A survey of non-invasive and semi-invasive flow meters for mining applications: Understanding and selecting the right technology for the application

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ABSTRACT

Selecting the right flow meter can in many cases simplify and reduce the cost of maintenance in a minerals processing plant, as well as save valuable time during plant stoppages. Furthermore, the correct selection of flow monitoring equipment is a key aspect of operation and process control required to maximize plant efficiency and throughput. Flow meters must be selected carefully based on the frequency of required maintenance, type of liquid flowing through the pipe, the liquid's properties (abrasive, corrosive, prone to scaling, etc.), whether or not the flow meter needs to be relocated frequently, whether or not the pipe needs to be replaced frequently, the desired accuracy of the measurement, as well as the meter's reliability, ease of installation, portability, etc. The overabundance of available technologies and marketing hype can make this a challenging process, which is made only more difficult by a lack of literature on the subject.

This paper will only review non-invasive flow meter technologies (time of flight ultrasonic, Doppler ultrasonic, and array-based sonar), their maintenance requirements, and their pros and cons when installed on challenging applications in the process plant. An explanation of the functioning principles will be given, as well as the strengths and weaknesses of each technology. Finally, examples of ideal applications for each technology will be provided.

This paper aims to help the plant operator correctly select the appropriate technology for a particular process application, while outlining the criteria considered, and simplifying the selection process for any application. The reader will come to understand the many maintenance benefits of non-invasive technologies, such as reduced down time, little to none maintenance requirements, low installation and lifecycle costs, and ease of installation and use.

INTRODUCTION

Selecting a flow meter always impacts maintenance requirements; however, this is seldom used as a selection criterion. The maintenance department will most likely have to deal with the decision once it has been made, with little or no chance of voicing its concerns. The aim of this paper is to educate the reader on the different non-invasive technologies that are available on the market and to give the reader a clear understanding of the selection criteria. The reader will find a clear explanation of the operating principles of each technology along with their particular advantages, disadvantages, and maintenance requirements. The scope of this paper is limited to non-invasive flow meter technologies to allow a more accurate comparison due to specific application demands.

NON-INVASIVE FLOW METERS

These meters are characterized by being able to measure the process flow without coming into contact with it. The advantages of not being exposed to the particular fluid in the process can translate to minimum maintenance requirements, semi or complete portability, easy installation, and very little signal drift over time.

Transit time ultrasonic flow meters

Transit time measurement is based on a simple physical fact. Imagine two swimmers standing diagonally across from each other on two opposite river shores. If they were to swim to where the other is standing, the swimmer swimming with the current would reach the shore faster than the one that is swimming against the current. Ultrasonic waves behave exactly the same way. A sound wave travelling in the direction of flow of the fluid is propagated at a faster rate than one travelling against the flow.

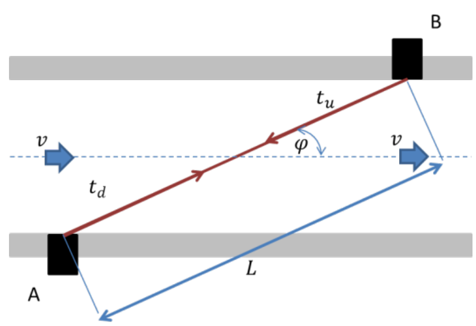

Figure 1 Transit time flow meter operating principle

Two transmitters / receivers (transceivers) are located on each side of the pipe. The transmitters send pulsating ultrasonic waves in a predefined frequency from one side to the other. The difference in frequency is proportional to the average fluid velocity, which can be expressed as:

$$v = \frac{L}{2 \cdot \cos \varphi} \cdot \frac{t_d - t_u}{t_d \cdot t_u},$$

where v = fluid flow velocity

L = distance between sensors

φ = the relative angle between the transmitted ultrasonic beam and the fluid flow

t_d = transmission time downstream

t_u = transmission time upstream

The actual configuration of the transceivers can vary by the pipe material and pipe size, as follows:

Table 1 Transceiver mounting considerations

Mounting configuration	Pipe material	Pipe diameter
W-Mount	Plastic pipe	2-3 inch
V-Mount	Any material	2-10 inches
Z-Mount	Any material	10-100 inches

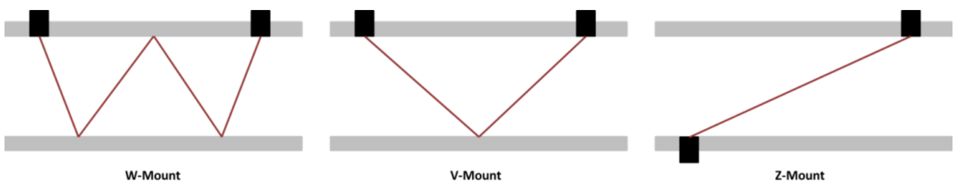

Figure 2 Transceiver mounting configurations

There is a need for different mounting configurations because of the effect of the signal strength on the transceivers, too little and no measurement can be made, too much and the transceiver gets saturated, hence the varying length of the signal path in the different mounting configurations.

Transit time ultrasonic flow meters can be used as portable or fixed meters on water or liquids with very low solids content. Gas bubbles and other impurities, such as solids particles exceeding 5% by volume, in the process flow render this technology unusable.

Advantages

Relatively easy to install, a single instrument can be installed on many different pipe diameters making this a very portable flow meter. These meters can be purchased and operated with a battery pack. Their accuracy generally is ±1% of reading in some cases, ±1% of full scale in most. They are able to measure bidirectional flow up to ±40 ft/s or ±12 m/s, and have a short start up and response time ranging from 0.3 to 30 seconds (depending on user configuration). Furthermore, the fact that they have no moving parts translates into zero maintenance on the actual flow measurement elements.

Disadvantages

Accuracy may not be enough for some applications control requirements, and the meter can only work with clear liquids. In extreme environments the coupling compound may dry, often causing a performance drop in the measurement and resulting in eventual loss of the signal. Scale build up decreases the accuracy of the meter due to the uncertainty of the inside diameter, the composition of the scale, and its corresponding speed of sound; especially in small diameter lines.

Maintenance

Transit time meters are very easy to install and maintain as there are no moving parts or contact with the process flow. When installing it is necessary to use a coupling compound, which may need to be reapplied either annually, whenever the compound diminishes, when the transducers need to be repositioned, or when the meter is moved. Additionally, the pipe straps securing the meter usually need to be retightened periodically.

Doppler ultrasonic flow meters

For a very basic explanation of the Doppler Effect, named after physicist Christian Doppler, imagine this. As an emergency vehicle approaches an observer, the pitch of the siren will be high (in comparison to the real pitch). As the emergency vehicle passes the observer, the pitch is identical to the real pitch. As the emergency vehicle speeds away, the pitch will sound lower to the observer. This same principle can be applied to flow meters that use a reflected ultrasonic wave to measure the fluid velocity. By measuring the frequency shift between the ultrasonic frequency source and the receiver, the relative motion of the fluid is measured. The frequency emitted by the frequency source must reflect on a medium, which in the case of process flow means either bubbles or suspended solids in the order of 100 ppm or more.

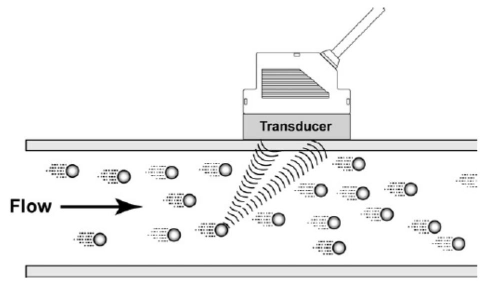

Figure 3 Ultrasonic wave Doppler frequency shift

The transducer transmits a continuous sonic wave inclined at some angle to the flow. Small inclusions of bubbles, solids, or coherent vortical structures in the flow reflect or scatter the sound back to a receiver. If there is any movement of the inclusions, a Doppler-shift appears in the frequency of the returned signal. The difference between the transmitted and received frequencies is proportional to the motion of the flow, which can be expressed mathematically as:

$$v = \frac{(f_r - f_t) \cdot C}{2f_t \cdot \cos\varphi},$$

where v = fluid flow velocity

C = velocity of sound in the fluid

φ = the relative angle between the transmitted ultrasonic beam and the fluid flow

f_t = transmitted frequency

f_r = received frequency

Several different Doppler ultrasonic models exist on the market, and most of them include the transmitter and receiver elements in a single transducer. As mentioned before, Doppler ultrasonic meters require the presence of entrained air or suspended solids particles in order to measure the flow rate.

Advantages

Doppler ultrasonic meters are easy to install, and a single instrument can be installed on many different pipe diameters, making this a very portable flow meter. These meters can be purchased and operated with a battery pack. Their accuracy is generally ±1% of full scale with the ability to measure flow up to 18 ft/s or 5.5 m/s. The fact that the meter has no moving parts translates into zero maintenance on the actual flow measurement elements.

Disadvantages

Accuracy is often not sufficient for certain applications control requirements and reduces with increasing solids content and increasing fines content. The meter can only work on liquids with a solids concentration of 100 ppm or more. The relatively low upper flow rate limit limits the number of applications this meter might be installed on. Additionally, in extreme environments the coupling compound may dry, causing a performance drop in the measurement and resulting in eventual loss of the signal. Scale build up decreases the accuracy of the meter due to the uncertainty of the inside diameter, the composition of the scale, and its corresponding speed of sound; especially in small diameter lines.

Maintenance

Doppler ultrasonic flow meters are very easy to install and maintain as there are no moving parts or contact with the process flow. When installing it is necessary to use a coupling compound, which may need to be reapplied either annually, whenever the compound diminishes, when the transducers need to be repositioned, or when the meter is moved. Additionally, the pipe straps securing the meter usually need to be retightened periodically.

Hybrid ultrasonic flow meters

These flow meters were conceived to share the advantages and have none of the limitations present in transit time and Doppler ultrasonic flow meters. This enables hybrid ultrasonic flow meters to measure flow in both clean liquids and liquids with a small amount of solids or entrained air. Hybrid flow meters rely on a switchover algorithm that determines which measurement principle should be used depending of the process flow composition. If the amount of reflectors in the liquid decreases or if the flow velocity exceeds Doppler measurable range, transit time method is used, if the amount of reflectors increase the Doppler measurement principle is used. The determining factor in switching over is the success rate of the measurements. As long as 70% or more channels are reporting a successful measurement, the measurement principle remains constant. Figure 4 details this process.

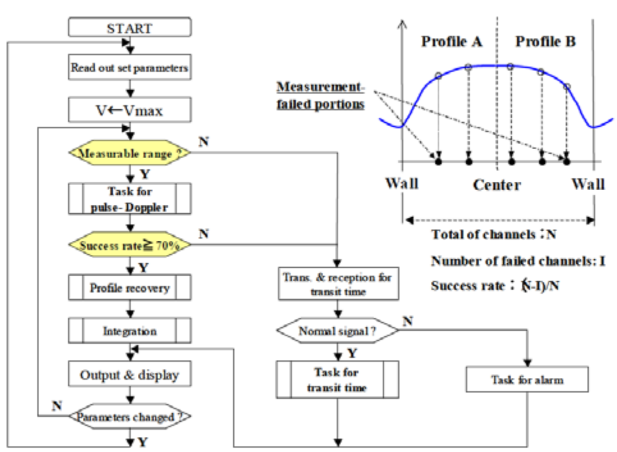

Figure 4 Hybrid ultrasonic flow meter switchover algorithm

Advantages

Hybrid ultrasonic flow meters are very easy to install, and a single instrument can be installed on many different pipe diameters, making this a very portable flow meter. These meters can be purchased and operated with a battery pack. Their accuracy is generally ±1% of full scale with the ability to measure flow up to 40 ft/s or 12 m/s in clear liquids and up to 18 ft/s or 5.5 m/s in dirty liquids. The fact that the meter has no moving parts translates into zero maintenance on the actual flow measurement elements.

Disadvantages

Accuracy is often not sufficient for certain applications control requirements and decreases with increasing solids content and increasing fines content. There is a question of accuracy at the switchover threshold. Additionally, in extreme environments the coupling compound may dry, causing a performance drop in the measurement and resulting in eventual loss of the signal. Scale build up decreases the accuracy of the meter due to the uncertainty of the inside diameter, the composition of the scale, and its corresponding speed of sound, especially in small diameter lines.

Maintenance

Hybrid ultrasonic flow meters are very easy to install and maintain as there are no moving parts or contact with the process flow. When installing it is necessary to use a coupling compound, which may need to be reapplied either annually, whenever the compound diminishes, when the transducers need to be repositioned, or when the meter is moved. Additionally, the pipe straps securing the meter usually need to be retightened periodically.

Array-based sonar flow meters

The array-based sonar flow meters utilize an array of piezoelectric sensors that are wrapped around the pipe. Flow rate is determined using array processing techniques to measure the rate at which coherent structures convect through the array of sensors. Examples of these structures that are present in virtually all industrial flows are vortices in turbulent flow and density or temperature variations in non-turbulent flow. The flow rate is calculated directly from the velocity of the vortical structures since they travel at the same velocity of the flow. Much like one can feel the turbulence of water passing through a garden hose, the array-based sonar flow meter "feels" and tracks the coherent vortical structures present in process flow.

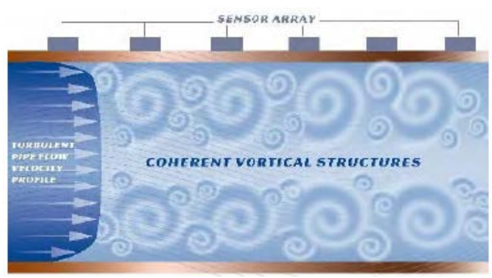

Figure 5 Sensor array detecting coherent vortical structures convecting with the flow

The array of sensors wrapped around the pipe is made of piezoelectric material, which changes in capacitance when stretched or compressed. Since the band is tightened around the pipe, each passing vortical structure creates a capacitance change in each sensor. The algorithm is able to individually track each vortical structure as it passes between each sensor and calculate the time it takes it to do so. Since the spacing between each sensor is known, the flow velocity can be calculated by this simple formula:

$$v = \frac{l}{t},$$

where v = fluid flow velocity

l = space between each sensor

t = time it takes a turbulent eddy to travel from one sensor to the other

The measurement principle used for liquids can also be used to measure gases or the fraction of gas contained in liquids.

Advantages

The clamp-on array-based sonar flow meters are easy to install. A good accuracy of ±1% of the reading along with excellent repeatability of ±0.3% of the reading make the array-based sonar flow meters an extremely stable flow meter not subject to drift, even after long periods of operation. No coupling compound is needed, thereby eliminating the need to periodically maintain the meter. The technology has no maximum upper flow rate limit and can measure clean or dirty liquids up to a very high solids concentration. It is also able to measure and correct for entrained air in the process flow. Furthermore, the quality of the measurement is very insensitive to changes in the process flow characteristics, such as density, temperature, viscosity, air content, or solids content.

Disadvantages

The meter has a low flow limit of 3 ft/s or 0.91m/s for most applications. There is also a relatively long startup time of 30 seconds plus before a measurement is registered. The smallest pipe diameter available is 2 inches. The meter can operate on battery power, but the manufacturer does not offer a bundled version. The meters are diameter specific, meaning they can't be installed on lines of different diameters.

Maintenance

The array-based sonar flow meter has no moving parts and does not come into contact with the process fluid, which means there is no maintenance required on any of the parts. Further, since there is no coupling compound used, it is not necessary to monitor the meter for issues with the coupling compound drying.

SEMI-INVASIVE FLOW METERS

These meters come in contact with the process flow through a small orifice drilled into the pipe, which does not usually exceed 2 inches in diameter. These meters are used in very large diameter pipes (60 inches plus) where installing invasive technologies is not feasible and in applications where either the pipe wall thickness is too thick to have a strong signal between transducers or the distance between transducers is too great. Also used in applications where the process flow is not conductive.

Wetted transit time ultrasonic flow meters

These meters measure flow using the transit time principle. Mainly used in applications where a higher accuracy is desired, its main advantages versus clamp-on meters are the better signal quality, long term stability, and no installation uncertainty. Since the ultrasonic wave travels directly from transducer to transducer the pipe wall thickness and material do not add uncertainty to the installation.

Insertion transit time ultrasonic flow meters can only be used as fixed meters on water or liquids with very low solids content. Gas bubbles and other impurities, such as solids particles exceeding 5% by volume, in the process flow render this technology unusable.

Advantages

Relatively easy to install, a single instrument can be installed on many different pipe diameters making this a versatile flow meter. Their accuracy generally is ±1% of reading. They are able to measure bidirectional flow up to ±40 ft/s or ±12 m/s, and have a short start up and response time ranging from 0.3 to 30 seconds (depending on user configuration).

Disadvantages

Scale buildup on the meters affects the accuracy of the meter and would require more frequent maintenance. The transducers have to be maintained periodically in aggressive applications. The pipe has to be drilled, which may compromise the pipe. If installing in a high pressure line (>5 bar) extreme care must be taken during the installation, in lines at higher pressure the process flow must be stopped or the pressure reduced before installation can take place.

Maintenance

Transducers might need to be checked periodically for scale build up or corrosion in certain applications.

Insertion magnetic flow meters

The basis for magnetic flow measurement is Faraday's law of induction. When a conductor moves in a magnetic field, a voltage is generated in this conductor. The generated voltage is proportional to the velocity of the conductor. The magnetic field is generated by two coils that are energized by an AC power line or a pulsed DC line. The flow velocity induced voltage is received by two insulated electrodes, usually located on the sidewalls of the flow tube.

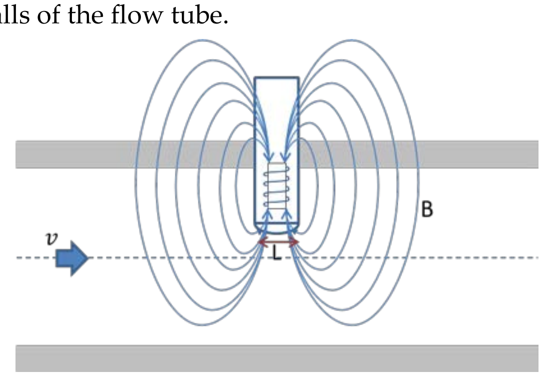

Figure 6 Insertion mag meter measurement principle

The electrode axis, magnetic field, and direction of flow are perpendicular to each other. The induced voltage at the electrodes (U) is proportional to the induction (B), the flow velocity (v), and to the distance between the electrodes (L). This can be expressed as:

$$v = \frac{B \cdot L}{U}$$

where v = fluid flow velocity

B = inducted magnetic field

L = distance between electrodes

U = induced voltage at the electrodes

Several different insertion ultrasonic meters exist on the market. They can be connected to a permanent power supply or run from a battery. They are commonly used in water applications where abrasion is not a concern.

Advantages

Relatively easy to install, a single instrument can be installed on many different pipe diameters making this a versatile flow meter. Usually installation can be performed without stopping the process. Their accuracy generally is ±2% of reading.

Disadvantages

Scale buildup on the meters affects the accuracy of the meter and would require more frequent maintenance. The pipe has to be drilled, which may compromise the pipe. If installing in a high pressure line (>5 bar) extreme care must be taken during the installation, in lines at higher pressure the process flow must be stopped or the pressure reduced before installation can take place. Upper velocity limit is typically 5 m/s or 16 ft/s. These meters can only be installed in lines which do not exceed 20 bar during operation. Process flow conductivity must be above 50 μS/cm. Probe is extremely sensitive to abrasion.

Maintenance

Depending on the application, the probe must be cleaned periodically to prevent scale buildup.

SUMMARY

The following tables summarize the information presented above:

Table 2 Non-invasive flow meter comparison

	Transit time	Doppler	Array-based	Hybrid ultrasonic
Accuracy	±1% of reading in some cases, ±1% of full scale in most	±1% of full scale	±1% of reading	Depends on measurement method
Repeatability	±0.5% of reading	±1% of range	±0.3% of reading	"
Clean liquids	YES	NO	YES	YES
Dirty liquids, slurries, gas bubbles	NO	YES	YES	YES
Minimum flow rate	No minimum flow rate	0.03 ft/s	3 ft/s	Depends on measurement method
Maximum flow rate	40 ft/s	18 ft/s	No maximum flow rate	"
Bidirectional flow	YES	NO	NO	"

Table 3 Semi-invasive flow meter comparison

	Wetted transit time	Insertion magnetic
Accuracy	±1% of reading	±2% of reading
Repeatability	±0.5% of reading	±0.5% of reading
Clean liquids	YES	YES
Dirty liquids, slurries, gas bubbles	NO	YES
Minimum flow rate	1.5 ft/s	3.3 ft/s
Maximum flow rate	60 ft/s	16 ft/s
Bidirectional flow	YES	NO

Ideal applications

These flow measurement technologies can sometimes be used interchangeably; however, each technology has a niche application where it excels.

Transit time flow meters

- Monitoring of remote water lines were power supply is limited or nonexistent due to ability to operate on battery power and ease of installation.
- 2” and smaller clean liquid lines.
- Quick surveys.

Doppler ultrasonic flow meters

- Runoff collection lines, as the higher solids concentration of this type of line and lower flow rates are outside of the operating ranges of other non-invasive flow measurement technologies.
- Quick surveys.

Hybrid ultrasonic flow meters

- Water lines that may contain entrained solids under certain conditions, such as tailings reclaimed lines.
- Quick surveys.

Array-based flow meters

- Hydrocyclone feed lines due to the aggressiveness of the slurry, which usually requires intensive maintenance when using invasive flow measurement technologies.
- Abrasive and/or corrosive flows, scale formation on pipe internal surface.
- Mixed flows of two or more types: liquid-only, liquid-solid, liquid-gas, liquid-solid-gas
- Long distance slurry pipelines due to the high accuracy and repeatability of the meter over time.

Wetted transit time ultrasonic flow meters

- Low pressure water lines where a higher accuracy is needed.
- Acid and PLS flows.
- Large diameter water lines

Insertion magnetic flow meters

- Low pressure water lines where a higher accuracy is needed.
- Large diameter water lines.

Case Study: Reduced maintenance on a hydrocyclone feed line

A large concentrator plant in Chile processing 100,000 TPD installed 4 non-invasive 22in array-based sonar flow meters to replace their existing fully invasive magnetic meters. These magnetic meters were maintained periodically once a year, but due to the coarseness of the slurry, they sometimes burst every one to three years. The failures were severe enough to require immediate shutdown of the line to replace the leaking meter with either a new mag meter, or replacement with a plain spool piece. During this unscheduled maintenance, one of their four grind lines was down for five hours, at a cost of $20k/hour or $100k total. This does not include the cost of maintenance labor. Since installing the array-based sonar flow meters, preventive maintenance has been reduced to 0 hours, and there have been no meter related bursts, saving the plant money and man hours.

CONCLUSIONS

Non-invasive flow meters require very little maintenance, which makes them attractive options in remote locations, plants with a lack of certified personnel, plants with heavy maintenance requirements, and abrasive or corrosive fluids. The fact that installation does not require process shutdown or major mechanical work makes these flow meters a viable solution in older plants or plants where it is preferable not to stop the process. Overall, non-invasive flow meters boast of reduced down time, minimal maintenance requirements, easy installation, and a low total cost of installation and ownership.

The selection of a particular type of non-invasive flow meter ultimately comes down to considerations, such as pipe size, desired portability, fluid type, and most importantly needed accuracy.

ACKNOWLEDGEMENTS

Luis Dartagnan of Minera Candelaria, Susan McCullough and Luis Gutierrez of CiDRA Minerals Processing are gratefully acknowledged for their assistance.

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