Reducing Thermowell Errors and Flow Stability Test Report

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Abstract. It is well known that conventional thermowells will thermally "couple" with the vessel in which they are mounted resulting in an error in the temperature measurement. Conduction error, commonly called immersion error, is present whenever a temperature gradient exist between the vessel or pipe the thermowell is installed into, and the substance being measured. Sources of conduction error in gas temperature measurement and methods of reducing it, specifically the use of finned thermowells, are discussed.

Introduction

In the gas pipeline industry, gas temperature, along with pressure and flow, is used to calculate volumetric flow. Any error in the temperature measurement results in an error in the flow calculation. This error directly shifts the bottom line, resulting in accounting for too much gas or not enough. This unaccounted error in the gas volume measurement can have significant cost associated with it. Any time there is a difference between the pipe temperature and the flowing gas temperature there will be a conduction error. Even the most accurate temperature measurement equipment will have errors. Understanding the sources of conduction error and how to minimize it will increase the accuracy of gas temperature measurement.

The Measurement Process

To accurately measure the flowing gas temperature, the sensor must be in thermal contact with the gas, but not disturb the gas temperature. Figure 1 shows a cut-away view of a typical thermowell installation in a gas pipeline. A threaded fitting, welded to the top of the pipe, provides the mount for the thermowell. A thermowell fitting connects the thermowell to a protection head or temperature transmitter to allow field wiring to the sensor. The thermowell fitting should include a spring to keep the sensor protection tube pressed firmly into the thermowell providing a good thermal contact between the sensor tip and the bottom of the thermowell. Thermally conductive grease at the sensor tip will also improve performance as any air gap between the sensor tip and the thermowell will add to the measurement error and reduce the response time.

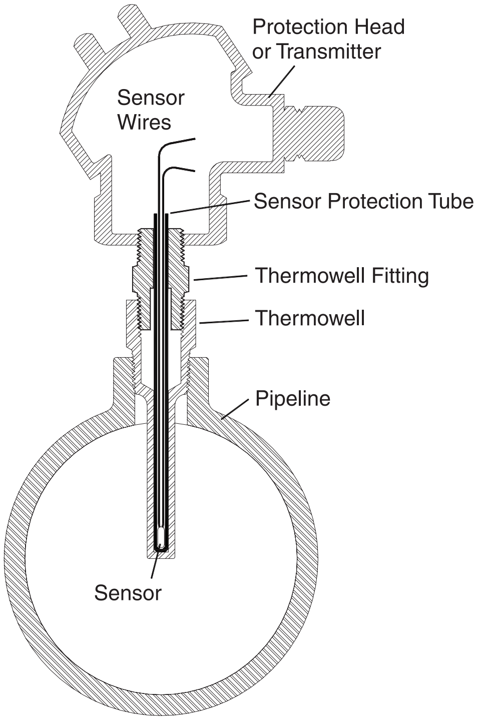

Figure 1. Typical sensor installation including thermowell and protection head for gas temperature measurement in a pipeline.

For the sensor to approach the temperature of the flowing gas there must be a thermal coupling or heat transfer between the two. For a net heat transfer from hot to cold to take place there must be a temperature difference between the sensor and the gas. When there is no heat transfer, the measurement system is in thermal equilibrium and the sensor is as close to the gas temperature as it will get. In reality, the sensor temperature will never be the same as the gas temperature due mainly to conduction errors.

Reducing Thermowell Conduction Measurement Errors in Gas Pipeline Temperature Measurement

Heat Transfer

Heat transfer can be subdivided into three categories, conduction, convection, and radiation. Conduction takes place when there is a temperature gradient in a solid, liquid, or gas. The molecules in the hot area increase the violence of their vibrations as they heat up. Then, as they collide with their slower moving neighbors, some of their energy of motion is shared, and they in turn pass it on from one molecule to the next. The equation for thermal conductivity(1) in one dimension is in Equation 1, below.

$$q_{cond} = kA\,\frac{T_2 - T_1}{L}$$

where:

q_{cond} is the quantity of heat flow per unit time
A is the cross sectional area
$T_2 - T_1$ is the temperature difference
L is the length

Equation 1. Thermal Conductivity in One Dimension

When a metal rod is heated on one end, heat will be conducted through the metal to heat the other end.

Convection is the transfer of heat from one place to the other by the actual motion or flow of the material. The equation for convection heat transfer(2), also called Newton's Law of Cooling, is shown in Equation 2, below.

$$q_{conv} = hA\,(T_S - T_\infty)$$

where:

q_{conv} is the heat power being transferred through the surface
A is the surface area
T_s is the surface temperature
T_∞ is the temperature of the fluid distant from the surface
h is the convection heat transfer coefficient (25 to 250 for forced convection gases[3])

Equation 2. Convection Heat Transfer (Newton's Law of Cooling)

An example of convection heat transfer would be a fan blowing on a hot object. The heat from the hot object is transferred to the cooler flowing air. In gas temperature measurement, the heat from the thermowell sensing-section and sensor is transferred from the flowing gas mainly by convection.

Heat can also be transferred by radiation, which is the continuous emission of energy from the surface of all objects. The equation for radiation heat transfer(2) is shown in Equation 3 below:

$$q_{rad} = \varepsilon A \sigma\,({T^4}_S - {T^4}_{SUR})$$

where:

q_{rad} is the radiated power
A is the surface area
σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} Watt/m^{-2} \times K^{-4}$)
T_S is the surface temperature of the object
T_{SUR} is the surface temperature of the ambient surroundings

Equation 3. Radiation Heat Transfer

At the relatively low temperatures seen in natural gas pipelines, typically less than 70°C, the rate of radiation heat transfer is small and is at long wavelengths producing little influence on the measurement accuracy. Radiation heat transfer can be minimized by manufacturing the thermowell of a low emissivity material, such as polished stainless steel with emissivity = 0.17(4).

Sources of Conduction Error

Conduction errors are present whenever there is a difference in temperature between the flowing gas and the pipe walls. The pipe running underground is kept at a fairly constant temperature but at the metering station, a section of pipe is brought above ground to allow access for the measurement equipment. The metering section of pipe and the equipment installed on the pipe, are heated and cooled by the changing ambient environment. As the temperature difference increases, the conduction error for any installation also increases.

To understand the sources of conduction errors, first consider a temperature sensor inserted into the gas stream as shown in Figure 2a.

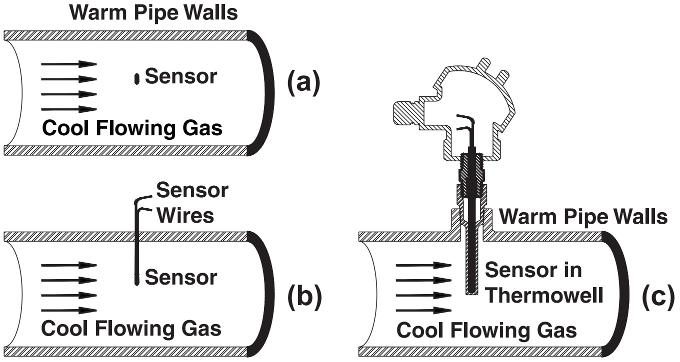

Figure 2. Cutaway pipe section showing **(a)** sensor in flowing gas without conduction path, **(b)** conduction path through the sensor wires, and **(c)** large conduction path through thermowell, production tube, and sensor wires.

The sensor is only influenced by convection and a small influence from radiation heat transfer and will eventually be equal to or very near the gas temperature. There is no conduction error because there is no conduction path to the sensor. In Figure 2b, sensor wires are added, which creates a conduction path between the warm pipe and the sensor. Heat is conducted from the pipe walls through the wires to the sensor, and actually shifts the sensor temperature, resulting in a conduction error.

As long as there is a temperature difference between the pipe and the gas, the sensor will never equal the gas temperature due to the thermal energy conducted through the sensor wires. In Figure 2c, the thermowell, sensor protection tube, and protection head are added to the sensor. This significantly increases the cross sectional area of the conduction path to the sensor. Referring to Equation 1, the increased cross sectional area increases the conduction heat transfer to the sensor, increasing the conduction error. If the pipe was cooler than the gas, the same error exists for the same differential temperature but in the opposite direction. The following relation may be used to determine the extent of the conduction error(5):

$$T_{sg} = T_i - \left[\frac{T_w - T_{sg}}{Cosh(mL)}\right]$$

where:

T_{sg} is the static temperature of the gas

T_i is the indicated sensor temperature

T_w is the pipe wall temperature

L is the immersion length

$m = (hp/ka)^{1/2}$

h is the convection coefficient of heat transfer

p is the surface area of the thermowell (at the sensor)

k is the thermal conductivity of the thermowell

a is the conduction cross-sectional area of the thermowell

Equation 4. Convection Heat Transfer (Newton's Law of Cooling)

The larger mL becomes, the closer the indicated temperature (T_i) approaches the true gas temperature (T_{sd}). Any means of increasing the mL product will result in a reduced conduction error. The steady state temperature of the sensor is a result of a balance between convection heat transfer from the gas to the thermowell, and conduction and radiation heat transfer between the sensor and its surroundings.

Reducing Conduction Error

The most common method for minimizing conduction errors is to increase the insertion length. Typically the insertion length of the thermowell should equal a minimum of 10 times the diameter of the thermowell(6). Increasing the insertion length will reduce conduction errors as shown in Equation 4 but in small diameter pipes this may be impossible. Reducing the thermowell diameter, to reduce the conduction path, is not practical in high pressure, high flow velocity pipelines because the strength of the well will be compromised. Flow rates can be as high as 30 meters per second with pressures up to 7,000 kPa.

Reducing the thermal conductivity of the thermowell material (k in equation 4) will reduce the conducted thermal energy between the pipe walls and the sensor, which results in a reduced influence to the measurement. The drawback is that it will also reduce the thermal conduction through the sensing section of the thermowell to the sensor, which reduces the influence of the coefficient of heat transfer (h in equation 4) and also reduces the sensor response time. The thermowell must be manufactured of materials compatible with the application. To minimize radiation heating, the material should have a low emissivity surface. Typically thermowells used in gas pipeline temperature measurement are made of polished stainless steel, a tradeoff between accuracy and strength.

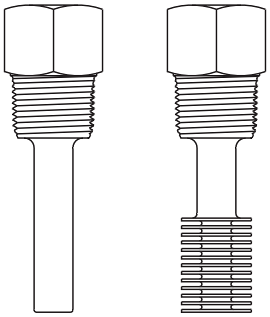

Figure 3.
(a) Conventional thermowell
(b) Finned thermowell

Further examination of equation 4 indicates that if the surface area of the thermowell at the sensor was increased (p in equation 4), without increasing the conduction cross sectional area (a in equation 4) or the thermal conductivity (k in equation 4), conduction errors will be reduced. This can be accomplished by adding an array of fins at the sensing section of the thermowell. Figure 3a shows a conventional thermowell for comparison to a thermowell with the added fins to increase the surface area of the sensing section, Figure 3b. Adding the 13 fins increases the surface area in the sensing section over 7.5 times that of a conventional thermowell.

Finned Thermowell Performance

The increased surface area at the sensing section of the finned thermowell significantly increases the convection heat transfer between the gas and the sensor, shifting the sensor temperature closer to the actual gas temperature, thereby reducing the conduction error. Equation 2 shows that an increase in the surface area, A, will increase the heat power transferred, q_{conv}.

Actual flow testing clearly shows the performance improvements the increased surface area provides. A conventional thermowell and a finned thermowell were run in a 7.5cm inside diameter schedule 80 pipe. The pipe was heated to 38°C and held at this temperature while various flow rates were observed.

Figure 4 shows the difference between the actual gas temperature and the indicated temperature. The finned thermowell, indicated by the bottom trace, was very close to the actual gas temperature. The conventional thermowell had over 1.6°C (3°F) error over the entire test. Slower flow velocities produced larger errors as expected. Sensor response time was four times faster using the finned thermowell(7).

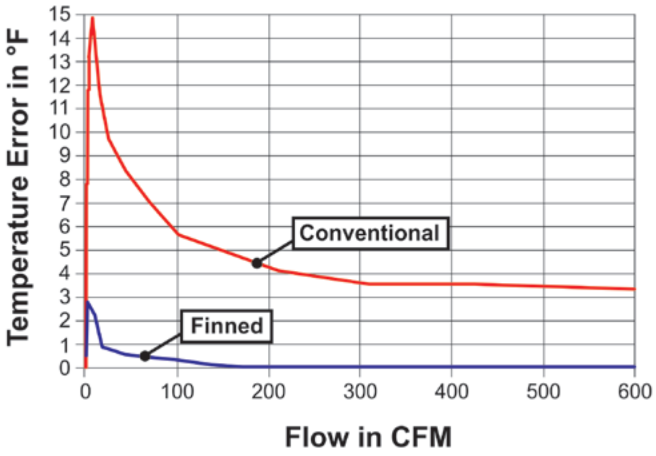

Figure 4. Flow comparison of a conventional thermowell, top curve, and a finned thermowell, bottom curve(7).

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7. TAN-34CO-L4 Thermowell Performance Evaluation, ThermoSync Temperature Measurement System, PGI International, October 2000.

Can a Few Degrees Make a Difference?

Using the flow lab test results, two flow rates were used to compare the conventional stainless steel thermowell to the ThermoSync temperature measurement system. At 60 CFM the temperature error for the conventional system is 7.5°F and at 300 CFM 3.8°F. For the ThermoSync system, 0.2°F at 60 CFM and 0.0°F at 300 CFM. These are conservative errors taken with only a 30°F difference between the pipe temperature and actual gas temperature. In extreme ambient conditions where the difference is larger, one should expect larger temperature errors. The two flow rates were converted to SCFH using 200 PSI at 70°F.

60 ACFM = 48 MCF/Hour
300 ACFM = 240 MCF/Hour

Using AGA3 equations, the following parameters were used to determine the effect of the temperature error on a calculated flow volume for an orifice plate flow meter.

Flange Taps	Upstream
Pressure Base	14 PSIA
Temp Base	60°F
Barometric Pressure	14.7
Static Press.	200 PSIG
Pipe I.D.	2.97"
Orifice	1.50"
Specific Gravity	1.00
CO2 Mole Percent	0.00
N2 Mole Percent	0.00

Dollar error per hour for the two temperature measurement methods (based on $3.96 per MCF)

Example:

Flow Rate	Thermowell	Temp (°F)	MCF/ Hour	MCF Error/ Hour	Dollar Error/ Hour	Dollar Error/ 24 Hours	Dollar Error/ 31 days
60 CFM	Actual	70.0	48.003	0.000	$ 0.00	$ 0.00	$ 0.00
	ThermoSync	70.2	47.991	0.120	0.05	1.14	35.35
	Conventional	77.5	47.584	0.419	1.66	39.82	1,234.47
300 CFM	Actual	70.0	240.000	0.000	0.00	0.00	0.00
	ThermoSync	70.0	240.000	0.000	0.00	0.00	0.00
	Conventional	73.8	238.931	1.069	4.23	101.52	3,149.53

$4.23 x 24 hours per day = $101.52
$101.52 x 365 days per year = $37,054.80!

Even under these conservative conditions, a conventional thermowell may be costing you ***$101.52 per day...or $37,054.80 per year!***

Temperature Induced Error in Turbine or PD Meters

To determine the measurement error in ultrasonic, turbine and PD meters, the SCFM is calculated using the actual gas temperature. This rate is compared to the SCFM calculated using the measured temperatures from the ThermoSync system and the conventional system.

Dollar error per hour for the two temperature measurement methods (based on $3.96 per MCF)

Example:

Flange Taps	Upstream
Pressure Base	14 PSIA
Temp Base	60°F
Barometric Pressure	14.7
Static Press.	200 PSIG
Pipe I.D.	2.97
Orifice	1.50
Specific Gravity	1.00
CO2 Mole Percent	0.00
N2 Mole Percent	0.00

Flow Rate	Thermowell	Temp (°F)	MCF/ Hour	MCF Error/ Hour	Dollar Error/ Hour	Dollar Error/ 24 Hours	Dollar Error/ 31 days
60 CFM	Actual	70.0	48.144	0.000	$ 0.00	$ 0.00	$ 0.00
	ThermoSync	70.2	48.124	0.020	**0.08**	1.90	58.92
	Conventional	77.5	47.404	0.740	**2.93**	70.33	2,180.22
300 CFM	Actual	70.0	239.981	0.000	0.00	0.00	0.00
	ThermoSync	70.0	239.981	0.000	0.00	0.00	0.00
	Conventional	73.8	238.095	1.886	**7.47**	179.28	5,556.61

$7.47 x 24 hours per day = $179.28

$179.28 x 365 days per year = $65,437.20!

Even under these conservative conditions, a conventional thermowell may be costing you $179.28 per day...or $65,437.20 per year!

ThermoSync Flow Stability Test Report

High Velocity—High Pressure Flow Test, CEESI Iowa
TAN-34CO-L2, TAN-34CO-L4, TAN-34CO-L8, TAN-34CO-L12
January 15, 2001

Background

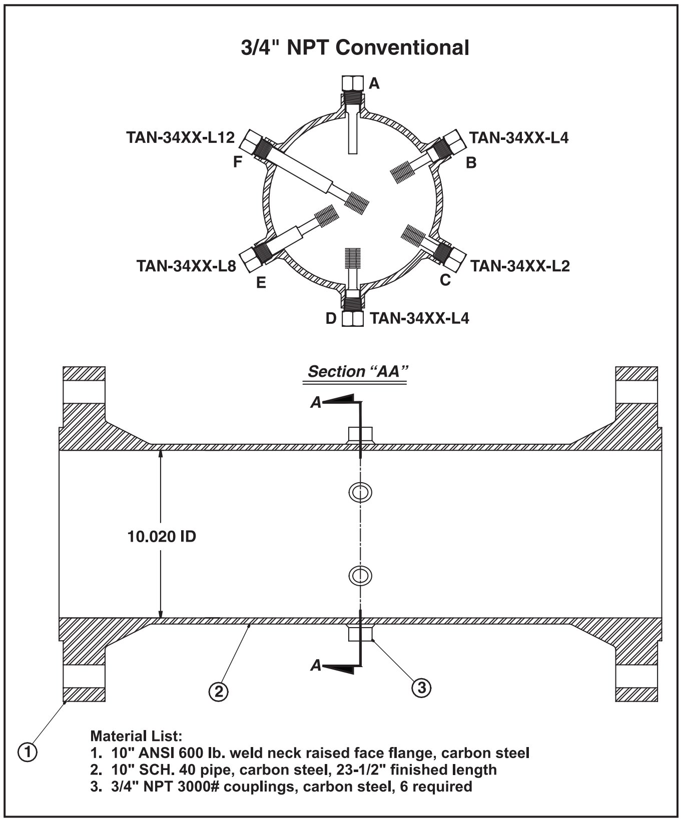
Design equations for the strength of a thermowell, natural frequency, and the wake or Strouhal frequency of thermowells have been available for some time, and are well-documented (*ASME PTC 19.3 Temperature Measurement*). These equations however, are developed around a conventional thermowell profile and do not apply to the finned ThermoSync design. To determine the application limitations for the ThermoSync thermowells, testing at the maximum operating conditions must be done. It was determined that the maximum pressure normally seen in a natural gas pipeline is 1,000 PSI. Similarly, the maximum flow velocity was determined to be 100 feet per second. Working with CEESI Iowa natural gas flow measurement facility in Garner Iowa, we were able to define the test requirements.

CEESI

The Colorado Engineering Experiment Station, Inc. (CEESI) is an independent commercial calibration and flow research facility. CEESI also participates in flow measurement standards committees organized by the ASME, AGA, API, and GRI. Many years of experience in meter proving have gained CEESI the international reputation as a leader in flow measurement. The CEESI Iowa high flow test facility has the unique ability to flow natural gas up to 20,000 ACFM at 1050 PSI in a controlled test environment.

Test Set-Up

To simplify the test, a spool was designed to allow six thermowells to be installed and tested together. The spool is a 10" schedule 40 pipe with ANSI 600 lb. flanges, as shown in Figures 5 and 6.



Material List:
1. 10" ANSI 600 lb. weld neck raised face flange, carbon steel
2. 10" SCH. 40 pipe, carbon steel, 23-1/2" finished length
3. 3/4" NPT 3000# couplings, carbon steel, 6 required

Figure 5. Test Spool Design

Figure 6. Test spool and thermowells installed in CEESI flow test pipe.

The thermowells in locations C, D, E, and F were fitted with Entran miniature EGA accelerometers to measure vibration. Each accelerometer shared the same amplifier/power supply with a gain of 41.6 making the output of each sensor 50mv/g *(1.2mv/g x 41.6 = 50mv/g)*.

Accelerometer Specifications

Model	EGA-250-/R
Range	+/-250g
Limit	+/-1,250g
Temp. Range	-40 to +250°F
Non-Linearity	+/-1%
Output	Approx. 1.2mv/g

The conventional thermowell in location A (with a conventional RTD probe) and the ThermoSync thermowell in location B (with the ATP-1000) were used for a temperature accuracy comparison. Both probes were connected to a Rosemount 3244MV transmitter. The transmitter was setup to provide an output proportional to the difference of the two temperatures. If both sensors are at the same temperature, with no thermowell error, the temperature output will be 12ma (1/2 scale). Any temperature error will shift the transmitter's output. While running the test, the pipe temperature was a fairly constant 60°F and the gas temperature 69.23°F (measured by CEESI). With a 9°F difference between pipe wall and gas, the measured temperature difference was between 0.1°F and 0.2°F at the 50ft/sec. flow rate.

Test Results

Flow Velocity = 100 feet per second (Figure 8)

Static Pressure	1,080 PSI
TAN-34CO-L2	8.8g
TAN-34CO-L4	9.2g
TAN-34CO-L8	10.4g
TAN-34C0-L12	11.2g

All of the thermowells produced only low level background vibration at 100 ft/sec.

Flow Velocity = 112 feet per second (Figure 9)

Static Pressure	1,080 PSI
PSI TAN-34CO-L2	22g
TAN-34CO-L4	20g
TAN-34CO-L8	112g
TAN-34C0-L12	> 250g

Increasing the flow velocity from 100 to 112 feet per second resulted in L12 oscillation at 540Hz. Most of the vibration in the other wells was produced by L12 interference. This is clearly shown by the data taken with L12 removed. When the wake or Strouhal frequency of a well approaches the natural frequency, the thermowell will begin to oscillate. An audible tone at the vibration frequency clearly indicated when this happened. The two waveforms to the right (Figures 8 and 9) show the L12 thermowell at 100 ft/sec and 112 ft/sec.

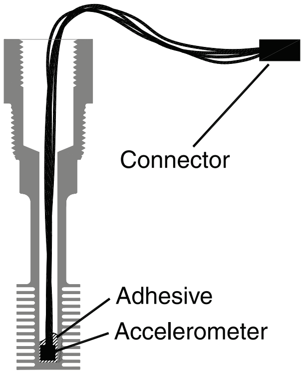


Figure 7. Accelerometer

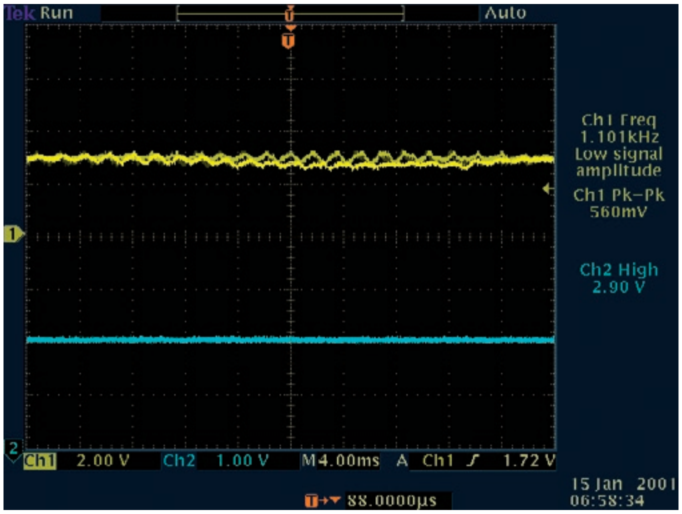


Figure 8. Flow Velocity 100 FPS

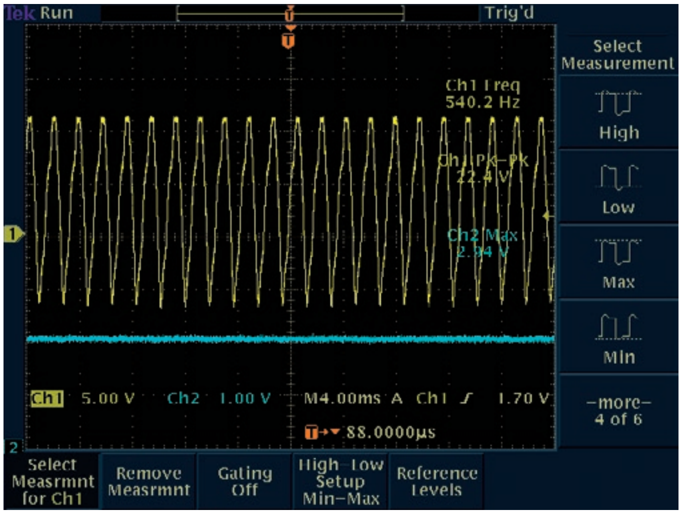


Figure 9. Flow Velocity 112 FPS

Flow Velocity = 112 feet per second, L12 Removed

Static Pressure	1,080 PSI
TAN-34CO-L2	8g
TAN-34CO-L4	11.2g
TAN-34CO-L8	14.4g

L12 was removed from the spool to allow the other probes to be measured at higher flow velocities. Removing L12 reduced the vibration levels measured on the other wells.

Flow Velocity = 135 feet per second, L12 Removed

Static Pressure	1,080 PSI
TAN-34CO-L2	10.4g
TAN-34CO-L4	17.6g
TAN-34CO-L8	25.6g

Increasing the flow velocity slightly increased measured vibration levels.

Flow Velocity = 150 feet per second, L12 Removed

Static Pressure	1,080 PSI
TAN-34CO-L2	15.2g
TAN-34CO-L4	31.2g
TAN-34CO-L8	28g

At 150 feet per second, there is no excessive vibration.

Summary

The L12 thermowell is unacceptable for use above 100 feet per second. The L2, L4 and L8 thermowells performed without excessive vibration up to the 150 ft/sec and should provide long-term performance in flow velocities up to 100 feet per second.

The L12 should be tested again without the other probes installed in the spool to determine if there is interference from the other thermowells. Notice in Figure 5 that the other probes may interfere with the L12 flow profile.

The measured temperature error between the ThermoSync L4 system and a conventional thermowell/probe (3" insertion length) at 50 feet per second was approximately 0.2°F. Calculating the volume using 69.23°F and 69.03°F, there could be a 5.7 MCF per hour error in the calculated flow volume due to pipe wall thermal coupling in the thermowell. **Example: At a gas price of $9.00 per MCF, that's a $51 per hour, $1,231 per day or $449,388 per year unaccountable error.** Using the ThermoSync system can significantly reduce pipe wall coupling errors.

Temperature Error vs. Flow Rate

Figure 10 – 3" Schedule 80 pipe at 100°F with a nominal supply of air temp of 70°F at 0 PSIG.

The zero error readings at zero CFM show the test pipe and temperature sensors have stabilized at 100°F. As the flow rate increases the temperature of the air at the air temperature sensor quickly drops to the nominal air temp of 70°F showing a large error. With continued increase in flow rate, the error drops as the cooling effect of the flowing gas overcomes the heating influence of the pipe. The error continues dropping with increasing flow rate, but levels out substantially beyond 200 CFM.

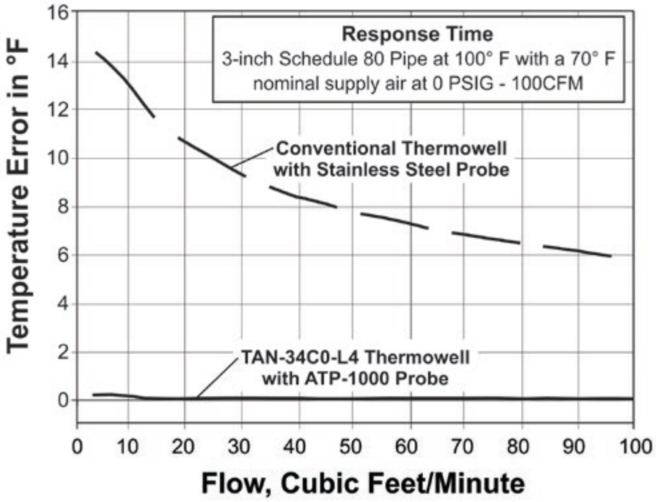


Figure 10. Temperature Error vs. Flow Rate

Probe Response Time

Figure 11 – 3" Schedule 80 pipe at 100°F with a nominal supply of air temp of 70°F at 0 PSIG. At time zero, test pipe and temperature sensors have stabilized at 100°F. At time zero, flow is switched from 0 to 100 CFM.

At time zero with the temperature sensors and the test pipe stabilized at 100°F there is no error. The flow rate was suddenly changed to 100 CFM causing a sudden maximum error. The flow rate is held at 100 CFM through the duration of the test. The response time for the ThermoSync thermowell is about 120 seconds. For the conventional thermowell, response time is about 480 seconds. The probe type had no effect on response time of either thermowell.

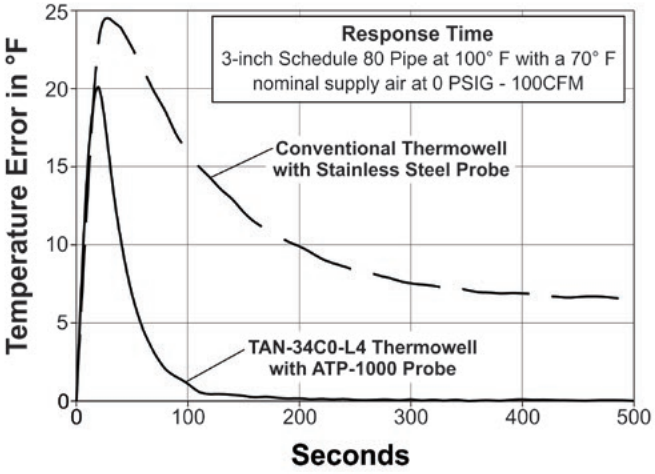


Figure 11. Temperature Error vs. Flow Rate

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