High viscosity hydrocarbon flow measurement, a challenge for ultrasonic flow meters?

Jankees Hogendoorn, Karsten Tawackolian, Peter van Brakel, Jeroen van Klooster and Jan Drenthen

Summary

The time of easy recoverable oil is fading away while at the same time the demand for refined products is rising. To meet this demand, oil has to be recovered from fields, such as tar sands, that are much more difficult to explore. Consequently there is also a large increase in the variety of products to be measured as well, including many high viscosity products.

Whereas for conventional mechanical meters the measurement of high viscosity flows is limited by the force on the bearings, one of the few meters that can successfully be applied in these is the ultrasonic flow meter. However, that is not an easy task either.

Major issues leading to an increasing measurement uncertainty of ultrasonic meters are:
- the attenuation of the acoustical signal
- the strong dependency of the viscosity on the temperature
- the unsteady flow profile in the laminar-turbulent transition region

In order to improve on this, a development project was started, specifically aimed at the measurement of high viscosity flows. As a result, a new meter has been designed, equipped with new powerful transducers and algorithms capable of solving the fluid dynamic challenges in the transition region.

The present paper describes:
- the meter design
- the design of the new transducers
- CFD calculations simulating the sensitivity of the 5-beam ultrasonic flowmeter to changing viscosity in the boundary layers due to for thermal effects at high viscosity applications.
- Test results of boundary layer disturbance test.
- And the test results obtained with a series of 24” flow meters tested at SPSE at 400 cSt and some field experience.

Contents

1. Introduction

Ultrasonic flow meters for custody transfer application were introduced in the industry in 1996. Supported by a significant number of national and international approvals, ultrasonic measurement techniques have been adopted by oil and gas industries and frequently used for custody transfer measurement of hydrocarbon products worldwide. After the introduction of the API standard 5.8 “Measurement of liquid hydrocarbons by ultrasonic flow meters using transit time technology” in February 2005 the confidence of industries rose and resulted in higher acceptance of this technology for custody transfer crude oil applications.
During the introduction of the first ultrasonic flow meters approved for custody transfer applications, manufacturers focussed on the generic applications where most of the applications were liquids with viscosities up to 140 cSt. Analysing the present crude oil exploration and production developments it is evident that highly viscous crude oils are being increasingly produced and make up a significant part of global crude oil production.

Definitions for the different types of crude do vary by the different institutes; but, the following descriptions are defined by the U.S. Geological Survey in an article dated August 2003 [1].

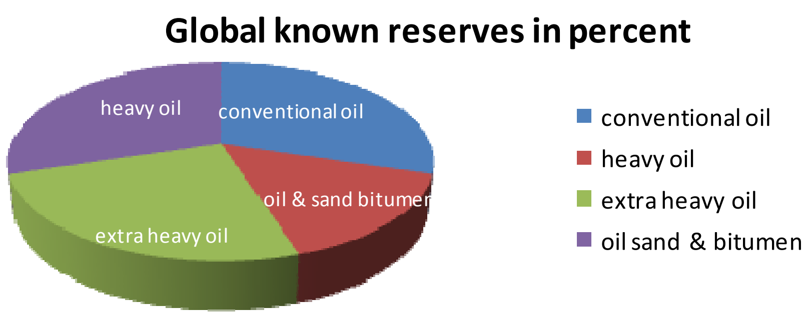
Light oil also called conventional oil with an API gravity of min. 22° and a viscosity < 100 cP.

Heavy oil is an asphaltine, dense (low API gravity), and viscous oil that is chemically characterized by its content of asphaltenes (very large molecules incorporating most of the sulfur and perhaps 90 percent of the metals in the oil). Although variously defined, the upper limit for heavy oil has been set at 22° API gravity and a viscosity of 100 cP.

Extra-heavy oil is that portion of heavy oil having an API gravity of less than 10° and a viscosity of above 100cP.

Natural bitumen, also called tar sands or oil sands, shares the attributes of heavy oil but is yet more dense and viscous. Natural bitumen is oil with a viscosity greater than 10.000 cP.

An estimation of the known global reserves was presented in an article from “Highlighting Heavy Oil” in the summer of 2006 as:



The information above implies that the demands of industries for the custody transfer measurement of crude oils changed and manufacturers are requested to develop products that will fulfil the industry demands for increasing the measuring capabilities for highly viscous crude oils.

2. Critical factors

The critical factors with ultrasonic flow measurement techniques using transit time on highly viscous products are [2]:

- Acoustic attenuation of the ultrasonic signals
- Cross talk
- Effect of low Reynolds numbers , i.e. laminar profiles
- Effect of temperature deviations on the liquid viscosity

2.1. Acoustic attenuation of the ultrasonic signals

The receiving signal will attenuate by means of:

1. Acoustic attenuation
2. 1/r - law

Acoustic attenuation

Acoustic waves generate micro movements in the fluid. These micro movements are attenuated by molecular friction which is directly related to viscosity.

Due to attenuation in the medium the amplitude of the acoustic pressure (P) decreases exponentially with the distance (L):

$$P = P_o \cdot e^{-\alpha \cdot L} \tag{1}$$

in which α is the attenuation coefficient calculated as follows:

$$\alpha = \frac{\omega^2}{2 \cdot \rho \cdot c^3} \cdot \left[\frac{4}{3} \cdot \eta_{dyn} + \eta_{bulk} \right] \tag{2}$$

The attenuation is a function of frequency (ω), density (ρ), dynamic viscosity (η_{dyn}), speed of sound (c) and the bulk viscosity (η_{bulk}). When we introduce the bulk factor K_v, we obtain:

$$\alpha = \frac{\omega^2}{2 \cdot \rho \cdot c^3} \cdot \eta_{dyn} \cdot K_v \quad \text{in which} \quad K_v = \left[\frac{4}{3} + \frac{\eta_{bulk}}{\eta_{dyn}} \right] \tag{3}$$

1/r - law

Due to the fact that the acoustic energy radiated by the transducer is radiated in ‘all directions’, the amplitude of the acoustic pressure decreases inversely proportionally with distance (L):

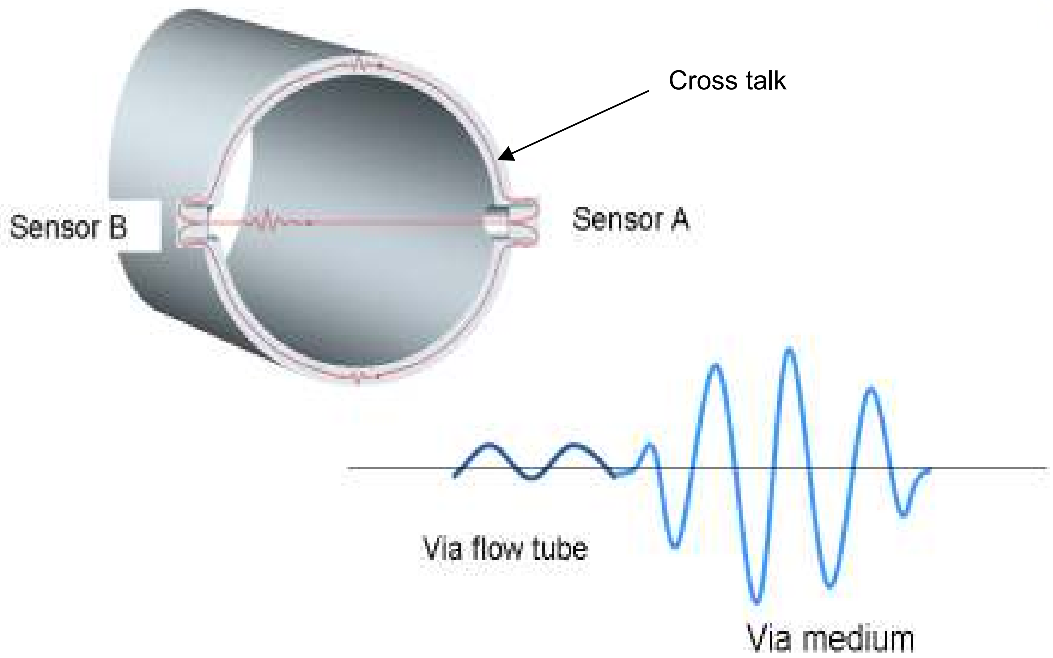
$$P = \frac{1}{L} \cdot P_o \tag{4}$$

This is called the 1/r - law.

Due to high acoustic attenuation of viscous crudes the measurement of these crudes with acceptable custody transfer uncertainty is complicated. The damping of the acoustic signal received will result in a reduced ratio between the emitted and received signals, and can in some applications result in complete loss of signal. The damping of the acoustic signal is directly related to the flow meter diameter and will increase for big sizes.

2.2. Cross talk

Cross talk is defined as the ultrasonic acoustic signal transported via the pipeline wall. The more viscous the medium is, the stronger will be the cross talk signal compared to the received signal. This will have a significant effect on the overall uncertainty.
The time measurement is based on the summation of the received signal and the cross talk signal, for viscous crudes the cross talk signal will have a higher contribution than the received signal and as a result an error will be introduced into the time measurement.



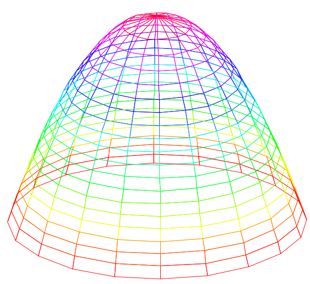
2.3. Low Reynolds numbers

Transit time ultrasonic technology is based on the measurement of the liquid velocity on different positions in the pipe. The average velocity is proportional to the volume throughput. Different flow profiles can influence the uncertainty of ultrasonic flow meters. The identification of flow profiles is based on the dimensionless Reynolds number. API Ch 1 defines Reynolds as follows:

$$R_e = \frac{\rho \times \overline{\upsilon} \times D}{\eta}$$

Where: D = inside diameter of the pipe
V = mean flow velocity
ρ = fluid density
η = fluid dynamic viscosity

2.3.1. Laminar range



For Reynolds numbers < 1000 the flow profile is laminar and has a stable parabolic shape. Here, the flow velocity in the middle is twice as high as the average flow velocity.

2.3.2. Transition range

Above Reynolds 1,000 the laminar flow becomes unstable.

Turbulent plugs start to arise. These turbulent plugs are carried along with the flow and start to grow in size. This causes an intermittent laminar-turbulent flow which is very unsteady. This region of intermittent flow is called the transition area and runs up to a Reynolds number of about 5,000. Above this Reynolds number the flow is fully turbulent.

Where and when these turbulent plugs occur and their frequency of occurrence is completely stochastic and among others dependent on external factors such as local sharp edges, local temperature differences, pipe vibrations, etc.; in other words, it is also installation dependent. In the transition range, the shape of the flow profile is unpredictable and this results in an increased uncertainty in the measurement.

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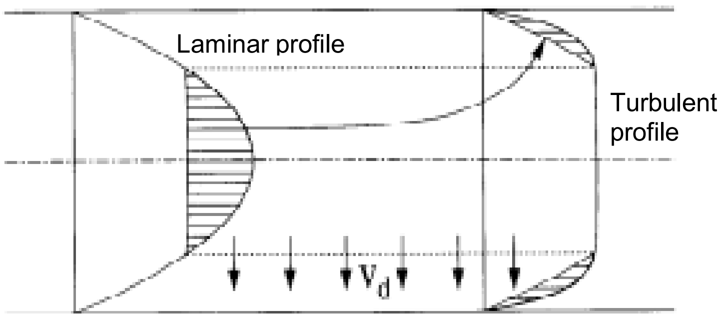
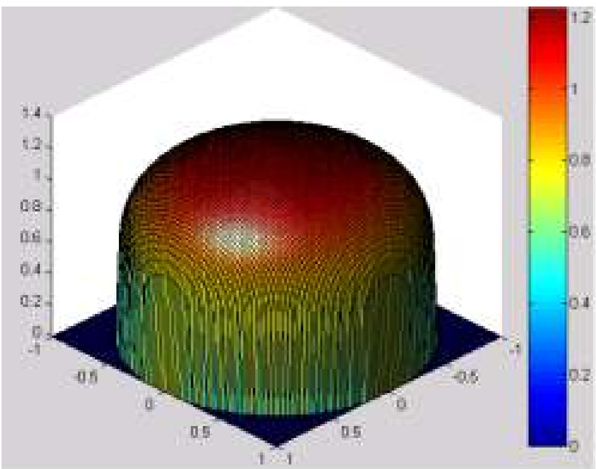


2.3.3. Turbulent range

In turbulent flow, unsteady vortices appear on different axes and interact with each other causing an exchange of energy in the radial direction; in other words the high and low velocities average out. Due to this effect the flow velocity profile will become much flatter than for a laminar flow. The flow range above Reynolds 5.000 is called the turbulent region.



2.4. Impact of temperature on viscosity

Because highly viscous crude oils are transferred at high temperatures, temperature fluctuations are commonplace. A direct consequence of these temperature variations is viscosity change, specifically for highly viscous crude oils, and as a result the Reynolds number i.e. flow profile will change gradually.

Another effect that easily occurs is a temperature profile over the pipe cross section. This causes a gradually varying viscosity with the pipe radius leading to an undefined velocity profile. This effect shall be addressed in chapter 4.

2.5. *Calibration of flow meters for High Viscosity products*

Another challenge is the calibration of highly viscous products. Thus far, no (laboratory) test facilities in the world exist where large size flow meters could be tested or calibrated with highly viscous products against a reliable reference. This necessitated the development of an alternative calibration method.
A solution has been found in calibrating ultrasonic flow meters using the so-called Reynolds calibration method.[3],[4].

First of all, it is essential to demonstrate that the flow meter linearity is a function of Reynolds only. This is clearly seen in Figure 1. This figure shows that there is a very clear correlation and overlap between the individual linearity curves for different products.

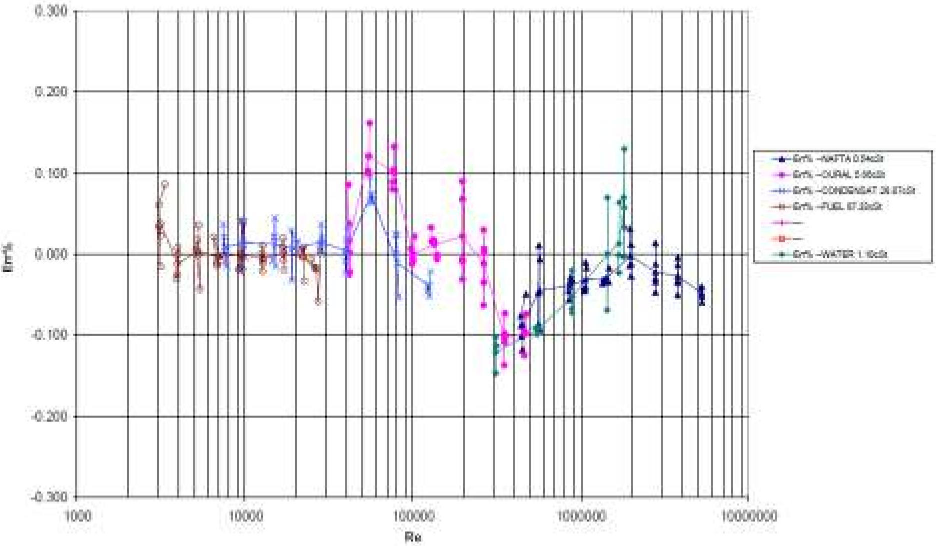


Figure 1 Linearity curve for different products with different viscosities. A clear correlation and overlap between the individual linearity curves for different products is observed.

Because ultrasonic flow meters are velocity measurement devices, and the performance depends on Reynolds, simulation techniques can be use that to simulate a highly viscous product using an alternative calibration medium by manipulating the flow rate such to achieve the requested Reynolds range.

In the table below an sample Reynolds calculation is shown for the following process conditions:

Pipeline size 24 inch
Product # 1 viscosity 150 cSt
Product # 2 viscosity 400 cSt
Product # 3 viscosity 600 cSt

Product	0.5 m/s	1 m/s	2 m/s	3 m/s
#1 150 cSt	2000	4000	8000	12000
#2 400 cSt	750	1500	3000	4500
#3 600 cSt	500	1000	2000	3000

It is evident that Reynolds numbers for highly viscous crude oils are significant lower than calculated for the more familiar products. However based on above table it is clear that, when

above mentioned flow meter i.e. 24", are used on High Viscosity oil of 600 cSt at 3 m/s the same Reynolds will be achieved as with a product of 150 cSt @ 0.75 m/s.
Based on above it is possible to calibrate ultrasonic flow meter for High Viscosity application by using a lower viscosity product and by adjusting the flow rate such that the required Reynolds is established.

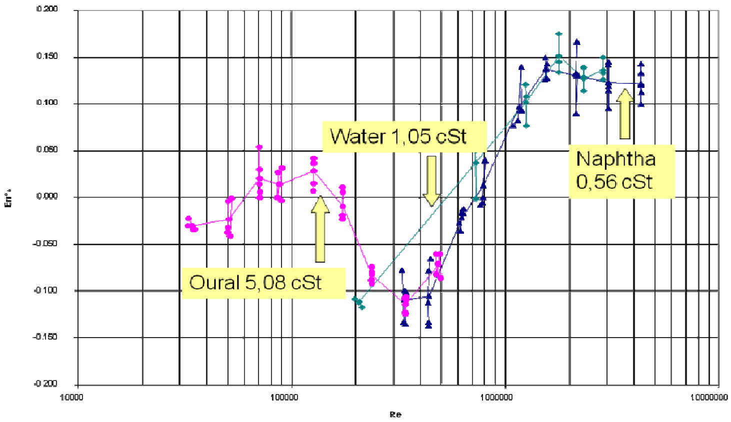


Figure 2 This graph shows a 24" flow meter calibrated on three products, Naphtha, Oural c.o. and water. It is clearly shown that the calibration with water, although a complete different product, shows the same errors as for naphtha and oural c.o. at the same Reynolds.

2.6. Long term stability

The long term stability of flow meters needs to be checked at pre-defined intervals by performing regular verifications. However based on the issues described earlier these actions are labour-intensive demanding and will result in down-time of the installation. Ultrasonic flow meters have proven to be extremely stable over time.

The characteristics which contribute to the long term stability of the ultrasonic flow meter include no moving parts and thus no wear and tear. The condition of the measurement section inside the meter body is not deteriorated by the medium and there is no shift of the k-factor due to changes in process properties. In this respect ultrasonic flow meters differ from, for example, mechanical flow meters where the internal parts are affected by process conditions and therefore there are shifts in the k-factor shifts and regular re-calibrations are required for a stable performance.

The long term stability or reproducibility of ultrasonic flow meters has been monitored several times [4]. An example of this is shown in Figure 3. The flow meter was calibrated in 1999 and verified in 2009. No significant deviation in performance was observed. In between no maintenance have been carried out and all original settings were used.

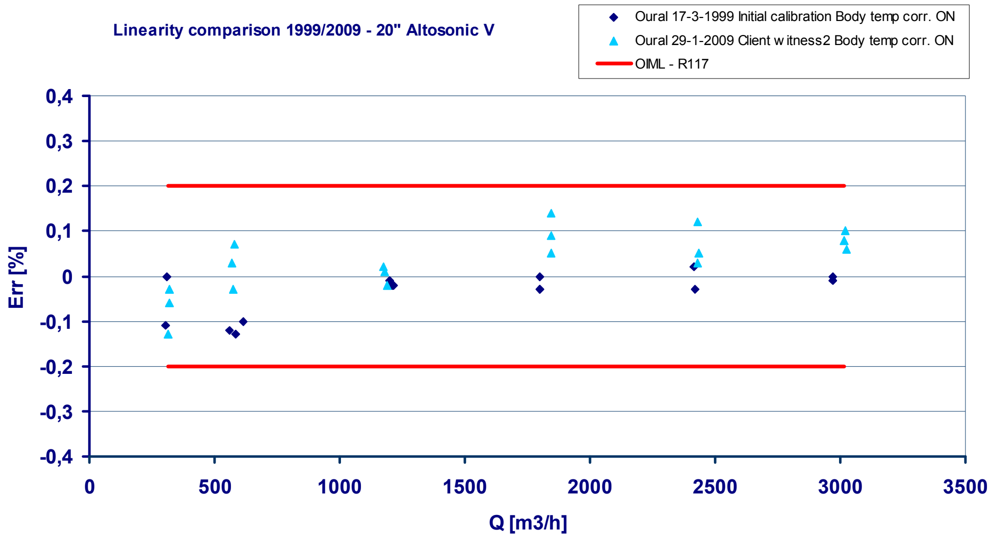


Figure 3 Long term stability data of a 20inch ALTOSONIC V. This instrument has been initially calibrated in 1999 and verified in 2009. No maintenance has been carried out in between. The original setting have been used during verification in 2009.

3. New developments

3.1. Transducer design

To reduce the influence of cross talk, there has been specific R&D focussed on reducing this effect. Because cross talk is a constant parameter that depends on the size and material of the flow meter tube, two approaches have been investigated:

1. Increasing the strength of the ultrasonic signal to reduce the ratio between cross talk and the received acoustic signal
2. Acoustically decoupled transducers.

The strength of the acoustic signal can be increased by decreasing the generated frequency: The lower the frequency the higher the strength of the received signal. Because ultrasonic transit time technology is based on accurate time measurement a lower frequency will automatically result in lower performance. For larger diameters > 24” this effect will be less significant because the delta time compared to smaller diameters is higher, and errors in delta time measurement are negligible.

The most significant reduction in the effect of cross talk can be expected from acoustically decoupled transducers. By isolating the transducers from the flow meter tube and reducing direct metallic contact, the cross talk effect is reduced to a minimum. Tests were performed on a flow meter tube using crude oil with a viscosity of 1500 cSt and a density of 950 kg/m³ (see Figure 4). A welded and decoupled transducer were compared simultaneously both at a frequency of 1 MHz.

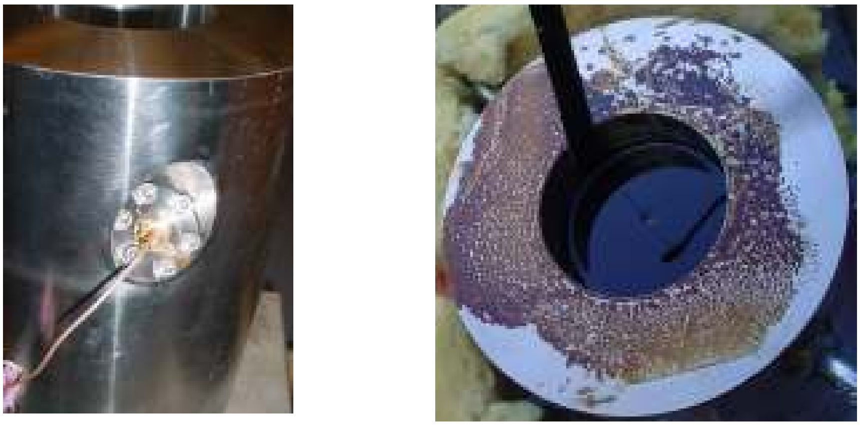


Figure 4 Test carried out during the development of the high viscosity transducer.

R&D test results prove that the signal to cross talk ratio is significantly lower for the decoupled transducers. For the welded transducer the ratio was maximum 1% and for the decoupled 0.18%, which is an improvement of a factor of 5.

3.2. Test Results plus certification

In January 2006 a number of ultrasonic flow meters were calibrated on highly viscous heavy fuel oil. The calibration was performed using a unidirectional ball prover with a base volume of 15 m^3, and witnessed by the Dutch authorities (NMi). The results (errors and repeatability) of one of these flow meters are shown in the graphs below. The horizontal line shows the requirements as stated in the OIML R-117 recommendation. The error band shown of +/-0.2% is specified in OIML R-117 Class 3.0. The associated maximum repeatability is 2 x 0.06% = 0.12%.
It is clear that the calibrated flow meter is well within the specifications. The flow rates used during the calibration are in the range of 250 to 2600 m^3/hr, which is equivalent to a Reynolds range of 400 to 5400.

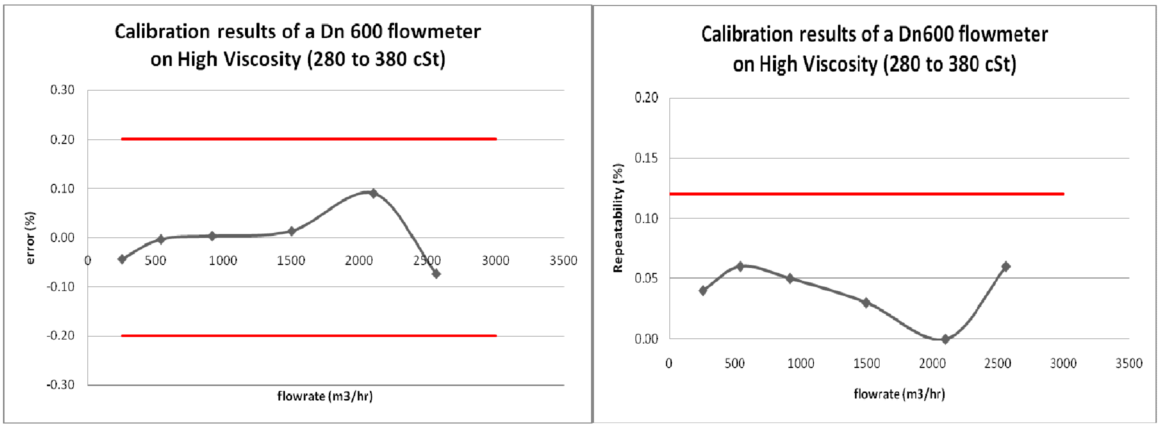


Figure 5 Test results on a 24" ALTOSONIC V running at viscosities of about 400 cSt.

Based on above calibrations the Dutch metrological institute (NMi) issued an OIML approval in which the maximum viscosity limit was given as 400 cSt for diameters up to DN 600 (24").

4. CFD simulations on thermal effects and boundary layer disturbance test

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 6 where the kinematic viscosity is shown as a function of temperature.

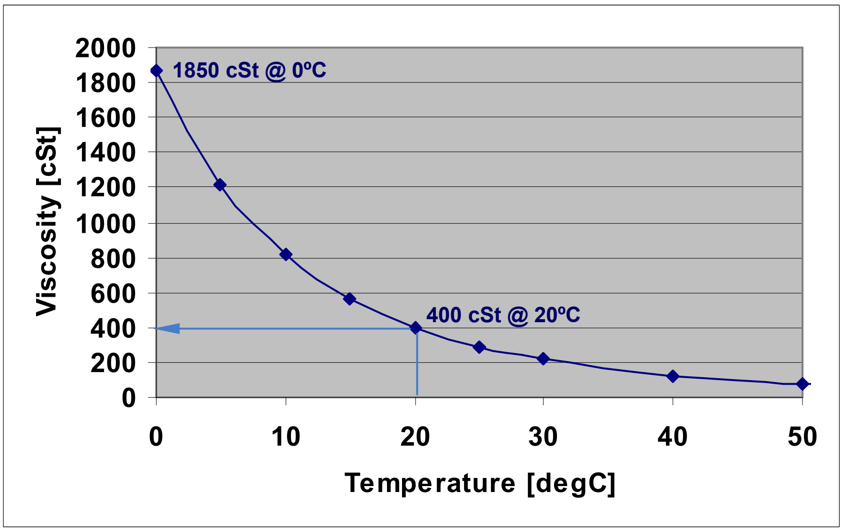


Figure 6 Relationship between viscosity and temperature of an extra-heavy-oil sample.

This temperature dependency has implications for practice.
Usually the oil temperature in the system is different from the environmental temperature. Consequently, heat transfer is induced, leading to a thermal boundary layer. This thermal boundary layer does affect the local viscosity, which in its turn does affect the flow profile. This effect is more pronounced in applications with high viscosity.

In this chapter CFD calculations are described that have been carried out to try to get a feel how strong these effects are and how the 5-path ultrasonic flowmeter responds [5]. Efforts are made to find a calculation example which is straightforward and which represents reality as much as possible.

The following assumptions have been made:

- The flow is always laminar because of the high viscosity of the medium.
- The laminar flow at the inlet is fully developed and has an uniform temperature. The assumption has been made that the pipeline system was subject to constant conditions for a long run, leading to an uniform temperature and fully developed laminar flow.
- Directly after the inlet, the heat exchanging process starts to play a role.
- In order to obtain a rather well developed thermal boundary layer, a relatively long distance of 50D has been chosen. Shorter distances shall lead to a flow situation which is less affected. In that respect this calculation example can be considered as a worse case situation.
- Furthermore, the temperature at the outside pipe wall has been prescribed. In practise the outside pipe wall temperature almost equals the fluid temperature inside the pipe. This is clearly illustrated in paper [6]. In this paper several situations have been simulated. An extreme example is the situation where gas at a pressure of 60 bar, a temperature of 37.7 °C, a flow speed of 10 m/s in an uninsulated 24 inch pipe was subject to a 5 m/s cold

wind at -10°C. The resulting outside wall temperature is only 1 to 2 °C cooler than the gas!
The (insulating) thermal boundary layer of the air outside the pipe has been neglected in the calculation example presented in this paper (see Figure 7). This leads to much higher heat exchange rate, and consequently a stronger thermal effect, than it would be the case in practice. This could be considered as a worst case condition as well.

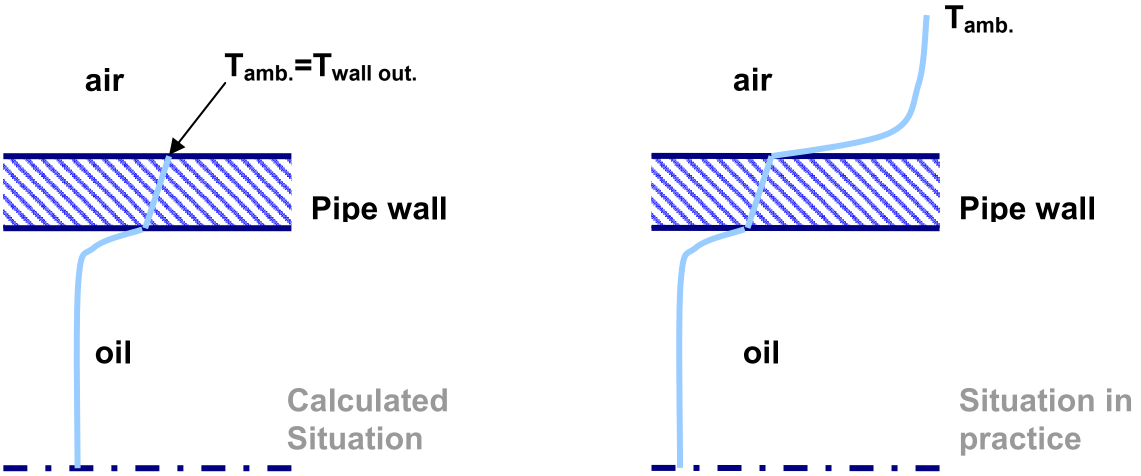


Figure 7 Left hand figure: temperature profile as been used in this CFD simulation. Right hand figure: temperature profile as it is in practice.

The boundary conditions and geometrical configuration for the CFD simulation have been defined in Figure 8 and Table 1.

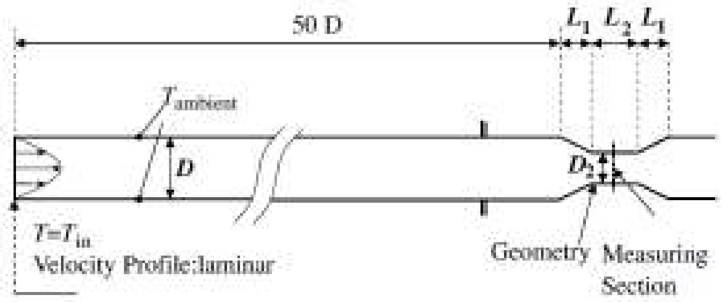
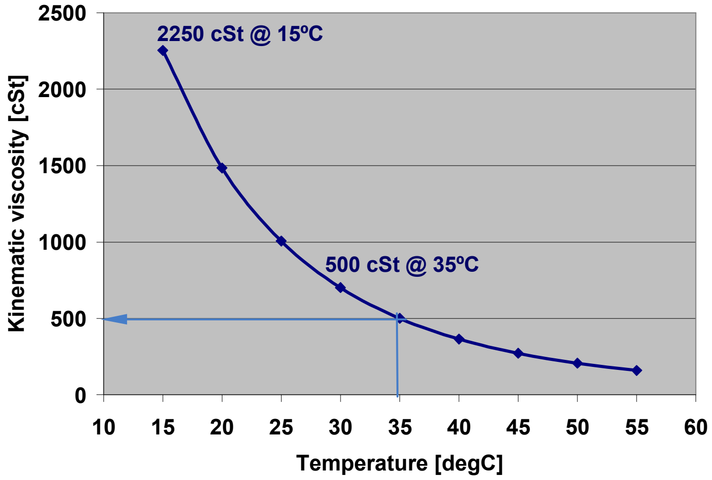


Figure 8 Sketch of the geometrical configuration and some boundary conditions which are used for the CFD simulation.

Reynolds Number	Re		100, 500, 1500
Volumetric Inlet Velocity	u_{im}	m/s	0.5, 2.5, 7.5
Inlet Temperature	T	°C	35
Ambient Temperature	T_{amb}	°C	15,30,35,40,55
Density	ρ	kg/m^3	900
Thermal diffusivity	α	m^2/s	$8\,10^{-8}$
Heat Capacity	C_p	J/kgK	2000
Wall Heat Transfer Coefficient	k	$\text{W/m}^2\text{K}$	3500
Flow Meter Heat Transfer	-	-	adiabatic
Kinematic Viscosity	ν	$\mu\text{m}^2/\text{s}$	see eq. 2.1
Inlet Diameter	D	mm	100

Table 1 Numerical values that have been used for the CFD simulation.

A rotational symmetric problem is investigated. All thermodynamic properties (density, heat capacity, thermal conductivity) except from viscosity are assumed to be constant. Buoyancy effects are neglected in this calculation. The relationship between fluid stress S and strain σ is described by the Newtonian model σ=ηS where η is the dynamic viscosity. All non-Newtonian effects are not accounted for and the fluid dynamic properties are described by the single viscosity parameter ν in dependence of temperature as given by Figure 9. Viscous heating effects are included in the calculations. This leads to some self-heating, especially for high Reynolds numbers.



$$\nu = 10^{10^{C_2 T^{C_3}}} - C_1 \ [\mu m^2/s]$$
$$C_1 = 0.94, C_3 = -3.23, C_2 = 8.47$$

Figure 9 The relation between kinematic viscosity [m^2/s] and temperature [°C] which has been used for the numerical simulation described in this paper.

ANSYS CFX 12 is used to solve the incompressible Navies-Stokes equations on a V-shaped slice of a pipeline section. The grid has 80 cells in the radial direction for the case Re=1500. For the other Reynolds number cases, a grid with 40 cells in the radial direction is used. At the inlet of the geometry, a parabolic velocity profile is prescribed. Convergence of the calculation typically requires about 10,000 iterations.

In total 15 test cases have been calculated. They are named by the Reynolds number and ambient temperature according to Table 2.

Test Case	Re No.	Ambient Temperature [°C]
re1t1	100	15
re1t2	100	30
re1t3	100	35
re1t4	100	40
re1t5	100	55
re2t1	500	15
re2t2	500	30
re2t3	500	35
re2t4	500	40
re2t5	500	55
re3t1	1500	15
re3t2	1500	30
re3t3	1500	35
re3t4	1500	40
re3t5	1500	55

Table 2 Coding scheme for the calculated test cases. Re1: Re=100, Re2: Re=500, Re3: Re=1500, t1: $t_{amb.}$=15 °C, etc. The initial oil temperature is 35 °C.

The velocity profiles at two positions have been studied being the meter inlet and the measuring section of the flowmeter. These positions are illustrated in Figure 10.

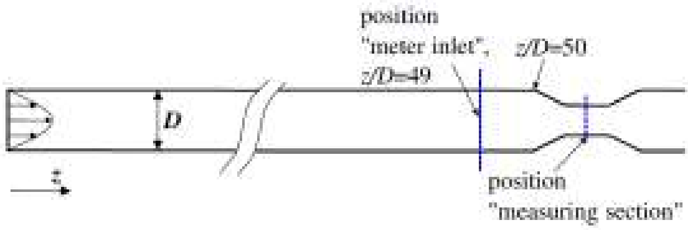


Figure 10 Locations where the velocity profiles have been investigated.

The boundary layer profiles are shown in Figure 11 for the meter inlet position and in Figure 12 for the measuring section position. In all investigated cases, the thermal boundary layer is found in the region r/R>0.85.

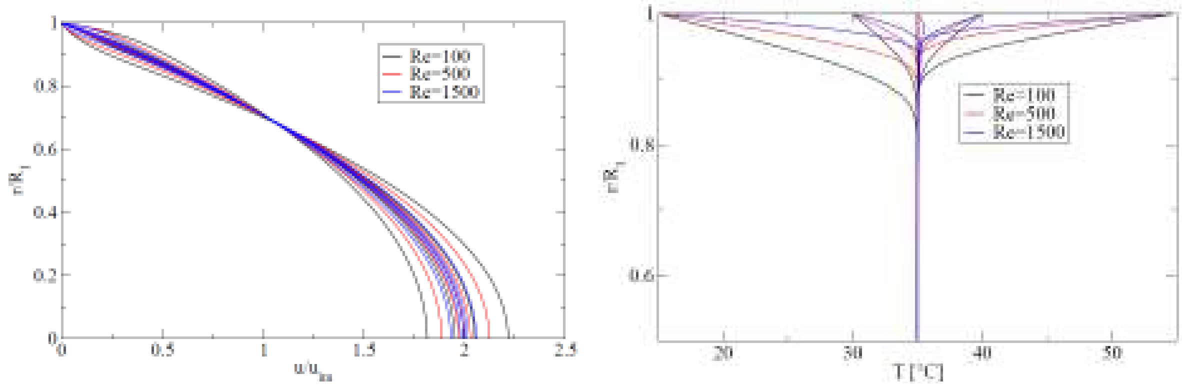


Figure 11 The velocity profile (left hand figure) and thermal boundary layer at the Meter inlet section (z/D=49) for the 15 different test cases.

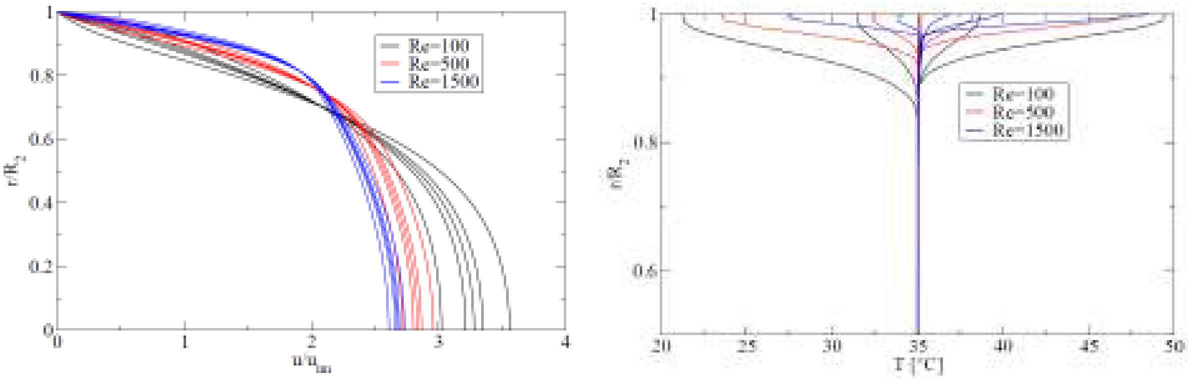


Figure 12 The velocity profile (left hand figure) and thermal boundary layer at the measuring section of the flowmeter for the 15 different test cases.

The curves that corresponds to different ambient temperatures have not been labelled since they can be identified by the steepness at the wall. The steepest curve belongs to the situation with the highest wall temperature. The thermal effects on the velocity profiles are less pronounced for higher Reynolds numbers because the thermal boundary layers are thinner.

It is remarkable to see from Figure 11 (left hand figure) that there seems to be one point where all velocities come together (around $r/R_1 \approx 0.7$) regardless the changing viscosity in the thermal boundary layer.

Inside the conical section, the fluid is accelerated. This leads to thinning of the velocity boundary layers. As expected, it is found that the higher the Reynolds numbers, the thinner the boundary layers. The flow in the central region becomes more homogeneous. This could also be observed from Figure 13 which depicts the temperature distribution in the meter for two different Reynolds numbers and two different ambient temperatures.

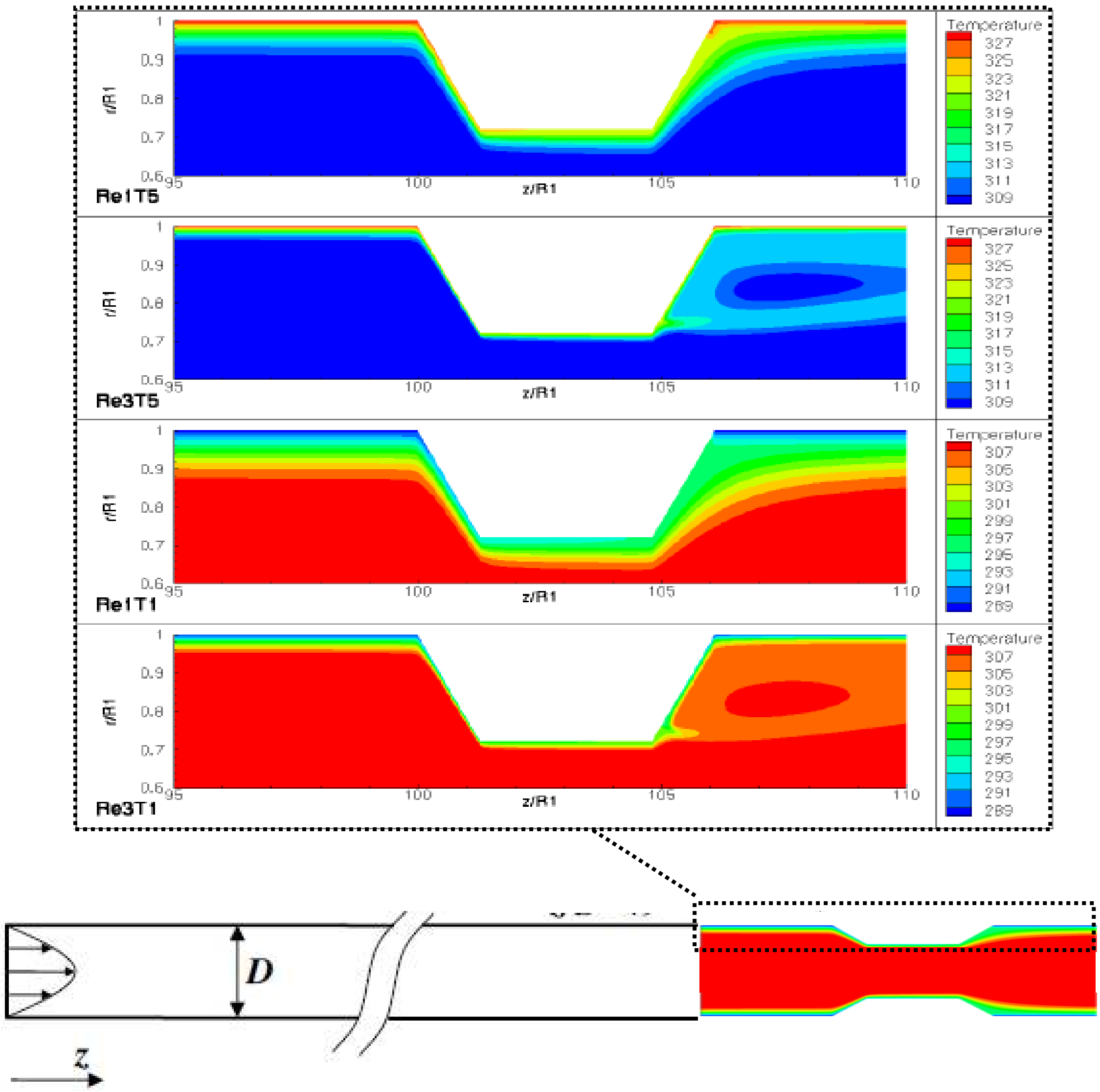


Figure 13 Temperature distribution [K] in the measuring section (Re1: Re=100, Re3: Re=1500, T1: $T_{amb.}$=15 °C, T5:$T_{amb.}$=55 °C). Note that the figures have strongly been compressed in horizontal direction.

The CFD data have been used as input for the ALTOSONIC V measuring algorithm. This enables us to simulate the behaviour of the ALTOSONIC V for these kind of profile disturbances.
The profile factors that have been obtained correspond to the profile factors that are observed in practice. The simulated 'reading' of the ALTOSONIC V has been compared with the

volume flow which is precisely known. This enables us to express the sensitivity of the ALTOSONIC V for these kind of disturbances in a percentual error (see Figure 14).

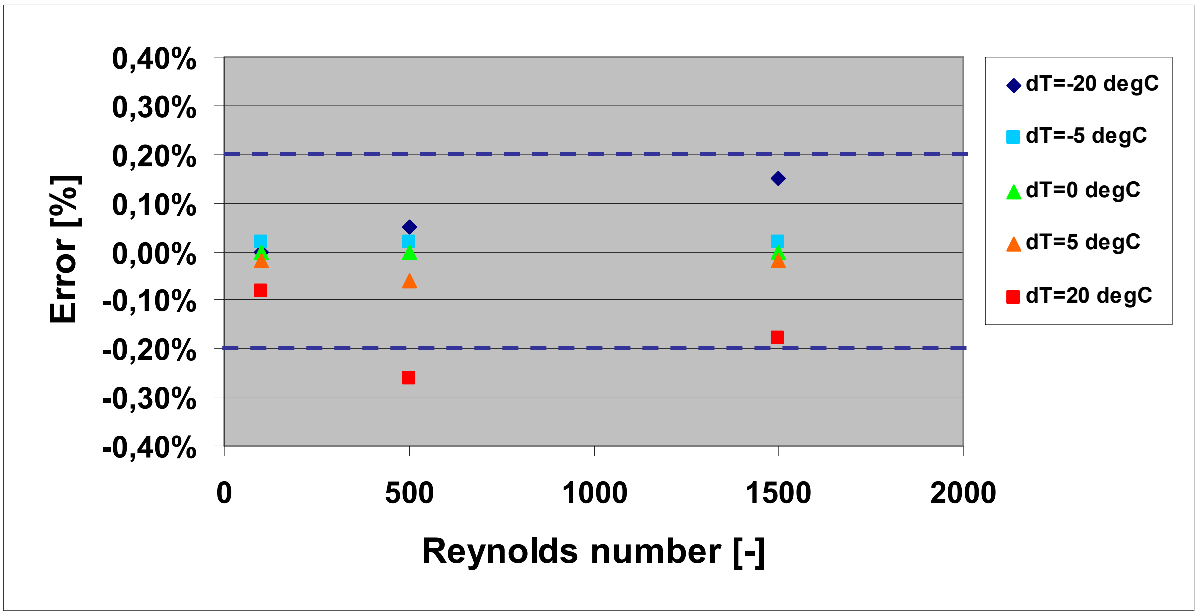


Figure 14 The response of an ALTOSONIC V to changing boundary layer viscosity as result of heat transfer to and from the environment. dT is the difference between fluid and prescribed outside pipe wall temperature.

Several conclusions could be drawn from these simulations:

- As expected, thermal boundary layer development for these Reynolds numbers (100 < Re < 1500) is a very slowly process. Even after 50D the thermal boundary layer is relatively thin: about 10% of the pipe radius.
- The conical measuring section has a positive effect on both the thermal and velocity boundary layer. The thicknesses are reduced, the profiles are more homogeneous.
- Temperature differences between outer pipe wall and fluid up to 5 °C doesn't lead to a significant measuring effect. This holds for the entire laminar flow regime that have been simulated.
- For temperature differences equals 20 °C, the effects become significant. However, it should be emphasized that this is an extreme situation simulating e.g. falling snow on a warm non-insulated pipe.
- When thermal insulation is being applied, the effect of ambient temperature is expected to be not significant at all.
- The results shown in this paper may be applied to even higher viscosities, taking into account reduced temperature differences such that the percentual viscosity changes stay within the limits as presented in this paper.
- Buoyancy effects have been neglected in this paper. We like to take these effects into account in the next simulations. Buoyancy could lead to non-symmetric flow situations.
- These results confirm the experience that we have with comparable situations in the field. We don't observe significant meter reading changes due to changing ambient conditions.
- These results also correspond to the experimental results described in the next paragraph: tests with protruding gaskets disturbing the boundary layer.

Tests with protruding gasket

In addition to the above mentioned numerical investigations, another boundary layer disturbance test have been carried out. By using a protruding gasket, the boundary layer just

in front of the flowmeter has been disturbed (see Figure 15). The response of the ALTOSONIC V to this disturbance type has been tested.
Two 12 inch flowmeters have been used for this test. The viscosity of the oil during this test was about 270 cSt. The gasket was protruding about 5 mm.

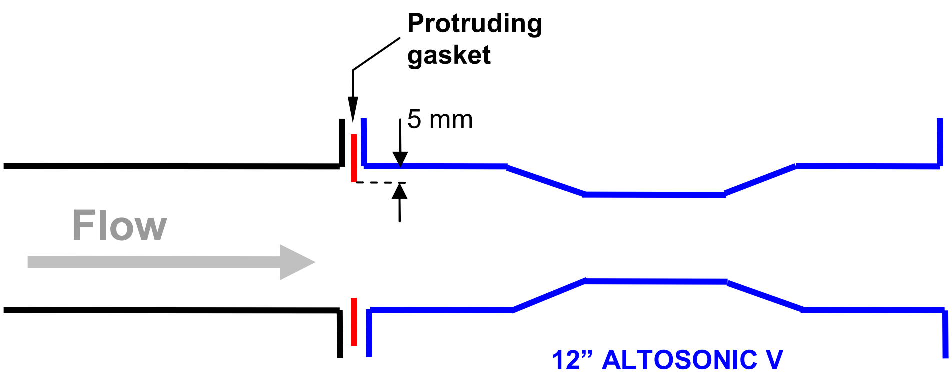


Figure 15 Schematic overview of a test with protruding gasket. The gasket protrudes about 5mm. The viscosity of the oil is about 270 cSt.

The performance of the flowmeters have been tested with and without this protruding gasket using unchanged settings. The result of this test is shown in Figure 16.

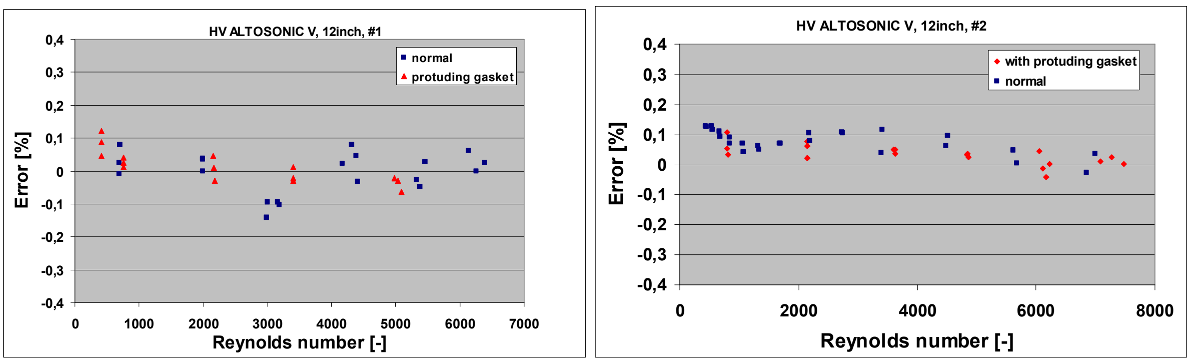


Figure 16 Response of 2 x 12inch ALTOSONIC V flowmeters to protruding gaskets at high viscosity applications.

No systematic effect could be observed. This holds for the laminar, transitional and turbulent region. The outcome of this test support the conclusion from the previous paragraph that the 5-beam design using a conical measuring section is not really sensitive to small disturbances in the boundary layer. This holds for high viscosity as well as for low viscosity applications.

5. Customer experience

5.1. Application in Norway Snorre-Vigdis [7]

Two identical ALTOSONIC V’s 8” (DN 200) have been in use since 1999 for the fiscal oil transfer between the Snorre and Vigdis process trains on the Snorre tension-leg platform since October 1997. One flow meter functions as the duty (transfer) meter and the other as the master meter. For calibrations the flow meters can be run in line. The customer required a flow meter that complied with NPD requirements, had a long-term repeatability, and required a minimum of maintenance.

Conclusions on this application:

- The k-factors of the duty ultrasonic flow meter, determined from comparison with the master ultrasonic meter after initial set-up adjustment, were all within +/- 0.10%. In similar applications, such good results could never be achieved with turbine meters even with frequent washing and cleaning. The average bias in k-factor from the pre-established curve in 1997, with all the registered data points, was within 0.02%.
- In addition, over for ten years no maintenance was carried out on the KROHNE ALTOSONIC V meters. The diagnostic tools built into the ALTOSONIC V have proven to be reliable, and a strong guide to whether the processing and piping installation is satisfactory.

5.2. Application in Brazil on different FPSO's [8]

Quote

"All the petroleum production in the Marlin Asset, Campos Basin, after treatment, is stored in the production platform tanks for some days, until is offloaded. During this period, the residual water is partially stratified, resulting in petroleum layers near the bottom of the tank with higher water content, more than what is allowed. In order to meet the specifications of the National Agency for Petroleum, Natural Gas and Biofuels (ANP), refineries or even international export market requirements, the high water content petroleum is removed from the treated oil tanks, being directed to another treatment process, and, therefore, being mis-accounted for the second time in the petroleum fiscal metering before tank storage.

In order to overcome this problem all the fiscal metering of the petroleum production in the Marlin Asset, Campos Basin is made in the offloading lines of the FPSO's."

Unquote

For this ultrasonic flow meters were installed and metrological certification of the flow meters required tests with high viscosity in an international laboratory and analysed by the Dutch Board for Weights and Measures (NMi).

The long term stability of ultrasonic flow meters was monitored resulting in the following data and is based on re calibrations at a certified calibration facility:

Meter size	No drift observed over a period of
6 inch	23 months
6 inch	9 months
6 inch	20 months
12 inch	8 months
24 inch	46 months

6. Conclusions

- Crude oil production will in the near future increasingly use high-viscosity oils and bitumen and therefore the industry is demanding ultrasonic flow meters capable of measuring such crude oils.
- The critical factors for using ultrasonic flow meters on High Viscosity products, as specified in this paper required extensive Research and Development efforts. These critical factors have been solved and as a result a NMi approval has been obtained for viscosities up to 400 cSt for diameters up to DN 24”
- Presently Ultrasonic flow meters can handle 500 cSt for diameters up to DN 24”, higher viscosities are feasible for smaller diameters.
- Calibration of High Viscosity ultrasonic flow meters based on Reynolds, by using lower viscosity products is well established and proven to provide excellent results
- The reproducibility and long term stability has been proven by internal tests and evaluations performed by KROHNE, many end-users, and independent authorities which resulted in NMi confirmation that the performance of the KROHNE ultrasonic flow meter only needs verification in intervals of 5 years.
- Thermal boundary layers does affect the viscosity in the boundary layer significantly. This leads to a changing laminar flow profile. However, temperature differences between outer pipe wall and fluid up to 5 °C doesn’t lead to a significant measuring effect. This holds for the entire laminar flow regime that have been simulated.
- For temperature differences equals 20 °C, the effects become significant. However, this is a very extreme situation simulating e.g. falling snow on a warm non-insulated pipe.
- When thermal insulation is being applied, the effect of ambient temperature is expected to be not significant.
- The conical measuring section has a positive effect on both the thermal and velocity boundary layer. The thicknesses are reduced, the profiles are more homogeneous.
- Buoyancy effects have been neglected in this paper. We like to take these effects into account in the next simulations. Buoyancy could lead to non-symmetric flow situations.
- These results confirm the experience that we have with comparable situations in the field. We don’t observe significant meter reading changes due to changing ambient conditions.
- These results also correspond to the experimental results described in the next paragraph: tests with protruding gaskets.

7. References

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