MYSTERIES OF TEMPERATURE MEASUREMENT OF THE CLAUS FURNACE

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> Ted Keys Delta Controls Corporation 585 Fortson Street Shreveport, LA 71107 +1 318-424-8471 tedkeys@deltacnt.com

Steve Croom Delta Controls Corporation 585 Fortson Street Shreveport, LA 71107 +1 318-424-8471 <u>sjcroom@cs.com</u>

ABSTRACT

Discrepancies are sometimes observed between the Claus furnace temperatures reported by a thermocouple versus the temperature reported by a pyrometer, even when the devices are mounted in the same area of the furnace. Sometimes these discrepancies are caused by installation or maintenance issues. At other times, the instruments are performing as well as can be expected, but are measuring different things. Computer modeling illustrates the measurement problems that can occur when there are large temperature gradients in the furnace.

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Steve Croom, Delta Controls Corporation, Shreveport, LA Ted Keys, Delta Controls Corporation, Shreveport, LA

"A man with a watch knows what time it is; a man with two is never sure." – Segal's Law

In monitoring the temperature of Claus thermal reaction furnace refractory, it is common practice to employ both thermocouples and infrared pyrometers on the same furnace. This practice is advisable as it provides redundancy and eliminates common-cause failures. However it has been observed that in some installations, there is a discrepancy between the temperatures reported by the thermocouple versus the temperature reported by the pyrometer, particularly when the devices are mounted in the same area of the furnace.

In these instances, the three possible causes are:

- 1. Each instrument is reporting actual temperatures, but the temperatures are different.
- 2. The thermocouple is wrong.
- 3. The pyrometer is wrong.

Of course, discrepancies can also be caused by any combination of the above.

Thermocouple Errors

The nature of thermocouples is such that they generally cannot read a higher than actual temperature. If the thermocouple is reporting a higher than expected temperature, strong consideration must be given to the possibility that expectations, rather than the thermocouple, are the issue. One reason for a high temperature reading is direct flame impingement on or near the thermocouple's thermowell. In this case, the thermocouple is not in error, but is reporting the high temperature to which it is exposed.

Thermocouples that read lower than expectation, or lower than the actual temperature, may be due to corrosion or contamination of the metallic thermocouple junction(s). Nearly all thermocouple failures in Claus service result from corrosion; the remaining question being how did the corrosion occur? The main causes for corrosion are the failure to maintain the proper purge flow and pressure over the long term or by mechanical breakage of the ceramic thermowell.

Thermocouples designed for Claus service are normally equipped with two separate thermocouple junctions, each providing its own independent output signal. These two elements are mounted in the same location adjacent to each other, but one of the two, the "reference" element, is embedded in solid ceramic in such a way that if the ceramic thermowell becomes broken, reaction gases do not readily come in contact with it, preventing immediate corrosive attack. (See Figure 1) The "operating" element, on the other hand, under the same breakage condition, is



directly exposed to reaction gases and corrosion immediately ensues, causing a deterioration of the output signal. Therefore, if the "operating" element signal is declining relative to the protected "reference" element's signal, it may be assumed that the thermowell has become broken. If the two separate thermocouple elements in a given thermocouple are reading within approx 20°C of each other, it may be assumed that they are reading accurately.

Thermocouples used in Claus service must be continuously purged to provide long term reliability and accuracy. But, the thermocouple can read low if this purge is significantly higher than the recommended purge rate (approx 11 liters/hour). This low recommended flow rate cools the thermocouple by only a few degrees, but cooling rapidly increases as the purge rate is increased. Excess purge cooling can easily be tested by temporarily turning off the purge flow



Figure 2 - Cooling Effect of Thermocouple Purge

and observing a rise in the indicated temperature. (Briefly turning off the purge will not harm the thermocouple.)

Of course, what may appear to be a thermocouple error may be the result of the temperature transmitter(s) to which they are connected. Therefore, to insure that the thermocouple is not at

fault, the mV values of each element may be taken directly at the thermocouple terminal housing (or more conveniently, at the input terminals of the transmitter). These values are then compared to the corresponding type thermocouple table to determine the temperature. The temperature transmitter must be checked to determine that the thermocouple "type" has been set properly as must the "zero" and "span" settings.

A review of the trend of the thermocouple's output signal is the key to diagnosing its health. If the signal trend shows that one element suffered a rapid decline in signal vs. the other element, it is likely that the ceramic thermowell failed. Should this occur, an evaluation of the device must be made to determine the cause of the failure. The cause may be breakage due to severe refractory shifting, but is more likely due to thermal shock resulting from upset conditions or by errant flame patterns, particularly during initial start up. A gradual decline in signal of both elements is usually because of inadequate continuous purge.

A sudden drop from normal to "zero" would indicate a broken / disconnected wire or a transmitter failure.

Pyrometer Errors

Occlusions

A pyrometer determines temperature by measuring the light, usually in the infrared (IR), that is emitted from a hot surface. The most common problem with pyrometers has to do with material coming between the furnace and the sensor and occluding the infrared energy. Usually, errors are detected as the pyrometer slowly decreases its signal relative to that of the thermocouple(s). The typical cause is from a layer of sulfur accumulating on the lens viewport glass. As this becomes more and more opaque, the IR energy reaching the sensor is attenuated, causing a lower and lower reading over time. Another cause may be buildup of sulfur compounds in the base of the nozzle or in the bore through the refractory, again, partly blocking the view path of the IR energy. This problem is minimized and often prevented by keeping the nozzle and viewport at a temperature above the freezing point of sulfur. Use of a heated lens assembly, a pre-heated low flow lens purge and insulation on the nozzle, block valve and lens assembly can prevent buildup of these sulfur deposits with pyrometers designed for the elevated operating temperature. High flow purging of the nozzle cools the nozzle and can actually encourage the formation of sulfur deposits in the nozzle. It can also sufficiently cool the carbon steel such that corrosion occurs in the area of the nozzle / vessel shell. Therefore, contrary to historic norms, high flow nozzle purging is not recommended.

Sensor Drift

Older IR designs for Claus service often experience drifting of the accuracy of the sensor / electronics, requiring frequent recalibration. Modern semiconductor sensors can go for years without recalibration, but these need to be isolated from the heat of the vessel nozzle.

Misalignment

Although uncommon, vibration or refractory shifting as the furnace heat rises, particularly upon initial start up, can cause a misalignment of refractory to the sight path of the IR lens, partially obscuring the 'view'. Most modern pyrometers provide for visually checking of the bore sight of the instrument to detect misalignment and occlusions.

Actual Temperature Differences

No two points in the furnace are at exactly the same temperature. Reaction gases start out at near ambient temperature at the burner and rise in temperature as they react exothermically in the front part of the furnace. Later reactions are endothermic, causing a drop in temperature towards the back end of the furnace. At the same time, heat is being lost through the furnace wall. High gas velocities, turbulence, and radiant heating tend to smooth out the temperature gradients somewhat, but temperature differences of several hundred degrees at different points along the hot-face are not uncommon. These differences can change with gas flow rate and gas composition.

Gas Composition Changes

For pyrometers intended to measure gas temperature or partial gas temperature (where the measurement is a combination of gas and refractory temperature), the measurement can be affected by changes in the gas composition. Figure 3 shows the transmissivity of a mixture of gases near the burner of a claus furnace. Here the feed gas is largely un-reacted. The atmosphere is mostly transparent over much of the near and mid-infrared wavelengths, except for the region around 2.7 microns, where the atmosphere transmits only about half of the light passing through it. A pyrometer operating at 2.7 microns would read about halfway between the gas temperature and the hot-face temperature.

Figure 4 shows the transmissivity of the same gases further down the furnace. Here, the reaction is about 25% complete. The transmissivity is dominated by water vapor that has been created by the reaction. A pyrometer operating at 2.7 microns would now be reading closer to the gas temperature, but still be affected by the refractory temperature behind it with about a 80%/20% weighting between the two temperatures.

Figure 5 shows the transmissivity of the same gases near the tube sheet. The composition has changed considerably during the course of the reaction along with a change in transmissivity. Figures 3, 4, and 5 are for a constant feed gas composition. Changes in feed gas composition and flow rate will further affect the transmissivity. While it is possible to compensate for the transmissivity for a given set of operating conditions, the accuracy will suffer as soon as the operating conditions change. Because of the changes in gas transmissivity, attempts to measure gas temperature with a pyrometer are not recommended.

Note that at around 2.1microns, the atmosphere is completely transparent under all normal operating conditions. A pyrometer operating at that wavelength will accurately read the refractory temperature regardless of gas composition.



Figure 3 Transmissivity of gases near the burner



Figure 4 Transmissivity of gases further down the furnace



Figure 5 Transmissivity of gases near the Tube Sheet

Effects of Emissivity and Reflectivity

Some surfaces are more effective at radiating infrared energy than others. All objects radiate less energy than that of a perfect radiator at the same temperature by a factor that is characteristic of the material being measured. That factor is referred to as the object's emissivity. The emissivity value ranges from 0 to 1. Most pyrometers include an emissivity adjustment to compensate for the emissivity of the target.

A characteristic related to emissivity of an object is its reflectivity. This is simply the ratio of the light reflected from the object to the total light incident on the object. It can be shown that for an opaque object, the emissivity, ε , and the reflectivity, r, are related by:

$r = 1 - \varepsilon$

A perfect radiator that has an emissivity of 1.0 would have a reflectivity of 0. (That is why such a radiator is called a 'black body'.)

An infrared pyrometer measures the total infrared energy leaving the surface of a target object. This energy is called the 'radiosity' and is made up of energy that is radiated from the surface due to its temperature as well as any reflected energy that came from elsewhere. The pyrometer is not capable of distinguishing between radiated and reflected energy.

Most discussions of emissivity in the context of infrared temperature measurement assume that the measurement is of a hot object that is surrounded by an ambient environment (i.e., the skin temperature of a furnace or pipe). In these situations, reflectivity is not a concern, since the ambient environment rarely produces a significant amount of infrared energy compared to the object being measured. Thus, in ambient environments, the reflected energy can often be safely ignored.

Inside a Claus furnace, where all the surfaces are radiating, there is an abundance of reflected energy, as shown in Figure 3. Thus reflections cannot be ignored.



What effect does this reflected energy have on the temperature measurement inside a Claus furnace?

It can be shown that if every surface was at exactly the same temperature, the radiosity of the target would be the same as that of a black body at that temperature. Thus a pyrometer pointed into the furnace would read the temperature of the furnace. In fact, this is why pyrometers are calibrated at the factory by pointing them into black-body calibrators that are essentially closed cavities at a uniform temperature. Such an environment precisely models the light from a furnace at uniform temperature.

It can also be shown that if the emissivity of the target was very high (approaching 1.0), then the reflected energy would approach zero and the measured temperature would be the temperature of the target spot.

However, as mentioned above, the temperature inside the furnace is not exactly uniform. Also, the emissivity of the firebrick is considerably less than 1.0.

In order to investigate the effects of emissivity on the pyrometer measurement, a computer simulation was created to calculate the total radiosity of a simple two-chambered furnace that is

typical of a Claus furnace with a choke ring. The radiosity at each point in the furnace (indicative of what a pyrometer would read) was then compared to the temperature at that point using various emissivity values. The temperature profile was chosen to reflect a temperature rise from the exothermic processes near the burner followed by a cooling due to the endothermic reactions farther down the furnace.

Figure 7 shows a simulated run with the emissivity of the refractory set to 0.9. The result is what most people would expect from a pyrometer measuring refractory temperature. The pyrometer reading tracks almost exactly with the hot-face temperature.



Figure 7 - Actual vs. Indicated Temperature with ε =0.9

However, the emissivity of high alumina firebrick is likely not nearly as high as 0.9. The fact that firebrick is nearly white indicates that at visible wavelengths its reflectivity is fairly high and thus the emissivity is fairly low. Figure 8 shows a simulation run using an intermediate refractory emissivity of 0.4. The effects of reflections are quite evident as the warmer areas read a bit low and the cooler areas read a bit high.



Figure 8 - Actual vs. Indicated Temperature with $\varepsilon = 0.4$

The value of 0.4 may be representative of the emissivity at mid-infrared wavelengths, but at the near-infrared wavelength, an emissivity of around 0.2 may be more realistic. Figure 9 shows a simulation using $\varepsilon = 0.2$ at near-infrared wavelengths and $\varepsilon = 0.4$ at mid-infrared wavelengths. The near-infrared pyrometer shows more 'averaging' since the higher reflectivity at its wavelength causes light to be bounced around the furnace more.



Figure 9 - Actual vs. Indicated Temperature with ε =0.2 (near-IR) ε =0.4(mid-IR)

The runs of Figure 7, Figure 8, and Figure 9 used a temperature profile that did not take into account the much cooler wall temperatures in the vicinity of the burner on the left and the waste heat boiler (WHB) tube sheet on the right. Figure 10 uses the same emissivities as Figure 9, but includes the effects of the cooler end conditions. Note that the indicated temperatures are reduced along the entire length of the furnace.

These simulations demonstrate that in a furnace with large temperature gradients, a perfectly calibrated pyrometer may not read the same as a thermocouple, even if the pyrometer is pointed directly at the thermocouple's thermowell as shown in Figure 6. This is because the thermocouple measures only the temperature at its junction whereas the measurement of a pyrometer may be thought of as a weighted average of the temperatures in the furnace, with the weighting strongly dependent on the emissivity of the refractory material. References in the literature give a wide range of emissivities for high-alumina ceramics, ranging from 0.01 to 0.8. Determining the exact emissivities at the operating infrared wavelengths and at operating temperatures is a subject for further investigation beyond the scope of this paper.



Figure 10 - Includes effects of cooler burner and WHB tube sheet

Mitigating Measurement Discrepancies

If the difference in measurements between nearby instruments is relatively small, (perhaps 30°C, although that number is somewhat arbitrary) things are probably doing as well as can be expected. Larger differences may require some diagnostics as mentioned above to determine

which instrument(s), if any, may be in error. Discrepancies that increase over time are a particular warning that something is amiss.

After verifying that the optical path is not occluded, the operator may decide to verify the pyrometer's calibration accuracy. The best method to calibrate a pyrometer is with another pyrometer. The process pyrometer is temporarily removed and replaced with a portable pyrometer that has matching optical characteristics. After reading the furnace temperature, the process pyrometer is placed back in service and adjusted to match the portable pyrometer reading. Note that the portable pyrometer should be one that is specifically designed for the Claus furnace. A general-purpose IR gun:

- typically has too wide of a viewing angle to accurately see down a valve, nozzle, and borehole into the furnace,
- may use wavelengths that are sensitive to the higher flame temperature, and
- may be sensitive to attenuation in the viewing window.

An easier, but less accurate method of calibration is to set the IR device to match the reported reading of the nearest permanent thermocouple.

Sometimes, a thermocouple is inserted through a special sealing gland that is temporarily installed on the IR port for calibration purposes. This does not usually allow a very accurate calibration, although it is the best method if the above methods are not available. When using the insertion thermocouple, it is wise to turn off any high flow nozzle purge, as this has a cooling effect. Note, the insertion thermocouple will likely be destroyed if introduced to a temperature higher than around 1400°C, which would melt the 'K-type' element. High temperatures could also cause physical damage to the insertion thermocouple's stainless steel sheath, possibly preventing its withdrawal.

Usually, trend data provides more useful data than mere instantaneous comparisons. If the deviation between a thermocouple and an adjacent pyrometer indicate that the pyrometer is slowly reading lower and lower relative to the thermocouple over time, the likely problem is occlusion of the IR sight path. If the thermocouple is reading lower and lower over time relatively to the pyrometer (and to expectations), it may indicate a failure of the thermocouple purge permitting gradual corrosion of the elements.

Consistent offsets among multiple temperature measurement devices are the key indicator of their overall performance. Multiple instruments (of at least two different technologies to minimize common cause failures) indicating the same relative temperature patterns is acceptable. A continuous disparity of as much as a couple hundred °C is not necessarily an indication of trouble.

Changes in instrument tracking trends, i.e., growing offsets relative to each other, with no changes in process conditions, likely indicates the need for instrument maintenance.