effort.

When reducing the uncertainty in linearity to 0.05%, the long term stability to 0.04% and the installation effects to 0.05%, the total uncertainty reduces from 0.17% to 0.10%. This is shown in Figure 13.

Contribution	***Value***		***Remarks***
Linearity	0.05	%	Random
Repeatability	0.03	%	Random
Long term stability	0.04	%	Random
Temperature effects	0.03	%	Random (after correction for systematic part)
Pressure effects	0.006	%	Random (after correction for systematic part)
Installation effects	0.05	%	Random
Calibration facilities	0.04	%	Random
Replacement	0.01	%	Random
TOTAL	**0.10**	%	Total uncertainty in volumetric flow rate

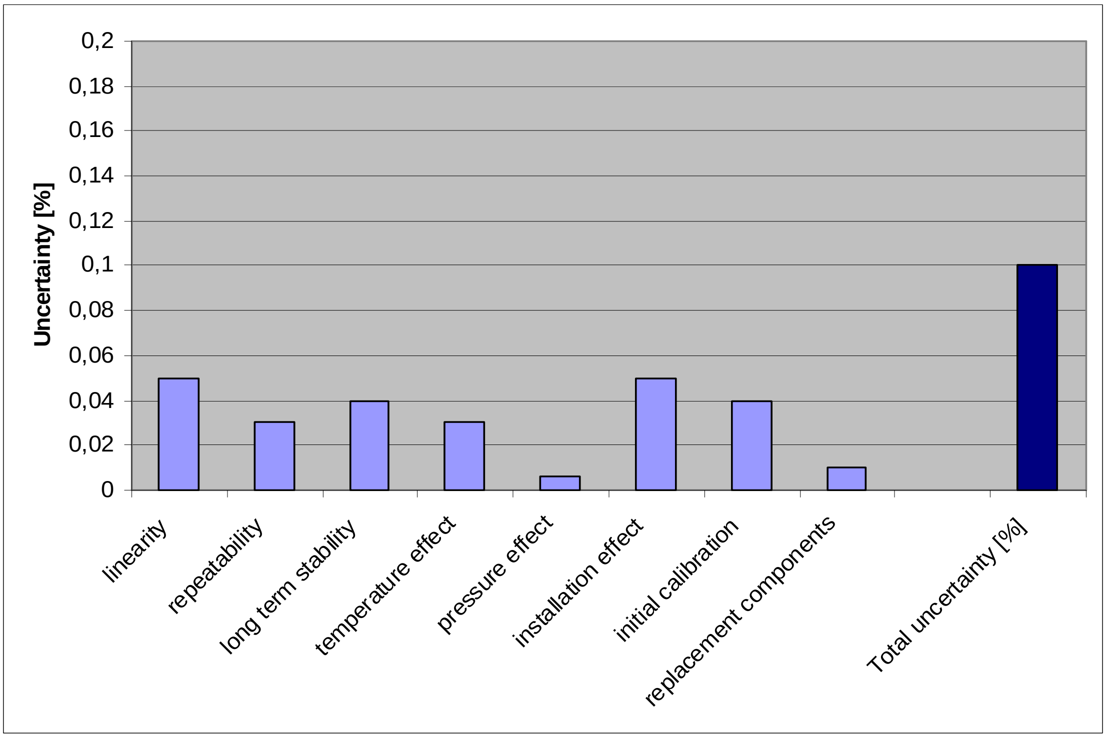

Figure 13 An example of the reduction of the total uncertainty from 0.17% to e.g. 0.10% when special attention is paid to the dominant sources of uncertainty (linearity, long term stability and installation effect).

The result as presented in Figure 13 shows that the overall uncertainty could be reduced by taking special dedicated measures to reduce the major sources of uncertainty.
However, the opposite is also true. When something is wrong in the system due to mis-operation a significant increase in one of the sources of uncertainty will occur, which will dominate the overall uncertainty heavily.
This is illustrated in Figure 14. As discussed in 3.4.1 the uncertainty in volumetric flow rate is directly proportional to the volumetric fraction of gas in the liquid. The implies that e.g. 0.3 Vol.-% of gas leads to an additional source of uncertainty equals 0.3%.
This additional source heavily dominates the total uncertainty. It therefore is very important that these heavily dominating sources of uncertainties are detected immediately by the diagnostics such that an alarm is created and proper measures can be taken.

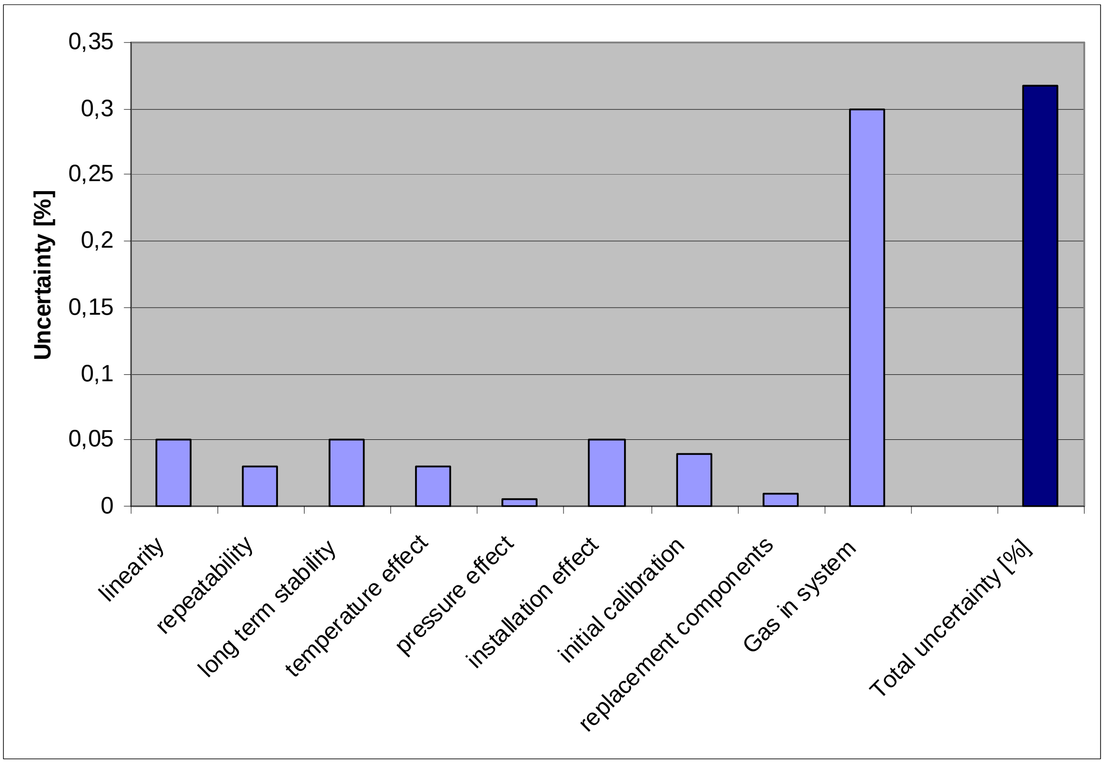

Figure 14 If one of the uncertainty sources is significantly larger than the other sources of uncertainty, it will dominate the overall result. In this graph an example of 0.3 Vol.-% of gas in oil shown, leading to an overall uncertainty of 0.32%.

8. Verification Procedure

One of the most significant features of ultrasonic flowmeters is their diagnostic capabilities. Despite mechanical flowmeters, ultrasonic flow meters are capable to provide instrument- and process data, based on which a conclusion can be drawn on the performance.
International institutes and end users acknowledge this diagnostic feature and use this data to convince inspectors/auditors on the performance of the flow meter installed. In some applications the diagnostic information is used to extend the re-calibration interval of the associated flow meter.

Based on the industry requirements KROHNE prepared a verification procedure document describing the diagnostic capability and all related parameters. The basis of this procedure is to provide a level of confidence in the operation of the ALTOSONIC V flow meter. The procedure is not designed to re-calibrate individual instruments but to demonstrate the functionality of the flow meter, based on confirmed parameter settings.

It is mandatory that an authorised institute or governmental body is present because during the process of verification governmental seals need to be removed and at the same time the verification tests and results are witnessed to confirm the stability of the flow meter.

The verification procedure contains a number of tests which can be divided in different categories as:

- Hard ware inspections: Cable connections, serial numbers, transducers
- Installation inspections: Flange alignment, cable glands
- Electrical inspections: Equipotential bonding, Power supplies, Acoustic signals
- Soft Ware inspections: SW versions, Checksums, Configurations
- Process inspections: Zero setting, Velocity Of Sound distribution, Alarm analysis
- Input & Output inspections: Calibration of analogue In- and Outputs & Frequency output
- Loop inspections: All loops will be checked/inspected

Content of the KROHNE verification procedure is as follows:

1 Signature & witness sheet
2 Introduction and description of the verification procedure
3 Test equipment details and certificates
4 UFS-V & UFC-V Field inspection:
   4.1 Serial numbers verification
   4.2 Flange alignment
5 UFS-V & UFC-V Field connections
   5.1 Equipotential bonding (UFS-V, UFC-V, in- & outlet)
   5.2 UFS-V and UFC-V transducers / cables
   5.3 Transducer cables
   5.4 UFS-V cable glands
   5.5 Transducer resistance
   5.6 Ultrasonic signals
   5.7 UFC-V connection (Power/RS-485)
6 UFC-V converter settings and software
   6.1 Converter configuration parameters
   6.2 Converter Soft Ware version
7 Control Room Connections
8 Control Room Power supplies
9 Control Room Settings and Soft Ware
   9.1 UFP-V Soft Ware version
   9.2 UFP-V CRC Checksums
10 UFP-V alarms
   10.1 UFP Alarm window F2
   10.2 Alarm analysis during previous batching
11 Control Room, Signal Values
   11.1 Speed Of Sound
   11.2 Zero Points
   11.3 Transducer stability at zero flow

12 Control Room Analogue I/O verification
  12.1 Analogue Inputs & Outputs
  12.2 UFP-V Analogue inputs
  12.3 UFP-V Frequency output

9. Summary and Conclusions

As stated in the Introduction, tens of thousands Custody Transfer Flowmeters are in operation for many decades in the oil and gas industry.
Very often these flowmeters are selected and judged on their initial performance. These flowmeters have been carefully calibrated on-site or in accredited laboratories and usually show very good results.

However, in practise many environmental factors do play a very important role. They all do affect the overall end uncertainty of the flowmeter more or less.
In this paper an overview has been given of the most important parameters. The effect of each parameter has been quantified. Attempts are made to give insight in the parameters that are dominating the overall uncertainty.
By means of dedicated measures, the effect of dominating sources of uncertainty could be reduced. An example is given by improving linearity of the flowmeter or reducing installation effects by taking proper measures on upstream piping configuration or flow profile conditioning.

In situ verification of ultrasonic flow meters can be used to determine if the flow meter is still operating within its specification. This is only possible due to excellent diagnostic features of ultrasonic flowmeters by which not only the flow meter but also the process can be observed and analysed.

Additional uncertainty due to long term stability could be reduced by implementing a verification procedure with which the measuring system could be thoroughly verified. By means of this procedure all vital parts of the measuring equipment are checked systematically. This procedure can be carried out in-situ and is briefly described in this paper.

It is obvious that once all sources of uncertainty are more or less equal, the overall uncertainty hardly could be reduced furthermore by taking a limited number of actions. In this case all sources of uncertainty have to be reduced one by one.

It is also clear that in case there is one dominating source of uncertainty is strongly dominates the overall uncertainty. An example is gas-in-liquid. In these cases the importance of diagnostic capabilities is clearly shown.

References

[1] Per Lunde, et.al., “Handbook of Uncertainty Calculations – Ultrasonic Fiscal Oil Metering Stations” 26th International North Sea Flow Measurement Workshop, October **2008**.

[2] Gordon Stobie, “Influential Factors in Flow Measurement” 28th North Sea Flow Measurement Workshop, October **2010**.

[3] Mr. Josaphat Dias da Mata (Petrobras), et. al.,“Petroleum Measurement And Diagnostics Of Ultrasonic Flow Meters In High Flowrates And Viscosities”, Paper 8.2 presented at the American Workshop **2008**.

[4] Jankees Hogendoorn, et. al., “An Ultrasonic Flowmeter for Custody Transfer Measurement of LNG: A challenge for Design and Calibration”, 25th International North Sea Flow Measurement Workshop, October **2007**.

[5] N 216 ISO_17089_V20_Measurement of fluid flow in closed conduit - UFM for gas_Part1.

[6] Jankees Hogendoorn, “Flow Measurement in Nuclear Power Plants”, Tokyo, KROHNE, May **2008**.

[7] Jankees Hogendoorn et. al.,“High viscosity hydrocarbon flow measurement: A challenge for Ultrasonic Flow Meters?” 27th International North Sea Flow Measurement Workshop, October **2009**.

[8] Maron Dalström,“KROHNE ALTOSONIC V with Master Meter Approach”, Paper 18 present at the NSFMW 2003, Statoil ASA Norway, **2003**.