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Key instrumentation technologies to tackle the toughest measurement challenges

Just as some people seek out extreme sports, process manufacturing has its extreme applications, and engineers who design for these environments must find ways to safely contain and monitor all manner of dangerous reactions and products. Consider a process where two feedstocks come together, generating a powerful exothermic reaction. The equipment must withstand what is, in effect, a continuous explosion capable of generating enormous amounts of heat and pressure, while ensuring safety for products that may be both highly corrosive and toxic.

Such situations are well beyond the capabilities of garden-variety equipment, including instrumentation. The need for accurate and reliable measurements is crucial to control critical processes and avoid serious safety incidents. If the continuous explosion cannot be monitored effectively, it could break out of its constraints, causing serious damage.

Extreme applications take many forms, some potentially violent, flammable and toxic, while others have more subtle hazards, but all these still have the potential to damage or shorten the service life of conventional process instruments. In this article, the authors will examine five types of difficult conditions. These include:

- Excessive vibration
- Difficult flows
- Demanding process fluids
- Extreme temperatures
- Severe pressures.

For each condition, the authors will consider what makes the process extreme, and then look at pressure and temperature instruments and associated tools designed to tame them. Most of the solutions involve specialized materials, physical design modifications and sensor signal processing, supported by software able to analyze the situation and offer practical alternatives.

PART 1: VIBRATION

In a refinery or chemical plant, there are few, if any, situations where vibration is desirable, so maintenance teams go to great lengths to minimize it. With rotating equipment (e.g., motors and pumps), excessive vibration indicates misalignment, failing bearings or other problems. If excessive vibration is transferred from a pump to adjacent piping, it can cause fittings and flange bolts to loosen, creating leaks.

FIG. 1. A proprietary wireless pressure gauge[a] does the same job as the mechanical version but with multiple advantages.

Such vibration is tough on mechanical instruments, especially pressure gauges, which operate using a delicate mechanism with springs and gears, making them vulnerable to shock and damage.

Most operators have seen typical results of vibration: leaking bourdon tubes, bent indicator needles or stuck needles from broken gears. Some models are armored with rubber covers and use beefed-up mechanisms, but these options add cost and have limited effectiveness.

Many users like the functionality of a traditional pressure gauge, but not its finicky mechanism and instability. Electronic gauges (**FIG. 1**) use an electronic sensor to provide the capabilities of a full process transmitter. Some include device diagnostic functions and *Wireless*HART connectivity, but in an analog gauge form factor with a traditional needle display. This approach checks the boxes for most-wanted features, without the problems of traditional pressure gauges.

Fluid-induced vibration. Vibrations can be created by flowing fluids in the piping configuration, causing wake shedding and peculiar eddy currents. This situation is very common where a thermowell is inserted into the fluid stream—perpendicular to the flow—to provide a temperature reading. Vortices form on both sides of the thermowell and create high- and low-pressure areas capable of inducing vibration (**FIG. 2**).

Sometimes, this vortex-induced vibration (VIV) is tolerable, but when severe, it can lead to two problems: sensor failure causing a lost reading or fatigue-induced failure of the thermow-

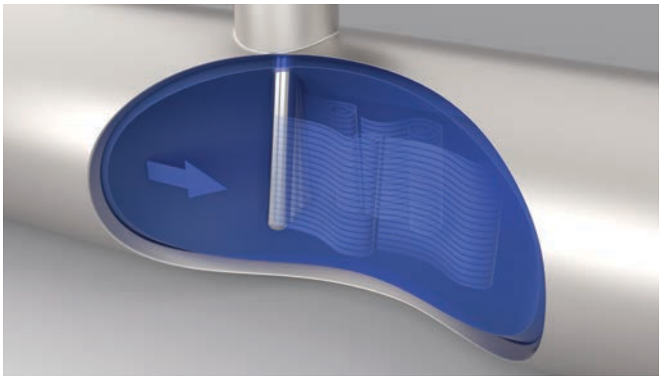

FIG. 2. Liquid flow around a thermowell can create vibrations sufficient to cause fatigue-induced failure.

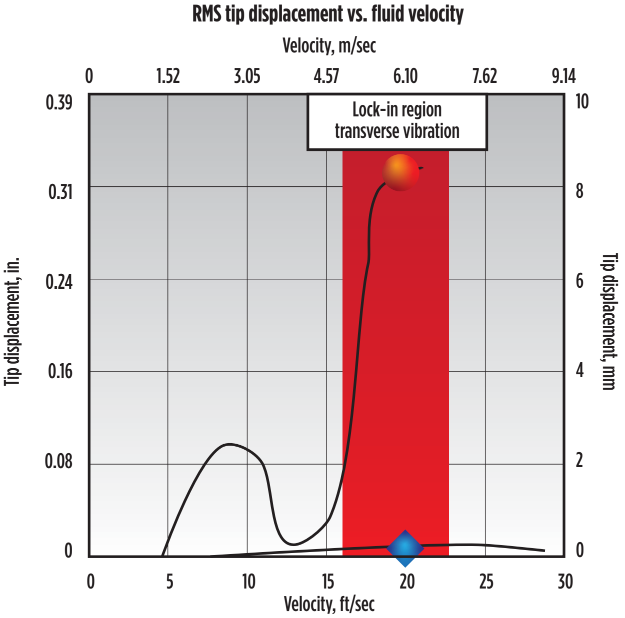

FIG. 3. When the frequency of the wake shedding matches the resonant frequency of the thermowell, the resulting vibration can be violent.

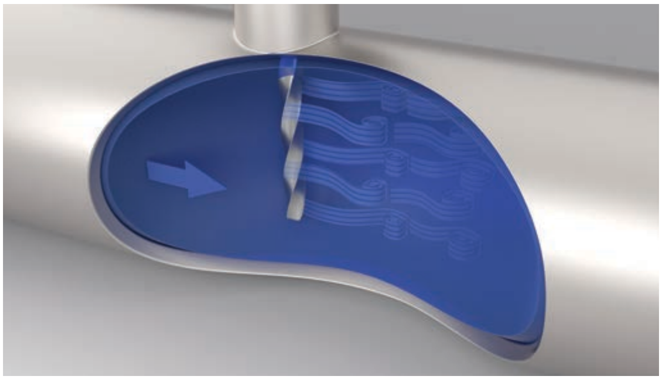

FIG. 4. Helical square designed thermowells[c] break up wake-shedding effects, reducing vibration by up to 90%.

ell itself. In this situation, the thermowell eventually bends or cracks, which can lead to process containment loss.

Wire fatigue and breakage. If vibration cannot be eliminated, one mitigation technique is using redundant sensors. Some temperature transmitters can process signals from two sensors, either from separately mounted sensors or from dual sensors built into a single sheath. If the values differ, transmitter diagnostics can trigger an alert. Similarly, if one sensor fails, the transmitter can switch immediately from the primary to the backup sensor without losing the reading.

The greatest reduction in risk is achieved with two independent sensors; however, this requires additional process penetrations. Two independent sensors—even if they are feeding one transmitter—can reduce the probability of losing the reading by 80%.

Thermowell durability. When VIV is an issue, the conventional solution is simply using a massively thick and/or very short thermowell that can stand up to the vibration. This is a problem for several reasons, including:

- A heavy cross-section causes significant time lag for the sensor to respond to changes in temperature
- Large diameter thermowells can be difficult to mount and can cause increased internal pipe blockage
- A short thermowell may not extend far enough into the process media stream to deliver an accurate temperature reading.

This leaves designers trying to determine how thin and long a thermowell can be and still withstand the VIV. For a given thermowell installed in each pipe, vibration will change with fluid velocity, but the two do not have a linear correlation. A certain fluid velocity will cause the VIV frequency to match the natural frequency of the thermowell, which can cause the amplitude to increase significantly (**FIG. 3**), with accelerated metal fatigue as the result.

These critical relationships can be analyzed mathematically using formulas outlined by ASME in its PTC 19.3 TW-2016 Standard. This calculation method has been built into free online thermowell calculation tools[b] that guide a design engineer through the sizing process by analyzing the likelihood of vibration problems for a specific thermowell shape in a specific installation. Each calculation involves about 20 variables for the dimensions and operating characteristics, so it is difficult to process manually. It must also be repeated for each set of operating characteristics, another reason to use automated online software.

Process data for various operational levels can be entered manually or uploaded using a template, so a designer can test multiple thermowell tags at once. The system performs calculations in the usual way, but also permits users to test what-if scenarios to see if a thinner thermowell might work or if a stock size already in use in the plant can do the job. These alternatives are offered as possibilities, providing designers with the flexibility to make the final call.

Avoiding fluid-induced vibration. Suppressing vibration at its source generally involves using a thermowell profile designed to avoid normal wake-shedding problems. Helical square designs (**FIG. 4**) disrupt the formation of long vortices, resulting in far less vibration—up to a 90% reduction in some cases.

Helical geometries have been used successfully with wind stacks and deep-sea risers to solve similar problems. This type of thermowell does not depend on a specific orientation when inserted and reduces the need for excessively-thick thermowells and large-diameter process penetrations.

PART 2: CHALLENGING FLOWS

Applications can become extreme based on fluid flow characteristics, with these three areas posing challenges for instrumentation: high-velocity flows, wide flow-turndown range and large line sizes.

High velocity. Historically, piping guidelines called for liquid velocities below 7 ft/sec to avoid excessive pressure loss, pipe wear and high pumping costs. Much of this practice has been abandoned as too expensive, with engineers increasing flowrates and/or using smaller pipes to save initial costs, resulting in higher velocities. The following are some ways velocity-related problems can be avoided or mitigated.

High-fluid velocities are particularly problematic for flow measurement. Many plants that routinely use differential pressure (dP) methods experience this directly. For those situations, there are straightforward cures. First, it is important to minimize the pressure drop across the primary element. Second, velocity gradients within the pipe increase with velocity, so an averaging reading across the full cross-section must be taken to ensure an accurate measurement, especially with large line sizes.

One way to solve both problems is to use a specific type of primary element design instead of a conventional single orifice. An averaging pitot tube sensor is minimally intrusive in the pipe, can work symmetrically for bi-directional flow and self-averages velocity gradients for high accuracy. It is suitable for liquid, gas and steam with velocities up to 300 ft/sec, and determines volumetric flow—which can be combined with a temperature measurement and known fluid density characteristics—to calculate mass flow.

Widely variable flow range. Most process units are designed to operate within a relatively narrow production range. With that knowledge, engineers can size instruments to fall in the measuring sweet spot during normal operation, but applications with a wide flow range can still create challenges. Coriolis flowmeters have an especially wide flow range but are not suitable for every application.

When conventional dP flow measurement techniques are used, some users resort to an outdated practice of double-stacking two dP transmitters with different measuring ranges on the same primary element. This works but is cumbersome for installation, maintenance and signal processing.

Today's dP transmitters are available with electronics that extend the measuring range to keep the percentage error range far more uniform. This avoids the problem of reduced accuracy at the low end of the range due to percentage-of-span accuracy characteristics.

Large line sizes. While many flowmeter types are highly scalable, creating versions for large pipe sizes can get expensive. An averaging pitot tube sensor is very well suited to large line sizes since it can be built for cross-sections up to 96 in.

Temperature measurements have different complications. Large line sizes call for long thermowells able to reach to the pipe center, but these are especially vulnerable to VIV. Again, using square helical thermowells verified by suitability calculations makes these difficult applications far easier to implement.

Help with dP flowmeter selection. DP meters have long been the most widely used technology for flow measurements thanks to their range of configurations and adaptability, but they can present challenges for a novice instrumentation engineer trying to choose from the variety of primary elements. Which best suits the application? Fortunately, any instrumentation engineer trying to make the best selection can use new online software tools[d] to simplify the choice. These tools streamline product sizing and configuration by generating flow calculations faster and with high accuracy.

Once the initial operating scope parameters are settled and the specific application is identified (instrument location, tag number, etc.), a flowmeter or primary element selection must begin with a detailed understanding of the application conditions, including piping size, process fluid and normal operating parameters.

Once these variables have been characterized, more subjective elements come into play. Questions to ask include:

- What degree of accuracy and turn-down range is expected?
- How much pressure loss can be tolerated?
- How easy is it to install a given type of primary element?
- How much straight pipe run is available and practical to deliver accurate readings?

These tools augment the limited experience of younger engineers, while expediting the selection process for their more experienced counterparts. The final presentation includes a table of data illustrating the operating characteristics in the application context. When the process is complete, the designer will receive a full configuration description and part number based on vendor catalog data.

PART 3: DEMANDING PROCESS FLUIDS

When considering instrumentation, it is important to look at what is flowing through the pipes—the process fluid itself—liquid, gas or steam. Characteristics that make a fluid extreme include some mix of abrasiveness, usually due to fine particulates or corrosiveness, due to highly acidic or caustic process media, or one containing aggressive chemicals, such as chlorine.

Some products can be highly toxic, flammable or environmentally dangerous, but these characteristics do not necessarily attack instruments and equipment. This section will concentrate on elements able to affect instruments and equipment directly.

The damage caused by these fluids is loss of metal, either eaten away chemically, worn away by abrasiveness or both. Solutions call for materials that are chemically inert relative to the fluid and/or hard enough to withstand the constant scraping action. When materials reach their limits, the solution may call for ways to live with a shorter service life.

For corrosiveness, the solution often requires wetted parts in a specialized alloy designed to withstand the service, including a large family of stainless-steels with high nickel (Ni), molybdenum and chromium content. However, the answer is not always so simple. Pressure instruments are particularly vulnerable to attack, so this calls for a closer look.

With severe fluids, containment is very critical, so engineers often use remote seals to eliminate the possibility of process fluid getting into impulse lines or the pressure instrument itself. These thin diaphragms have unique flexing characteristics to provide the necessary measuring sensitivity and accuracy. Fortunately, diaphragms can be manufactured from a variety of materials, including stainless-steels, tantalum and Ni-based alloys such as alloy C-276 or alloy 400.

All diaphragm materials have their limits for protection against abrasive fluids. The durability of these diaphragms can be increased with coatings of hard-carbon nanostructured material. The micro-thin coating withstands abrasion, extending service life up to 10 times compared to a standard 316 stainless-steel diaphragm in abrasive service but does not impact remote seal accuracy or sensitivity. The range of coating options also includes a variety of metallic and polymer materials.

Another problem is a seal's permeability to atomic hydrogen if present in the process fluid. Hydrogen atoms can migrate through the diaphragm and once in the fill fluid, form molecular hydrogen. Because molecular hydrogen is too large to permeate back through the diaphragm, it gets trapped and forms hydrogen bubbles in the fill fluid. These bubbles can severely affect transmitter performance. Depositing a 5-micron thick layer of gold to a stainless-steel diaphragm provides protection against hydrogen permeation.

Avoiding wetted parts. Where conditions make adding a conventional thermowell impractical, some users clamp a temperature sensor to the pipe. This provides a reading, but heat dissipation keeps the external temperature from fully reaching the internal value. Adding insulation can help, but the reading will likely never reach the degree of accuracy needed and changing external conditions will cause unpredictable fluctuations.

Specially designed temperature transmitters[e] make measurements outside of the pipe while solving the normal problems by using a different methodology to correct for heat loss (**FIG. 5**). These transmitters use an algorithm to compensate for heat transmission and external conditions. The user enters factors for the pipe material and thickness, and the instrument provides a process temperature measurement, often as accurate as a traditional thermowell installation.

When clamped on a pipe, the bracket holds a resistance temperature device (RTD) in contact with the pipe surface to ensure consistent heat transfer. Once insulated and operating, an algorithm compares the reading from the pipe's RTD to a second RTD in the transmitter. These two readings are continuously compared to precisely calculate the temperature inside the pipe, even when ambient and other conditions change significantly. The result is a highly-accurate temperature reading without the need for a process penetration.

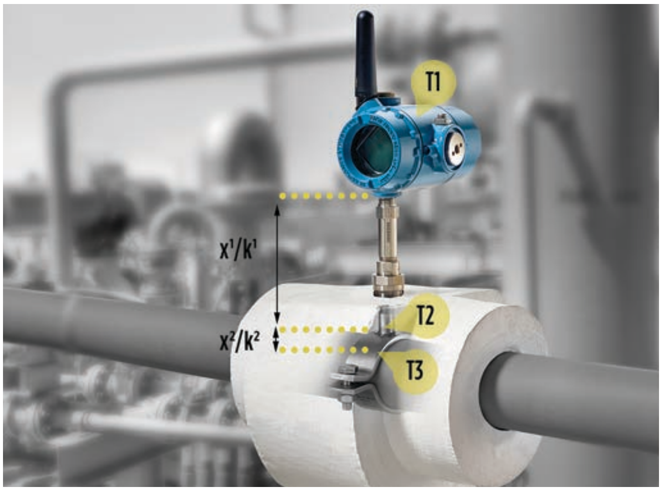

FIG. 5. A specially designed temperature transmitter[e] provides a highly accurate process temperature reading through a pipe wall without a penetration.

Designed for durability. Flammable or dangerous fluids require equipment designed with features that ensure reliable and safe operation in these environments. This often calls for construction using industrial strength proportions able to take the punishment, while allowing for changing out parts when necessary, with minimal disruption. Since dP flowmeters are frequently used in tough refinery service, this technology has been beefed-up to withstand the abuse.

This flowmeter is built upon a fully welded spool section with built-in isolation valves and temperature input. It comes fully assembled to the dP transmitter and is leak tested at the factory, and it uses a multi-orifice primary element to minimize the need for upstream and downstream straight pipe run. The impulse lines are short, and the dP transmitter is close-coupled to minimize the potential for plugging. The impulse lines also have gate-type isolation valves and clean-out ports so they can be rodded out while the unit is in operation. The entire dP transmitter can be removed and replaced without a process shutdown.

The assembly can include an integral temperature sensor that sends its information to the main dP transmitter, which can report the value to the automation host system. When the fluid temperature is combined with the dP volumetric flowrate and a known fluid density, the transmitter can provide a mass flow measurement.

The dP transmitter can also provide static line pressure values to enhance the mass flow measurement without the need for an additional pipe penetration. A setup such as this can typically handle fluids up to 315°C (600°F) or higher, depending on the application and installation.

PART 4: EXTREME TEMPERATURES

When considering difficult temperatures, hot usually comes first, but cold also presents challenges, particularly in cryogenic ranges. With either extreme, the first step is protecting electronics since circuit boards and components have limited temperature operating ranges.

As for instrument configurations, many of the same techniques used to protect from aggressive fluids protect from cold and hot temperatures, although there are some specialized variations. The following will detail how these solutions work together.

Low environmental temperatures. The cold end of the temperature range is doubly problematic because it can reflect not only the process fluid, but also the environment. Some oil production areas in Canada and Russia routinely experience winter temperatures of –40°C (–40°F), which affect equipment as well as people.

Many electrical devices work better in mildly colder weather. However, problems begin to develop when sophisticated devices—such as the A/D converters and other elements of field device transmitters—move out of a moderate range. Fortunately, many transmitters have more robust circuits, and the internal components are less affected by colder temperatures.

Many transmitters can operate at temperatures down to –40°C (–40°F), but this limit can be extended to guarantee startup down to –60°C (–76°F). However, the transmitter

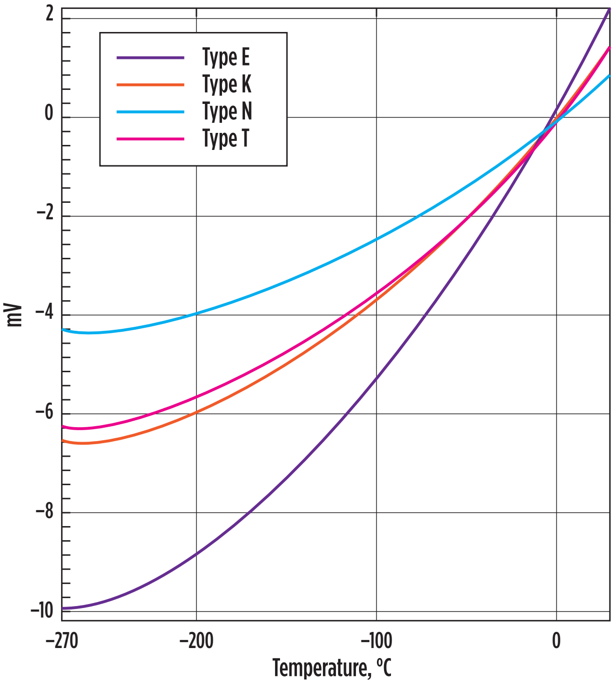

FIG. 6. Thermocouples are better than RTDs for low temperature, but it is critical to compensate for changes in linearity.

may not deliver full accuracy if the temperature remains below −40°C (−40°F).

In these environments, more extreme measures are often used, including the liberal use of heat tracing and heated instrumentation cabinets. Fortunately, specialized instruments are available to handle the most extreme cold temperature ranges without the need for extra protection.

Measuring cryogenic temperatures. Conventional temperature sensors can often be used even at the low end of the spectrum; however, there are limitations. Whereas RTDs are often a first choice for many normal applications, when reading below −50°C (−58°F), it is critical to know the sensor's rating. Different classes of RTDs have different low limits, ranging from −50°C to −200°C (−58°F to −328°F). Thermocouples are better adapted to handling low temperatures, provided an appropriate type is selected. Some—such as type B—simply are not suitable for low temperatures. Types E, K, N and T have ranges down to −270°C (−450°F), with Type T especially popular in cryogenic applications.

Once below −100°C (−150°F), most thermocouples begin to lose linearity (**FIG. 6**). This is not necessarily a problem since it is a known characteristic and can be corrected in the transmitter. However, not all temperature transmitters or controllers are set up to work at the low end, so users must ensure any device intended for these applications has the required capabilities.

DP flowmeters for low temperatures. Out of the many potential flowmeter technology choices, dP flowmeters using appropriate dP transmitters are well suited for cryogenic liquids, such as LNG. Users must pay particular attention to the placement of the various devices and the material selection for components.

For dP flowmeters in conventional liquid applications, the typical mounting position places the transmitter and impulse lines below the pipe to prevent air and gas entrapment. LNG applications reverse this, positioning the transmitter above the primary element (**FIG. 7**) so there is an insulating gas barrier preventing contact of the cold liquid directly with the transmitter diaphragm. Brief direct contact should not cause the instrument to fail, but it will slow responsiveness.

FIG. 7. DP flowmeters can be used with LNG and other cryogenic liquids, but the transmitter should be placed above the pipe.

The transmitter has a stainless-steel body that can handle the cold, but it is important to look at other parts, such as the impulse lines. Designers must ensure gaskets, O-rings and bolts are also compatible with these low temperatures, as the wrong materials can become brittle and lead to leakage. DP flowmeters equipped with welded impulse lines reduce the potential for sealing material embrittlement by moving gaskets away from the frost line. Impulse tubing should have a small diameter—typically 0.25 in. (6 mm)—to help maintain the gas barrier.

Isolating the transmitter. Treatment of high- and low-temperature applications uses similar techniques as those employed for handling aggressive fluids. A diaphragm seal can be used for pressure or level measurements, but extreme temperatures call for specialized fill fluids designed to retain their fluidity at the operating temperature without freezing or boiling. In cases where the length of the capillary lines allows the fill fluid to come to ambient temperature, it can slow response or cut it off entirely.

Some stand-off mounts use two fill fluids, one optimized for the process temperature and the other for the ambient temperature. Each fill fluid is tailored to the application and environment, eliminating the need for heat tracing or other protection meth-

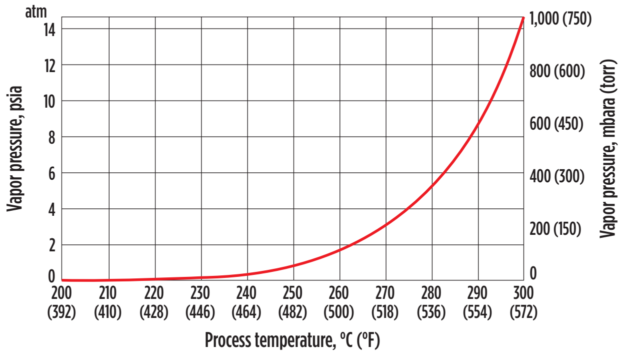

FIG. 8. Pressure and temperature figure into selection of a fill fluid in a high-vacuum application.

ods. With appropriate fill fluids, dual-fluid mounts can be used for temperatures up to 410°C (770°F) or down to –105°C (–157°F).

PART 5: SEVERE PRESSURES

Like temperatures, extreme pressures can be high or low, and both ends of the spectrum present their unique challenges. A pressure gauge or transmitter must be able to operate continuously—potentially for 1 yr—within its expected operating range, and it should also withstand pressure spikes. Countless mechanical gauges have suffered damage in this way due to their delicate internal mechanisms. A bourdon tube pushed past its limits will not return to the correct shape or may simply burst. Fortunately, electronic transmitters provide more robust construction, allowing them to absorb severe increases in process pressure and return to normal operation as if nothing happened.

Most general process instrumentation providers max out at 20,000 psi (1,379 bar), since applications beyond this are rare and highly specialized. A proprietary electronic pressure gauge[a] does not have a conventional mechanical mechanism. Instead, it uses the same sensor technology as electronic transmitters, thus avoiding common traditional gauge failures. This pressure gauge can measure up to 10,000 psi (690 bar), with overpressure protection up to 1.5 times its range.

When a more conventional pressure transmitter is needed, in-line pressure transmitters cover a variety of ranges—up to 20,000 psi (1,379 bar) gage pressure or absolute pressure. Many are SIL 2/3 certified for use in the most safety critical applications. In addition, many include basic and advanced device diagnostic capabilities.

Panel-mounted transmitters can also handle up to 20,000 psi (1,379 bar) gage pressure or absolute pressure. These devices are compact, lightweight and can come with all-welded, stainless-steel construction, providing a stable and robust solution for harsh environments.

Tough dP flow measurement. Consider the challenge of measuring flow of a high-pressure line—e.g., 5,000 psi (345 bar)—using a dP transmitter and conventional primary element. There will be a pressure drop across the primary element, but if the application is engineered well, it should only be around 30 psi (2 bar) at normal operating range. This presents a serious challenge for the transmitter to produce a precise reading of a very small pressure differential in an environment where the static pressure can easily be hundreds of times more than the differential.

Some dP transmitters[f] are designed exactly for this scenario. They have a modest measuring range up to 150 psi (10.3 bar) but can withstand static line pressures up to 15,000 psi (1,034 bar). Their construction can resist overpressure and line pressure effects to maintain high accuracy and stability, even in harsh environments.

Working in a vacuum. Low pressures are anything below atmospheric: 14.7 psi (1 bar) absolute. Measurements made in these conditions still use the same instruments and associated equipment, including diaphragm seals, but special consideration must be given to the fill fluid. When enough vacuum is applied to a liquid, it can reach its boiling point and vaporize. If this happens to the fill fluid, it can cause the whole system to fail. These issues are exacerbated when ambient or process temperatures are high.

When the process is under vacuum conditions, the fill fluid will vaporize under a lower temperature than when it is operating under normal atmospheric or greater pressure. Fortunately, there are a variety of fill fluids for remote seal systems, each with a specific vapor-pressure curve (**FIG. 8**) indicating the pressure and temperature relationship where a fluid remains in a liquid state. When a diaphragm seal is used in a vacuum application, all-welded construction avoids drawing air into the capillary system.

The right tools. Any reasonable person participating in extreme activities, whether for pleasure or work, will want to have the right protective equipment because it is critical to success and even survival. In a similar manner, products for extreme applications are designed to ensure reliable performance and safety in the most challenging applications. The technologies and practices suggested here are designed to improve instrumentation performance, increase reliability and reduce maintenance. None require major capital projects, nor do they have to be executed on a grand scale. Each improvement can be implemented one-by-one to deliver incremental gains and a quick return on investment, eliminating obstacles to effectiveness and profitability. HP

NOTES

[a] Rosemount™ wireless pressure gauge
[b] Emerson's Thermowell Design Accelerator
[c] Rosemount Twisted Square™ thermowells
[d] Emerson's dP Flow Sizing and Selection Tool
[e] Rosemount X-well™ technology
[f] Rosemount 3051S High-Static DP Transmitter

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