Understanding Electromagnetic Flowmeters

Consisting of a flow tube, field-generating coils, electrodes, and a transmitter, a magmeter accurately measures the flowrate of conductive fluids over a wide range of conditions.

Electromagnetic flowmeters, or magmeters, account for about 20% of all flowmetering applications in processing plants. They operate based on the principle discovered by Michael Faraday in the 1830s: An electrical conductor moving through a magnetic field produces an electric signal (Figure 1). In a magmeter, the flowing liquid is the conductor and electromagnetic coils surrounding the flow tube generate the magnetic field. Two electrodes embedded on opposite sides of the flow tube detect the signal, which is linear and proportional to the intensity of the magnetic field, the diameter of the pipe (distance between electrodes), and the flow velocity.

For many applications, magmeters are preferred over other flow-measurement technologies because they offer several advantages. Their design is considered obstructionless so they create virtually no pressure drop, and they have no moving parts subject to wear that would require maintenance and/or replacement. The output signal is linear over a wide velocity range and can be regarded as directly proportional only to flow velocity since the magnetic field is relatively constant and the distance between the electrodes is fixed. All these characteristics provide flexibility and versatility.

A magmeter’s electrodes and insulating liner are wetted. For applications needing a grounding ring (e.g., those with nonconductive piping), the grounding ring is also wetted to ensure a stable electronic reading. Magmeters are available in a variety of materials that can be selected for compatibility with corrosive chemicals or to meet sanitary requirements for food applications. They can operate over a wide flow range (1,000:1) while maintaining an accuracy as good as ±0.2%. Magnetic flowmeters are equipped with digital signal processing (DSP) technology, which eliminates noise that can lead to performance degradation.

On the downside, the fluid measured by a magmeter must be conductive (Table 1), which rules out their use for most petroleum-based flows. Magmeters also have physical pressure and temperature limits. While pressure limits depends on the flange configuration, temperature depends on the chosen material, such as 158°F for polypropylene, 176°F for ceramic carbide, and 356°F for paraformaldehyde (PFA).

In the typical magmeter configuration used in chemical process applications, the coils producing the magnetic field are mounted on the outside of a nonmagnetic pipe section (flow tube). An electric current passing through the coils generates a magnetic field within the pipe. The flow passes through the pipe section perpendicular to the plane of the magnetic field.

The voltage developed across the magmeter electrodes is low — often in the single-digit mV range. To avoid external interference, the signal should be carried via shielded cable to a nearby transmitter. The transmitter converts and boosts the raw signal to a useable standard milliamp (4–20 mA) or frequency (0–5,000 Hz) output that is sent to a display or controller. The combination of the flow tube (the primary element) and the transmitter (secondary) is considered a magmeter system. The transmitter may be mounted remotely from the magmeter and connected by the shielded cable, as shown in Figure 2, or it may be integral to the magmeter.

Generating magnetic fields

The coils produce the magnetic field through either AC or DC excitation. With most AC excitation techniques, a line voltage of 110 V or 220 V powers the magnetic coils, and the resulting flow signal has a sine-wave shape, the amplitude of which is directly proportional to the flow velocity. AC excitation produces a high magnetic-coil current. These designs have a better signal-to-noise ratio, making them more impervious to noise from external influences than DC designs.
AC-excited magmeters, however, consume more power than DC designs. DC-energized coils are a pulsed system and are powered intermittently, so power consumption is not a function of meter size, which is the case with AC systems.

Traditional AC systems are inherently prone to zero drift. In addition to the flow signal generated by the conductive process fluid passing through the changing magnetic field, wires and other conductors near the alternating magnetic field of an AC system can also produce a signal voltage unrelated to flowrate. To compensate for changes involving stationary conductors (for example, new electrode coatings), operators often shut off flow and reset the transmitter for zero output.

With DC coil-excitation designs, a lower-frequency square-wave pulse excites the magnetic coils. The transmitter reads both the flow and noise signals during a pulse. But between pulses (when there is no electromagnetic excitation), it sees only noise, permitting noise cancellation after each cycle (Figure 3). Thus, zero drift is typically not a problem for pulsed-DC designs. The low coil current (0.1–0.5 A) comes with a smaller signal and a low signal-to-noise ratio. Low-frequency designs also have longer response times and, therefore, are not well-suited for pulsating flow.

### Table 1. The fluid's conductivity affects a magmeter's functionality.

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Concentration, wt.%</th>
<th>Temperature, ºC</th>
<th>Conductivity, μS/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alum (Aqueous)</td>
<td>Any</td>
<td>25</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Ammonia</td>
<td>100</td>
<td>−79</td>
<td>0.13***</td>
</tr>
<tr>
<td>Ammonia</td>
<td>≤31</td>
<td>15</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Ammonium Chloride</td>
<td>5–25</td>
<td>18</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Barium Nitrate</td>
<td>4–8</td>
<td>18</td>
<td>&gt;1,000</td>
</tr>
<tr>
<td>Benzyl Alcohol</td>
<td>100</td>
<td>25</td>
<td>1.8**</td>
</tr>
<tr>
<td>Cadmium Bromide</td>
<td>≤43</td>
<td>18</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Cola Syrup</td>
<td>100</td>
<td>20</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Coffee Extract</td>
<td></td>
<td>84</td>
<td>&gt;1,000</td>
</tr>
<tr>
<td>Corn Syrup</td>
<td></td>
<td>32</td>
<td>16</td>
</tr>
<tr>
<td>Fudge</td>
<td></td>
<td>57</td>
<td>46</td>
</tr>
<tr>
<td>Gin</td>
<td>90 proof</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>Hydrogen Peroxide</td>
<td>90</td>
<td>60</td>
<td>2**</td>
</tr>
<tr>
<td>Hydrogen Peroxide</td>
<td>35</td>
<td>60</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Isopropyl Alcohol</td>
<td>25</td>
<td>25</td>
<td>3.5**</td>
</tr>
<tr>
<td>Latex Paint</td>
<td>25</td>
<td>25</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Lime Slurry</td>
<td>22</td>
<td>18</td>
<td>&gt;1,000</td>
</tr>
<tr>
<td>Mercuric Chloride</td>
<td>0.229</td>
<td>18</td>
<td>4.4**</td>
</tr>
<tr>
<td>Mercuric Chloride</td>
<td>1–5.08</td>
<td>18</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Potassium Chloride</td>
<td>5–21</td>
<td>18</td>
<td>&gt;1,000</td>
</tr>
<tr>
<td>Propionic Acid</td>
<td>1–69.99</td>
<td>18</td>
<td>&gt;85</td>
</tr>
<tr>
<td>Propionic Acid</td>
<td>100</td>
<td>25</td>
<td>&lt; 0.07**</td>
</tr>
<tr>
<td>Sugar Solution (Pure)</td>
<td></td>
<td>10</td>
<td>3**</td>
</tr>
<tr>
<td>Toothpaste</td>
<td>25</td>
<td></td>
<td>&gt;100</td>
</tr>
<tr>
<td>Water (Distilled)</td>
<td>100</td>
<td></td>
<td>&lt; 0.05*</td>
</tr>
<tr>
<td>Water (New York City)</td>
<td>25</td>
<td></td>
<td>72</td>
</tr>
</tbody>
</table>

* Conductivity is below the minimum required for the magmeter.
** Ask factory applications personnel for the appropriate magmeter.
*** Temperature is too high or too low for a magmeter.
Although the pulsed-DC method has become the predominant means of magnetic field excitation, it has not replaced AC excitation entirely. Each system has advantages over the other: The pulsed-DC design is superior to traditional AC systems in terms of zero stability, and the AC system is superior for noisy applications that require a high signal-to-noise ratio and faster response times.

In addition, the technologies underlying both are continually being improved to minimize disadvantages. A new AC-excited magmeter that effectively deals with zero drift has reached the marketplace, combining the advantages of both excitation techniques. This allows for a high signal-to-noise ratio and continuous measurement of pulsating flows, yet with a stable zero that does not drift.

Directly measuring the strength of the magnetic field and keeping it constant addresses the issue of zero drift. Through the use of an integrated diagnostic coil that measures the strength of the magnetic field (as opposed to utilizing a constant-coil-drive current), the measured value of the magnetic field can be fed back into the coil-drive circuit so that a constant magnetic field is maintained. Accordingly, changes to the magnetic field’s strength that would otherwise affect meter performance in traditional AC meters are dramatically reduced.

With the advent of a more-robust AC system that operates outside a high-noise spectrum (at 70 Hz) and addresses zero drift, magnetic flowmeters can better handle demanding applications involving vibration, slurries, entrained gas, and temperature fluctuations. And unlike DC technology, this AC design is also well-suited for pulsating flows.

**Magmeter construction**

The electromagnetic coils used in most process applications generate the magnetic field from outside the meter body, which is usually made of a nonmagnetic material. This allows the magnetic field to pass through the meter body into the pipe area to develop the flow signal.

If the meter body is made of metal (e.g., Type 304 stainless steel, which has very limited magnetic properties), it must be insulated from the electrodes. A liner installed between the meter body and the electrodes prevents the flow signal from shorting out. The only wetted parts of the magmeter are the electrodes, the insulating liner, and a grounding ring. These can be selected for compatibility with the most corrosive and abrasive chemicals, as well as to meet the requirements of sanitary applications.

Plant engineers can choose from a wide variety of nonconductive liner materials — such as polytetrafluoroethylene (Teflon), ethylene-tetrafluoroethylene (Tefzel), rubbers, and ceramics — to suit the liquid being measured.

Electrodes are available in a wide assortment of materials, including Type 316 stainless steel, Hastelloy B, Hastelloy C, titanium, tantalum, and platinum. Tantalum and platinum are the most chemically compatible, but are also the most expensive.

Typical velocities are 3–15 ft/s for water and clean chemicals, 3–6 ft/s for abrasive fluids, and 6–12 ft/s for coatings and liquids with entrained air. Magmeter flow tube sizes range from 1/25 in. to 96 in. and flows range from about 0.003 to 750,000 gal/min.

For flow velocities of 0.5 to 50 ft/s, accuracies are usually stated as a percent of flowrate; for lower velocities, accuracies are stated as a percent of span. A good practice is to consider the process medium when determining meter size and velocity through the meter.

**Conducting fluids**

The primary factor in determining whether a magmeter is appropriate for a given application is conductivity. The process liquid must be sufficiently conductive to meet the minimum requirement as a conductor. The requirement varies from manufacturer to manufacturer and for different magmeter types.

Conductivity is measured in microsiemen/cm (µS/cm) or µmho/cm, which are equivalent. The mho is the reciprocal of the ohm, the unit of measure for resistance (mho is ohm spelled backwards). Both terms appear in the literature.

Magmeters, especially DC-coil-excited magmeters, typically require a minimum fluid conductivity of 5 µS/cm. Some magmeters, however, require a minimum of 20 µS/cm. Since temperature can affect conductivity, the value must be determined at normal process temperatures.

A magmeter used on a relatively low-conductivity (5 µS/cm) liquid one day can be used on a high-conductivity (1,000 µS/cm) liquid the next day with no change in calibration. Calculations have shown that signal loss over this conductivity range is insignificant.

Magmeters with special designs can measure process flow where the liquid conductivities are well below 5 µS/cm. At these levels, electrical noise becomes a problem. The amplitude of the noise varies directly with the flow velocity and is inversely proportional to conductivity and viscosity. Therefore, low-conductivity magmeters should be sized so that the maximum flow is about 3 ft/s. On the other hand, as either the conductivity or the viscosity drops, the amount of noise will also increase. Normally, viscosity is not a concern in applying magmeters, since it is not a factor in the development of the flow signal. Low viscosities will, however, add to the amount of noise present in the process.

**Selecting the right magmeter**

Whether a magnetic flowmeter can withstand a given application depends primarily on the selection of the proper material for the liner, electrode, and grounding ring. These are
the only parts of the magmeter in contact with the process. Excessive wear on these parts could cause the meter to stop functioning and result in damage to other parts as well.

The principal factors to consider when making liner and electrode material selections are the operating temperature, the chemical composition and concentration, and the abrasive characteristics of the process. In most applications, the concern is the effect these three process parameters may have on the liner and electrodes.

However, in some applications (such as sanitary processes), the process may be affected by contact with the liner or electrode materials. The materials could be acceptable based on the chemical, temperature, and abrasive characteristics of the process but might be unacceptable because they could contaminate the process. In addition, some materials act as a catalyst to the process. For example, platinum, which is perhaps the most inert of all electrode materials, accelerates the decomposition of hydrogen peroxide.

The pH of the process liquid should also be considered. For example, heavily chlorinated water can have a low or high pH, depending on whether the source is chlorine gas dissolved in water or sodium hypochlorite in water. Not all material combinations are compatible with the full range of process conditions. At low pH, chlorine gas can permeate a Teflon liner and damage the meter housing. At high pH, several electrode materials are subject to attack. Therefore, some materials act as a catalyst to the process. For example, platinum, which is perhaps the most inert of all electrode materials, accelerates the decomposition of hydrogen peroxide.

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Liner and electrode materials must also be compatible with the materials used to clean the piping. For example, tantalum is an excellent electrode material for use in a ferric chloride process. However, if sodium hydroxide (caustic) is used to clean this line, the electrodes will be destroyed. The life of tantalum electrodes depends on the concentration, temperature, and length of time the cleaning process requires.

Steam cleaning should be limited to about 300°F (149°C) and to high-temperature liners such as Teflon. Rapid cooling after steam cleaning could create a partial vacuum in the process line and cause a ceramic liner to crack or a Teflon liner to collapse. Installation of a vacuum breaker in the line often prevents these problems.

Electrode and liner coating

A common concern is electrode coating. Particles can attach to the pipe wall, grounding devices, liner, and electrodes. Very heavy coatings that significantly change the diameter of the magmeter and the pipe cause errors due to increased velocity and reduced area at the electrodes. However, this is more of a piping problem than a magmeter problem. Although thin coatings are often a major concern among users, their effects are usually minimal.

Some thin coatings can cause span shifts and zero shifts. Coatings with a higher conductivity than that of the electrodes create a low-resistance path or short circuit between the electrodes and ground, reducing the flow signal.

Periodic flushing of the pipeline and the magmeter can minimize the buildup of coatings. In addition, sizing the magmeter for flows of 5 ft/s or higher will reduce the probability of coating. A dense, slick liner material such as Teflon may resist coating more than a rougher material like rubber.

Two relatively new solutions to electrode coating include ultrasonic cleaning and self-cleaning electrodes. In ultrasonic cleaning, crystals are attached to the back of the electrode, and an ultrasonic generator causes the crystal and electrode to vibrate. This method is effective on hard coatings, but not soft, sticky coatings. Self-cleaning electrodes are bullet-shaped and protrude into the flow stream, and turbulence around the electrodes keeps them relatively clean.

Proper installation

The installation should ensure that the magmeter is filled with process liquid at all times during flow measurement. The preferred orientations are vertical or sloping with upward flow through the meter; a horizontal orientation is acceptable, and perhaps most common. A vertical installation with upward flow through the magmeter ensures that the magmeter will remain filled, even under low-flow conditions (Figure 4). This minimizes wear on the meter lining from abrasive particles that may be in the liquid. To prevent entrained air from contacting the electrodes and causing errors in the flow signal, electrodes should not be placed at the top of the pipe in a horizontal or sloping installation.

Magnetic flowmeters do not require exceptionally long, straight pipe runs before and after the meter. This is because they measure the velocity of the process fluid in the plane between the electrodes, rather than throughout the entire cross-sectional area of the meter. This allows for the contributing velocities within the pipe to be summed, leading to an accurate

![Figure 4](https://www.aiche.org/cep)

*Figure 4. When installing a magmeter, avoid downward flows and provide a sufficient length of straight pipe between the magmeter and an elbow.*
measurement that is representative of the entire flowrate.

Some basic guidelines, however, apply to the placement of magmeters relative to elbows, control valves, blocking valves, pumps, and reducers. The following separation distances (measured as straight runs of pipe from the centerline of the magmeter to the mating flange of a pipe fitting) are recommended for the upstream side of the magmeter:

- elbows — a minimum of three pipe diameters (Figure 5)
- control valves — ten pipe diameters (Figure 6)
- pumps — ten pipe diameters
- tees — five to ten pipe diameters, depending on whether the major flow direction is inline or perpendicular to the flow through the magmeter.

The upstream side of the magmeter is more critical than the downstream side. Locating a device as close as two pipe diameters downstream from the magmeter is acceptable in most cases. If possible, locate control valves downstream of the magmeter.

Reducing a pipeline to match a smaller-diameter magmeter has little effect on accuracy. Reducers (concentric or eccentric) of 8 deg. or less have often been installed immediately upstream of a magmeter with little or no adverse effect. For larger reducing angles, however, guidelines suggest two to three pipe diameters between the magmeter and the reducer (Figure 7).

Magmeter grounding combines standard grounding with bonding of the meter body to the process liquid. By far, the most important part is the bonding, which is simply ensuring that the meter body is in electrical contact with the process liquid. If this is done improperly, the meter will function poorly; in the case where there is no bonding, flow signal circuits that are completed through the process liquid will not function at all.

Stray electrical currents are common in magmeter installations. These currents can develop from electrical leakage due to deteriorated insulation on motors, as well as from capacitive or inductive coupling to motor windings and other conductors. Pipelines are excellent conductors of these stray currents. When a magmeter is installed in a pipeline, it becomes part of the path for any stray current traveling down the pipeline or in the process itself. If these currents are allowed to pass through the magmeter, a zero shift may occur. The degree of error that this causes depends on the magnitude of the stray current and the conductivity of the process. Bonding provides a short circuit by which the stray currents can be routed around the magmeter instead of through it.

If the piping is conductive, grounding straps can be attached between the flanges of the magmeter and then to a good earth ground. If the pipeline is made of a nonconductive material, or is lined with one, then grounding rings or similar conductive devices should be installed to create a conductive path between the magmeter body and the process liquid. This allows stray currents traveling along the pipeline to pass from the liquid to the grounding ring to the body of the magmeter and back to the process fluid on the other side of the magmeter, following the path of least resistance (Figure 8).

Grounding rings must be compatible with the process chemicals. Consequently, the electrodes and the grounding rings are often made of the same material. To save money and/or delivery time, the grounding ring may be made of a slightly less corrosion-resistant material than the electrode. This is acceptable because a grounding ring has much more bulk than the electrode and will take a much longer time to wear away. For example, tantalum and platinum are the preferred electrode materials for sodium sulfate, but they are also the most expensive. On the other hand, most of the less-costly materials for grounding rings are rated only slightly less corrosion-resistant for this service.

A typical grounding ring is a paddle-type orifice plate with a bore equal to the nominal magmeter size. Its function is simply to make contact with the process liquid without developing a pressure drop. Consequently, the plate thickness can be much less than that of a standard orifice plate used for measuring flows.

Figure 5. Since two elbows in different planes introduce swirl to the flow, keep a very long straight run of pipe after such a disturbance to avoid adversely affecting measurement accuracy.

Figure 6. Control valves mounted upstream of the magmeter require a minimum distance of 10 pipe diameters between the valve and the magmeter to condition incoming flows. The same is true for pumps mounted upstream from the meter.

Figure 7. For reducing angles larger than 8 deg., guidelines suggest two or three pipe diameters of straight pipe between the magmeter and the reducer.
A magmeter should not be treated as though it is merely another piece of pipe. Its flange bolts should not be tightened beyond what is required to provide a good seal between the magmeter and the mating pipe flanges.

Teflon-lined magmeters are very susceptible to damage during installation. The Teflon lining is a sleeve that is inserted into the meter body and flared over the face of the body flanges. Lining protectors hold the liner against the face of the flange during shipping and installation. After the magmeter is placed in service, they protect the leading edge of the liner from abrasion by suspended particles in the process fluid. The protector also serves as a grounding ring.

**Magmeter calibration**

To achieve true calibration of the magmeter, a known volume of liquid must be passed through it and the output of the meter checked against this known value. For example, one technique is to divert the liquid flowing through the magmeter into a tank and then weigh the tank. Although this is a very accurate calibrating method, it has some practical limitations, such as slowing down the production process and increasing production costs. In addition, magmeters larger than 20 in. can fill a typical weigh tank in seconds. A low-cost alternative is to use master meters.

Master meters are frequently turbine meters or magnetic flowmeters that are installed in the hydraulic flow loop with the magmeter that is being calibrated. The master meter is calibrated by the weigh tank method and is accurate to better than 0.15%. The master meter is then used to calibrate the process magmeter. Using master meters for calibration makes it possible to maintain flow through the magmeter for longer periods of time to obtain a more-accurate measurement.

Magmeters are not normally calibrated for the specific range of the user. Their well-established linearity makes it possible to calibrate a magmeter over a standard range. For example, a magmeter calibrated over a range of 1–10 ft/s and a user range of 3–30 ft/s will have the same calibration factor. This makes it possible to accurately calibrate for 120,000 gal/min at 30 ft/s using a calibration flowrate of 40,000 gal/min at a velocity of 10 ft/s.

**Advances**

Over the past several years, the performance of magnetic flowmeters has improved significantly. Among the advances are digital signal processing and improvements in noise-reducing capabilities.

Insertion magnetic flowmeters are an economic alternative to full-bore metering. They consist of an electromagnetic sensing head mounted on the end of a support rod. The entire assembly can be installed in existing pipelines without the major excavations or alterations to pipework associated with full-bore meters, and without interruption to the flow. It can also be easily removed for periodic calibration or inspection, or inserted at a second location.

Key features of an insertion magmeter are the wide flow range, with minimum velocities well below those of insertion turbine or differential-pressure (DP) devices, and no moving parts, resulting in improved reliability and reduced maintenance. Insertion magmeters are suitable for both temporary and permanent installations. Insertion magmeters also provide generally acceptable accuracy (±2%) in large lines to monitor water usage.

New noise-reduction technologies act like a damping function in that they reduce or eliminate process-generated electrical noise. However, these techniques do not slow down the response to flow changes as much as conventional damping does. Damping is used to smooth out pulsations in the flow, which are generally caused by pulsating pumps; it slows the response to every change in flow and to any noise that may appear in the process. Noise reduction, on the other hand, selectively eliminates large, short-duration signals that are not associated with flow changes, but rather are unrelated electrical noise that has appeared at the electrodes.

It is a good idea to discuss noisy process applications with the vendor’s application engineers to ensure that the proper system is selected, including electrode type, coil-energizing frequency, and any noise reduction that may be required.

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**Figure 8.** For conductive piping (top), use one gasket per grounding ring and connect the grounding strap flange-to-flange. For nonconductive piping (bottom), use two gaskets per grounding ring and connect the grounding strap from the flange to the grounding ring.