A survey of pipe density measurement technologies

Measurement of the density of chemical solutions and slurries in pipes has been a need of many industries for over 80 years. With ever tighter regulatory requirements and the drive for improved operational efficiency/productivity, the need for better data is now a higher priority for many firms.

This document will summarize the various technologies used to make this important measurement, highlighting the pros and cons of each.

Many industries transport materials as a fluid inside of a pipe. Maximizing operational efficiency and safety requires real-time knowledge of the density of that solution or slurry. In olden days, the only method of this measurement included sampling the material and measuring the density in a lab - a messy, and sometimes dangerous undertaking.

Then came the nuclear measurement solution. In the mid-1950s, Phillip Ohmart used a radioactive isotope and a gamma ray detector mounted outside of the pipe that allowed the density of the solution or slurry inside of the pipe to be inferred. After the initial calibration, no further sampling was needed, and the non-intrusive nature of the measurement provided an inherently maintenance-free solution.

To this day, this solution provides reliable and maintenance-free density measurement in pipes; but it does require a low level radioactive material to generate the gamma rays used to infer the density. Since its first use for the measurement over 65 years ago, detector sensitivity has improved over 100 fold through the use of scintillation materials as opposed to gas filled tubes, and the isotope encapsulation and source housings include greatly improved reliability. But still…there's that darned radioactive isotope.

Recent attempts to build a better density mousetrap typically come with the phrase "pipe density measurement made without a radioactive source". Quite an attention grabber. Will they pan out? After hearing about these solutions for over 10 years now, feedback on them and an analysis of their measurement methods sheds light on that question.

The survey will look at the following technologies:

1) Radiometric, or nuclear, density meters
2) Ultrasonic spectroscopy systems
3) Percussion technology systems
4) Gravimetric density systems
5) Industrial tomography systems

Each technology will be evaluated based on two characteristics:

1) Does the instrument provide long-term reliability with a lack of regular maintenance?
2) Does the integrity of the physics used to make the measurement allow accuracy over the full span?

Radiometric, or nuclear, density measurement

It is appropriate to discuss radiometric first, since it was the first technology used for reliable and long-lasting measurement of the density of liquids/slurries inside pipes. The basic concept is that a small radioactive isotope, housed in a shielding body, shines gamma rays through the pipe walls and the media, then over to a detector which monitors the relative radiation field strength. Similar to a medical x-ray, a denser media will attenuate (block or scatter) the gamma rays and produce a weaker radiation field on the detector. A less dense media will attenuate less radiation and produce a higher field of radiation on the detector. The gamma method provides a non-intrusive measurement of the density of materials inside of a pipe.
By its nature and history, the radiometric solution provides long-term reliability with little to no maintenance. It's been demonstrated to be a set-it-and-forget-it solution, for over 60 years.

On the topic of the suitability of the physics to allow accurate measurement of density over the span, the physics used to make the measurement with radiation is the well-defined equation of radiation mass attenuation:

$$I = I_0 e^{-\mu\rho t}$$

where: I = measured radiation field strength
I_0 = initial radiation field strength
μ = mass attenuation coefficient
ρ = density of the material
t = path length through which the gamma rays travel, or pipe ID in this case

Since the fluid is contained within a pipe, t then is constant and equal to the inner diameter of the pipe.
For all practical purposes μ is also constant for the solution or slurry in the pipe over the density span in question.
Therefore, ρ can be solved for directly using the change in radiation field strength. The density over the full span of measurement is determined by the change in a single variable: the radiation field strength measured by the detector. Therefore, the physics of the radiometric technology provides reliable measurement over the full span of the density range of interest.

In summary: the radiometric solution, which requires a low-level radioactive isotope, provides long-term reliability with minimal regular maintenance and the physics of the technology allows for reliable measurement over the full span of density.

Density measurement without a radioactive source

In the past decade, several inline density technologies have been brought to market with a selling proposition that no radioactive source is needed. We'll explore those technologies next.

Ultrasonic spectroscopy

This technology consists of an ultrasonic emittance probe inserted into the wall of the pipe, and in direct contact with the process media.

From that description alone, and an understanding of the process materials running inside of the pipe, it's clear that this technology will not produce long term reliability. Mining slurries are aggressively abrasive, and wear all materials into which they come in contact, including measurement devices and the pipe itself. Various process materials for which the density is measured are corrosive and require attention to intrusive sensor material compatibility. Buildup on the pipe walls, and intrusive sensors, is another serious issue that requires a regular schedule of sensor cleaning. Intrusive technologies inherently require preventative maintenance.

On the reliability of the physics used to make the measurement, ultrasonic methods are influenced by changes in material properties such as temperature, pressure, and viscosity of the medium. In the case of a solids/liquid slurry, the particle size of the solids will also affect the ultrasonic mechanical wave. Using ultrasonic technology to infer density requires that several other material properties are known or controlled. While it provides benefit at a single combination of these variables, in situ process measurement in manufacturing operations include changes of these parameters throughout the day or at each stage of the process. In that case, the measurement of density then becomes a complex multivariate analysis exercise.

In summary: ultrasonic spectroscopy methods are intrusive, requiring a regular schedule of routine maintenance for proper operation; and will likely require hardware replacement after prolonged use.
The physics of ultrasonic spectroscopy includes multi-dependent variables such as temperature, pressure, density, viscosity, and particle size in the case of a solid/liquid slurry. The use of this technology to precisely measure density over a span is an interesting exercise in a lab environment, but includes much uncertainty when used in manufacturing operations for process control.

Percussion technology

Percussion technologies utilize a striker hammering onto the outside surface of a pipe; a density measurement is then inferred from a spectroscopic analysis of the induced vibrations.

Percussion technology is non-intrusive, but the device includes moving mechanical components - particularly the hammer - that continuously strikes the pipe at regular intervals. Those components will require periodic evaluations of function, and likely complete replacement, with time.

The physics of percussion measurement is not straightforward, and customer feedback from use of this technology asserts this to be a major failing. The "quality" of the process material is inferred from a spectral analysis of the vibration setup by the hammer at the measuring point. The basic assumption is that on a pipe - at one location and with a product of constant density - the spectral response to vibration induced into the pipe will be reproducible. While that may be the case, inferring the density of product at anything other than the initial condition is futile. From a practical standpoint, the user of a pipe density measurement system wants to know that value over a range of densities so that proper correction to the process can be made. A reproducible vibrational spectral pattern at a single value of density does not a measuring system make. Feedback from field setups of these devices corroborates this issue. While the system can be tuned by an expert to recognize a single vibrational spectral pattern, it is not good at inferring measurements at other values of density.

In summary: the technology is non-intrusive, but does require movement of mechanical components to make the measurement. System wear is typical and maintenance is commonly required. Although the device may be able to indicate if a single value of density is in the pipe, the physics of the technology does not allow for measurement over a range of density states to be determined.

Gravimetric density systems

A few companies promote gravimetric density systems, whereby the weight of the slurry/solution in the pipe is physically measured. In all of these systems, the sample section of the measuring system must be allowed to move in order to determine the physical weight. The sensing elements are either load cells or lasers. Load cells require regular maintenance, which is a known and significant cost based on their use in other applications. One laser-based system measures the physical displacement of a flexible cartridge as the material flows through it. A flexible cartridge. Long term flexing and the use of the term “cartridge” clearly demonstrate the need for regular maintenance and replacement.

On the physics of the measurement, let us consider the effects of vibration and the change in volume of the cartridge on gravimetric density measurement. Vibration of the measuring system is a factor in the resolution of weight or density with any gravimetric system. Gravimetric systems rely on the force of gravity to remain constant. In the case of vibration, the measuring system will experience G-forces that would add to and subtract from the nominal force of gravity, thereby inducing measurement noise and error. Resolving and removing gravitational forces due to vibration from any measuring system is not a trivial matter, and includes much uncertainty.

Specific to the laser-based system, the flexible cartridge component of the laser based system is just that: flexible. Density is the measurement of mass per unit volume. When the cartridge flexes, the volume changes, which could be due to change in flow rate, or a heavier, more dense, product in the cartridge. This system uses a laser to measure a displacement, but is not able to determine whether the displacement is due to change in density or in flow rate.

In summary: gravimetric systems require movement of some element as the slurry passes through it so that it can be weighed, and therefore require preventative maintenance and replacement of system components, leading to process downtime and potentially significant costs. In addition, vibration - commonly present on pipes in which solutions/slurries flow - will induce error into the measurement produced by a technology that utilizes a weight measurement. The laser-based gravimetric system invokes an equation with too many variables.

Industrial Tomography

Industrial tomography is a technology that promotes non-nuclear density measurement; it is commonly utilized as an analytical tool, and is being proposed by some equipment manufacturers as a process control tool. This system uses an electrical conductivity profile to determine the percent concentration in liquid/solid slurries. The system is non-intrusive, mounting completely outside of the pipe. This suggests a lack of required maintenance, but it is difficult to find any sort of customer testimonial to back this up..

By definition, tomography is visualization or imaging. These systems do a good job of providing a visual image of the electrical conductivity profile of the slurry in the pipe, but translating this into a discrete specific gravity, percent solids, or other density value used to control a process is questionable. From the standpoint of physics, there is not a direct method of translating differences in electrical conductivity to product density.

In summary, industrial tomography systems can be non-intrusive, with a potential to be low maintenance. While such systems can provide a good image of the electrical conductivity profile in the pipe, since translating this to a true density value for process control is questionable, these systems are better used as diagnostic scanners.

Comparison of Technologies

The following table highlights the pros and cons of radiometric density systems compared with the other technologies highlighted above.

From the standpoint of its mounting arrangement, its 65 year history of use, and its method of measurement - which is related directly to basic physics - it can be said that nuclear/radiometric density technology is the tried and true method for long term low maintenance density measurement in pipes.

Technology	Nuclear source	Intrusive	Mechanical movement	Maintenance required	Reliability of the physics	Output efficient for process control
Nuclear/ radiometric	Yes	No	No	No	Yes	Yes
Ultrasonic spectroscopy	No	Yes	No	Yes	No	Yes
Percussion	No	No	Yes	Yes	No	No
Gravimetric	No	Yes	Yes	Yes	No	Yes
Tomography	No	No	No	No	No	No