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Innovations & Best Practices

Table of Contents

Novel devices and new superpowers. 4

How best to apply multiple-hole
orifice plates? 12

'Best bet' use cases for Ethernet-APL 17

A power-law approach to
orifice calibration 19

Ad Index

Krohne 3

Sierra Instruments 11

Endress + Hauser 16



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Novel devices and new superpowers

Ethernet-APL promises to open the digital field to entirely new types of devices. The higher power and faster bandwidth of HART-IP over Ethernet-APL will also make possible a host of new capabilities in the field instruments of tomorrow

The first leg of the journey to Ethernet-APL is to fully liberate all that secondary instrument data that has long gone underutilized across the process industries. Indeed, a growing number of progressive process manufacturers are using multiplexer technology to extract all that rich, digital HART data from their 4-20mA analog loops—and already are using that data to effectively advance their digital transformation initiatives. HART-IP over Ethernet-APL will just make that access simpler, faster and easier.

Over the past several years, network infrastructure specialist Phoenix Contact has seen a significant uptick in the number of users retrofitting their plants to bring previously stranded HART data up into asset management and other monitoring systems, according to Garrett Schmidt, senior product manager.

“We know that most of these devices are going into brownfield facilities,” Schmidt explains. “They’re connecting to 4-20mA HART instruments with the highest value data first—typically more complex instruments such as valve controllers and flowmeters—then building out from there.” A confessed IoT junkie, Schmidt attributes the growing interest in continuous, full-time access to HART data to organizations’ digital transformation initiatives.

3M is among those end-user companies that has placed a new emphasis in recent years on the value it can derive from continuous access to HART data, according to Robert Sentz,

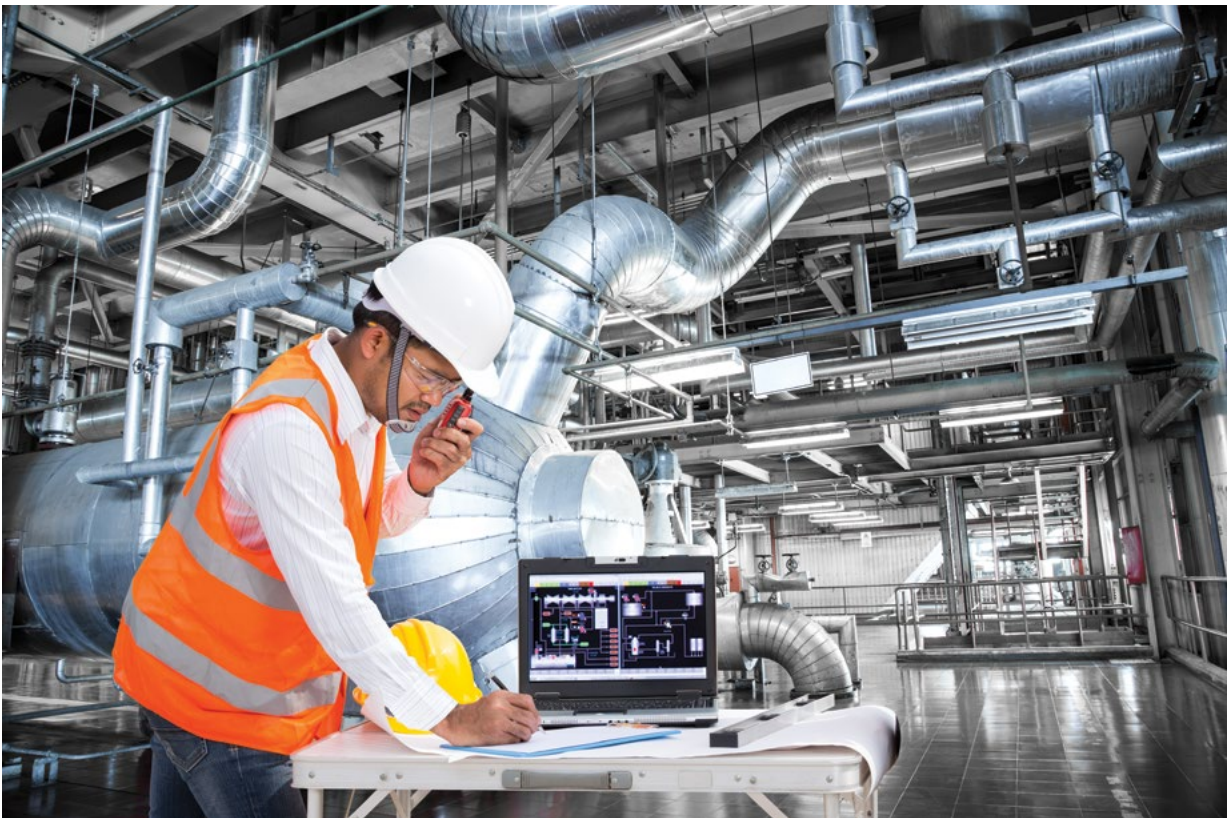
senior engineering specialist. “We are using more and more of that the available diagnostic data from smart valve positioners, smart pressure, temperature and flow instrumentation,” he says. Indeed, the company is betting its operational future on digital technologies such as performance-driven analytics and prescriptive maintenance enabled by instrument data. “All that HART information is getting to be almost as critical as the process measurement, the process control piece itself,” Sentz says.

“HART over analog loops is very robust, but it’s also slow,” Sentz adds. “So, I’m very intrigued by the potential to further improve plant performance and availability with Ethernet-APL and HART-IP.”

And while HART-IP over Ethernet-APL will dramatically improve the accessibility and utility of data in today’s instruments, the second leg of the Ethernet-APL journey will pair that new speed with higher instrument power and protocol independence to launch a whole new world of transformative possibilities.

ENHANCED CAPABILITIES

Higher bandwidth and more available power will allow makers of today’s process instruments to create new sources of value in their next-generation, Ethernet-APL-enabled devices. Future pressure transmitters, for example, may include multiple, automatically ranging sensors, which would allow a given transmitter to cover a broader



range of pressures without sacrificing accuracy, envisions Jonas Berge, senior director, applied technology, Emerson. Notably, this would solve the problem of needing to stock a large inventory of pressure transmitters for various applications.

Similarly, more available power will allow makers of two-wire flowmeters to increase the excitation signal of Coriolis or magnetic flow-tubes, enabling higher turndown ratios—and more accurate measurements at low flow rates. It will also allow two-wire, Ethernet-APL flowmeters to handle larger pipe sizes than currently possible.

More available power would also allow two-wire flowmeters to continuously perform a broader range of process diagnostics, for example, detecting corrosion in Coriolis meter tubing, says Andy Kravitz, instru-

mentation connectivity product manager, Emerson. Currently, the negative effects of corrosion can be detected by initiating a Smart Meter Verification test. However due to the speeds of today's protocols, most users only receive a pass/fail signal alerting them to a problem after it has affected meter performance. With Ethernet-APL, users will be able to easily pull the underlying diagnostic variables into their analytics systems. "In effect their ability to monitor the corrosion in their meter would change from reactive to proactive, allowing them to mitigate problems before a meter failure has occurred," Kravitz explains.

Process-induced measurement noise is a problem for many sensors today, adds Berge. But with more power for the micro-processor, future sensors may feature more advanced signal processing to overcome



the effects of noise. And in extreme cases, the sensor may be able to leverage the capabilities of a remote server to provide further analysis. “Perhaps next-generation, non-intrusive ultrasonic flowmeters will perform at a level high enough to calculate mass and energy balances on heat exchangers,” Berge says. “This would solve the problem of having to cut and weld pipes or otherwise disrupt the process to get a reliable flow measurement.”

Pressure drop, flow, vibration and acoustic noise are useful inputs in detecting and predicting control valve failures, but typically go unmeasured on a routine basis. With Ethernet-APL networking, it will be more practical to measure and integrate such

external variables into valve diagnostics to provide more predictive and prescriptive analytics.

The scope of diagnostics for instruments such as digital valve controllers will also begin to include other related data from “peer” devices on the network, predicts Kurtis Jensen, valve instrumentation portfolio manager, Emerson. “Instruments will become more process aware,” he predicts. “If my valve controller shows the valve is closed, yet there’s still pressure drop across a downstream orifice plate, it can tell me there’s a problem.”

More broadly speaking, Ethernet-APL will make it possible to utilize instruments’



auxiliary variable measurements more fully. For example, measures of ambient temperature across all instrumentation points in a plant could be used to create a thermal map of the entire facility, providing early detection of a fire or fire hazard. Most field instruments already include such auxiliary measurements today, but they usually go unutilized.

Another transformative aspect of Ethernet-APL technology will be to replace the patchwork of application-specific networks used in process environments, building toward a single, unified network architecture. For example, today's addressable fire and gas (F&G) detectors use proprietary application protocols and therefore require dedicated networks. In the future, F&G detectors of various kinds may share the same Ethernet-APL/HART-IP network with the rest of a plant's instrumentation. Such solutions will likely be more economical to deploy, allowing more detectors for better coverage in tight spaces such as offshore rigs and production units. The units will be safer, and the systems easier to maintain as a result.

One significant new capability of Ethernet-APL instrument networks actually has nothing to do with the instruments. Rather, it's built into the network itself. Sometimes referred to as intelligent networking, the communications chips provided by Analog Devices continuously measure noise levels

on each network segment and can alert if link quality degrades. Devices can be configured to run such link quality diagnostics on a regular basis, and if there is an issue, the diagnostics can even indicate the location of the problem, explains Fiona Treacy, marketing manager, Analog Devices. "We can pinpoint the location of a problem to within 1%," she says. "So, for a kilometer of cabling you can tell where a short is to within 40 meters."

Novel devices, complementary protocols. Some in industry envision a real-time digital field network as just a replacement of 4-20mA process variables, control commands and secondary diagnostic and configuration data using digital HART-IP signals. But the possibilities are much greater than simply enhancing the capabilities of current field instruments and rapidly sharing their data with the people and applications that can put it to work. Rather, we should also recognize the potential for Ethernet-APL to enable entirely new kinds of field instruments solving previously unsolved problems.

Setting the range in a pressure transmitter without applying an input might have been impressive 30 years ago. But today we expect far more from a "smart" device. We should expect other time-consuming tasks to be eliminated or simplified in similar ways. And with 4-20mA signals replaced by HART-IP over a fully digital Ethernet-

APL infrastructure, field instrumentation will finally be able to benefit from the dramatic technology advances that have transformed computing and communications in our personal lives.

Indeed, today's expectations for new smart devices for industry should model the breakthroughs brought about by the mobile phone network. Once the GSM network supported GPRS data, it wasn't long before the first smartphone appeared. Little did we realize; the smartphone was a full-fledged pocket computer and communicator that coincidentally made phone calls. So, expectations for industry's future should not be just better transmitters, but also new classes of field devices.

Among other implications, digital transformation of plant operations means that many monitoring tasks which have until now been done manually by operators on rounds with portable testers will instead be done continuously and automatically by permanently installed sensors. Common examples of this include vibration, temperature, acoustic noise and corrosion (wall thickness) measurements.

Audible noise sensors (microphones) that share the common Ethernet-APL backbone may be used to identify noisy hotspots, helping to assure protective measures for employees, the tranquility of neighboring communities and compliance with ever

more stringent regulations. The abundant power and high bandwidth of Ethernet-APL networking may also enable noise spectrum analysis, identifying sources of noise and possibly diagnosing process and equipment problems from changes in noise patterns.

Machine vision has been used in discrete manufacturing for years. In the future, perhaps there will be two-wire infrared cameras for liquid leak/spill detection sharing the same Ethernet-APL network as other devices. And instead of portable thermographic cameras to measure equipment temperatures, there may be permanently installed two-wire thermographic cameras to automate manual inspection. Other possible applications include flare monitoring and smoke detection, recognition of unauthorized intruders as well as proper use of personal protective equipment by authorized personnel. All these measures could reduce hazards and improve security and safety.

A field-mounted two-wire vibration transmitter sharing the same HART-IP over Ethernet-APL network as other field instruments may in the future support sophisticated, fast-Fourier-transform (FFT) edge analytics to head off quickly developing problems with pumps, fans and other rotating equipment. Operations, maintenance and reliability personnel may even collaborate over a livestreamed vibration spectrum, including waveforms and orbits, to better understand potential issues.

While HART-IP over Ethernet-APL is suitable for many of these new devices, others will operate best through other Ethernet application protocols often developed specifically for that type of device. A key attribute of Ethernet-APL is that contrary to previous field device communication alternatives, it is non-exclusive. That is, a mix of application protocols can be used simultaneously, even on the same pair of wires. On the industrial side, HART-IP can co-exist with Profinet, EtherNet/IP, OPC UA and others. Meanwhile, it can also coexist with non-automation protocols such as RTP or RTSP for digital video.

So, all devices on the network need not use the same protocol. Not even all the instrumentation. A transmitter using HART-IP and a valve using Profinet can even participate in the same control loop—but the controller in between must be able to handle both protocols.

A MORE TRANSPARENT FUTURE

A key advantage of implementing Ethernet-APL together with HART-IP is the extensive, global interoperability ecosystem supporting HART together with industry-wide familiarity with HART and the tools and work processes that support it. Preserving this common ground will be critical to easing industry's transition to an Ethernet-APL future.

Longer term, higher bandwidth and more powerful devices will make understanding the underlying protocols less significant for end users, predicts Peter Zornio, CTO Automation Solutions, Emerson. “Eventually, talking about whether a particular instrument is using HART-IP, Profinet or EtherNet/IP will be like talking about whether our cell phones are using CDMA or TDMA.” Similarly, intelligent device management software promises to abstract the management of field devices from the details surrounding Field Device Integration technology and underlying profiles.

In the near term, however, what doesn't go away is the interoperability ecosystem that underlies the HART configuration and management tools in every distributed control system (DCS) and asset management system on the market, Zornio stresses. “When you sit down at the DCS to configure a new Ethernet-APL device, you don't have to care about the new physical network or the protocol—it's just a HART device like 4-20mA HART and WirelessHART devices,” he says. “Granted, a lot more data comes out a lot faster than it used to. And if we can deliver that impact without changing a lot of processes along the way, we'll have accomplished our goal.”

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How best to apply multiple-hole orifice plates

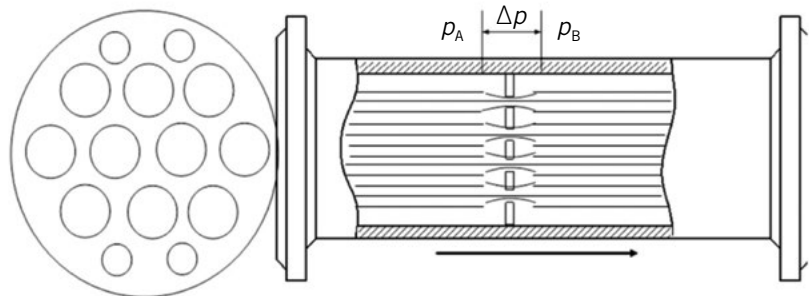
They can help measure d/p with shorter straight pipe runs, as well as tame cavitation and excessive noise

by Béla Lipták

Q: With a conditioning orifice plate, how many holes are allowed? Is the maximum limit for the pressure drop through an orifice plate the same as the maximum differential pressure of the transmitter? Are there any other limitations?

M. Ulaganathan

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RESTRICTION ORIFICE SECTION

Figure 1: One advantage of a multi-hole orifice section is it requires much less straight pipe run (about 2D on each side) than regular orifices, and can be mounted in horizontal and vertical pipe runs.

A1: Some multiple-hole orifice plates are used as “restriction orifices” (RO), serving to reduce or eliminate noise and/or cavitation. ROs are also used in front of safety devices (rupture discs, relief valves), which

if they suddenly open, can overpressure downstream equipment. Therefore, it’s desirable to limit the flow and the rate of pressure reduction through them, so the pressure on the upstream, protected equip-

ment doesn’t drop too fast. In a multi-hole plate, the flow is channeled into several streams through multiple holes (Figure 1). This reduces the noise that could be above acceptable limits if a single-hole device is used.

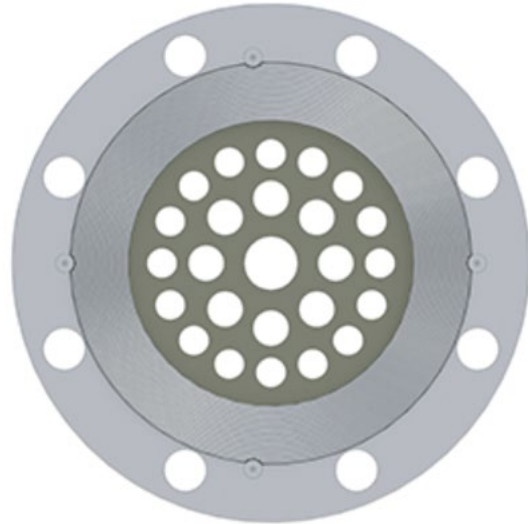
Such a unit can also be used either for pressure differential or flow measurement, depending on which variable is known. I usually estimate the flow through each opening as the total flow divided by the number of holes, ρ , as the density of the fluid, while the pressure drop (ΔP) is measured. Therefore, if ΔP is known, the flow (Q) is:

$$Q = \frac{kA \sqrt{\Delta P}}{\rho}$$

where A is the cross-sectional area of the pipe and k is a constant that includes the effects of the ratio between the total area of the holes and that of the pipe, the engineering units used and such meter characteristics as the thickness of the plate and the quality of the holes (Figure 2). For an area ratio of 0.5, the pressure drop across the multi-hole orifice is about 70–75% of the conventional single-hole orifice.

The orifice thickness is usually twice the hole's diameter, so a large diameter hole could involve an excessively thick plate. Also, while in the case of a single-hole plate there's no "neighbor turbulence" effect that chokes pressure recovery, for a multiple-hole plate the expansions of one jet will impact expansions of the others, limiting pressure recovery. That can be one reason why, for high-pressure drop applications, multiple-hole orifices are chosen.

Some studies suggest the optimum number of holes is seven, but that view is not uni-



REDUCE NOISE AND CAVITATION

Figure 2: The flow at the inlet of a restriction orifice is channeled into several streams. Among other characteristics, this reduces the noise and/or cavitation that might occur with a single orifice.

formly shared, and there are other considerations concerning strength and dimension. Accuracy greatly depends on the quality of the holes, and is usually estimated at only 1-2% over a range of 3:1, but the repeatability is usually better than the accuracy. The range of the differential pressure (d/p) transmitter is usually selected to be 1.2 times the maximum ΔP expected.

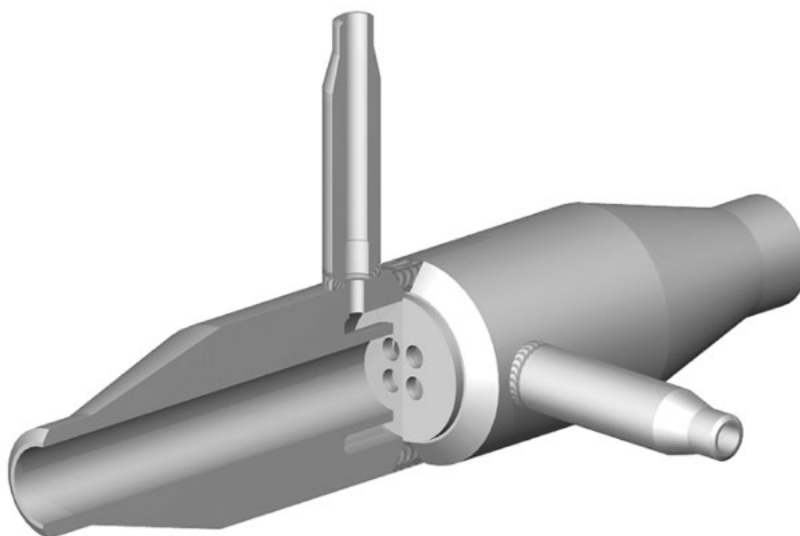
Béla Lipták

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A2: There are no codes or standards governing conditioning orifice plates—the formulas are proprietary to the suppliers of these plates. Also, there are practical limitations based on particulates and clogging of the holes. This is best discussed with the vendor.

The limit of the d/p across the orifice plate has nothing to do with the transmitter. The limitations are purely from a process sizing perspective (e.g. Reynolds number). Read ISO 5167 or other good texts such as Lipták or Miller. The transmitter range is then specified to match the orifice sizing requirements

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CONDITIONING ORIFICE SPOOL-PIECE

Figure 3: Welded-in, spool-piece designs featuring conditioning orifices and pressure taps can be used to measure flows in both vertical and horizontal pipe runs.

A3: Generally, orifice plates have either one or two holes: one for the flow and one for the drain or vent. In special applications, where you may have slurries or special fluids, then you may have more, but be aware that calculating the pressure drop is a complicated process and making the orifice plate even more difficult.

The majority of manufacturers have a maximum pressure drop that the sensing element can respond to accurately before you need

to change to a sensor with different characteristics. The maximum pressure loss will depend on several factors such as line pressure and maximum line pressure drop. For example, at a line pressure of 1 bar, the pressure drop should be less than 0.1 bar, otherwise the line hydraulics will be affected.

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A4: There is no simple answer here, but a range of standards and handbooks show typical designs and

applications. In general, the intent of a multiple-hole orifice plate is to serve as a flow conditioner, that is, to make the flow velocity pattern similar to one in a very long straight-pipe run. Again, see the handbooks and the standards.

Usually we don't want to waste energy across a flow-meter, so d/p is normally in the range of 20 to 200-inH₂O (500 - 5000 mmH₂O). This is high enough to realize d/p transmitter accuracy and to be certain of the Reynolds number inside the bore.

For an area ratio of 0.5 (hole area to pipe cross-section), the pressure drop across the multi-hole orifice is about 70-75% of the conventional, single-hole orifice plate.

In the case of liquids near boiling temperature, excessive d/p may lead to vaporizing of the media. For gases, excessive d/p leads to inaccuracy due to the expansion of the gas not being fully compensated for in the equations. Some standards and handbooks will show at least a plot of the pressure recovery after an orifice plate; this depends mostly on the beta ratio, which is ratio of bore diameter to inside pipe diameter.

An orifice plate will deform or fail if the pressure drop is very high; this is a strength of materials issue. This is very rarely an issue except for flow restriction orifice plates. Flowmeter suppliers can provide further details.

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‘Best bet’ use cases for Ethernet-APL

While industry awaits the opportunity to deploy a critical mass of Ethernet-APL devices in a new plant or unit, we’ll also be looking for opportunities to verify the benefits of the new technology when adding new instruments to an existing operation. These “best bet” use cases that can begin to bring value in the absence of a full architectural shift will be those instruments that will benefit most from the dramatically faster data rates or higher power that Ethernet-APL can deliver. Here, then, a roll call of top prospects.

Digital valve controllers are among the most promising use cases for Ethernet-APL plus HART-IP in part because there’s so much HART data related to their operation that it’s hard to gain an accurate picture of their operation in a timely fashion via traditional HART communications. That usually means a trip out into the field with a handheld communicator or PC, but “running a detailed valve analysis might still take 15 or 20 minutes to complete,” notes Kurtis Jensen, valve instrumentation portfolio manager, Emerson. “But with HART-IP over Ethernet-APL, engineers and technicians will be able to see things that they hadn’t before.”

Coriolis meters are similarly complex and pack a lot of localized intelligence such as for remote verification that the meter’s operating characteristics have remained unchanged since installation. With today’s communication technologies, most users rely on a simple pass/

fail command to transmit their verification status back to the control room, but the increased bandwidth of HART-IP over Ethernet-APL would allow personnel to dig into the raw data behind the test and determine the root cause—all from the relative safety and comfort of the control room or even a remote service center.

Magnetic flowmeters also include sophisticated onboard diagnostics to verify the continued integrity of the tube, coil and electronics. Again, HART-IP over Ethernet-APL would allow a remote user the ability to dig into the raw data behind these pass/fail tests.

Radar level gauges are a third group of instruments whose sensors have a characteristic signature that can be used to verify proper operation or alert the operator to problems such as an antenna coating interfering with its proper operation. Such signatures consist of a large amount of data that cannot be efficiently communicated via

traditional HART and would benefit from HART-IP over Ethernet-APL.

Process analyzers are a good candidate for Ethernet-APL because the new physical layer can deliver nearly 10 times the intrinsically safe power of a 4-20mA analog loop. So, one may be able to provide both power and high-speed communications over a single, two-wire Ethernet-APL connection rather than the power wiring plus four-wire Ethernet connection traditionally required.

Multivariable measurements are yet another promising use case for HART-IP over Ethernet-APL, making it easier to power and communicate HART diagnostics from multiple related instruments, such as the multiple sensors included in a temperature-compensated, differential-pressure flowmeter. It could also allow for one Ethernet-APL spur to connect with multiple temperature sensors, obviating the need for separate transmitters.

A power-law approach to orifice calibration

Fine-tune the ideal orifice flow rate equation with an additional term and baseline measurements.

by R. Russell Rhinehart

The ISO method for orifice design and calibration [1] is grounded in the ideal square-root relation between pressure drop and flow rate; specifies the in-pipe structure for an orifice; and corrects the nonideal relation with empirical relations. Unfortunately, for the empirical correction, the complexity of the 28-coefficient Reader-Harris/Gallagher equation and the eight-coefficient expansibility relation add potential for implementation error. Further, in many applications, the structure of the device or piping can't meet ideal specifications.

Of course, for official and legal situations, you should use the methods for orifice calibration as indicated by standards. However, engineering practice desires to minimize complexity. Accordingly, for internal use, you might find that relaxing the square-root basis provides a power-law relation that's much simpler and just as accurate [2]. Further, it doesn't require the piping structure that seeks to create near ideal up- and down-stream conditions, easing installation design constraints. However, it does require application-specific calibration.

ORIFICE ESSENTIALS

An orifice is a one-point restriction in a flow line. It's commonly a disk with a hole in the center. The disk blocks the flow, all of which must squeeze through the hole. The high fluid velocity in the low diameter area reduces the pressure relative to the larger diameter up-stream entrance section. The higher the flow rate, the greater is the pressure difference.

Since pressure difference is easy to measure, and since orifice assemblies are inexpensive to make and easy to adjust, orifice flow measurement is very common. In the following analysis, the pipe diameter is indicated by D and the orifice diameter by d_o .

Analysis of the orifice flow rate-to-pressure drop relation typically starts with the Bernoulli equation, which is idealized for potential flow conditions (inviscid, constant density, isothermal, no lost work) along a streamline. Commonly derived as an undergraduate exercise, one form of the resulting orifice equation is:

$$\dot{Q} = \frac{\pi}{4} d_o^2 \sqrt{\frac{2g_c \Delta P}{\rho (1 - \beta^4)}} = a \sqrt{\frac{\Delta P}{\rho}} \quad (1)$$

Where $\beta = d_o/D$, and a is a combination of the several constants for a particular application.

The “hole” however, could be any number of shapes, or it could have an eccentric location, both features to permit entrapped gases or solids to pass through. Further, actual devices have many other features, such as piping flanges and pressure taps at various locations. Further, turbulent flow does not have the ideal flat profile that leads to the classic square root relation. Note also that the points of pressure measurement are not where the flow has an effective diameter of either D and d_o . At the upstream pressure tap, the flow begins converging into the orifice, and has a smaller effective flow area than D would indicate. And the

flow continues to converge as it exits the orifice, so the effective flow diameter at the downstream pressure tap is less than d_o . These realities are dismissed in the conventional orifice equations, and a generally accepted correction to the ideal relation is:

$$\dot{Q} = C_d \varepsilon \frac{\pi}{4} d_o^2 \sqrt{\frac{2g_c \Delta P}{\rho_1 (1 - \beta^4)}} \quad (2)$$

Where ρ_1 is the upstream density, and C_d is a factor to correct for both fluid flow and assembly geometric nonidealities. C_d has a characteristic value of 0.62, for high Reynolds number situations. And, ε is a factor to correct for fluid compressibility effects. Both correction factors are empirical. The standard C_d relation uses flow rate (Reynolds number), so the calculated flow rate is required to calculate the C_d value needed to calculate the flow rate. Accordingly, obtaining $\dot{Q}$ from Equation (2) requires an iterative calculation procedure. That is an undesired complexity.

Further, the physical design of many orifice applications is not compliant to ISO standards. These include process installations without flow conditioners, without adequate upstream run, with pipes of less than about 2-in. diameter or integral orifice assemblies, such as flow devices on equipment and those used in pilot-scale applications. Without compliant geometries and installation, the standard equations don't provide accurate results. Providing an accurate calibration equation for non-compliant devices will improve their utility.

POWER-LAW PROPOSAL

Considering these issues, we find that a power-law relation provides an excellent and much simpler fit of the actual flow rate with respect to differential pressure. Accepting that the transmitted signal from an orifice differential pressure transducer, such as 4-20 mA, is linearly proportional to ΔP and that geometric factors are fixed for a specific installation, there's a convenience associated with combining all coefficients into one constant and representing ΔP with the scaled signal, such as $i - i_o$. This reduces the power-law orifice calibration equation to:

$$\dot{Q} = a \left(\frac{i - i_o}{\rho_1} \right)^b \quad (3)$$

Here, i is the transmitted mA signal, and i_o is the mA value at zero flow rate.

Note that Equation (3) is equivalent to the ideal Equation (1), but with an extra coefficient to account for the nonideality of fluid and device. The values for the a and b coefficients will be determined empirically to best fit experimental data.

Note that the value for the coefficient b should be close to the ideal 0.5, and that coefficient a should have a value close to the expected:

$$0.62 = \frac{\pi}{4} d_o^2 \sqrt{\frac{2g_c \Delta P_{max}/16}{(1 - \beta^4)}}$$

where ΔP_{max} is the ΔP range that corresponds to the 4-20 mA signal, and 16 is the range of the 4-20 mA signal.

For devices where off-line or even in-line calibration is possible to determine values of coefficients a and b , Equation (3) specifies a direct, not iterative, calculation. It's simple to understand. With little complexity and few coefficient values, it reduces the opportunity for implementation errors in equation transcription, unit consistency and coefficient value transcription.

PROVEN BY EXPERIMENT

The ISA Transactions article [2] provides experimental evidence for the utility and precision of Equation (3), using both pilot-scale experiments and the database that was used to generate the C_D and ε relations [3]. Coefficient values were obtained by a best fit of model to the data. Although a linearizing log-transform can convert this nonlinear regression exercise into a simpler linear regression, linearization distorts the relative importance of high-range and low-range data [4]. Accordingly, the power-law study used nonlinear regression to determine coefficients a and b for Equation (3) to best fit the data.

On a range of liquid and gas applications, the values of power b vary from 0.4858 to 0.5255 for our experimental air and water tests on the pilot-scale devices, and from 0.4887 to 0.4943 on the NIST database (flanged orifice types, compliant geometries and fluids that included water, gas oil, nitrogen gas and natural gas). Further, if the square-root functionality, $b = 0.5000$

is presumed, then the C_D correction should express a functionality that has the complementary power (for instance $0.5000 - 0.4887 = 0.0113$), which we found it does.

The accuracy and precision of Equations (2) and (3) were also compared. Accuracy is a measure of the model closeness of fit to the data, which can be indicated by any of several measures. In all of 10 cases investigated, the flow rate accuracy of Equation (3) was better than either Equation (1) or Equation (2).

Precision of the equations was assessed by a propagation of variance, which relates uncertainty on an input to the uncertainty of the calculated flow rate. The relative uncertainty values for the power-law model are lower than those for the ISO standard model. Further, they indicate that the power-law model proposed here will be useful over a wider range.

PARAMETERS AND LIMITATIONS

Even with the improved accuracy of the power-law model, orifice meters are not as accurate as some other flowmeter types. Best expectations cite a 2% error. If measurement accuracy and range are critical, another flowmeter type will likely outperform the orifice.

The power-law calibration procedure (to experimentally get values for two coefficients) requires calibration data that's

specific for the device, whereas using an ISO-compliant device will rely on standard equations. A case-by-case analysis is required to determine if the accuracy benefit and device geometry convenience are worth the calibration effort.

The calibration of the two-parameter Equation (3) does require at least two experimental data points. However, experimental noise will bias the coefficients. The accuracy and precision of this study was achieved with 15 or more experimental datasets throughout the operating range. However, such extensive calibration testing may not be desirable. If accuracy is important, use another flow metering device. If operational convenience is important, then the two-point calibration may be adequate.

The computational device you're going to use might not have the ability to compute a power-law.

Noise on the i value in Equation (3) and/or calibration drift on the i_0 value could result in the quantity $(I - i_0)$ having a negative value at very low or zero flow rates. To prevent an execution error, add a conditional to reset $(I - i_0)$ to zero if it is negative.

Replacing the standard equations with a power law require a case-by-case analysis of the infrastructure surrounding the orifice technology and practice (maintenance,

training, manuals, computer software, data acquisition hardware, etc).

For many industrial applications, in-line or off-line calibration testing is not practicable or compliance to standards is important. For these, compliance to the appropriate standard remains as best practice.

In conclusion, where flow conditions and assemblies don't approach ISO-compliant attributes, where off-line or in-line calibration is applicable and where the measurements are for internal use, my investigations find the power-law approach matches the nonideal fluid and device attributes, and offers advantages of calculational simplicity, precision, accuracy and rangeability over the use of the ideal square-root model.

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