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ULTRASONIC GAS FLOW METERS CONTINUE THEIR RISE

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INTRODUCTION

The introduction of multipath ultrasonic flow metering for custody transfer, also requires proper explanation of the principles to the customer.
Often heard remarks and questions are: " ...but it must be dependent on the speed of sound!?", ".... how valid are the appropriate weighting factors, and how are they determined?", ".... what is self checking and how does it work?", ".... what is the value for the price?", "What are the experiences of people who bought the system and why did they decide on ultrasonic flow measurement?" "Will it be approved for custody transfer?"

These are all valid questions if ultrasonic flow measurement is considered. This paper will answer the above.

The ultrasonic theory is approached from a different perspective. A new look is presented on the velocity measurement, speed of sound and the effect of velocity profiles. The speed of sound is used to check the validity of the measurements, and supports the self checking capabilities of ultrasonics.

The paper demonstrates velocity profiles influencing the measurement and the compensation by multiple paths and appropriate weighting factors. A math-model is used to calculate the effect of velocity profiles on a four path meter. The effect will be demonstrated with velocity profiles from an upstream 90° bend on the meter error.

Possible error sources in ultrasonic flow metering are discussed and how they are revealed in practice.
The value/price ratio in relation to orifice systems is discussed and shows possible savings. Also total station weight and length savings are conceivable with ultrasonic flow meter systems when compared to conventional systems.

Over 40 meters have been sold and some have been put into operational service. Others have been flow calibrated and are being installed at their operational sites. In the mean time test work is continuing.

For the future, Daniel is pursuing the second generation of the Ultrasonic Meter, with improved performance and extended applications.

EXTENDED THEORY

The flow equation for time of flight ultrasonic metering can be derived using a different approach. The new derivation takes in

account that the travel path of the signal (acoustic path) is not a straight line.
The difference with the common known derivation is that the velocity vectors are resolved to an independent orthogonal coordinate system along the pipe wall and across the pipe. See figure 1.

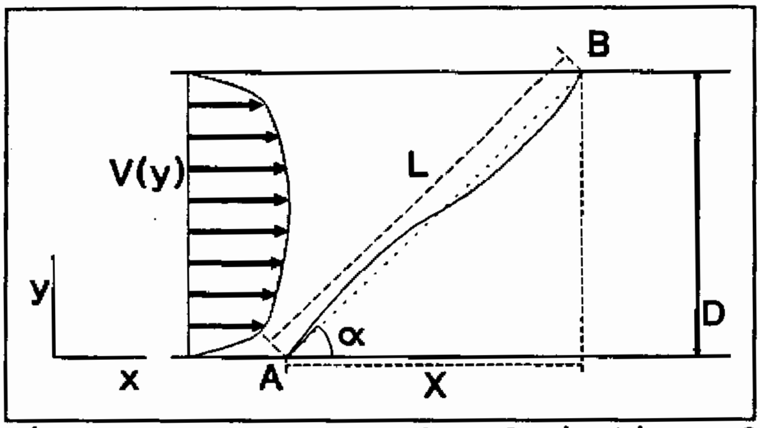

Figure 1 Parameters for derivation of flow equations in schematic setup.

At t = 0 a pulse is fired from A in direction α. The pulse leaves transducer A with the speed C.
The component in the y direction is: $C \cdot \sin(\alpha)$.
The component in the x direction is: $C \cdot \cos(\alpha)$.

The medium is flowing in the x-direction with velocity V(y). The velocity is not uniform over the diameter.

After time t the pulse position in the y-direction is given by:

$$y = C \cdot t \cdot \sin(\alpha) \qquad (1)$$

At time T (=transit time) the pulse is to arrive at the other side and has travelled the distance D in the y-direction.

$$D = C \cdot T \cdot \sin(\alpha) \qquad (2)$$

The velocity in the x-direction at time t is given by:

$$V_x = C \cdot \cos(\alpha) + V(y) \qquad (3)$$

with y given by equation (1).

The distance covered in the x-direction between t and t+dt is dx,

$$dx = V_x \cdot dt = [C \cdot \cos(\alpha) + V(y)]\ dt$$

Hence the distance covered in the x direction between t=0 and t=T is X and is given by

$$\int_0^T [C\cdot\cos(\alpha) + V(y)]\, dt = X$$

Since $t = y/[C\cdot\sin(\alpha)]$ therefore $dt = 1/[C\cdot\sin(\alpha)]\, dy$

Also by definition $\int_0^D V(y)\, dy = VD$
with V is the mean velocity of the fluid across D.

Note : Since V(y) is not uniform the acoustic path is not a straight line.

Continuing,

$$X = CT.\cos(\alpha) + VD/[C\cdot\sin(\alpha)]$$

Then using (2)

$$= [C\cdot\cos(\alpha) + V]\cdot T \qquad (4)$$

From eq. (2) : $C\cdot\sin(\alpha) = D/T$
From eq. (4) : $C\cdot\cos(\alpha) = X/T - V$

Combining these equations results in:

$$C^2 [\ \sin^2(\alpha) + \cos^2(\alpha)\ ] = [D/T]^2 + [X/T - V]^2 = C^2$$

Combined with the similar equation for the downstream traveling signal it can be written as:

$$\overline{V} = \left(\frac{L}{T} - \frac{L}{T'}\right) \frac{L}{2X}$$

$$\overline{V} = \frac{L^2}{2X} \left(\frac{T - T'}{T.T'}\right)$$

The last equation is identical to the one commonly known for ultrasonic flow metering. The equation is worked towards the known (and measurable) physical dimensions of the measuring section.
It is derived without any assumptions and the dependency on the angle α is eliminated. The equation is independent of the speed of sound and the velocity distribution.
Even if α is a function of x,y or t, since α is eliminated in the derivation, it does not matter. The only assumption is that C does not change between the firing of the upstream and downstream

travelling pulses.

The equation calculates the average gas velocity on a path and it is dependent on two transit times and some geometrical dimensions. Provided the dimensions are known and the transit times are properly measured, the velocity can be calculated. Once the velocity is known, the flow rate can be calculated.

VELOCITY PROFILES

The calculated gas velocity is the average velocity on the line AB (line velocity, figure 1). This is not equal to the average pipe velocity (area velocity).
If the velocity profile was flat, the line average velocity and the area average velocity would be equal. The velocity profile is not flat in real pipe flows. So a correction is needed to adjust the line velocity to the average pipe velocity.

Fully developed flow will be represented by the non-uniform Power Law. The exponent N of the Power Law is not constant, it is dependent on Reynolds number and wall roughness. In normal gas applications N varies between 7 and 11.

Lets consider a single path ultrasonic meter on the center line. The line velocity has to be corrected to estimate the average pipe velocity. The correction factor is given, as a function of the exponent N in figure 2. It shows an average correction of about 5%, but more important it shows a 2% shift from N=7 to N=11. Thus if N (= velocity profile) changes, the correction factor changes. If the velocity profile is not known or changes with conditions the correction factor is uncertain.

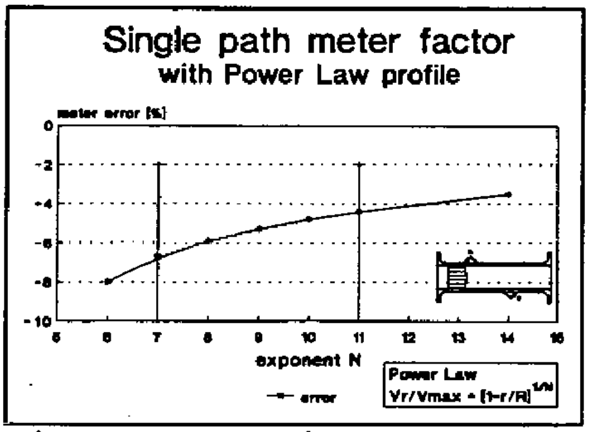

Figure 2 Single path performance

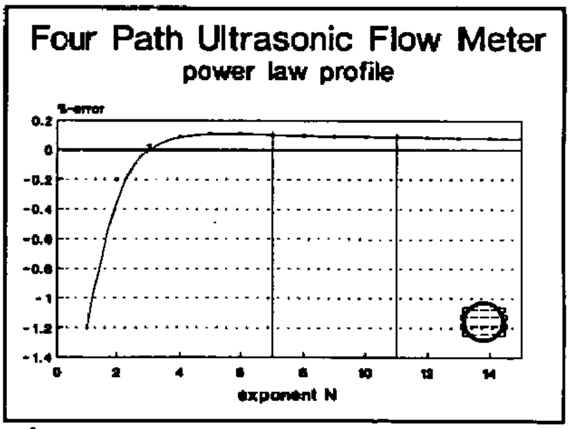

Figure 3 Four path meter performance.

Consider a four path meter, with appropriate weighting factors. Four line velocities are measured and multiplied with their weighting factor. The correction factor for a four path meter as a function of the exponent N is given in figure 3. The offset of 0.1% is caused by the discontinuity in the Power Law. The change in correction for N between 7 and 11 is smaller than 0.05%. This means that a four path meter with appropriate weighting is not dependent on fully developed velocity profiles. This effect is incorporated in the repeatability of the meter.

WEIGHTING FACTORS

How does appropriate weighting work? The weighting factors are determined mathematically, based on geometry. They are independent on the velocity profile (Gaussian integration).
The integration is based on the area of horizontal cross sections. The weighting factor associated with each path (and area) can be calculated. The weighting factor takes the associated area for a path into account. For symmetry reasons the weighting factors on the outer paths, W1 and W4, are equal and similarly W2 and W3 are equal. Together they add up to 1, figure 4.

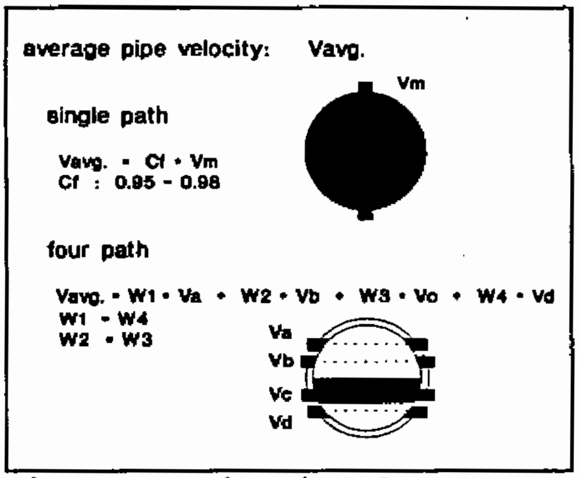

Figure 4 Weigthing factors

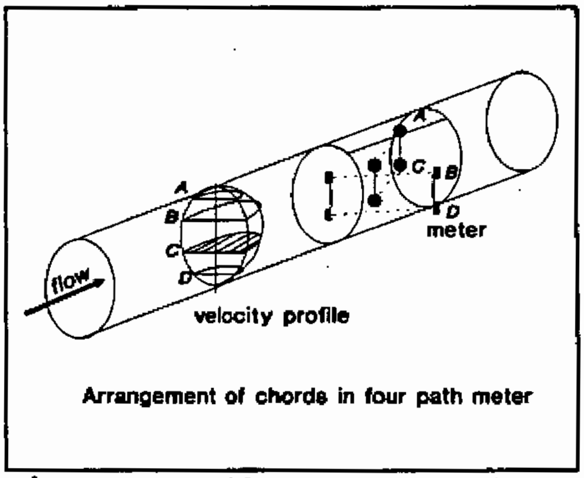

Figure 5 Path arrangement on radius

The optimized solution is obtained when the paths are at specific positions on the radius. Those positions are a fixed ratio of the bore radius, R and approximately 0.3*R and 0.8*R from the center. Figure 5.
With a computer simulation program it is possible to generate asymmetric velocity profiles and observe the theoretical performance in non ideal conditions. From reference 1 the axial velocity measurements downstream of a 90° bend were adopted. Profiles were measured in the horizontal and vertical plane at

three different positions downstream of the bend, 1.5D, 5D and 22D. The measurements were taken at a Reynolds number of 10^5 in water. This represents the lower design limit: minimum size, low pressure, minimum velocity. No data however is available for higher Reynolds numbers.

The challenge is to get the interpolation between horizontal and vertical measurement. 10th order and broken polynomials were used to match horizontal and vertical profiles and a third polynomial to smooth the interpolation.
A velocity profile in 3D representation is given in figure 6.
The axial profile appears a lazy arm chair with comfortable armrests. The armrests and the back seat disappear with increasing

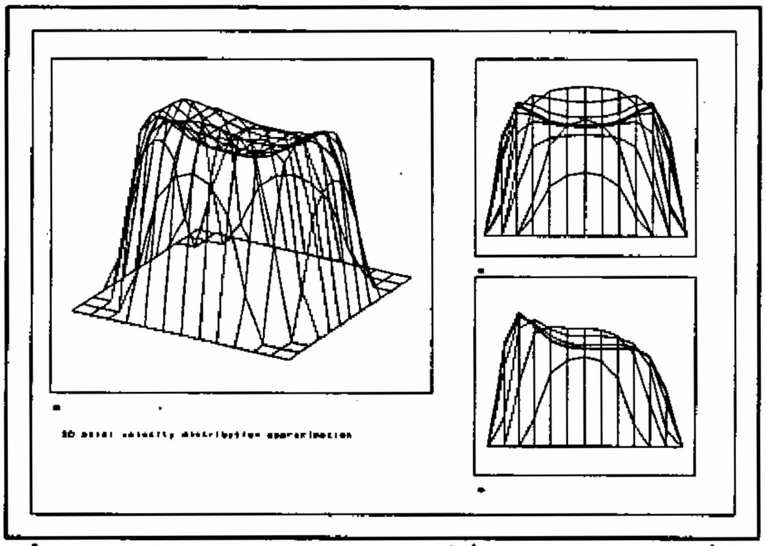

Figure 6 3D representation of velocity profile from 90° bend.

distance from the bend.
For fixed distances after the bend the hypothetical ultrasonic meter performance is given in figure 7. The performance curve is formed by rotating the meter housing relative to the bend. So the meter is rotated along its axis, while the bend is fixed. As expected the performance of the meter improves at larger distance from the bend. This performance is not tested in practice, and it suffers some incompleteness. Turbulence, radial velocities in the flow and finite sensor size may affect this theoretical performance. The simulation program is only a tool to evaluate performance.

From these evaluations and from field testing it is believed that the weighting factors of the four path meter are appropriate in most, if not all applications. Ref 3 and 4 show test results with

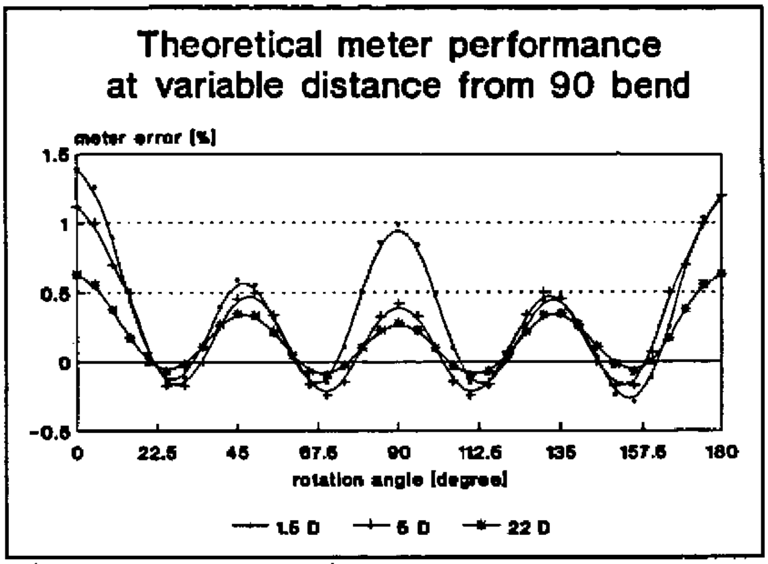

Figure 7 Theoretical meter performance at 90° bend.

distorted profiles and the performance usually is within 1% of reading. This model was also used to study the effect of machining tolerances. If the paths are not positioned as required for Gaussian integration, what change in flow performance should be expected for an "offspec" meter.
The simulations show that the weighting factors are not very sensitive to machining tolerances. The meter performance stays adequate, provided the correct dimensions are used.

SELF CHECKING

An interesting feature of the ultrasonic flow meter is the self checking capability. As already discussed in a previous paragraph, the velocity of sound is calculated from the basic set of equations. It is measured with an accuracy of about 0.1%.
The velocity of sound is a function of temperature and gas composition. However within a typical measurement time interval the velocity of sound will not change. The velocity of sound appears constant and is therefore suited to check the validity of transit time measurements.

Three examples:
Given the speed of sound and the flow rate from the previous batch, a time window is defined for the next signal to arrive. If a "signal" is outside the expected time window this measurement is not validated and removed from the total batch.

The velocity of sound on each of the four paths are in very close agreement. If they are not, this indicates something is wrong. All measurements on the disagreeing path are eliminated and an alarm is given.

The spread in the transit times is a function of flow rate. So at a specific flow rate or gas velocity the spread in the time is limited. The limited spreading is used to further qualify measurements.

In total seven tests are performed on the measurements to assure only validated measurements are used in the flow computations.
If the number of rejections is extreme high something is wrong.

The self checking capabilities of ultrasonic flow meters provide useful information about the condition and quality of the flow measurement and the electronic equipment.

POSSIBLE ERROR SOURCES

The basic equation for the flow velocity reads:

$$V = \frac{L^2}{2X} * \frac{(t_1 - t_2)}{t_1 . t_2}$$

The possible error sources in the equation are errors in L, X, t_1 and t_2. The effect of small errors in L and X can be demonstrated in the (partial) differential equation for V.

$$\frac{\delta V}{V} = \frac{2 . \delta L}{L} - \frac{\delta X}{X}$$

This equation shows that if $\delta L/L$ is -0.002, (-0.2% error) and $\delta X/X$ is 0.001 (0.1% error) the resulting error in the velocity V equals 2.-0.002 - 0.001 = -0.005 or -0.5%
Obviously the measurement accuracy is strongly dependent on the geometrical parameters. Added to this are the errors in the pipe area (D^2), to arrive at flow rate.

These sources, L,X and D, contribute all to a systematic offset from zero error. Figure 8 shows the hypothetical case of a systematic dimension error. The equations can also be used to calculate the effect of temperature expansion on the meter housing.

The effect of the timing accuracy on the measurement is more complicated. After some working, rearranging and defining some terms we end up with:

$$\frac{\delta V}{V} = -2 . \frac{\delta t_{avg}}{t_{avg}} + \frac{\delta t_{diff}}{t_{diff}}$$

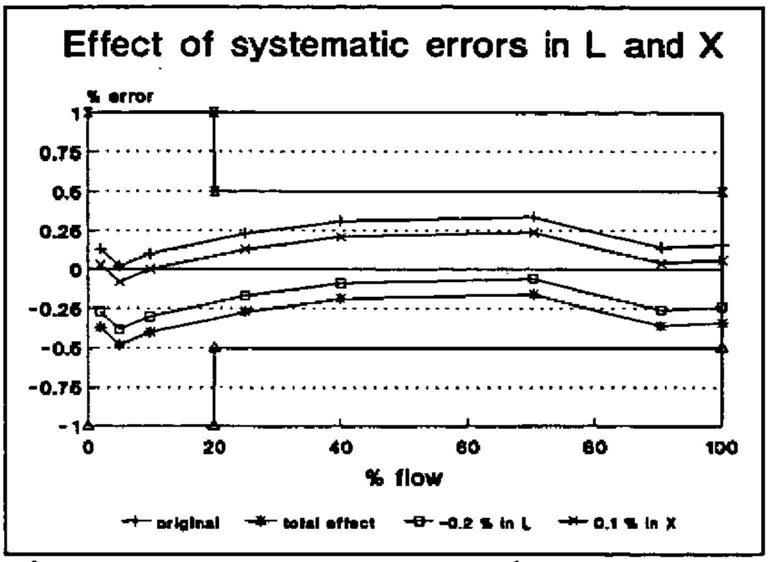

Figure 8 Effect of errors in L and X.

with t_{avg} the average transit time (proportional to vel. of sound)
t_{diff} the difference of transit times (proportional to gas vel.)

An error in the average of transit times will result in a systematic error at all flow rates. Thus 0.1 % error in average timing is 0.2% error in the velocity measurement at all velocities.

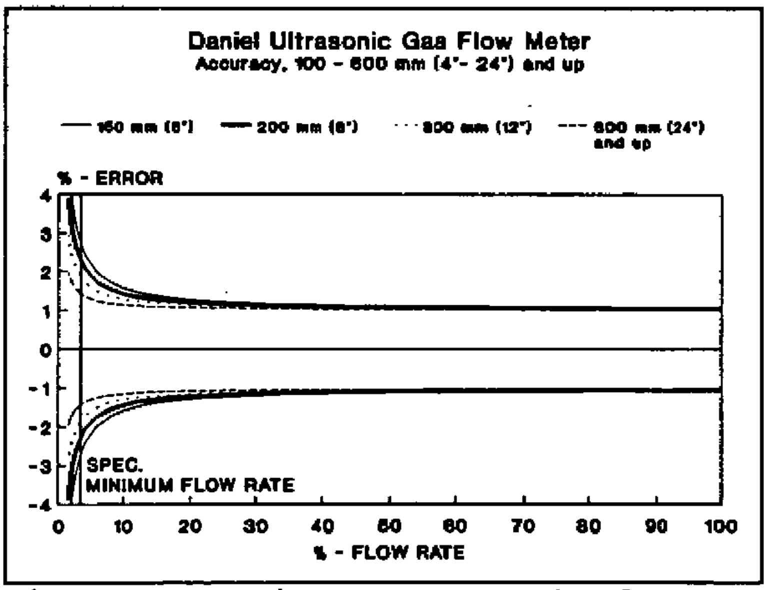

Figure 9 Typical error bands for ultrasonic meters.

The second term affects the accuracy at the low flows. The error term δt_{diff} may be constant, but t_{diff} decreases with proportionally with flow rate. This means the timing error increases with decreasing flow rate. The meter accuracy is a bell shaped error band, well known for instrumentation, figure 9.

To eliminate this last error a zero time difference has to be established. This can be performed in the factory and is part of the factory calibration.

Timing errors can result from a time base shift of the oscillator, change in signal characteristics or improper operation of the timing circuits in the electronics.

The error sources mentioned here are associated with the apparatus itself. To ensure proper operation in the field, all the components involved in the measuring process should be of equal and proper quality and operate accordingly. Provided this is all under control the ultrasonic flowmeter has all of its measurement parameters known from the factory. An ultrasonic flowmeter therefore does not need a flow calibration.

The advantage of the four path configuration is that random errors in L,X and t are compensated by averaging over four L,X and t. Systematic errors in L,X and t most likely cause parallel shift of the calibration curve.

THE VALUE OF ULTRASONIC METER SYSTEMS

Typically the flow range of an ultrasonic meter is 1.5 times the flow range of a gas turbine meter of the same size, with an equivalent turndown ratio: 20:1 (extended 50:1).

The flow rate in comparison to an orifice metering system is given in figure 10. It shows dual, triple and quadruple skid mounted orifice units on the x-axis, and the standard flow through such units on the y-axis. Those skids are compared to ultrasonic skids. It shows that a dual system with 200 mm (8") ultrasonic meters can replace a triple unit of 300mm (12") orifice meters, over the full (recommended) beta range. The savings are based on the skid mounted systems.

PROGRESS IN FIELD APPLICATIONS

Gasunie in the Netherlands decided to use ultrasonic meters as the backup meter to gas turbine meters in their export stations after an intensive evaluation. [ref 4,5]. The meters were mostly in 20" size. About fifteen meters have been flow calibrated at the

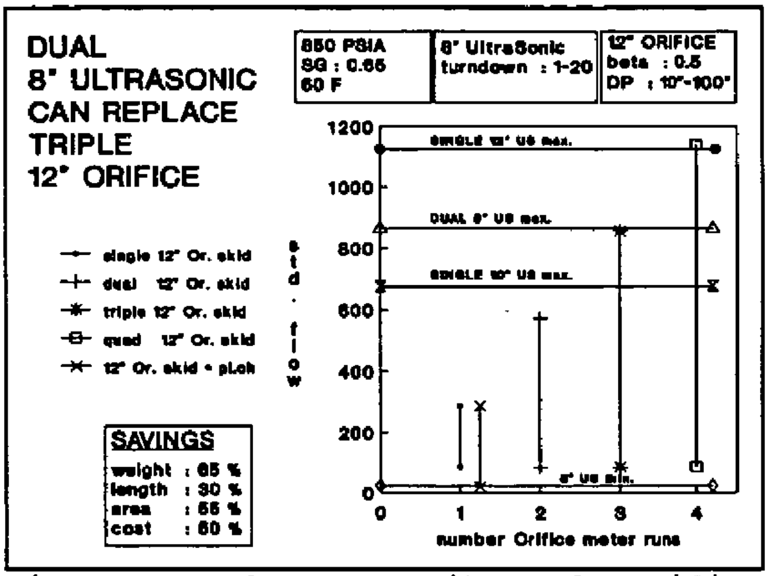

Figure 10 Flow capacity of orifice meters versus ultrasonic meters (skid mounted).

Westerbork station before their installation at the export stations. Gasunie has not released the results of the calibrations before actual operation. In general the fifteen calibrated meters have identical shaped error curves in a 0.5% band, while the calibration error was within 1% over the flow range 20-100% and within 2% in the range 5-20%. After normalization those limits were cut in half and match the ranges that Gasunie requires for turbine meters.

The Gasunie order put Daniel through the transition from the production of single meters to the production of small series of meters. This transition made us aware of the production capabilities and pointed out some areas were additional quality assurance was needed. Although each individual unit is tested before it leaves the factory some did not perform as specified. Those matters were brought to our attention and corrected.
The final installation and the operational conditions at the export station are still under investigation. The first meters will be put into operational service soon.

PROGRESS IN CUSTODY TRANSFER APPLICATIONS

It is recognized by transmission and production companies that the ultrasonic meter has potential for direct custody transfer applications. Custody transfer however requires approval of the (local) authorities. The first authorities to enter this discussion with a transportation company are the Dutch authorities NMi.

They are considering type approval in the Netherlands on the basis of the Gasunie test work.

Further testing for type approval is anticipated in the ULTRAFLOW working group. This is a group of users, whose goal is to develop a standard code of practice and performance control for ultrasonic flow metering. The ultimate goal is to pass legislation allowing ultrasonic meters for custody transfer. The group is potentially sponsored by the European community.

The work of the ULTRAFLOW group is considered as paving the way to an ISO standard. ISO TC 30 has formed a working group on ultrasonic flow meters to investigate requirements and routes for standardization.

The ULTRAFLOW group also wants to develop ultrasonic meters that are capable of measuring wet and sour gases. Those applications are not yet covered by the present meters.

THE NEAR FUTURE

Daniel is pursuing the second {next} generation in ultrasonic flow measurement. This meter will comprise a similar meter body but will have newly developed electronics and transducers. The new electronics will eliminate some boards compared to the present system. The signal detection will be fully digital and advanced statistics for signal recognition and digital filtering techniques are used.
Daniel expects extended application areas and improved performance from this second generation ultrasonic meters.
The first proto types are expected by the end of 1991. The knowhow gathered over the past years is incorporated in this new unit.

CONCLUSION

Daniel is steadily progressing in the field of ultrasonic flow metering. The present device will be updated to the newest technology. The new and updated versions will be available shortly.

It has been shown that the ultrasonic meter can meet custody transfer accuracies, as e.g. laid down in OIML requirements. The ultrasonic meter is capable of handling fully developed and distorted velocity profiles, without significant loss of accuracy.

The work by authorities, working groups and standard committees shows the validity of the ultrasonic technique for custody transfer applications.

ACKNOWLEDGEMENTS

The author likes to thank all persons involved in the project who knowingly or unknowingly contributed to this paper. Special thanks to Bill Freund and Mike Nolan. Bill did the error analysis part, and is within Daniel technically responsible for the next generation ultrasonics. Mike inspired the derivation of the ultrasonic equations.

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