White Paper

Achieve Accurate Process Temperature Measurement with Surface Sensor Innovation

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Process Management

Achieve Accurate Process Temperature Measurement with Surface Sensor Innovation

Temperature is the most commonly measured variable in the process industry. It is often a critical factor in determining process efficiency and product quality. There are several ways to measure temperature in the process industry and each present their own unique challenges. This paper will detail how a new surface sensor innovation can address the challenges and alleviate the pain inherent to traditional process temperature measurement practices.

A thermowell and temperature sensor assembly is the most frequently used method of measuring a temperature internal to a process. Thermowells allow for direct sensor immersion into a process which helps provide an accurate measurement, but introduces many complex design challenges and risks associated with creating a possible leak point.

A traditional surface sensor measurement can remove the challenges presented by a thermowell by eliminating the need for a process intrusion. Unfortunately, this method comes with its own challenges as it cannot provide an accurate or repeatable representation of an internal process temperature due to various factors that can impact the measurement.

A new surface sensor innovation eliminates the challenges presented by thermowells and process intrusions while providing comparable measurement performance. This new innovation uses a heat flux algorithm that applies known thermal conductivity properties of both the process pipe or vessel and the surface temperature measurement assembly to calculate an accurate and repeatable internal process temperature value.

Traditional temperature measurement technology challenges

Thermowell technology challenges

A thermowell installation is the most common method of measuring temperature in the process industry. A thermowell is a component of a temperature measurement point that acts as a protective barrier between the temperature sensor and process. It enables insertion of the temperature sensor into the process where it might not otherwise survive the harsh conditions present. These conditions include flow-induced stresses, high pressure, and corrosive or erosive process fluids.

A thermowell allows the sensor to be put directly into a process (see Figure 1) where the temperature measurement is needed but, in doing so, also introduces a possible leak point and safety concern as a penetration into the process is required.

Since the thermowell directly contacts the process, several considerations are required for design and installation. The process fluid type, density and state as well as properties such as pressure, temperature, flow-rate and viscosity all play roles in the design of a thermowell to ensure a proper selection and safe installation. Material compatibility is also a concern for corrosive or abrasive process fluids. Wake frequency calculations (based on ASME PTC 19.3TW) are performed to ensure proper design for thermowells, however, this calculation is based on a single set of process data points. If the process parameters change from those used for wake frequency calculations, the thermowell may no longer be appropriately designed for the application. This could lead to fatigue, breakage and ultimately failure of the thermowell (see Figure 2). To alleviate this risk, wake frequency calculations are often performed multiple times for each measurement point for several process cases across a range of temperatures, pressures and flowrates.

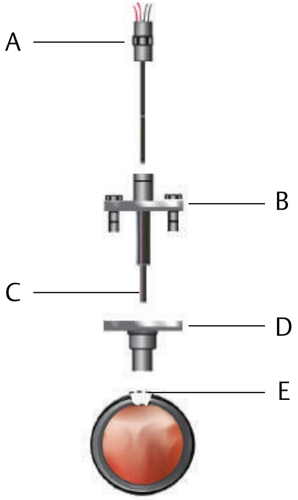
All these considerations drive increased complexity in thermowell design which can require change if process requirements change. Design specifications for a thermowell include but are not limited to:

- Stem profile
- Immersion length
- Material type
- Process connection type
- Extension length
- Tip thickness
- Bore diameter

Temperature measurement in small line sizes presents yet another challenge for thermowells. Stem conduction error (i.e. error induced on a temperature measurement by the ambient temperature and other external temperature sources via heat conduction) impacts accuracy when the immersion length is less than 10 times the thermowell tip diameter. It is often impossible to achieve this immersion length to tip diameter relationship in small line sizes. For example, a thermowell with a tip diameter of 0.5 inches would require a minimum thermowell immersion length of five inches to avoid stem conduction errors. Obviously, this is difficult in line sizes under five inches. Thermowell installation in a pipe elbow can provide the proper immersion length in a small line size but this is not always available.

Finally, since a thermowell is in direct contact with the process, any instance of visual inspection, new installation, or replacement requires process shutdown.

Figure 1. Traditional Thermowell Temperature Measurement Assembly Components



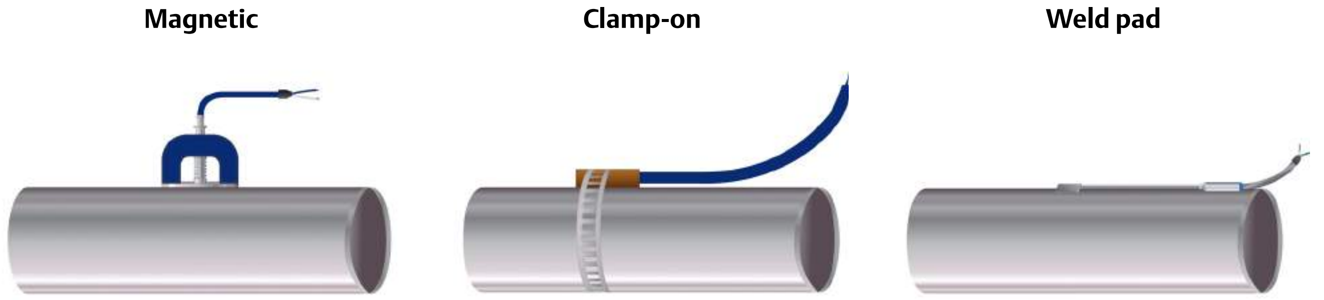
A. Sensor
B. Thermowell flange
C. Thermowell
D. Process flange, nipple and butt weld branch connection
E. Hole in pipe

Figure 2. Examples of Thermowell Failure

Traditional surface measurement technology challenges

A surface temperature measurement installation (see Figure 3) alleviates many of the pains associated with a thermowell installation as it does not require direct contact with the process. Since the measurement point is external to the process being measured, there is no threat of internal conditions physically damaging it or creating potential leak points. The need for wake frequency calculations and other complex design considerations are eliminated.

Figure 3. Surface Temperature Measurement Sensor Types



Although a traditional surface temperature measurement installation addresses many of these pains and challenges, in many cases it cannot match the measurement performance of a thermowell installation. If an internal process temperature measurement is required, a surface temperature measurement is often not capable of providing an accurate or repeatable representation of an internal measurement.

Ambient factors can severely impact the surface measurement reading, producing unpredictable results and complicating any attempt to relate surface temperature to process temperature. The relationship between surface temperature and process temperature is heavily dependent on the difference between ambient temperature and internal process temperature. Even a uniformly applied correction to the surface temperature measurement as an attempt to equate it to an expected temperature drop through a pipe or vessel wall loses validity if either process or ambient temperature changes. The temperature surface sensor and associated assembly can act as a “heat sink”, absorbing heat from either the process or external environment, producing inaccuracies similar to stem conduction errors common in small line size thermowell installations.

Figure 4 shows an example of how temperature from a pipe to a transmitter head can propagate in a surface sensor assembly. This non-linear relationship is difficult to model for a correction scheme. Application of insulation over the temperature assembly can reduce the majority of nonlinear heat flow, and help create a one-dimensional heat flow profile through the temperature assembly and transmitter head. This linearization of the heat flow does not remove all inaccuracies from a surface measurement but provides a path for a solution to correct for a varying ambient and process conditions.

Figure 4 and Figure 5 illustrate heat loss profiles on a surface temperature assembly to the environment in both free and forced convection environments.

Figure 4. Free Convection Modeling

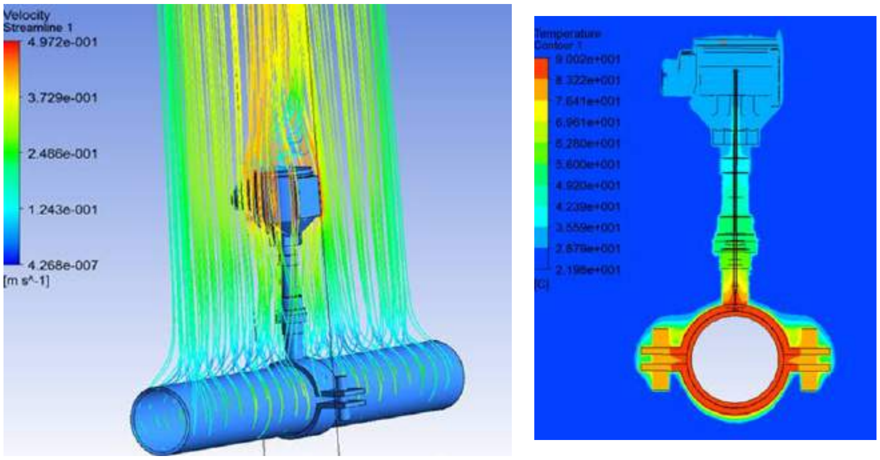


Figure 5. Forced Convection Modeling (wind speed 2 m/s)

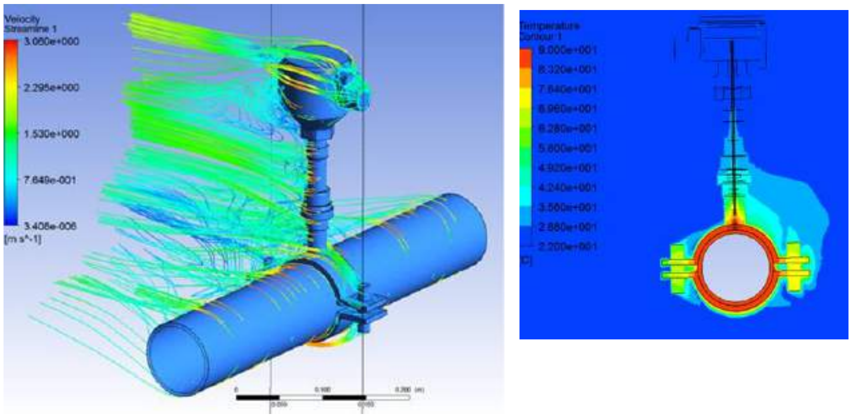
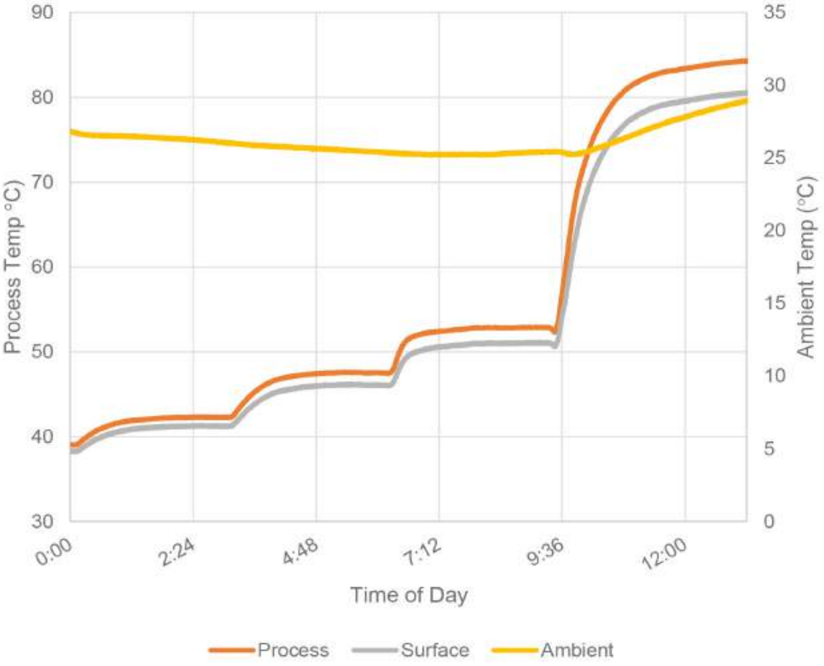


Figure 6 shows data from a water flow loop comparing an inserted RTD (resistance temperature detector) sensor temperature measurement and an insulated surface temperature measurement. In this trial, ambient temperature is kept fairly stable between 27 and 29 °C while process temperature is increased from 40 to over 80 °C in a series of ramps. As the differential between process temperature and ambient temperature increases, the difference between process and surface temperatures increases from 1 °C to nearly 5 °C.

Figure 6. Changing Process Temperature: Insulated Surface Sensor and Inserted RTD Sensor Comparison (1-in. Carbon Steel Schedule 40 Pipe)



Conversely, the same behavior can be observed from similar ambient temperature changes as shown in Figure 7. Under the same test setup, ambient temperature is decreased from 80 °C to over –40 °C. As the differential between process temperature and ambient temperature increases, the difference between process and surface temperatures increases from 2 °C to nearly 5 °C.

Figure 7. Changing Ambient Temperature: Insulated Surface Sensor and Inserted RTD Sensor Comparison (1-in. Carbon Steel Schedule 40 Pipe)

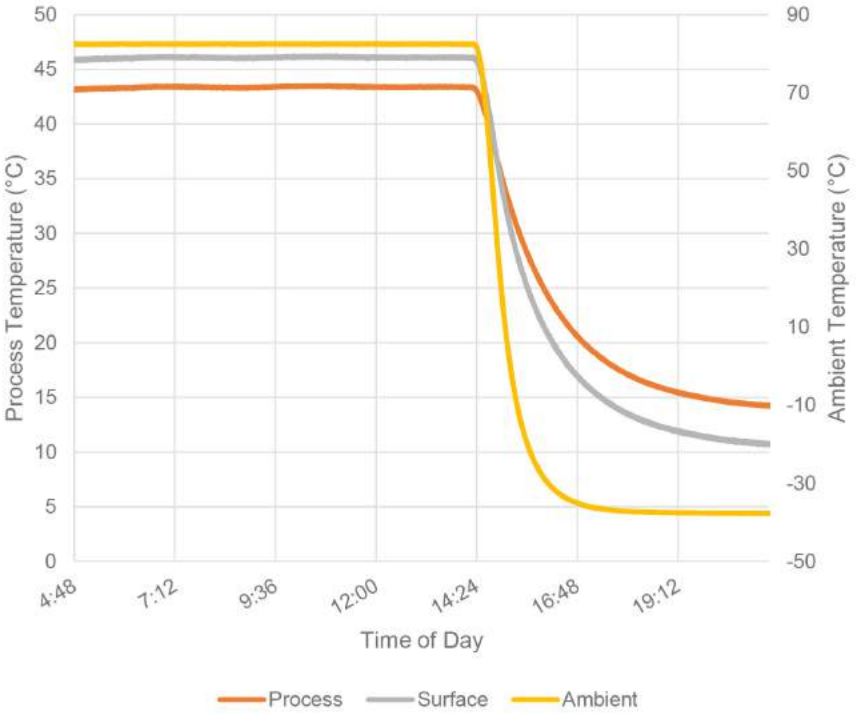
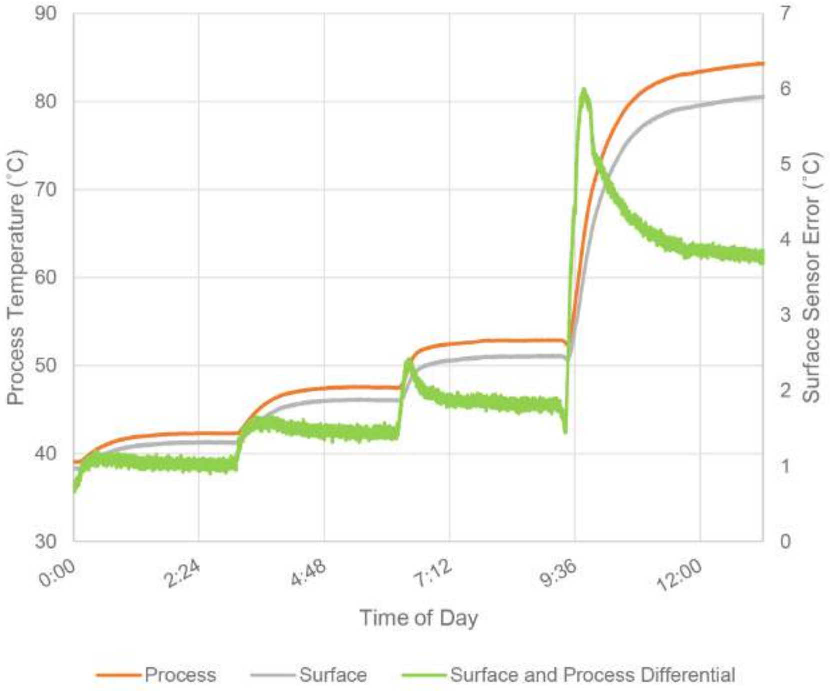


Figure 8 revisits the first trial and plots the difference between process temperature versus surface temperature as a variable. As process temperature is increased, the error, or difference between process and surface temperature, increases. This relationship makes a comparison between the two values difficult as it is dependent on process temperature, ambient temperature and the thermal conductivity of the measurement installation.

Figure 8. Surface Sensor Error: Insulated Surface Sensor and Inserted RTD Sensor Comparison (1-in. Carbon Steel Schedule 40 Pipe, Ambient Temperature Constant)



New surface measurement innovation addresses challenges of both thermowell and traditional surface measurement technologies

As detailed in the previous section, there are many factors that can impact a traditional surface temperature measurement reading. This makes it difficult to use as a simple point of inference when determining the temperature of the associated internal process. However, by implementing an algorithm with an understanding of the thermal conductive properties of the temperature measurement assembly and corresponding piping or vessel, a surface temperature sensor solution can be utilized to accurately calculate internal process temperature.

By inputting ambient and surface temperature measurement values from Figure 6 into a thermal conductivity algorithm, process temperature values can be calculated. Figure 9 shows the comparison between calculated “Corrected Temperature” and internally measured process temperature. The calculated values nearly overlay onto the measured values.

Figure 10 shows the comparison between calculated “Corrected Temperature” and internally measured process temperature for the example shown previously in Figure 7. Again, the calculated values track the measured process temperature values very closely.

Figure 9. Correction Applied to Changing Process Temperature: Insulated Surface Sensor and Inserted RTD Sensor Comparison (1-in. Carbon Steel Schedule 40 Pipe)

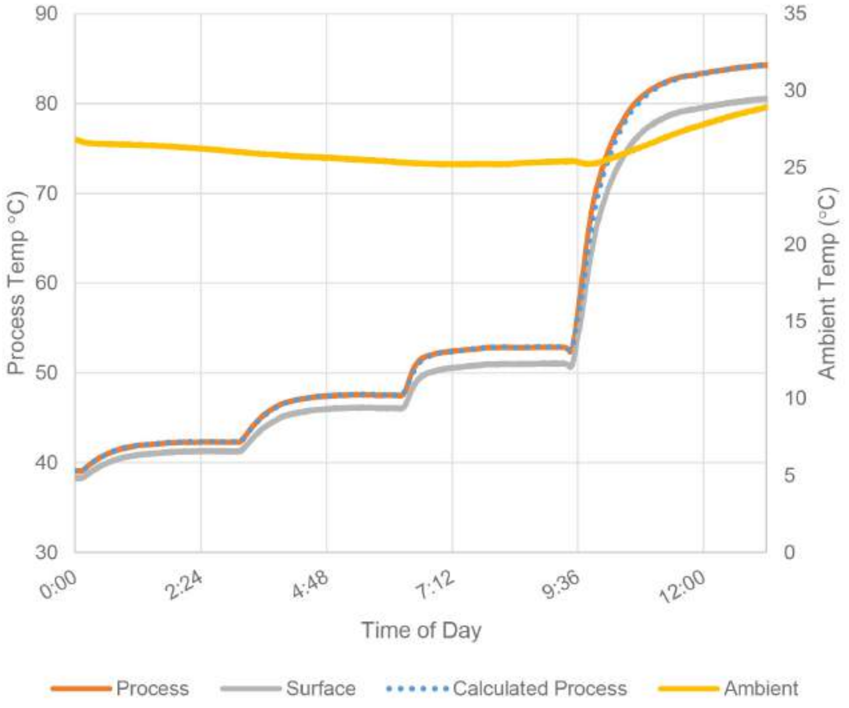
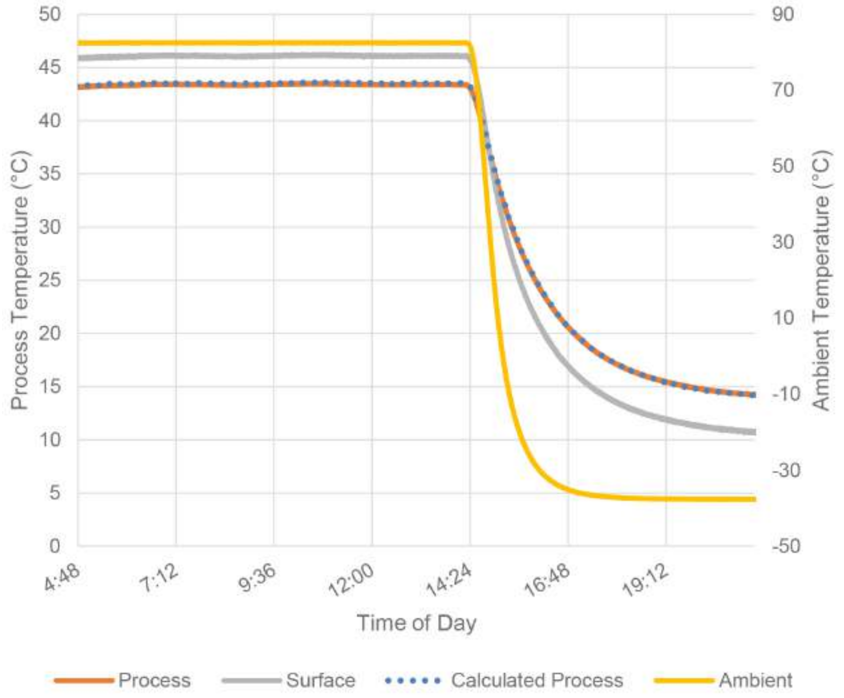
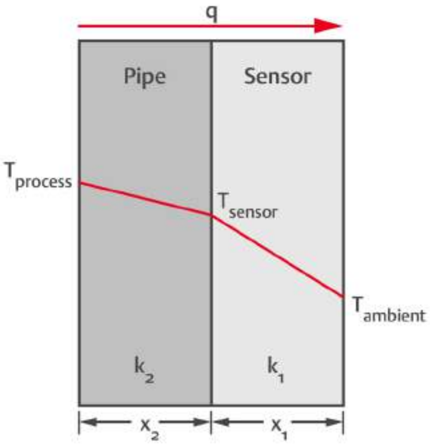


Figure 10. Correction Applied to Changing Ambient Temperature: Insulated Surface Sensor and Inserted RTD Sensor Comparison (1-in. Carbon Steel Schedule 40 Pipe)



Assuming steady state conduction and negligible impact of ambient heat convection which is eliminated by proper use of insulation, the process piping and temperature measurement assembly can be viewed as a series of planes with different thermal conductivities as shown in Figure 11.

Figure 11. Simplified Heat Flux through a Pipe and Temperature Sensor Installation



Where:

q = Heat flux

$T_{ambient}$ = Measured ambient temperature

x_1 = Thickness of sensor assembly

k_1 = Thermal conductivity of sensor assembly

T_{sensor} = Measured surface temperature

x_2 = Thickness of process pipe wall

k_2 = Thermal conductivity of pipe wall

$T_{process}$ = Calculated process temperature

By applying Fourier's Law, heat flux can be calculated and used to solve for the internal process temperature. For one-dimensional heat flow, Fourier's law is simplified to:

$$q_x = -k\frac{dT}{dx}$$

If process pipe or vessel wall thickness and thermal conductivity is represented by x_2 and k_2 and sensor assembly length and thermal conductivity are represented by x_1 and k_1 respectively, Fourier's Law can be used to express one-dimensional heat flow through the assembly as follows:

$q_{sensor} = (T_{ambient} - T_{sensor}) / (x_1/k_1)$ and $q_{pipe} = (T_{sensor} - T_{process}) / (x_2/k_2)$

In this application, one-dimensional heat flow can be assumed constant throughout the assembly therefore q_{sensor} and q_{pipe} are equal.

$$q = (T_{ambient} - T_{sensor}) / (x_1/k_1) = (T_{sensor} - T_{process}) / (x_2/k_2)$$

Ambient temperature $T_{ambient}$ and surface temperature T_{sensor} can be measured and in turn be used to calculate process temperature $T_{process}$. Solving for $T_{process}$ gives the following:

$$T_{process} = T_{sensor} + (T_{sensor} - T_{ambient}) \times (x_2/k_2) / (x_1/k_1)$$

A patent-pending innovation in surface temperature measurement technology addresses the challenges of traditional thermowell and surface measurement technologies by placing this process temperature calculation functionality into a temperature transmitter and surface sensor assembly. By implementing this algorithm in a temperature transmitter, the process temperature calculation is greatly simplified for the user.

Performance considerations

Total system performance of the surface measurement innovation can be viewed in terms similar to a standard temperature measurement assembly (i.e. transmitter digital accuracy and ambient temperature effects, sensor accuracy, etc.) In the case of applying the thermal conductivity algorithm to calculate process temperature from a surface measurement, one additional uncertainty component is required and is dependent on the differential between ambient and process temperature. This additional uncertainty consideration is called Process Temperature Effect (PTE) and testing has shown it is less than 1% of the ambient/process temperature delta. This uncertainty is due to imperfections of sensor-to-pipe surface contact. If the pipe surface inhibits any direct contact with the entirety of the sensor surface, accuracy is impacted, part of which is considered and included in the PTE specification, but extremely uneven or dirty surfaces will further impact accuracy. Examples of contact inhibition would be dimples or any physical imperfections in the pipe surface. Application of a thermal compound or material to improve sensor–to-pipe surface contact is not recommended as it introduces a new material and thermal characteristics that are not accounted for within the algorithm, which will result in additional error.

Other considerations for performance are proper fluid mixing and sensor placement. Fluid must be flowing enough in a pipe to produce a uniform cross-sectional temperature. Without this, large temperature gradients may develop within the pipe. It is also important that the surface sensor be in contact with the part of the pipe that contacts the internal fluid (i.e. if the pipe is half full, the sensor must be on the lower half of the pipe).

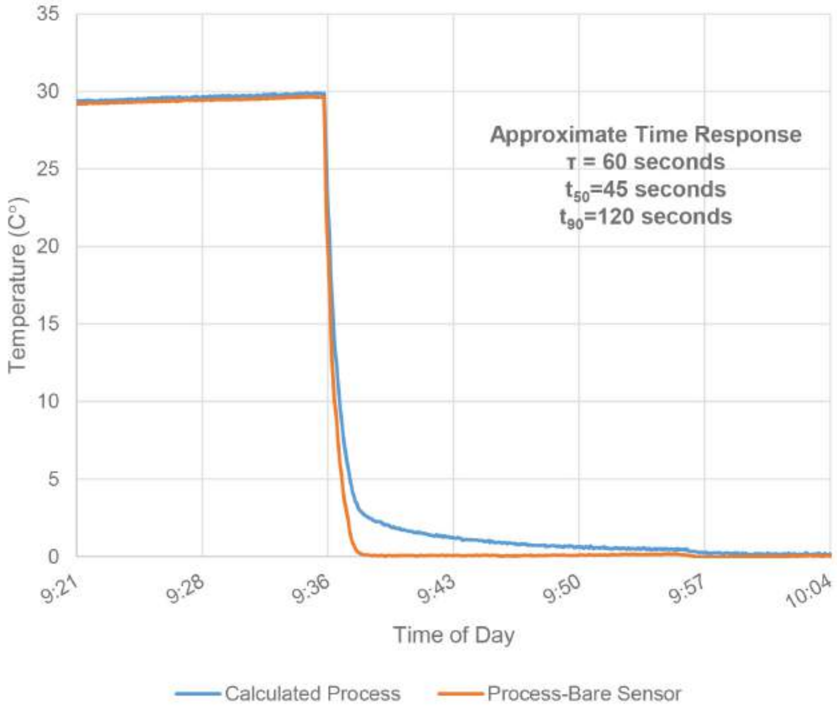
The surface measurement innovation works best in steady state applications. If there is a fast process or ambient temperature change, there may be a delay in the correction due to time response characteristics of the sensors being used as well as the associated time response with taking a measurement through a pipe or vessel wall.

A surface measurement may exhibit an increase in time response in comparison to an intrusive thermowell. Time response in this comparison, however, is dependent on many factors including:

- Pipe material
- Wall thickness
- Fluid type
- Flowrate
- Ambient/process delta
- Thermowell material type and design
- Sensor type
- Transmitter update rate

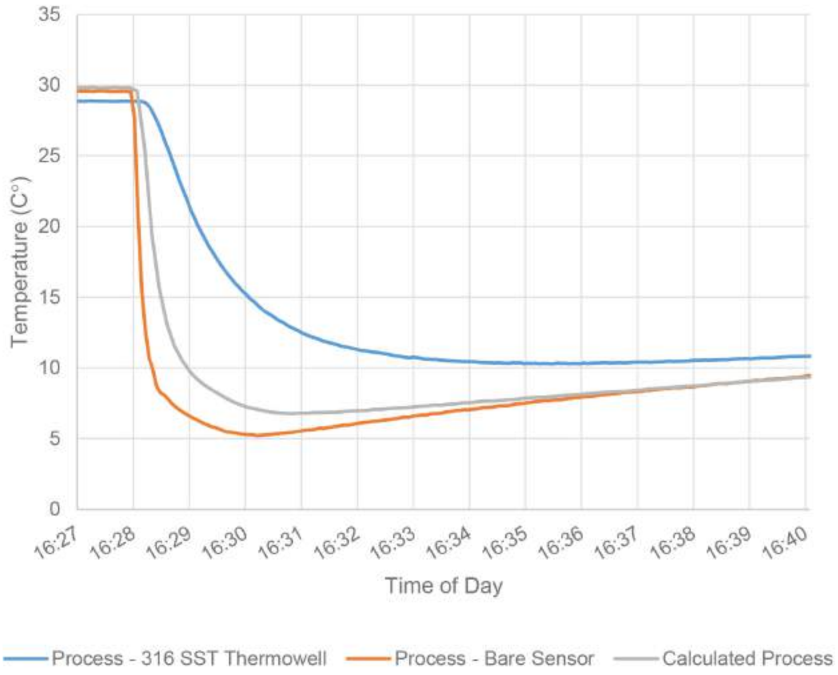
Time response data from internal testing is shown in Figure 12.

Figure 12. Approximate 30 °C Step Change Performed on Test Flow Loop (Water, 1-in. Carbon Steel Schedule 40 Pipe)



Test data has also shown that the surface temperature-to-process temperature calculation outperforms standard thermowell assembly on small line sizes due to stem conduction error of the thermowell. Figure 13 shows behavior of 316 SST thermowell in comparison to a bare inserted RTD and a calculated process temperature value from a surface measurement.

Figure 13. Approximate 25 °C Step Change Performed on Test Flow Loop (Water, 1-in. Carbon Steel Schedule 40 Pipe)



Changes to pipe or vessel wall properties will impact the algorithm performance. The algorithm is based on a set collection of pipe property parameters and if a change occurs, accuracy will be affected. Scaling or buildup inside the pipe will impede thermal conductivity through the pipe and negatively affect accuracy of the temperature measurement calculation. External buildup on pipe (at sensor contact point) and thinning of the pipe material will similarly impede accuracy.

Suitable applications

This technology is suitable for many applications, including the majority of pipe processes:

- Pipeline monitoring
- Small line size applications
- Retrofit projects that need new points
- Pipeline requiring frequent cleaning
- High velocities
- Slurries and heavy particulate fluids
- Clean-In-Place (CIP) processes
- High viscosity fluids
- Harsh processes requiring exotic materials

Due to reduced time response in certain conditions, it is not currently intended for safety loops, fast control applications or for custody transfer (fiscal metering) applications.

This technology is currently being used in the following applications: small line sizes, heating loops, oil and sand separators, water lines and more.

Summary

This paper addresses thermowell and surface temperature measurement challenges, new surface sensor technology and how it solves these challenges, performance and time response considerations, impact of ambient temperature, and suitable applications for this new technology.

Emerson currently offers this capability as Rosemount™ X-well™ Technology. It is available in the Rosemount 648 Wireless Temperature Transmitter and Rosemount 0085 Pipe Clamp Sensor Assembly. These components work together to calculate process temperature via the transmitter's thermal conductivity algorithm. Rosemount X-well Technology works by measuring the pipe surface temperature and ambient temperature, and combining this information with an understanding of the thermal conductivity properties of the installation and process piping.

Rosemount X-well Technology offers accurate process temperature measurement without requiring any intrusions or penetrations into the process, eliminating possible leak points, allowing quicker and easier installation, along with simplified long-term maintenance. Users do not have to design, size, or maintain thermowells. Wake frequency calculations are eliminated, as well as time spent determining material compatibility, the right insertion length, and the necessary profile.

With Rosemount X-well Technology, users can also add temperature measurement points without having to shut down a process. Rosemount X-well Technology can be installed with a standard pipe clamp procedure and ordinary hand tools, and does not require a skilled contractor. Applications include pipelines, high velocity flows, slurries, heavy particulate fluids, wellheads, CIP processes, high viscosity fluids, and harsh processes in the following industries:

- Oil and gas
- Chemical
- Refining
- Life sciences
- Metals and mining
- Pulp and paper

For more information on Rosemount X-well Technology, see EmersonProcess.com/Rosemount/Temperature/Wireless-648.

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