

Advances in flow and level measurements enhance process knowledge, control

By Gregory K. McMillan

Smart measurements help analyze, diagnose, predict, control, and optimize process performance



Jobs in research, process development, process design, process technology, automation, operations, or maintenance depend upon the ability to see, trend, analyze, diagnose, and collect the information from measurements. Ultimately, what you want to know as an engineer or technician is “why.” Modern instruments have made great progress in not only answering “why” but also offering a higher level of plant performance. The material balance is at the core of the process and the “why.” Flow and level measurements determine the material balance, and hence, process behavior.

More obvious is the performance and integrity of control systems and safety systems depend upon the accuracy, reliability, and speed of the measurements. You cannot control or protect something you cannot measure.

Modern flow and level measurement instruments have made significant advances in addressing an industrial plant’s requirements through:

1. Technological advances in sensing element technology
2. Indication and integration of multiple measurements
3. Compensation of application and installation effects
4. Online device alerts and diagnostics
5. Remote configuration and calibration
6. Digital signals with extensive embedded user-selected information
7. Wireless communication

Transmitters with features 1 through 6 are classified as “smart” or “intelligent.”

Since the 1980s, the out-of-the-box accuracy of modern industrial instrumentation has improved by an order of magnitude. Consider the differential pressure transmitter (DP). The 0.25% accuracy of an analog electronic DP has improved to 0.025% accuracy for a smart microprocessor-based DP. Furthermore, analog DP accuracy often deteriorated to 2% when it was moved from a nice bench-top setting to service outdoors in a nasty process with all its non-ideal effects of installation, process, and ambient conditions. A smart DP with its integrated compensation for non-ideal effects will stay close to its inherent 0.025%

accuracy. Additionally, a smart DP takes 10 years to drift as much as an analog DP did in one year. (Note: Drift is an error that increases with time.)

Smart instruments offer the ability to report additional process variables, such as the local ambient and process temperature, and alerts based on a broad spectrum of device diagnostics. These variables and alerts are communicated digitally on the same signal as the primary process variable that is being measured. The visibility of this wealth of additional information has been greatly improved in the modern distributed control system and the associated asset management systems. The use of the Electronic Device Description Language standard technology for the interface to smart instrumentation enables easier and more effective access to and visualization of the information. Instrument suppliers can readily provide an interface that optimizes the look and feel of the data items in their devices.

Relative accuracy of inventory measurements

Accurate flow and level measurements are needed to control material balances (control material residing in the process and entering and exiting process) and residence times (amount of time material stays in a particular unit operation). Flow and level measurements can be calibrated online by the change in inventory detected by an accurate inventory measurement.

An example of the accuracies of properly set up and calibrated inventory measurements for changing process fluid compositions are listed below where 1 is the highest and 10 is the lowest accuracy. For the level devices, random errors are most important because we are looking for a change in level that would cancel out fixed (offset) errors. Note: Even the lowest accuracy device might be perfectly adequate for many applications where knowing the exact level or change in level is not necessary, such as surge tank level. For applications where residence time and material balance control are important, such as continuous reactor and column overhead receiver level, measurement noise

and sensitivity are more important than overall accuracy.

1. Radar level measurements (provided dielectric constant effects are negligible)
2. Coriolis flowmeter total (provided pipeline inventory effects are negligible)
3. Load cells (provided structural support and wind effects are negligible)
4. Ultrasonic level (provided vessel vapor effects are negligible)
5. Multivariable DP level (provided DP sensing line effects are negligible)
6. Magnetic flowmeter total (provided velocity and conductivity are above low limit)
7. Vortex flowmeter total (provided velocity and Reynolds number are within limits)
8. Multivariable DP flowmeter total (provided flow and Reynolds number are within limits)
9. Single direct connect DP level (provided DP sensing line effects are negligible)
10. Bubbler DP level (provided DP sensing line and bubbler effects are negligible)

A measurement device with higher installed accuracy can be used for the online calibration of devices with lower installed accuracy. For example, radar level and Coriolis flowmeter totals could be used to calibrate the other level and flow measurement devices on the list.

There are many opportunities for accurate level measurements to increase the tightness of accounting, custody transfers, batch charges, feed rates, residence times, and material balances. Some of the more prominent application examples involve tanks, columns, crystallizers, and reactors.

Storage tanks

Raw material and product storage tanks require the best level measurement accuracy, particularly resolution, sensitivity, and repeatability when used in the calculations for:

- Inventory accounting
- Custody transfer
- Batch charges
- Continuous feed rates
- Material balances

FAST FORWARD

- New sensor technologies with integrated intelligent compensation, diagnostics, and communication have made a dramatic improvement in the accuracy and maintainability of flow and level measurements.
- Level measurements are important for the inventory and control of the quantity and residence time of material essential for product quality and financials.

Load cells were long considered to be the best means of inventory measurement for these tanks. Since load cells incur a large engineering and installation cost for the special piping, support, and calibration system, there has been an effort to seek alternatives that offer as good or better performance on the plant floor.

Radar gauges for inventory measurements are capable of an exceptional accuracy of 0.04 inches (1.02 mm). Since radar is a surface level measurement, the accuracy in percent of span gets better as the span increases. For a 15 foot (3.8 m) tall tank, the 0.04 inch accuracy corresponds to an incredible accuracy of 0.01% of span. When used in combination with a strapping table and a Coriolis meter for density measurement in a recirculation line, a radar device is capable of an unexcelled calculated mass or volume measurement in addition to level measurement.

Columns

One of the biggest and least recognized opportunities for sensitive level measurement and tight level control is overhead receivers on distillation columns. The most widely used column strategy control is the direct material balance scheme where temperature manipulates the distillate flow from the overhead receiver. The level in the receiver is controlled by the manipulation of reflux flow to the top of the column.

Vapor flow from the reboiler bubbles up through the column, condenses in the overhead exchanger, and accumulates in the overhead receiver. Reflux flows down the column and accumulates in the sump. A decrease in vapor flow from a decrease in steam to the reboiler or a sudden shift in wall temperature from a cold wind or cold rain will

cause a decrease in overhead receiver level. For tight level measurement and control, a small change in level will quickly translate to a change in reflux flow that will balance the change in vapor flow. This inherent self-regulation provides some internal reflux control and helps decouple the energy balance from the material balance. Since reflux flow is typically higher than distillate flow (reflux/distillate ratio >1), the level controller has plenty of muscle to keep the level exactly at set point.

The performance of the temperature loop depends upon a sensitive level measurement and tight control. When the temperature loop makes a change in the distillate flow, the change in controller output has no effect on column temperature until the overhead receiver controller makes a change in the reflux flow. If the level control is tight, the correction to the column is fast. In fact, to bring the level back to set point, there is some lead-lag action because the reflux must be driven momentarily past the balance point where reflux flow equals the distillate flow to keep the level constant. What is important here is not total accuracy but the ability of the level device to consistently distinguish as small a change in the level as possible. The level measurement must have excellent resolution, sensitivity, and repeatability (precision) and negligible noise or sufficiently filterable (e.g., high frequency) noise.

Crystallizers and reactors

From the 1960s to the 1980s, load cells in weigh tanks were the way to ensure the charges to reactors were accurate. Accuracy was typically 0.1% to 0.25%. Loss in weight was used to determine the charge and to provide a mass flow rate. Today, DP level and radar level transmitters with Coriolis flowmeters provide a lower cost alternative for accurately feeding critical unit operations.

In batch and continuous crystallizers and reactors pushed to capacity, the level is operated close to its high limit. Operation above this limit is undesirable because it may be above the heat transfer area and may allow some loss of material into the overhead vent system due to foaming and swelling from

bubbles, sloshing from agitation, and liquid entrainment in the vent gas.

For batch operations, a higher level offers a higher product mass per batch cycle. For continuous operations, a higher level enables a higher feed rate for the same residence time requirement. Conversion to product in continuous reactor vessels depends on the reactants or super-saturated components having enough time to complete the product or crystal formation. Most reaction and crystallization rates are not instantaneous. The conversion depends on residence time (inventory divided by throughput flow). Level should be kept proportional to production rate to keep the conversion constant. Excessive residence time can increase byproducts, product degradation, and crystal agglomeration.

Surge tanks

The normal purpose of a surge tank is to provide surge capacity. The level should be allowed to move up and down to absorb mismatches in process equipment operating rates upstream and downstream of the surge tank. However, when production rates are high or low, it may be desirable to operate at the tank's level limits. There may be residence time limits similar

to those stated above for reactors and crystallizers to keep the product concentration and quality constant or enable the product formation rate to continue to meet production rate requirements. Operation at level or residence time limits put greater demands on level measurement accuracy.

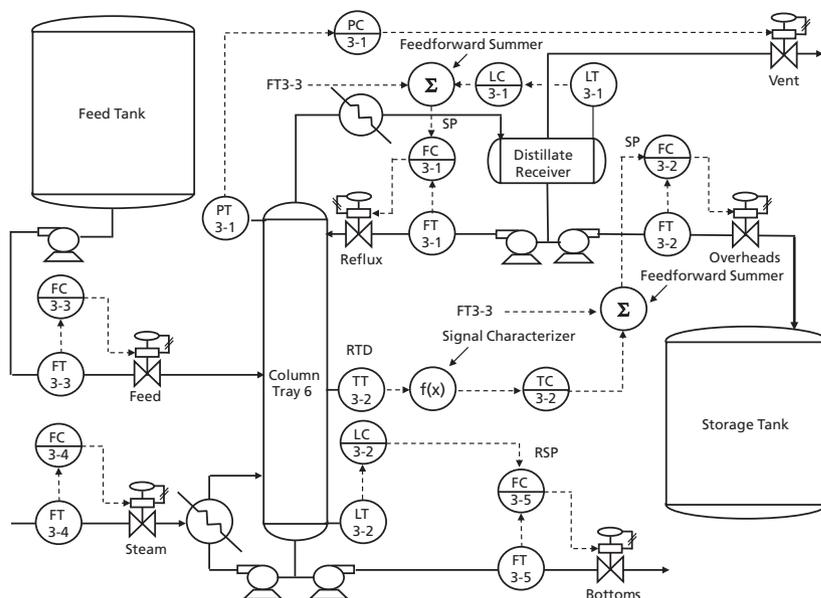
The primary way of affecting the process is by changing a flow. Whether you are considering supervisory, model predictive control (MPC), or PID control systems, what is finally manipulated is a flow in the process industry. In production units, the final control element is typically a control valve that introduces a nonlinear gain that is the slope of the installed characteristic.

Cascade control opportunity

A flow control loop can be closed around the control valve to provide a correction of valve position to maintain a flow set point regardless of the shape of the installed valve characteristic. If the valve is manipulated by process control loops, the effect of the non-linearity and uncertainty of the installed characteristic is moved from the primary process variable (e.g., composition, level, pH, pressure, or temperature) to the secondary flow loop where it is corrected by reset.

Flow feedforward for column temperature control

The addition of flow feedforward for column temperature control provides pre-emptive action for flow disturbances.



Feedforward control opportunity

There are flow disturbances from streams going into and out of the process. If a disturbance can be measured and the effect of the disturbance on the primary process variable can be calculated or identified, the measurement of the disturbance can be used to set the manipulated flow in anticipation of the disturbance's effect on the primary process variable. The primary controller then corrects the ratio of the manipulated flow to the disturbance flow. The use of a secondary flow loop removes the nonlinearity and uncertainty of the valve characteristic from the ratio calculation. This preemptive action, taken before the feedback measurement of the primary process variable fully sees the disturbance, is called *feedforward control*.

Some examples of flow ratios for feedforward control in the process industry are:

- Coolant/feed flow ratio for crystallizer, cooler, extruder, or exothermic reactor temperature control
- Steam/feed flow ratio for distillation column, evaporator, heater, dryer, or endothermic reactor temperature control
- Distillate/feed or reflux/feed flow ratio for column temperature control
- Reagent/feed flow ratio for pH control
- Additive/feed flow ratio for blend control (e.g., percent solids)
- Air/fuel flow ratio for boiler or furnace combustion control (oxygen control)
- Feedwater/steam flow ratio for boiler drum level control (three element control)
- Blowdown/feedwater flow ratio for boiler drum total dissolved solids (conductivity control)
- Supply/demand flow ratio for header pressure control

Process analysis

For billing and yield and cost-of-goods calculations, accurate flow measure-

ments are needed. As the cost-related importance of a stream increases, the need for flow measurement accuracy increases. The importance can be related to direct cost or to indirect cost from process impact.

Data analytics, such as principal component analysis (PCA), require flow measurements that are repeatable and linear. The use of valve positions instead of flow is generally unproductive because of installed valve characteristics. The use of split-ranged valves is even more problematic for PCA because of the discontinuous and nonlinear behavior from the additional stick-slip and flattening of the valve characteristic at the split range point.

Process modeling

Each of the following types of models benefits from accurate and repeatable flow measurements:

- Projection to latent structure or partial least squares (PLS)
- MPC
- PID adaptive controller tuning
- Neural network
- First principle

Flows determine what is going on in a process. If you do not get the flows right, not much else matters. Because of valve backlash, stick-slip, nonlinearities, and variable pressure drop, all types of process models have suffered from the use of valve positions rather than flow measurements. PLS, MPC, and PID models assume dynamics that are linear and independent of direction and size—all bad assumptions when valve positions rather than flows are used as inputs. Additionally, the valve nonlinearity from the installed characteristic varies with pressures at the inlet and outlet of the valve. Even first principle models with pressure-flow solvers to compute pressures have not fared well because of the uncertainties in

pipings resistances and valve responses. Additionally, parallel pressure-flow solvers have exhibited numerical instabilities resulting in simulation crashes for the extreme operating conditions that occur during batch operations and the startup and the activation of safety instrumentation systems in continuous processes.

Pioneering advances in dynamic modeling offer a next generation of pressure-flow solvers in dynamic models that will be robust and adapted enough to provide flows from valve positions. The ability to consistently and comprehensively compute flows for all streams will enable these models to reach the highest levels of fidelity required for research, development, and design of automation systems. Presently, models can only move up in fidelity when flow control loops are installed on the key streams so feedback action removes the nonlinearity and unknowns of the valve and piping system. New pressure-flow solvers can eliminate this precondition. A side benefit will be the demonstration by these models of the process control improvement that can be gained from cascade, feedforward, and ratio control. The quantifiable benefits from demonstrable test cases can justify new flow devices to provide missing flow measurements or improve the accuracy of existing flow measurements.

Source: *Essentials of Modern Measurements and Final Elements in the Process Industry: A Guide to Design, Configuration, Installation, and Maintenance* by Gregory K. McMillan (ISBN: 978-1-936007-23-3) www.isa.org/finalelements

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