

## **AN ULTRASONIC MEASUREMENT SYSTEM FOR CUSTODY TRANSFER**

**Highly accurate ultrasonic flowmeter system  
Innovative technology to set new standard in custody transfer**

The Ultrasonic Flowmeter 5 beams is a unique flowmeter system for custody transfer flow measurement of hydrocarbons. It offers substantial improvements in accuracy and turndown required for custody transfer of high value petroleum products. Until now, ultrasonic flowmeters were not capable of meeting the stringent requirements for true fiscal and commercial metering.

**Authors:**

Eng. João Carlos de Mendonça – Eng. De Produtos – CONAUT  
Eng. Ton Leenhoven – KROHNE Holanda

## Ultrasonic Flowmeasurement Principle

The average velocity  $v_m(x)$  over measuring line  $m$  at position  $x$  is obtained by transmitting and receiving acoustic signals along the measuring line and determining the transit times in upstream and downstream direction. In the figure below an axial cross-section of the measuring section in the plane of the measuring line is shown. Two acoustic transducers transmit and receive an ultrasonic signal along measuring line  $m$ , which forms an angle  $\beta$  with the axis of the measuring tube.

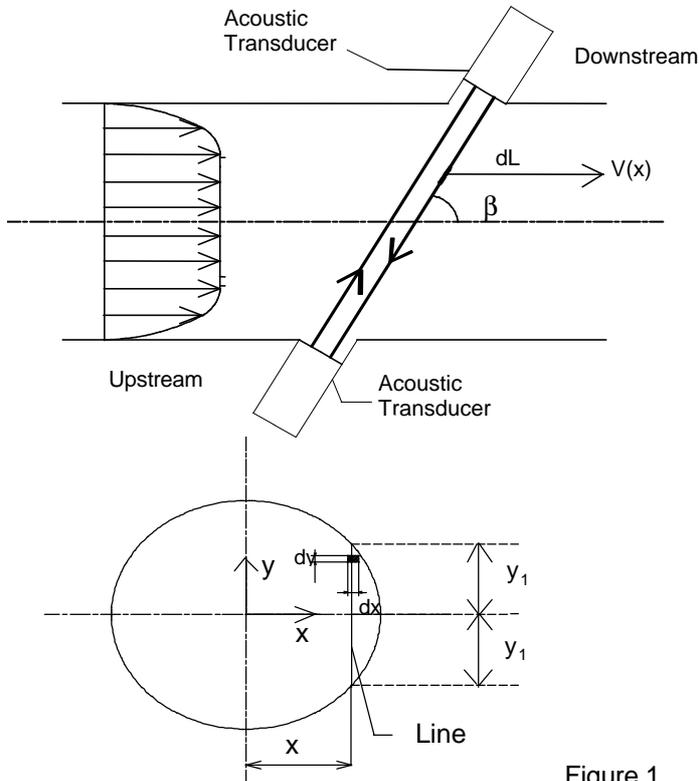


Figure 1.

The transit time in upstream direction is:

$$t_{\text{upstr}} = \frac{L}{c - v_m(x) \cdot \cos(\beta)} \quad (1)$$

where  $c$  is the sound velocity,  $L$  is the length of the measuring line and  $\beta$  is the angle between the measuring line and the axis of the measuring tube. In downstream direction the equation is:

$$t_{\text{downstr}} = \frac{L}{c + v_m(x) \cdot \cos(\beta)} \quad (2)$$

From equations (1) and (2) follows the well-known formula for the average velocity  $v_m(x)$  along measuring line  $m$  at position  $x$ :

$$v_m(x) = \frac{L \cdot (t_{\text{upstr}} - t_{\text{downstr}})}{2 \cdot t_{\text{upstr}} \cdot t_{\text{downstr}} \cdot \cos(\beta)} \quad (3)$$

The difficulty lies in converting the average velocity, measured along several measuring lines (see drawn thick lines of figure next), to an accurate measurement of the average velocity of a flow through cross-section and subsequently to a flowing through volume.

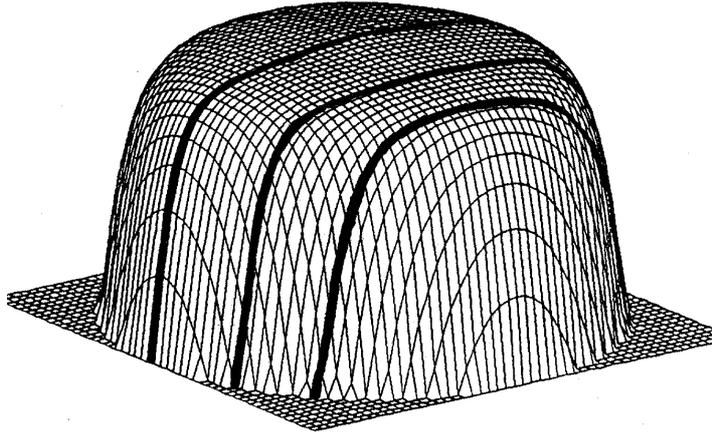


Figure 2

### Elimination of effects of viscosity

The figure below represents axial cross-section of the measuring section preceded and followed by a confusor. In front of the confusor there is a fully developed flow profile which passes into the actual profile which is the object of the measurements.

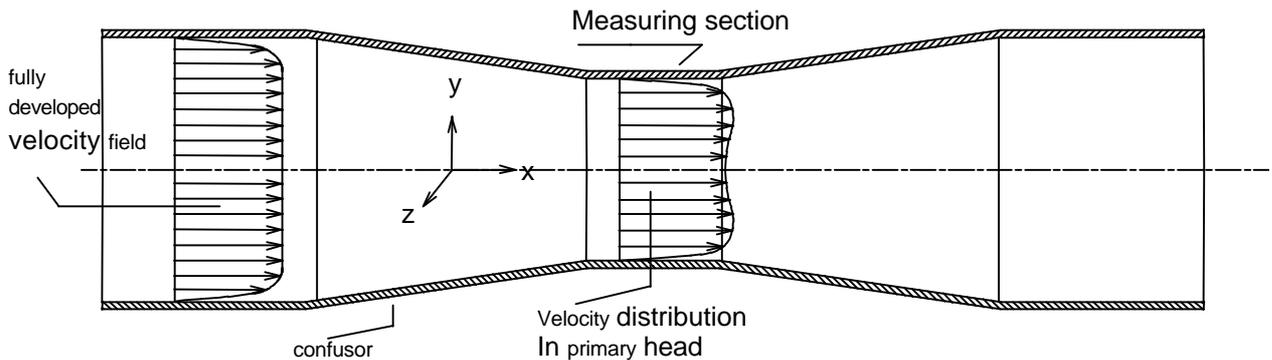


Figure 3

The velocity distribution of the incoming flow is fully developed and axisymmetrical. The meter is built axisymmetrically, which makes the measuring section axisymmetric as well.

$$V(x,y) = f \text{ (velocity distribution at the inlet side, geometry meter)}$$

The velocity distribution in the inlet section is dependent on  $Re$  with a fully developed flow. If the meter has a fixed geometry the velocity measurement in the measuring section is also a function of Reynolds:  $v=f(x,y,Re)$

The average velocity along a cross-section of the meter is:

$$\langle v \rangle = \frac{l}{p R^2} \int_{-R}^R \int_{-\sqrt{R^2-x^2}}^{\sqrt{R^2-x^2}} v(x, y, Re) dx dy \quad (4)$$

where  $R$  is the radius of the meter cross-section and  $v(x, y, Re)$  is the velocity distribution. The average velocity  $v_m(x)$  along a measuring line  $m$  can be formulated as follows:

$$v_m(x, Re) = \frac{l}{2 \bullet \sqrt{R^2 - x^2}} \int_{-\sqrt{R^2 - x^2}}^{\sqrt{R^2 - x^2}} v(x, y, Re) dy \quad (5)$$

If formula (5) is applied to formula (4) the next formula follows:

$$\langle v \rangle = \frac{l}{p R^2} \int_{-R}^R 2\sqrt{R^2 - x^2} \bullet v_m(x, Re) dx \quad (6)$$

For  $N$  measuring lines this equation is approximated in practice by  $N$  terms:

$$\langle v \rangle = \sum_{i=1}^N w_i \bullet v_m(x_i) + e(Re) \quad (7)$$

Here  $v_m(x_i)$  is the average velocity along a line at  $x_i$ ,  $w_i$  is the constant weight factor; and  $e(Re)$  is the residual term which originates as a result of this discretisation. The best place for the sensor  $x_i$ , and the weight factors  $w_i$  is determined in such a way that the residual term  $e(Re)$  is minimal at various values of  $Re$ . In the figure next different fluids  $e$  are set out as a function of  $Re$  by way of an example.

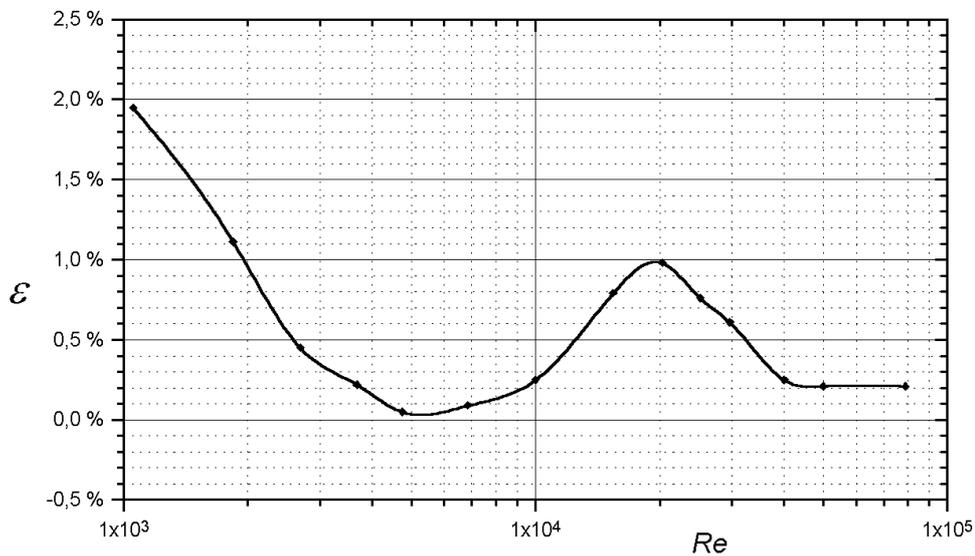


Figure 4

As described earlier, the dimensionless velocity distribution in the measuring section is a function of  $Re$ . Various relations of measuring line velocities can serve as dimensionless number for the dimensionless velocity distribution. To give an example, in the figure below two typical relations  $v'$  between the average measured velocities of measuring lines are presented as a function of  $Re$ .

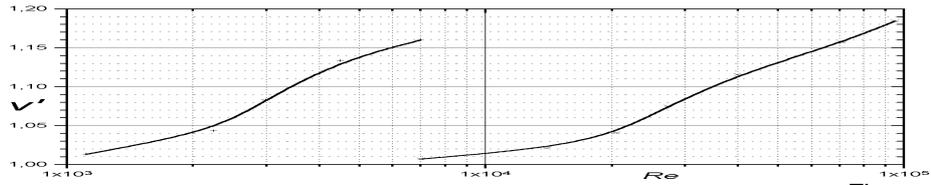


Figure 5

During calibration the measured relation is stored between correction  $\epsilon$ , which will have to be applied and  $Re$ , which is determined from the typical relations between velocities. Next, by measuring the velocity relations in real-time,  $Re$  is determined which makes it possible to determine the correction  $\epsilon$ , which will have to be applied. With these  $\epsilon$  values the linearity of the flowmeter is corrected in real-time.

### Correction for flow profile disturbances

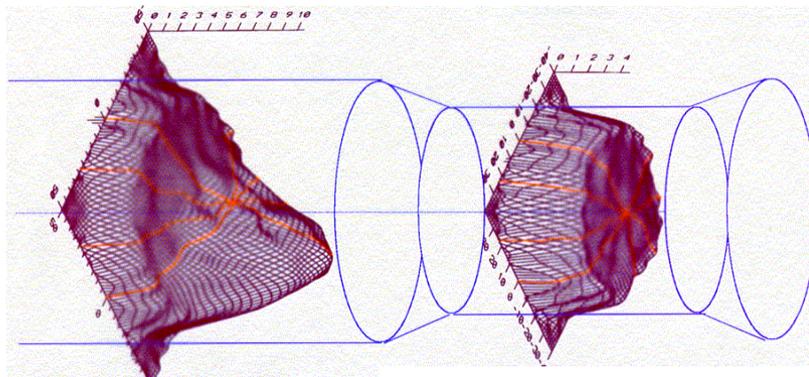


Figure 5A

During the past 10 years a lot of experimental research

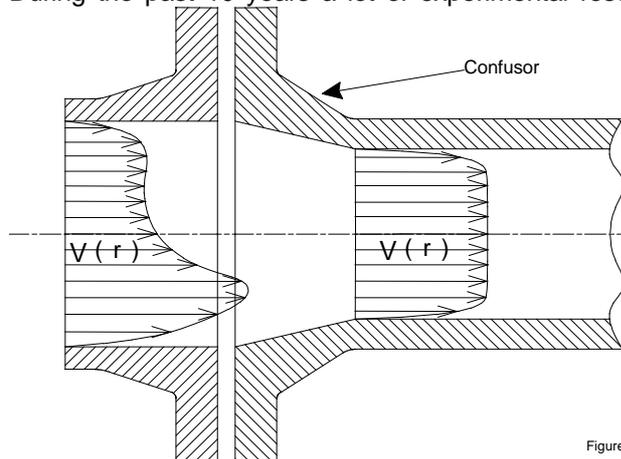


Figure 6

has been done into reducing the flow profile dependency of ultrasonic flowmeters. A new development uses a geometrical method to reduce this dependency. The idea behind it is that an undisturbed, fully developed profile does not show any effects of flow profile dependency. A confusor is an important device, which ensures that the disturbed profiles are straightened to a shape, which approximates the original axisymmetrical undisturbed shape. The figure below illustrates how the influence of the confusor is apparent from the disturbed flow profile in the inlet section on the left and the straightened flow profile in the measuring section on the right.

### System description Ultrasonic Flowmeter

The flowmeter uses the well-known principle of acoustic transit time measurement in order to establish the flow velocity. For this instrument however flowvelocity information from the individual measurement channels is gathered and processed primarily into:

- Volumetric flowrate

- Totalised volumetric flow

Additionally this system gives extra information such as:

- Sound velocity
- Reynolds' number

There are 3 executions available consisting of:

Execution 1	Execution 2	Execution 3
<b>(Also) in the hazardous area zone 1+2:</b> <ul style="list-style-type: none"> <li>• Multichannel flowmeter body</li> <li>• Field mounted signal converters on beam</li> </ul> <b>In the non-hazardous area:</b> <ul style="list-style-type: none"> <li>• Computing Controller</li> </ul>	<b>(Also) in the hazardous area zone 1+2:</b> <ul style="list-style-type: none"> <li>• Multichannel flowmeter body</li> <li>• Field mounted signal converters in a stainless steel cabinet</li> </ul> <b>In the non-hazardous area:</b> <ul style="list-style-type: none"> <li>• Computing Controller</li> </ul>	<b>(Also) in the hazardous area zone 1+2:</b> <ul style="list-style-type: none"> <li>• Multichannel flowmeter body</li> <li>• Field mounted signal converters + computing controller in a stainless steel cabinet</li> </ul>

The field mounted signal converters drive the acoustic sensors in the flowmeter and perform the flowmeasurement per acoustic channel. All measurements are then transferred via a serial dataport RS485 to the computing controller. This unit then calculates the average flow, totalises and checks the plausibility of the incoming measurements. The outputs of this controller are:

- Pulse outputs (0-1 kHz) (dual pulse phase shifted 90° - 180°)
- Analog outputs (4-20 mA)
- Status outputs (3 binary outputs)
- Control inputs (4 binary inputs)
- RS 485 output (Modbus<sup>®</sup> protocol)

On the pulse and analog output, information such as volumetric flow, liquid sound velocity, or viscosity can be made available. The status outputs are there for monitoring the functioning of the equipment. Conditions such as acoustic path error, flow profile error and field converter error can be monitored. Via the control inputs e.g. the totalisers and status functions can be reset. Finally also via the RS 485 output all measurement information, like flow, sound velocity, viscosity and status can be obtained.

### Ultrasonic Flowmeter Multichannel Flowmeter Body

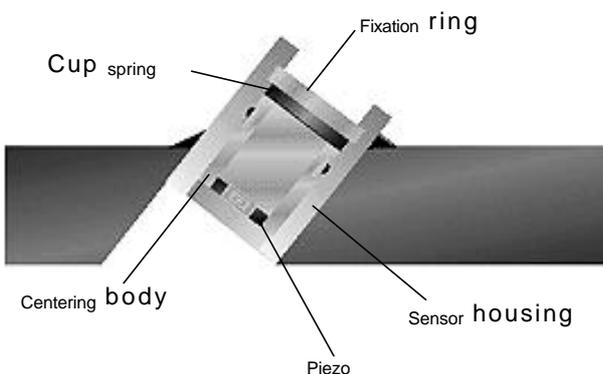


Figure 7

The flowmeter tube consists of a centre part made from a solid block of metal (up to 300mm/12" in size) that holds the 5 acoustic measurement paths. To this centre part an in- and outlet cone, with flanges, is welded. The flowmeter construction is symmetrical which means it can measure bi-directional flows. The cones play an important part in the shaping of non-axisymmetric flowprofiles, ensuring a symmetrical flowprofile inside the measurement section of the flowmeter. Resulting from the location of the measurement beams the Reynolds number inside the measurement section can actually be measured. Using this Reynolds number measurement as basis the liquid viscosity

can even be derived! The sensors inside the flowmeter tube are made of an all-metal construction and allow for an exchange of their inner parts under full operating conditions. The flowmeter body also holds a skin temperature sensor to allow for temperature compensation due to expansion of the flowtube.

### Specifications Ultrasonic Flowmeter Multichannel Flowmeter Body

<b>Flowmeter size</b>	DN 100 (4") up to DN 1000 (40")	
<b>Pressure ranges</b>	Standard available in the ISO/DIN ratings up to PN 160 and in the ANSI class ratings up to class 900.	
<b>Stated meter performance</b>	(See flowtable)	
Uncertainty (in % of rate)	± 0.15 over a 2:1 turndown ratio ± 0.20 over a 10:1 turndown ratio ± 0.25 over a 20:1 turndown ratio	
Repeatability (in % of rate)	± 0.025	
<b>For comparison:</b>	Acc. to international recommendations <b>OIML</b> R117 class 0.3 measuring systems for liquids other than water: ± 0.20 over a 10:1 turndown ratio ± 0.06	Acc. to <b>NPD</b> (Norwegian Petroleum Directorate) 1995 regulations relating to fiscal measurement: ± 0.15 over a 2:1 and ± 0.25 over a 10:1 turndown ratio ± 0.02
Uncertainty (in % of rate)		
Repeatability (in % of rate)		
<b>Liquid specific gravity range</b>	490 kg/m <sup>3</sup> – 1200 kg/m <sup>3</sup>	
<b>Viscosity range</b>	0.1Cst – 300 Cst (high viscosity has negligible effect on the meter performance)	
<b>Calibrations</b>	Standard calibrations are performed on the Altometer testtrigs. The testfluid on these testtrigs is water. If other or multiple viscosity calibrations are required Altometer must be consulted. Available calibration fluids other then water are:	
Naphtha	Specific gravity @ 15 °C (59 °F) = 730 kg/m <sup>3</sup> Viscosity @ 15 °C (59 °F) = 0.83 Cst Viscosity @ 25 °C (77 °F) = 0.73 Cst	
Oural	Specific gravity @ 15 °C (59 °F) = 850 kg/m <sup>3</sup> Viscosity @ 15 °C (59 °F) = 8 Cst Viscosity @ 25 °C (77 °F) = 6.4 Cst	
Condensate	Specific gravity @ 15 °C (59 °F) = 900 kg/m <sup>3</sup> Viscosity @ 15 °C (59 °F) = 43 Cst Viscosity @ 25 °C (77 °F) = 26 Cst	
Fuel oil	Specific gravity @ 15 °C (59 °F) = 940 kg/m <sup>3</sup> Viscosity @ 15 °C (59 °F) = 230 Cst Viscosity @ 25 °C (77 °F) = 100 Cst	

<b>Influence of the Reynolds number</b>	Negligible
<b>Applications in hazardous areas</b>	Suitable for installations in Zone 1+2
Applicable certifications	PTB nr. Ex-96.D.2110X PTB nr. Ex-96.D.2109X
<b>Process temperature</b>	-10 – +120 °C / 12 – +248 °F
<b>Ambient temperature</b>	-60 – +60 °C / -58 – +140 °F
<b>Protection class according to IEC 529 / EN 60 529</b>	IP 65 or IP 67 equivalent to NEMA 4/4X and NEMA 6
<b>Materials of construction</b>	
Meter body	Stainless steel 316 L (comparable with stainless steel 1.4404) Other materials (Duplex, SMO, etc.) on request
Meter housing	Steel with polyurethane Other materials on request
<b>EMC</b>	EN50081-1 and EN 50082-2

Ultrasonic Flowmeter Field Mounted Signal Converters

In the field, in the Ex zone 1 conditions, the field mounted converters are located. The converter is either mounted near the flowmeter (compact) or at a location of maximum 10 m (30 ft) away from the flowmeter. The components of the field mounted converter are standard components used with standard productline for short delivery, cost and serviceability. The output of these field mounted converters is digital due to the

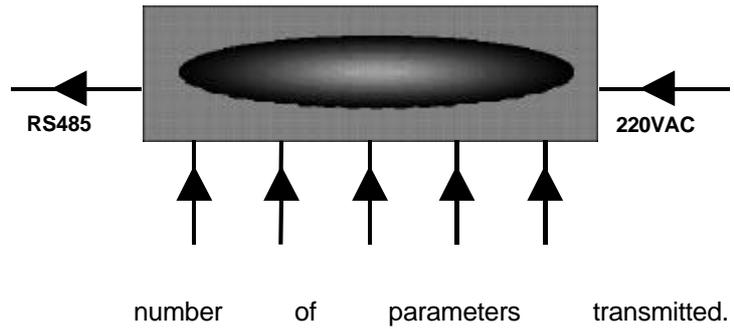


Figure 8

The RS485 allows a long distance (up to 1000m) between the field mounted converter and the computing controller. The protocol of this RS 485 communication line is proprietary. Optionally a pressure, temperature and possibly a density sensor can be connected to this RS 485 bus for referenced flow computations in external flowcomputers.

### Specifications Ultrasonic Flowmeter Field Mounted Converters

Power supply	1. AC version	2. AC Version		AC/DC version
	1. Rated voltage Tolerance band	230 / 240 V 200 - 260 V	200 V 170 - 220 V	24 V AC 20 - 27 V AC
2. Rated voltage Tolerance band	115 / 120 V 100 - 130 V	100 V 86 - 110 V	- -	- -
Frequency	48 - 63 Hz		48 - 63 Hz	
Power consumption	Ca. 50 VA		ca. 50 VA	ca. 40 W
	When connected to functional extra-low voltage, 24 V, safety separation (PELV) is essential (to VDE 0100/VDE 0106 and IEC 364/IEC 536 or equivalent national standard).			
Protection class	IP 67 equivalent to NEMA 6			
Vibration level (IEC 68-2-6)	2.2 g, frequency range 10 - 150 Hz			
Cable (number, type)	3 or 5x Coaxial-cable between the ALTOSONIC® V Flowmeter and the 5 separate field mounted converters			

### Ultrasonic Flowmeter Computing Controller

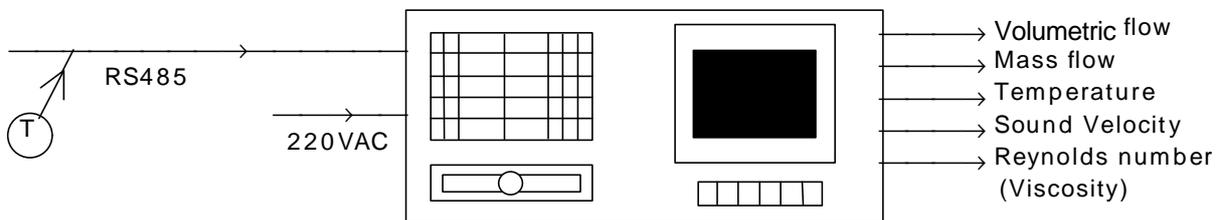


Figure 9

The computing controller receives the signals from the field (flowvelocity 5x, sound velocity 5x, P, T and density) and converts these in an average volumetric flow under operating conditions. Additionally sound velocity per measurement line, raw flow velocity per measurement line, liquid viscosity, body-temperature and status signals are available as output signals.

The measurement results are made available to a (DCS) system, or a flow computer, by way of a digital output (RS485, MODBUS protocol) and the volumetric flow is available as a frequency output 1 kHz. Additionally system configuration and / or flow data can be viewed by way of a CRT and a keypad. Raw

input data may be logged for at least a period of 24 hours on SSD. The system will start up automatically at powering up. The use of a hard disk will be avoided.

The computing controller of the Ultrasonic Flowmeter has:

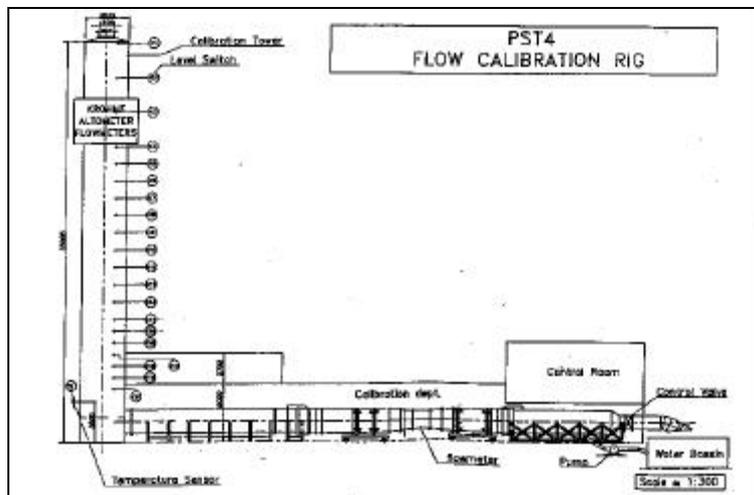
- **5 outputs**
  - 4 - 20 mA
  - 0 - 1 kHz
  - 3 status outputs
  - 4 binary inputs
  - RS485
  
- **User interface**

## Calibration of the Ultrasonic Flowmeter

The flowmeter is calibrated using the NKO (the Dutch Council for Accreditation, operating as accreditor for calibration laboratories), certified calibration facilities at Altometer. The calibration procedure corresponds with the requirements of the "Norwegian Petroleum Directorate" *Regulations relating to fiscal measurement of oil and gas etc.* ISBN 82-7257-437-3, 1995 and OIML International Recommendation for custody transfer measuring systems for liquids other than water (OIML R117, 1995). A copy of the NKO certification of the Altometer calibration rigs as well as the OIML certification of the Ultrasonic Flowmeter, can be found in chapter 16 'General information'.

## Calibration installation

The Ultrasonic Flowmeter is tested in comparison with a measuring tank (Altometer tower), this in turn is tested for accuracy by the Dutch calibration authority "Nederlands Meetinstituut (NMI)" in Dordrecht. The accuracy is 0.03% and the calibration product is water.



A schematic representation of measuring installation PST4

Figure 10

Measuring installation PST5 has a different capacity. The certificates for measuring installation PST4 and PST5 can be found in chapter 16 'General information'.

## Test conditions

Measuring systems must be built and installed in such a way that during normal use, neither retained air nor released gas can be found in the totalizer. The inlet section is 20 DN, the outlet section is 5 DN. The

calibration product is water, product temperature is  $(15 \pm 15)^\circ\text{C}$  and the ambient temperature is  $(15 \pm 15)^\circ\text{C}$

## Calibration

For installation check and zero point check please refer to chapter 15 'Service'. The flow calibration is carried out at a constant volume (minimum of  $30\text{ m}^3$ ) of the Altometer tower. The calibration is carried out at  $Q_{\max}$ ,  $Q_{\min}$  and at 3 intermediate flows, hereby  $Q_{\max}$  is the maximum flow and  $Q_{\min}$  is the minimum flow. At each flowrate 5 measurements are carried out, during which the errors  $E_i$  are measured 5 times.

The repeatability is calculated at each flow:

$$R_i = \pm \frac{E_{i\max} - E_{i\min}}{2} \times 100\% \quad (1)$$

where  $E_{i\max}$  and  $E_{i\min}$ , are the maximum and the minimum errors of 5 measurements at i-flow. The repeatability may not be greater than  $\pm 0.025\%$ .

The linearity is calculated at the required flow range:

$$L = \pm \frac{\bar{E}_{i\max} - \bar{E}_{i\min}}{2} \times 100\% \quad (2)$$

where  $\bar{E}_{i\max}$ ,  $\bar{E}_{i\min}$  are the maximum and minimum average errors of the measured value in a flow range. The non-linearity may not be greater than  $\pm 0.15\%$  for measuring range 2:1 and not greater than  $\pm 0.20\%$  for measuring range 10:1. If the error curve is more than 0.1% 'unsymmetrical', then the primary constant of the totalizers will be corrected according to Appendix 5. The K-factor is calculated as follows:

$$\text{K-factor [pulses/m}^3] = \frac{3600 F_{fs} [\text{Hz}]}{Q_{fs} [\text{m}^3/\text{h}]} \quad (3)$$

where  $F_{fs}$  is the full-scale value for the frequency output and  $Q_{fs}$  is the full-scale value of the flow.

## The calibration report and the calibration certificate

The results of the calibration procedure are recorded in a calibration report (see below) which forms an integral part of the calibration certificate. When the results of the calibration procedure are positive, a calibration certificate can be drawn up.