BASICS OF ULTRASONIC FLOW METERS

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Introduction

The purpose of this paper is to explain the measurement of natural gas for custody transfer applications through the use of ultrasonic meters. Specifically, this paper explains the operation of ultrasonic meters, issues surrounding their performance in natural gas, calibration procedures, and proper installation considerations. Additionally, the electronics making the measurements generate calculated values relating to the operation of the meter and as a result a database is available to provide analysis of the meter's ongoing performance. Meter health parameters can be evaluated to verify the meter's operation and these principles are explained.

Background

The ultrasonic meter measures and calculates volumetric flow by summing weighted fluid velocities across the meter diameter. Piezo electric transducers are mounted on opposite sides of the meter to form one or more measuring paths and these measuring paths provide the average fluid velocity. The volumetric flow calculation is the fluid velocity of each path times the cross sectional area. The conversion of individual path velocities into volumetric flow is performed through the use of Gaussian integration techniques.

Both liquids and gases are measured using ultrasonic flow meters. The reasons most frequently cited for implementing ultrasonic flow meters are:

Low Pressure Loss – Ultrasonic meters have no moving parts and the pressure losses are typically equal to the length of equivalent pipe.

High flow rates - An ultrasonic meter handles exceptionally high flow rates with a single meter. There are installations of ultrasonic meters with meter diameters of 30 inches.

Wide Turndown – Ultrasonic meters easily provide 10:1 turndowns while performing with linearities of +/- 0.1% or better.

Small installation footprint – A typical installation involves a single ultrasonic meter compared to multiple meters in individual runs and the associated piping and valves.

Minimal maintenance requirements – Electronic based measurement eliminates moving parts which are subject to wear with usage. There is no known correlation between the amount of fluid measured by the meter and a change in the meter factor.

Fundamentals of Operation

All sound travels as a wave with a corresponding frequency through a medium, such as liquid or gas, to transport the vibrations over a distance. The human ear can detect sounds within a frequency range of 20Hz to 20kHz. The term "Ultrasound" is used in reference to acoustic energy traveling in waves with a frequency higher than the normal human audible range, hence ultrasound refers to frequencies above 20kHz. In the ultrasonic flow meter, ultrasound is generated by transducers that operate at specific frequencies. These transducers are typically constructed from a piezoelectric ceramic based material that vibrates when a voltage pulse is applied. The reverse is also true, meaning an electrical output will be generated with the material changes shape. (Brown, 2013) Transducers are designed to operate at a specific frequency and this directly relates to matching a specific frequency range of transducer to the fluid properties to be measured.

Figure 1

As stated earlier, an acoustic wave requires a transmission medium, and some materials more readily transmit the energy compared to other materials. This ability to transmit energy directly relates to the speed the wave may travel, or stated differently, the velocity of sound. There are two material properties, elasticity and density that impact the velocity of sound. In the case of hydrocarbon streams, this typically relates to fluid flow where the fluids are liquids, such as crude oil, refined products, streams of NGL or LPG (C_2 to C_{6+}), or natural gas. The molecules of liquid are closely packed against each other where the molecules of natural gas are separated. The sound wave travels by passing energy from molecule to molecule and since molecules in liquids are in constant contact instead of separated as in a gas, the speed of sound is faster in liquids than in gases.

This property relates directly to the frequency of transducers used in ultrasonic meters designed to measure a fluid stream of gas or liquids. The frequency of ultrasonic transducers used to measure natural gas are around the 50kHz to 500kHz range and the speed of sound in natural gas at 14.7 Psia and 60 F is in the range of 1,366 Ft/Sec to 1,412 Ft/Sec. (Smith & Clancy, 2011) At the same time, the frequency of transducers used to measure hydrocarbon liquid streams can range anywhere from 500 kHz to 2.0 MHz with a velocity of sound over 4,000 Ft/sec.

In the ultrasonic flow meter, pairs of transducers are mounted opposite each other and at a specified angle relative to the pipe centerline, Θ. They are also separated by a distance, L.

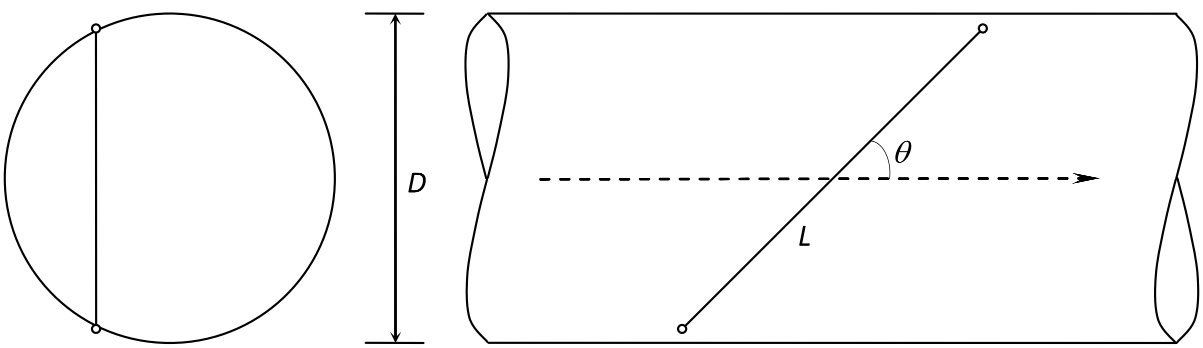


Figure 2

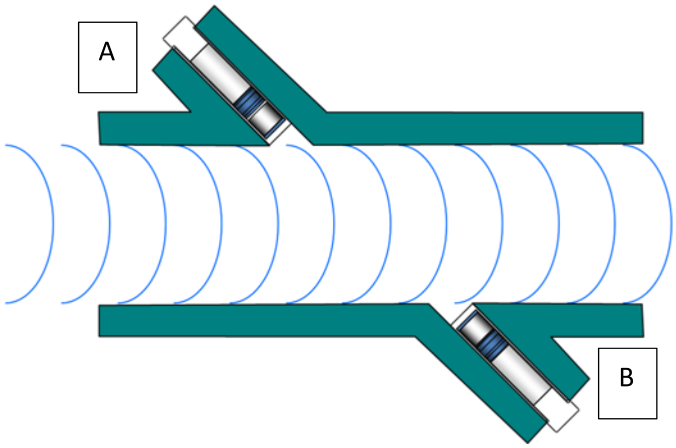


Figure 3

In actual operation, an electrical pulse is sent to transducer A, resulting in a sound wave that travels to transducer B and in turn, this generates an electrical analog output. The reverse is also true, and an electrical pulse is sent to transducer B, resulting in a sound wave that travels to transducer A that generates an electrical analog output. The equations below determine the length of time taken for the sound to travel between points A and B.

$$t_{ab} = \frac{L}{\left(c_f - \bar{v}\cos\theta\right)} \qquad t_{ba} = \frac{L}{\left(c_f + \bar{v}\cos\theta\right)}$$

Figure 4

Where:

L = the distance between the transducers

V_f = Velocity of the fluid

C_f = Speed of Sound in the fluid

Θ = Angle of the transducers relative to the centerline of the axis

It takes sound less time to travel the distance, L, between the two transducers when the sound wave is traveling with the flow of the fluid than it does against the flow of the fluid. The difference in time sound takes to travel upstream and downstream directly relates to the bulk velocity of the fluid. This is indicated in the equations below:

Solving the two equations above for the V_f:

$$\left(\frac{1}{t_{ba}}\right) - \left(\frac{1}{t_{ab}}\right) = \frac{\left(c_f + \bar{v}\cos\theta\right) - \left(c_f - \bar{v}\cos\theta\right)}{L}$$

$$\frac{t_{ab} - t_{ba}}{t_{ab}\,t_{ba}} = \frac{2\bar{v}\cos\theta}{L} \qquad \bar{v} = \frac{L}{2\cos\theta}\cdot\frac{\Delta t}{t_{ab}\,t_{ba}}$$

After calculating the velocity of the fluid between the two transducers, flowrate is calculated by multiplying the fluid velocity by the cross sectional area of the meter:

$$q_v = A\frac{L}{2\cos\theta}\cdot\frac{\Delta t}{t_{ab}\,t_{ba}}$$

(Brown, 2013)

Note that the flowrate of the fluid is calculated independently of the speed of sound of the fluid flowing through the meter, which means this calculation works for all fluid types regardless of the speed sound travels through the fluid. This independence from the Velocity of Sound (VOS) enables the meter to measure all types of hydrocarbon streams, gases, crude oils, refined products, along with NGL's and LPG's.

Using variations of the above equations, it is also possible to solve for the (VOS) of a particular fluid. The VOS is useful in ultrasonic meters for analysis of operational data. This will be discussed in more detail later in the paper. In meters measuring natural gas, this calculation for the Velocity of Sound compares the meter calculated value of sound against the AGA 10 calculated value based upon the actual gas composition provided by a gas chromatograph. Differences in the VOS between the meter and the Chromatograph usually imply the gas chromatograph requires maintenance.

Starting with the equations above in Figure 4,

$$\frac{1}{t_{ba}} + \frac{1}{t_{ab}} = \frac{\left(c_f + \bar{v}\cos\theta\right) + \left(c_f - \bar{v}\cos\theta\right)}{L}$$

$$\frac{t_{ab} + t_{ba}}{t_{ab} t_{ba}} = \frac{2c_f}{L}$$

$$c_f = \frac{L\left(t_{ab} + t_{ba}\right)}{2\, t_{ab} t_{ba}}$$

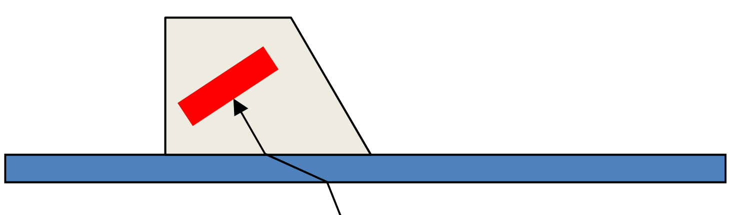
Figure 5

One assumption that the equations above have used requires that the entire fluid stream moves at the same velocity across the pipe, which is likely not the case. The modern ultrasonic flowmeter recognizes this issue and provides multiple measurement paths.

Transducer Arrangements

The measurement paths in an ultrasonic meter used for custody transfer are mounted in spool pieces that utilize multiple measurement paths. Spool pieces with external transducers, or transducers mounted externally on piping are typically referred to as clamp on meters.

The advantage of externally mounted transducer arrangements is that they require no cutting of the pipe for installation and can quickly provide a measurement for low cost. The drawback to these types of arrangements is that the sound must travel from the transducer into the exterior of the pipe and then into the gas from the interior wall of the pipe. At the opposite side the reverse occurs.



Keeping in mind that the distance the sound must travel is L, Snell's Law of Refraction indicates there will be a change in the angle of the sound wave path when it impacts the outer wall of the pipe and again when it encounters the same arrangement on the opposite side of the pipe. The angles will change based upon a change in temperature and also will change with different densities of fluids being transported. The angle change directly changes the length the sound must travel between the transducers and with a longer distance of travel, the time required will change slightly as well. The result is that there is an added component of uncertainty that comes with externally mounted transducers because of Snell's law. These meters do operate in a number of installations and the uncertainty is expected to be around 3% to 5% in some liquid applications. Some installations may provide an installed uncertainty around 1%, but this will only occur when great care is taken regarding the installation and the calibration process. These types of meters are typically not used for custody transfer applications.

The more common transducer arrangement utilized in ultrasonic meters with linearity in the range of 0.1% mounts two transducers aimed directly at each other to avoid errors from refraction. This fixes the distance, L, between the transducers and also fixes the angle of the sound path relative to the meter centerline. During manufacturing, the distance L is carefully measured and entered into the transmitter's database as a constant value. While it is impossible to measure this distance perfectly, the difference between the actual and measured path length are compensated for during the meter calibration process.

There are two methods of mounting transducers to measure fluid velocity. The first directly mounts the transducer into the fluid stream which is referred to as a "wetted" transducer. The second involves two components, a housing permanently mounted in the meter body and a transducer assembly designed to slide into the housing. The housing forms the pressure barrier and permits removal of the transducer under pressure without a special tool or blowing down of the piping section. The transducer assembly is inserted into the housing and the transducer face is then pressed against the transducer window in order to form a tight acoustic bond that efficiently transfers the sound wave from the transducer into the fluid stream. When the transducers are mounted directly into a housing the exact distance and angle are fixed in the meter. The transducer is also protected from exposure to the gas because it is isolated from the process stream, leading to the possibility of a longer service life.

When housings contain the transducer, they form the pressure barrier and contain the process fluids. This ability to contain the full working pressure of the meter enables the user replace a transducer without bleeding off the gas or draining the process fluid from the associated piping. Transducers have been developed to withstand a wide range of temperatures, from 500F for power plant feedwater applications to -260F for LNG metering applications.

Figure 6 Transducer Assembly and Housing

Transducers mounted in spool pieces can have a variety of mounting arrangements as shown in Figure 7 below. The industry refers to a meter using this type of arrangement as a chordal ultrasonic meter.

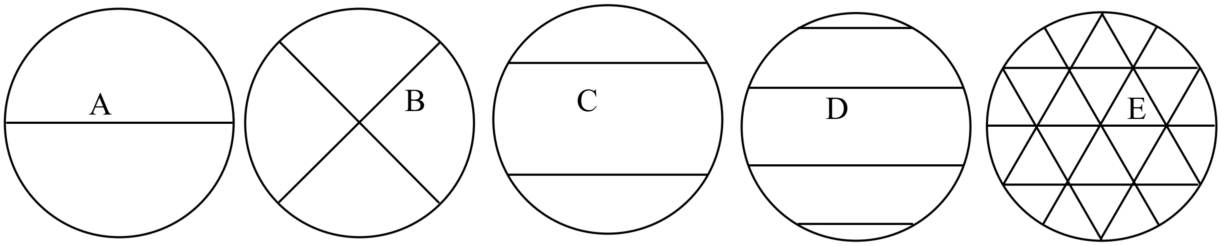


Figure 7 Possible transducer arrangements for Spool piece meters

The use of externally mounted transducers limits the possible mounting arrangements to measuring paths that must pass through the center of the pipe.

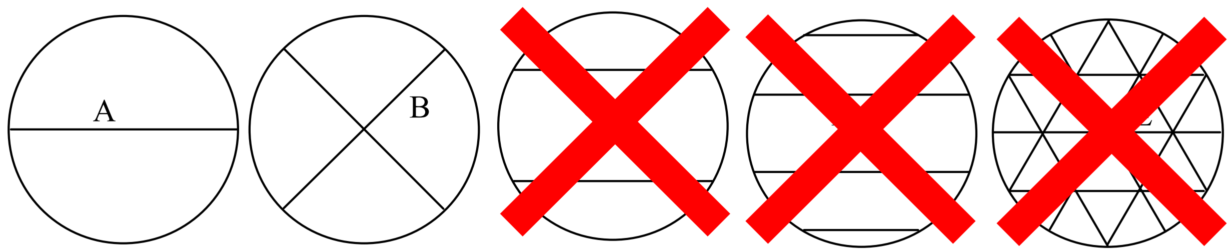


Figure 8 Externally mounted transducers measuring arrangements

Additional Transducer considerations relating to the process fluid

Sound travels more efficiently in liquids than gas because the molecules are in constant contact each other to pass along the energy of the wave from molecule to adjacent molecule. Transducer frequencies used to measure liquid streams are on the order of 1 million Hertz. In higher viscosity liquids, such as Canadian crudes with viscosities that approach 1100 cSt, the fluid absorbs, (attenuates) the sound. The following conclusions can be reached regarding measuring fluids at higher viscosities:

High viscosity fluids can be measured
The limit of viscosity increases with increasing flow velocity
Selecting the correct transducer frequency can extend operation to higher viscosities
(Dr. Gregor Brown, Terry Cousins, Donald Augenstein, Herbert Estrada, 2009)
Gas ultrasonic meters typically utilize lower frequency transducers of 200K Hertz because the molecules of gas are not in continual contact with each other and the ability to transmit sound is diminished significantly at higher frequencies compared to the lower frequency sound wave.

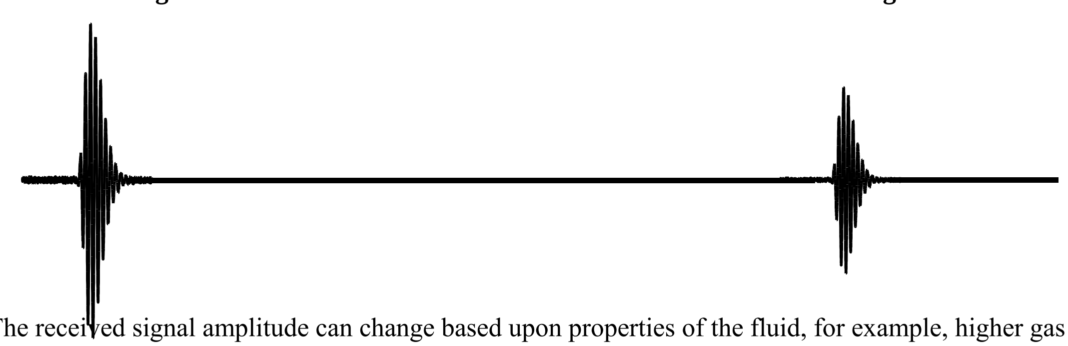
Meter Electronics

The electronics used to measure and calculate flow rates, consists of a transducer signal generation and timing circuit, circuits responsible for calculating flow rates, Input and Output signal processing to provide either a pulse output and/or analog inputs/outputs, and a communication section designed to pass or receive data from external devices or SCADA systems.

The transducer pairs alternate in being the transmitter and receiver as they measure the time it takes for sound to travel downstream with the flow and upstream against the flow. The transmitting transducer is driven by a short electrical pulse that causes it to vibrate while the receiving transducer "hears" the transmitted signal. This waveform has a frequency determined by the transducer design and electronics. This is illustrated in the figure below:

Drive Signal

Transmitter Signal **Receiver Signal**



The received signal amplitude can change based upon properties of the fluid, for example, higher gas pressure increases the acoustic impedance of the gas and means a stronger signal is received. Lower gas pressures mean the received signal is

weaker in amplitude. Keep in mind that the time it takes a soundwave to travel length, L, the distance between the transducers, will increase or decrease based upon the velocity of sound in the fluid and the diameter of the meter.
The receiving transducer also receives a reflected signal that could be interpreted incorrectly as the timing end point. In order to avoid error, the receiving transducer timing must occur within a specific time window after the transmitter has sent the pulse. This is referred to as range gating.

The receiving transducer has an amplification circuit to boost the received signal and this is referred to as the Gain. The meter's electronics fire the transmitting transducer at a constant voltage and the received signal is amplified anywhere from 100 to 1000 times in order to provide the analog to digital convertor with a strong enough signal to generate a voltage output that can be analyzed and timed. The gain is adjusted automatically to match conditions.

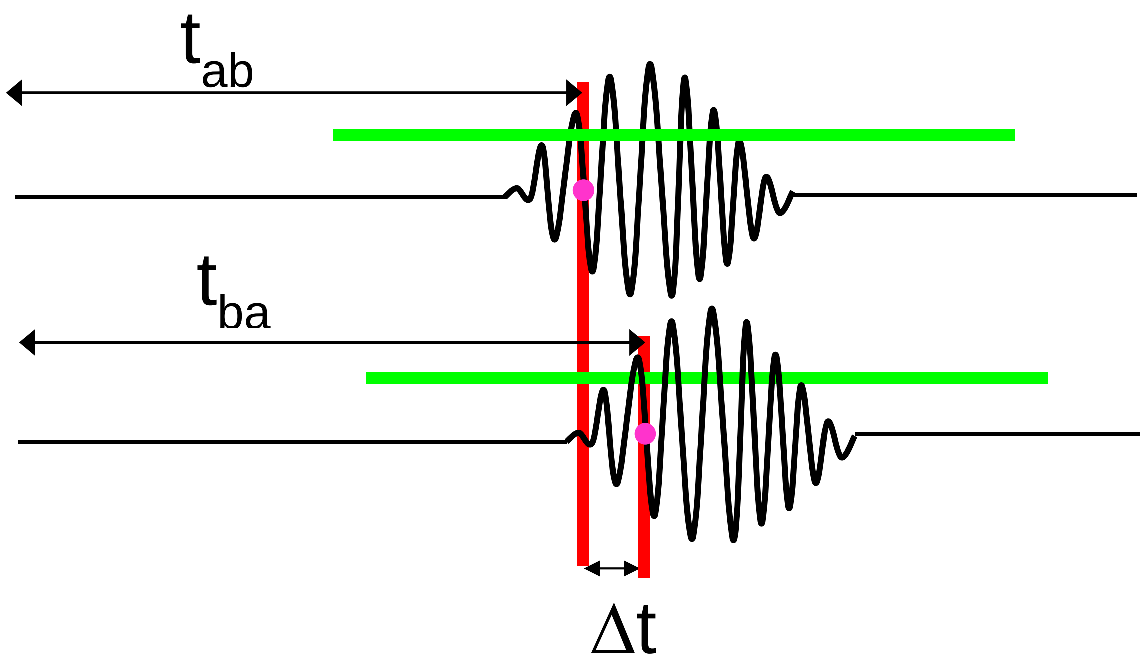


Figure 9 Sound wave detection using the Leading Edge Pulse

Timing of the Sound Wave
As shown in Figure 9 above, the time it takes the sound to travel with the flow is represented by $t_{ab.}$ Note that the end point of the timing is the zero crossing after the voltage signal has exceeded the Zero Crossing Detection level, represented by the green line. The Zero Crossing Detection level is designed to insure the measured signal is correctly selected as the timing signal. There is random and coherent noise in the system that could cause false triggering and this is the means to insure the correct soundwave is measured. Next, the time represented by t_{ba} is measured and represents the time the sound takes to travel distance L upstream against the flow. The difference in the time $t_{ba} - t_{ab}$ is used to calculate the velocity of the fluid across the specific measuring section.

Other factors influencing the Measurement
In addition to measuring the length of time it takes a sound wave to cross there are system delays as well. These delays originate in the cables, transducers, and electronics. Meters are typically calibrated during manufacturing to eliminate the effects of these system delays upon the measurement of time.

Overall Meter Uncertainty
The installed uncertainty of the meter is determined with several factors:

- Calibration Laboratory Uncertainty
- Linearization errors during calibration

- Changes in the piping between the calibration lab and field
- Transmit time measurement accuracy in application conditions
- Installation effects
    - Velocity Profile
    - Swirl

The number of transducers and their placement within the meter can affect the meter's linearity and uncertainty of calculating the total flow volume. Single transducer pair meters or clamp on transducers whose measurement path(s) pass through the diameter of the meter, will not produce a custody transfer grade measurement. This is because the fluid near the pipe wall travels at a slower velocity than the fluid in the center of the pipe due to boundary layer effects. A single measurement cannot take these differences into account and results in measurement error.
However, meters using multiple measurement paths can more readily calculate the hydraulic flow profile and typically incorporate higher mathematics to solve for the flow rate based upon a better understanding of the individual path velocities.

Gaussian Integration
When additional measurement paths are utilized to calculate fluid velocities, Gaussian Integration is implemented to solve for the overall flowing volume. This calculation accurately calculates flow rates based upon a limited number of inputs. There is no need to make an assumption about the shape of the flow profile when using these equations. The original Westinghouse patents filed in the late 1960's indicate the use of four measurement paths positioned at specific distances from the centerline of the meter in order to solve for the overall flow volume.

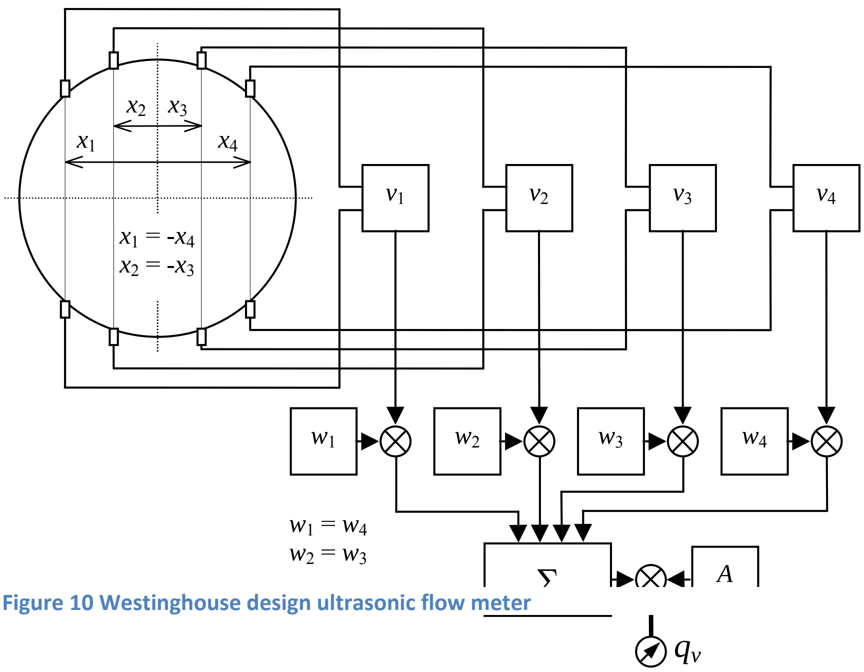


Figure 10 Westinghouse design ultrasonic flow meter

The Gaussian method integrates the flow profile both horizontally along the paths and vertically by approximation using optimal path location and weighting factors.

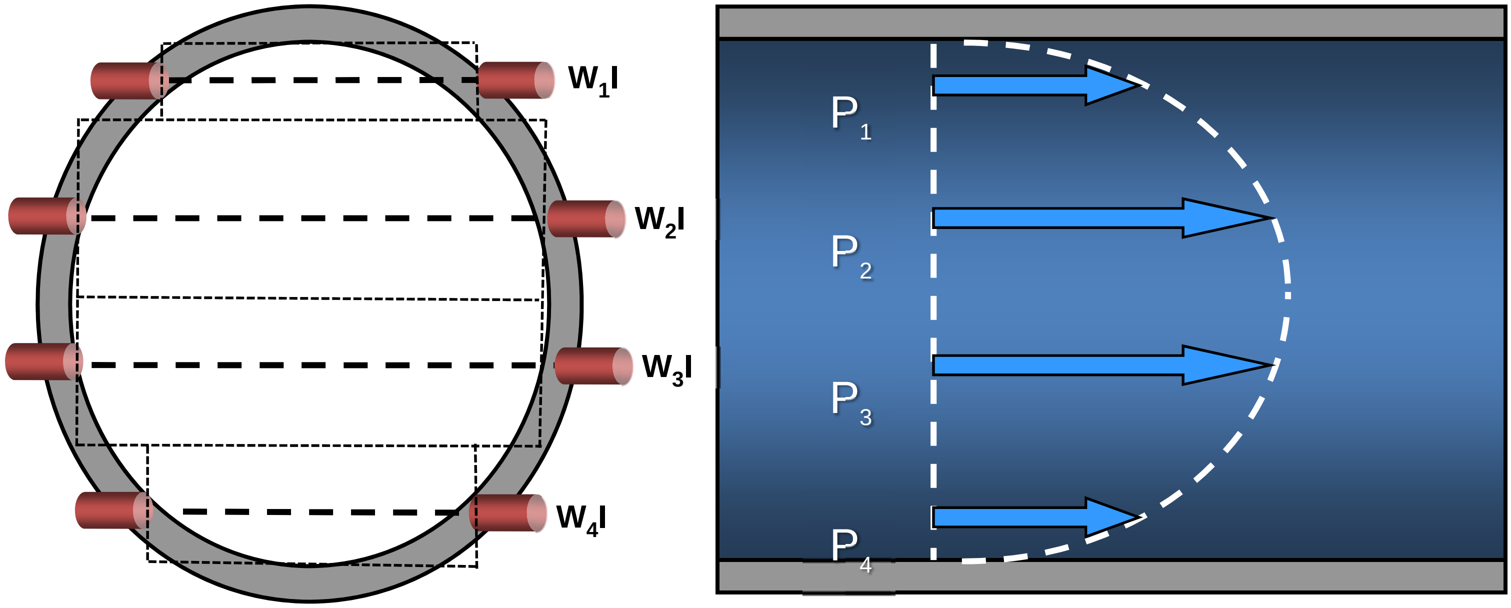


Figure 11 Velocity Profile

Reynolds Number

Fluid flows through piping in one of three regimes, laminar, turbulent, or transitional. Laminar flow is defined as each molecule slipping past the other as it proceeds directly down the pipe axis. This regime has slower velocity near the pipe wall with increasing velocity towards the center of the pipe. Maximum velocity is directly at the center of the pipe. Turbulent flow, however, contains eddys and the individual molecules do not move directly down the center axis of the pipe, but rather move in irregular patterns. Transitional flow is neither laminar nor turbulent, but rather a combination of the two and this exists whenever there is a transition between the laminar to turbulent or turbulent to laminar regime. Regardless of the overall flow rate, velocity of the fluid at the pipe wall is always zero.

The Reynolds number is a dimensionless number defining what state of flow the fluid is currently experiencing. The calculation for the Reynolds numbers in fluids is:

$$Re = \rho V D / \mu$$

Where: Re = Reynolds Number
ρ = Density
V = Velocity
μ = Viscosity

When the Reynolds number is lower than 2,000 the flow is laminar, transitional flow is considered to be between 2,000 and 8,000-10,000, and turbulent flow is above 10,000 Reynolds number. Ultrasonic flow meters behave very predictably at Reynolds numbers below 2,000 in laminar flow and above 10,000 when turbulent flow is present because the Gaussian equations fit the fluid profile. In general, most straight through bore ultrasonic meters have an increase in the uncertainty of their performance when the Reynolds number is between 2,000 and 8,000. However, in the transition region, there is a specialized meter designed to measure linearly through this region.

The Reynolds number is impacted by the viscosity of the fluid. High viscosity crude oils, like Canadian crudes as one example, are typically listed with a viscosity around 350cSt, but this increases with dropping temperature and can be as high as 1100cSt if the oil has been in storage at -40C or if the pipeline has a cold start. In this case, the Reynolds number will likely be below 10,000 which creates additional measurement uncertainty in a full bore ultrasonic meter. If the fluid is refined products or NGL/LPG streams, then the Reynolds number will likely always be above 10,000 and the meter will have turbulent flow and a well-developed flow profile. In the case of measuring gas flow, the Reynolds numbers are always well above 10,000 and the flow is always defined as turbulent.

The flow profile of the fluid generally relates directly to the Reynolds number and this in turn is an indication of the fluid velocity in the center of the pipe compared to the fluid velocity at the pipe ID. With higher Reynolds number the fluid velocity near the pipe wall increases to more closely match the fluid velocity at the pipe center. This is illustrated in the Figure 11 above.

Reynolds Numbers and Ultrasonic Flow Meters

Ultrasonic flow meters calculate the fluid flow volume through the use of Gaussian equations applied to fluid velocity measurement. Because the velocity measurements are taken at both the outer wall and at interior locations, the measurements are, in effect, measuring the fluid velocity of the boundary layer and the interior of the pipe. Because of the velocity differences between the outer wall compared to the inner portion of the pipe, we can calculate the velocity ratio of the outer paths to the inner paths. This is referred to as the flatness ratio in liquid meters or the profile factor in gas ultrasonic meters. The relative velocity if these two measurements actually defines the flow profile of the fluid. Ultrasonic meter performance correlates with the Reynolds number, and this forms the basis of the calibration of an ultrasonic meter in the case of liquid flow. What is not immediately obvious is that Reynolds numbers can be equal by using two different viscosity fluids at different flow rates if the piping, diameter of the meter, and the temperature of the fluid are maintained at constant values. This means the velocity of the fluid at the outer wall relative to the velocity at the center of the pipe can be identical. This permits ultrasonic flow meters to be calibrated at particular Reynolds numbers, even though the viscosity of the fluid used in the calibration procedure does not match the fluid viscosity in the field.

Natural gas flow has Reynolds numbers in the millions, so there is no likely possibility of transitional or laminar flow and the calibration is based upon correlating actual flowing volumes of sonic nozzles in the calibration at specific velocities and comparing the volume the meter calculates at those velocities to the volume of the sonic nozzle. While the Reynolds number influences the calculations, at higher Reynolds numbers, the boundary layer is very thin, meaning the fluid velocity near the pipe wall increases rapidly to equal the velocity of the fluid at the pipe center where there is a maximum distance from the pipe wall. There is a correspondingly smaller amount of change in the meter factor for a given increase in gas velocity compared to the meter's volume calculation at lower Reynolds numbers with a similar change in velocity in an ultrasonic meter. In other words, the meter's pre-calibrated performance curve changes more at lower Reynolds numbers compared to the performance curves at high Reynolds numbers.

Non-Axial Flow
Upstream piping impacts fluid flow characteristics, such as swirl and asymmetry. The sources of changes are elbows upstream of the meter, changes in the piping diameter (larger or smaller), valves, exits from manifolds, etc. These changes typically result in fluid flow that includes additional flow velocity that is not parallel to the pipeline axis. This is called Swirl, and it is typically encountered whenever the flow passes through elbows. A single elbow can result in a double swirl pattern. Double elbows result in bulk rotational swirl. The length of time the swirl persists depends upon the Reynolds number of the fluid, meaning the more viscous fluid with lower Reynolds number resists the swirl more and will dissipate quicker than a light fluid, such as natural gas, that will continue the swirl for many diameters downstream. There is a myth that 20 diameters of upstream piping will dissipate swirl, but this is simply a myth, swirl can persist for 100's of diameters in the case of natural gas. One LNG installation in Alaska contained swirl 37 Diameters downstream of the last elbow.

Additionally, the center of the swirl may not be in the center of the pipe, but may be off-center.

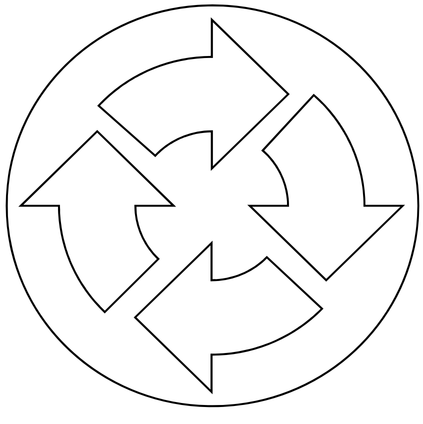


Figure 12 Swirl in Flow

Asymmetry

Asymmetry is defined as a difference in the fluid velocity between the top half of the pipe and the bottom half of the pipe.

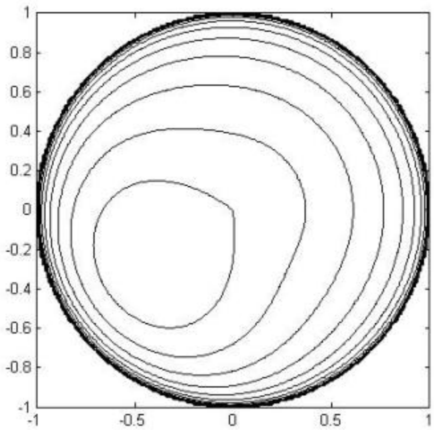


Figure 13 Asymmetric Flow

Additional Ultrasonic meter path arrangements

There are several different designs of ultrasonic meters, most of which employ differing arrangements of the transducers. These designs are primarily derivatives of the original Westinghouse design of the 1970's. The original Westinghouse design was a four path ultrasonic meter as shown below and in Figures 10 and 11. The eight path meter design is popular today for liquid applications and is gaining popularity in gas applications because this meter design is immune to the effects of swirl and asymmetry and will measure fluid flow that includes swirl and asymmetry without the use of a flow conditioner.

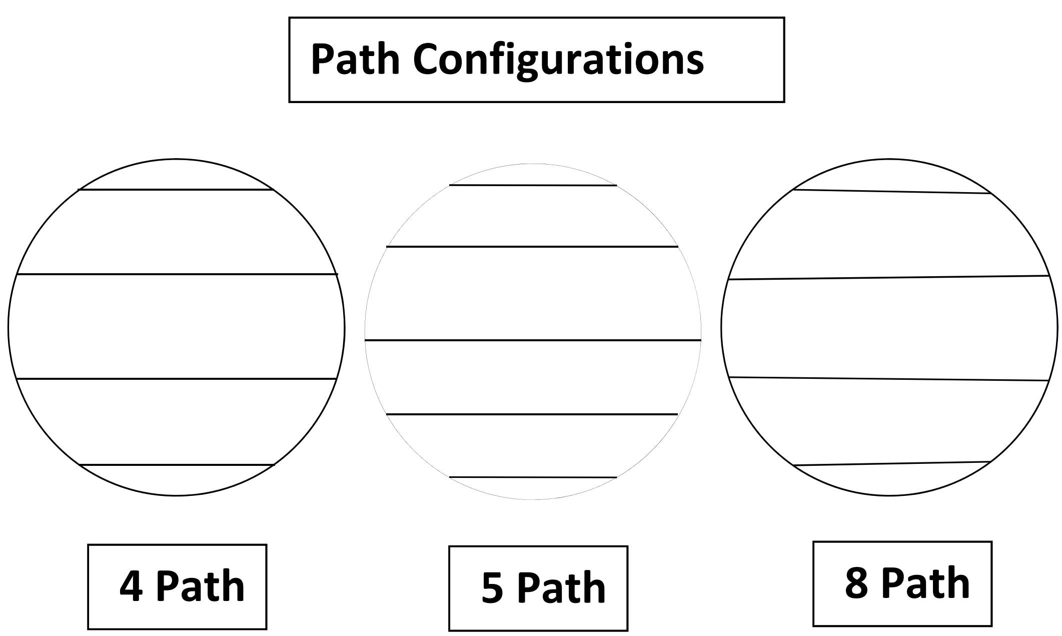


Figure 14 Various Ultrasonic Transducer arrangements

Ultrasonic meter path arrangement vs. Measurement in Swirl

The figure below provides four different swirl patterns in order to compare the impact on measurement to a variety of commercially available ultrasonic flow meters. As can be seen from the chart, if the bulk swirl is singular and rotation centered around the axis, most of the meters can provide an acceptable level of measurement. However, in the event the swirl is not centered, then the 8 path ultrasonic meter will properly compensate and measure within its linearity or uncertainty. This is not to say that only 8 path meters are acceptable for custody transfer measurement. Commercially available flow conditioners are available to remove swirl and asymmetry from the flow stream. This makes ultrasonic meters with fewer than 8 paths acceptable for use in custody transfer service.

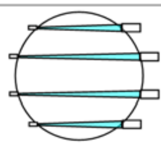
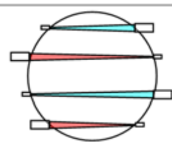
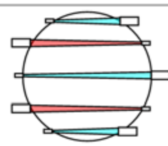
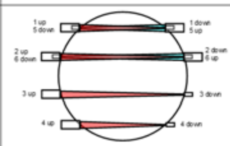
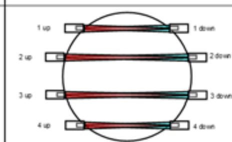
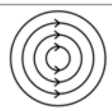
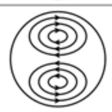
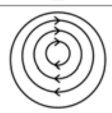
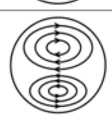
	4 paths, 4 chords, planar	4 paths, 4 chords, non-planar	5 paths, 5 chords, non-planar	6 paths, 4 chords, two crossed chords	8 paths, 4 chords, four crossed chords
					
	✓	✗	✓	✓	✓
	✗	✓	✗	✓	✓
	✗	✗	✗	✗	✓
	✗	✗	✗	✗	✓

Figure 15 Summary of ultrasonic meter sensitivity to swirl

Installation Considerations

AGA 9, the Performance Standard dealing with ultrasonic flow meters in gas custody transfer applications, currently implies flow conditioners should be used with ultrasonic meters whose calculations are impacted by swirl and asymmetry in custody transfer applications. Since it is a Performance based standard only it does not require installations follow particular designs. The last revision of AGA 9 was completed in 2007 and at that time, an 8 path gas ultrasonic flow meter immune to the effects of swirl and asymmetry capable of achieving AGA 9 performance criteria was not widely commercially available. Today this meter is commercially available to the industry.

As this paper is being written in April of 2017, AGA 9 is in process of revision and voting is occurring. This revision may include three installation drawings of ultrasonic flow meters in custody transfer applications. Each of these drawings will illustrate acceptable installations for ultrasonic meters used in custody transfer applications if they meet the performance requirements of AGA 9. One will include a meter ten diameters downstream of a flow conditioner, one will illustrate a meter installed without a flow conditioner, and another will include a flow conditioner and meter with less than ten diameters separating the flow conditioner from the meter.

Outside north America, ISO standards often apply to gas ultrasonic meters employed in custody transfer service. The ISO standards require meters be submitted to third party testing to meet or exceed measurement performance outlined in ISO Standard 17089. The standard calls for a variety of tests using different upstream piping configurations in order to measure the impact the fluid hydraulics have on the meter's performance. These include a single elbow, two elbows out of plane, step changes between meter ID and inlet piping, step changes in upstream piping, and two elbows out of plane with a half-moon plate installed between the two elbows. The meter is subjected to these tests at ISO certified calibration facilities and witnessed by third party personnel. Based upon passing the testing defined in ISO 17089-1: 2010 Accuracy Class 1, a meter can be granted an OIML R-137-1&2:2012 Accuracy Class 0.5 certificate which is a requirement for meters installed in many parts of the world. Canada carries a similar certification requirement via Measurement Canada Approval testing. All meters destined for custody transfer of natural gas in Canada must be submitted to these tests, which are similar to the ISO tests, in order to receive approval for installation into custody transfer applications. There is no similar requirement for testing and third party approvals of metering equipment in the United States and end users are free to install any equipment they deem acceptable. In these situations, AGA 9 is typically referred to as the performance standard.

There is no such standard for liquid meters in API requiring or suggesting the use of flow conditioners in custody transfer applications. This may be in part because custody transfer of liquids involves the use of provers, which require the meter to establish a meter factor uncertainty (repeatability). This is not the case in the natural gas business because the prover in natural gas is not typically commercially available.

The ultrasonic meter must be installed with a sufficient length of straight upstream piping. The length of piping required depends upon whether or not the meter's performance degrades below the acceptable uncertainty of the installation when not using a flow conditioner. Typically, if the meter employs fewer than 8 paths, then the installation will require a flow conditioner to maintain custody transfer grade performance.

Figure 16 below is a typical installation of a meter using 4 measurement paths. The upstream piping required in this case is 5D or 10D diameters upstream of the flow conditioner, then the flow conditioner, and an additional 10 D between the flow conditioner and the meter. There is a new design of flow conditioner permitting the distance between the flow conditioner and the ultrasonic meter can reduce from 10D to 7D.

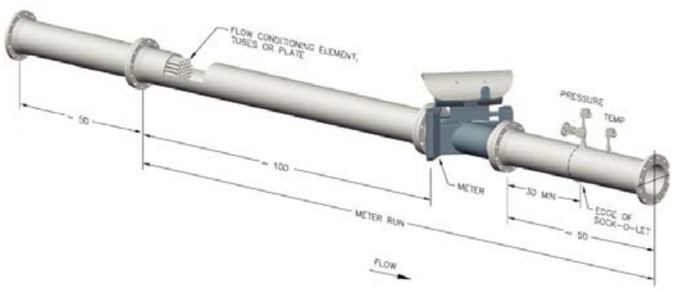


Figure 16 Typical Installation of an ultrasonic meter using a flow conditioner

If the ultrasonic meter uses 8 measurement paths the installation and the upstream piping is free of control or pressure regulating valves, the meter will only require 5 diameters of upstream piping ahead of the meter. This is illustrated in Figure 17 below.

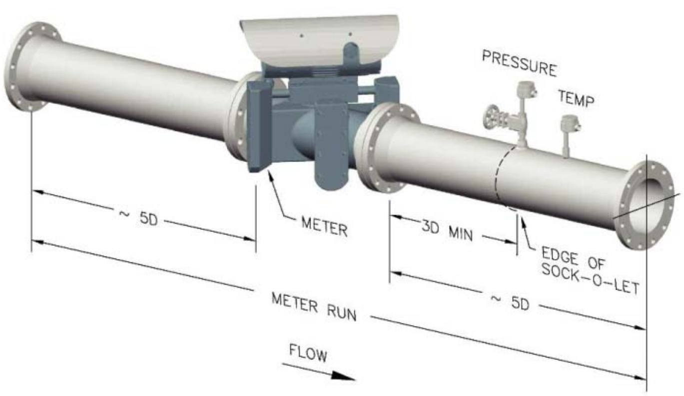


Figure 17 Eight path ultrasonic meter installation without a flow conditioner

The schedule (internal diameter) of the upstream piping should be the same as the schedule of the meter in order to match the ID's and avoid diameter step changes into the meter. AGA 9 specifies a pressure tap to be provided in the meter of the body. Temperature measurement should be carried out downstream of the meter. In the case of natural gas meters, there are special considerations for installations designed primarily to avoid noise from control valves from interfering with the transducers frequency. Those installations require 10D, flow conditioner, 10D, meter, and downstream piping of 5D. Downstream piping in either installation is not as critical, but it should be aligned carefully and be of the same schedule as the meter.

In order to maintain the best transfer of the calibration to the field, it is best to keep the meter bolted to the piping after the calibration.

Plate conditioners are preferable to tube bundles because the tube bundles are hard to manufacture consistently and can have variability in performance, in some cases they can introduce swirl. They also freeze flow distortions into place and make these distortions last longer than would occur without the bundle. Plate conditioners can be reproduced with accuracy and attempt to replicate a symmetrical fully developed flow profile. (Cameron, 2012)

Ultrasonic meter Data Evaluation

Unlike mechanical meters, the ultrasonic meter incorporates an immense database of information that can be used to evaluate the health of the electronics, provide hydraulic analysis of the flow, and highlight possible meter maintenance requirements. These values may be retrieved using software and reviewed to determine if the meter requires maintenance and verify that the fluid hydraulics are within parameters required by the metering assembly to maintain its installed uncertainty or linearity.

In general, the electronic based measurement is highly reliable. The meter generates large amounts of data that is evaluated to verify parameters known to determine the status of the measurement. This list typically includes:

Signal to Noise Ratio (SNR)

Gain

Velocity of Sound (VOS)

Rejects (Percent Good)

Normalized Path Velocity comparison

In addition to this very basic list, there are hydraulic analysis parameters that may be compared to verify the meter is operating within its original calibration range. If the meter is operating outside of these limits, this is a sign that upstream hydraulics may have changed within the installation. This may also point to the need of maintenance to insure the meter's measurement is calculated within the calibrated range of the meter.

The basic hydraulic parameters are:

Flatness ratio (Liquids Measurement) or Profile Factor (Natural Gas measurement)

Asymmetry

Plane Balance (Cross Flow)

Standard Deviation (Turbulence in Gas Measurement)

Electronic Term Explanation

Signal to Noise ratio (SNR) – The transducer generates a sound wave in the meter body when it is sent. Some of this noise also results from the electronics generating electrical noise in the circuit. The Signal to Noise ratio simply points to the amount of sound signal compared to the noise level in the circuit. A change in the SNR over time can point to possible issues with the health of the transducer.

Gain – The receiving transducer generates a weaker analog electrical signal that must be converted to a digital signal that is processed by the meter's electronics. An amplification circuit is utilized to boost the receiving transducer signal to a voltage level the Analog to Digital converter can measure. Changes in gain can indicate the onset of transducer failure or the need to clean the face of the transducer(s). Gain is reported in decibels and an amplitude change of 6dB is equivalent of doubling or halving.

Velocity of Sound

One of the calculated values is the velocity of sound calculation. The objective here is to verify that each path has close VOS agreement with the other meter paths. The calculated velocity of sound is used in gas ultrasonic meters to compare against the AGA10 calculation, which compares the actual measured gas mixture velocity of sound against a theoretically calculated value. Since the ultrasonic meter is accurately calculating the velocity of sound of the gas mixture, this is compared against the gas chromatograph composition. In gas ultrasonic meters, this is primarily used as an indication the chromatograph requires service and not the ultrasonic meter.

The VOS changes with product composition, product density, and temperature, but the values should be consistent between the paths. Variation in VOS can point to material buildup in the pockets of the meter.

Rejects (Percent Good)

The transmission and receipt of the sound wave is critical for the proper operation of the meter. The term Rejects or Percent Good indicates the percentage of times the transmitted sound wave was correctly measured as a result of the receiving transducer detecting transmitted sound waves. Rejects is simply the number of times out of 100 transmissions that the signal measurement failed. Percent Good is the number of times out of 100 that the signal measurement passed. Failure typically indicates debris has built up on the face of the transducer or that ports are plugged. The meter can tolerate a few percent of missed signals and still provide an adequate measurement.

Normalized Path Velocity Comparison

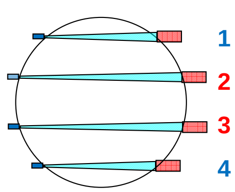
Normalized velocity is the ratio of an individual path velocity relative to the average of all path velocities. This will result in numbers that are generally within a range around 1.0 with the outer paths typically displaying lower velocities compared to the inner paths. These may be plotted in order to generate the flatness ratio (profile factor), asymmetry, plane balance, and swirl. When a meter utilizes 8 measuring paths, changes to these values in general do not impact the calculated flow rate values. If a meter run includes a flow conditioner, the meter was calibrated against very specific flow patterns that must be maintained for the meter to calculate the flow rate after the meter has been installed in the field. This means that the flow characteristics in the lab will be repeated in the field and that meters using flow conditioners are designed to operate with the hydraulics being maintained between the calibration lab and the field. The Normalized Velocity numbers are used to evaluate hydraulics to look for changes over time.

Parameters

Flatness Ratio (Profile Factor)

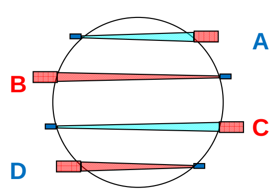
The flatness ratio is simply the ratio of the outer paths normalized velocity divided by the inner paths normalized velocity. The calculations below are the inverse of the flatness ratio, which is referred to as the Profile Factor. The calculations are illustrated below in Figure 18.

- Profile factor (profile flatness)



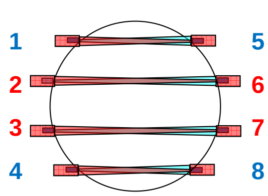
$$\frac{2+3}{1+4}$$

Plane A



$$\frac{B+C}{A+D}$$

BG 1



$$\frac{2+3+6+7}{1+4+5+8}$$

8-path

Figure 18 Profile Factor Calculations

Asymmetry

Asymmetry is the ratio of the velocities of the top paths relative to the bottom paths. This indicates differences between the upper and bottom sections of the pipe.

- Asymmetry

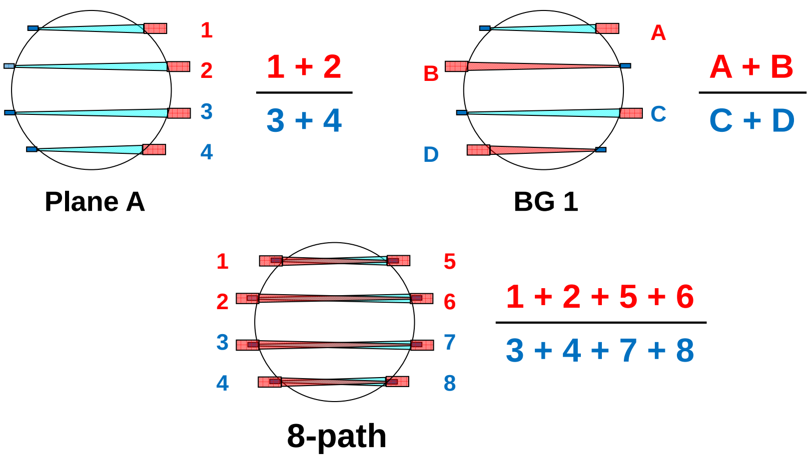


Figure 19 Asymmetry Calculations for different path designs

Plane Balance or Cross Flow

Plane balance is simply the comparison of one measurement plane compared to the other plane. If the flow is aligned with the pipe axis, then the two planes velocities should very closely match each other. Note that the single plane four path meter does not support this calculation.

Plane Balance

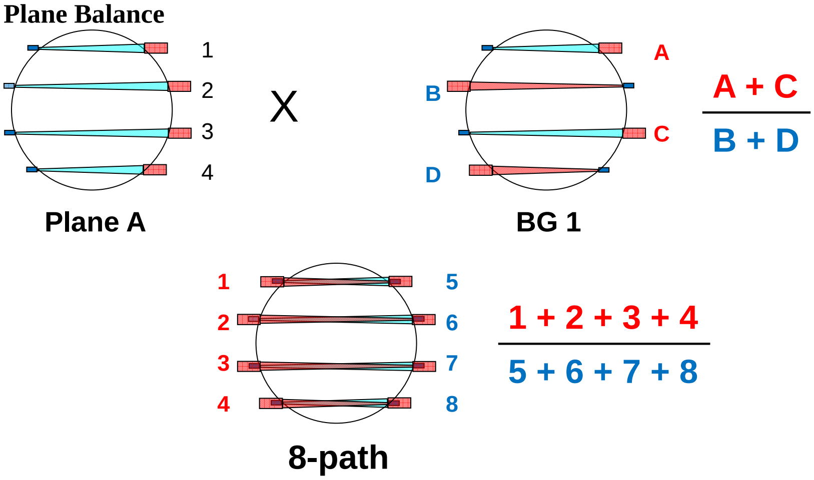


Figure 20 Plane Balance or Cross Flow Based upon different path designs

Standard Deviation or Turbulence

Standard Deviation or Turbulence indicates the instantaneous path velocity relative to the average of that same path velocity. The average velocity is calculated over a period of time and from that, the Standard Deviation is calculated. In general, the instantaneous velocity should fall within a spread represented by the average. If there is a change in the upstream hydraulics, such as something blocking a flow conditioner, then the path velocity may vary outside of a normal average. An excessive variation in path velocity compared to the average is an indication that upstream piping is causing the issue and it requires more analysis as to the root cause. The term Turbulence is used in the natural gas industry to represent this same characteristic. In natural gas applications, the use of the term turbulence creates a little confusion with the normal hydraulics experienced when operating above a Reynolds number of 10,000. At Reynolds numbers greater than 10,000, the flow is considered to be turbulent and this turbulence is normal. It does not present an issue for an ultrasonic meter to measure turbulent flow, but the use of the term Turbulence often leads users to come to a false conclusion that normal turbulent flow is an issue.

Summary

Ultrasonic Flow Meters are used to measure hydrocarbon liquids and gases in custody transfer and leak detection applications because of their ability to measure across a very wide range of flow with very low pressure drops. Since these meters are electronic based measuring devices instead of mechanical, users can expect a long lifetime of low operating costs. In addition to measuring the flow rate, the meters include an extensive database that can be mined to compare the operation of the meter today compared to when it was originally calibrated. This powerful analysis capability of ultrasonic meters enables users to measure fluid flow with low overall uncertainty.

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