Improved IR Pyrometry in Furnaces using a Radiation Shield

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ABSTRACT

Reflected furnace radiation can lead to large errors in temperature measurements using infrared (IR) pyrometers with surroundings hotter than the target surface. This is a problem for the steel industry when reheating steel strip in an annealing furnace. There are several ways to avoid this problem, one common way is to measure the temperature in a roll gap and another is to use a gold cup pyrometer. This paper will present theory and practical results from the use of a radiation shield to minimize the effect of reflected furnace radiation.

Pilot trials were made in the chamber furnace at MEFOS with a Williamson Pro 81 IR pyrometer and two types of radiation shields. Reflected furnace radiation could be nearly eliminated when the radiation shield was placed close to the target. A fixed radiation shield can interfere with heat transfer to a stationary target, but this is less of a problem if the target is moving. Therefore this technique could be applied to steel annealing furnaces since the strip is moving.

A bright metallic steel surface typically has a much lower surface emissivity than an oxidized steel surface, which gives a relatively high surface reflectivity. Knowing the emissivity of the steel strip is insufficient for making accurate IR temperature measurements if the temperatures of the surroundings are not sufficiently lower than the target surface temperature.

Keywords: radiation, IR, infrared, pyrometry, furnaces, shield, accuracy, steel

1. INTRODUCTION

High temperature infrared (IR) pyrometers are available with manufacturer’s rated accuracies of ±2°C at 800°C (or ±0.25% error of the target temperature) [1]. Measurements with this high accuracy require that the surroundings do not interfere with the measurements. A ratio pyrometer or a multiple wavelength pyrometer can be used if the surface emissivity varies or is unknown, but a major problem with IR pyrometer measurements in furnaces is reflected radiation. P. Saunders writes ”In furnaces, where reflection errors are involved, multi-wavelength thermometers are invariably unreliable”[2]. He presents a method for calculating a correction factor for the influence of furnace radiation for furnaces used in the petrochemical industry. Another way is to measure the temperature in a roll gap or to use a gold cup pyrometer. Gold cup pyrometers
which are placed on a hot surface can eliminate both the influence of an unknown emissivity and reflected radiation. These are normally designed for intermittent use, and they are unsuitable for moving objects.

A project organized by The Swedish Steel Producers Association has investigated this problem [3] for steel annealing furnaces. A steel strip is moving through a hot furnace so contact methods are unsuitable. Mathematical compensation for furnace radiation requires knowledge of surface emissivities. The steel strip emissivity can be low and varying depending on the steel grade and previous processing, so this approach is difficult. A method to improve pyrometer accuracy using a radiation shield and a ratio pyrometer will be described in this paper.

2. Theory

The purpose of the radiation shield is to block furnace radiation, so it could be a cylinder or a hollow shell or a hemispherical body. Sighting tubes placed close to the target act as radiation shields. The effect of the size of the radiation shield versus the distance from the target can be evaluated using geometric configuration factor (view factor) equations. This was done by modeling the pyrometer spot as a uniform disk 30 mm in diameter, and the radiation shield as a uniform disk with a diameter from 55 to 200 mm using the equation for disks given by Siegel and Howell [4]. The curves given in Figure 1 show that a 200 mm radiation shield can give a view factor close to 1 for a standoff distance under 10 mm from the surface.

![Figure 1: View factors when varying the distance from the target and the diameter of the radiation shield](image)

The principles of thermal radiative heat transfer can be used to evaluate when a radiation shield is necessary. The black body signal strength $S(T)$ from a target is proportional to the integral of the spectral radiance for the spectral responsivity of the pyrometer for the temperature of the target $T$ in Kelvin. A monochromatic pyrometer operates at a narrow bandwidth which can be approximated using the center wavelength. This monochromatic approximation together with Wien’s approximation for Planck’s law gives a simple equation [5] for converting pyrometer signal strengths to temperatures or vice versa in equations 1 and 2:

$$S(T) = \exp \left( -C_2/\sqrt{T} \right)$$  \hspace{1cm} \text{Eq. 1}
T = \(-C_2/(\mathcal{R}\ln S(T))\)  \hspace{1cm} \text{Eq. 2}

where

\[ C_2 = h\lambda/k = 0.014388 \text{ m}\lambda \] (the second radiation constant)
\[ \mathcal{R} = \text{IR pyrometer wavelength (in meters)} \]

P. Saunders presents a useful method for analyzing the effect of reflected radiation [6] using the above simplifications for radiative signal strengths. The temperature measured by the pyrometer is based on the emissivity setting and the total target radiance signal, which gives the term on the left in equation 3. This is equal to the sum of the effect of the emitted radiance and the effect of reflected radiance. The first term on the right is the component of the radiance signal strength due to the target and the second term due to reflected radiation from the surrounding walls. The target emissivity \(\varepsilon\) and reflectivity \(\rho\) are related since the reflectivity is one minus the emissivity for opaque targets (that is, \(\rho = 1 - \varepsilon\)).

\[ \hat{\varepsilon} S(T_m) = \hat{\varepsilon} S(T_t) + (1 - \hat{\varepsilon}) S(T_w) \]  \hspace{1cm} \text{Eq. 3}

\(\hat{\varepsilon}\) = effective object or target emissivity
\(\hat{\varepsilon}\) = pyrometer emissivity set point
\(T_m\) = radiance temperature measured for target
\(T_w\) = radiance temperature measured for wall
\(T_t\) = true target temperature

The temperature error due to reflected radiation can be estimated using the above equations. Figure 2 shows the error expected when varying the temperature for the walls or surroundings for a monochromatic pyrometer operating at 0.8 microns with a target temperature of 800°C and a target emissivity of 0.8. The effect of wall radiation is insignificant if the surroundings are about 200°C below the target temperature. If the radiant temperature of the surrounding walls is the same as the target, then using an effective emissivity of 1 is an option. The temperature measurement errors can increase rapidly when the wall temperatures are higher than the target temperature, which can give problems when using IR pyrometers in furnaces.

Figure 2: Temperature error expected for a pyrometer operating at 0.8 microns with a target temperature of 800°C and a true emissivity of 0.8.
3. Experimental

A Williamson PRO 81-20-C dual wavelength pyrometer was tested with a radiation shield in MEFOS chamber furnace. The pyrometer has an operating temperature range of 475-1750°C using wavelengths close to 1.5 microns and an accuracy of 0.25% of reading or 2°C [1]. The pyrometer was mounted on the top of a 66 mm ID sighting tube above the furnace with the radiation shield on the other end of the tube (see Figure 3). Nitrogen was used to keep the pyrometer lens clean.

Two radiation shields were made (1) from a stainless steel bowl 0.22 m in diameter and 0.11 m deep and (2) another from a bowl lined with a castable refractory giving an interior diameter of 0.2 m (see Figure 4). A brick platform was built under the radiation shield to hold a stainless steel strip specimen (0.35 m x 0.3 m x 0.004 m) for temperature measurements (see Figure 5). The temperature of the steel specimen was monitored with Type N thermocouples, with one above and two below the specimen and a thermocouple in the radiation shield.

The furnace was fired with a propane burner on the opposite end of the furnace from the pyrometer equipment. A cooling lance could be placed under the specimen to vary the specimen and furnace temperatures.

Figure 3: Schematic figure of the placement of the radiation shield in MEFOS chamber furnace
RESULTS AND DISCUSSION

Unstable furnace temperatures were desired in the chamber furnace to make temperature measurements more difficult for the following trials with the two radiation shields. An example of the temperatures logged for a trial run with the stainless steel metal shield is given in Figure 6 with the furnace temperature increasing and a series of tests varying the shield height. Initial tests showed that increasing the pyrometer lens purge nitrogen (at 14:58) with the shield close to the surface (15 mm) gave a cooling effect and increased the temperature error, resulting in a the pyrometer temperature below the thermocouple temperature of the target. Therefore the purge nitrogen flow rate was reduced and the pyrometer alignment was checked at about 15:00. The period of interest for this paper is with a low flow rate for the purge nitrogen (ca. 5 l/min), when the temperature errors were logged for a series of step changes in pyrometer height until 15:25. The temperature
errors are plotted in Figure 7 for these experimental conditions when the radiation shield height was not noticeably affecting the temperature of the target. A series of temperature measurements were chosen for each height setting after a short stabilization period to show the statistical noise in the data. The temperature errors increased non-linearly with height, but they are relatively linear when the shield is close to the surface. The temperature errors are seen to approach zero when the shield height is extrapolated to zero for the first three points (well within the temperature errors possible for the instrumentation). Note that after this period the radiation shield was suddenly lowered to 15 mm and the temperature of the radiation shield and thermocouples experienced also a noticeable temperature drop. The radiation shield should be designed so that it does not significantly affect the temperature of the target, as seen for the experimental conditions chosen for Figure 7. When this is possible, then a radiation shield can be used to give a series of temperature measurements versus shield height close to the target surface, which together with an extrapolation curve can provide a method which can essentially eliminate temperature errors due to stray furnace radiation. Using the radiation shield close to the surface (8 mm) gave a large reduction in the temperature error even without extrapolation to a height of zero, which is an improvement compared to using an IR pyrometer without a radiation shield or correction for furnace radiation.

Figure 6: Temperatures logged for a trial with the metal shield
Figure 7: A linear extrapolation of the effect of changing the shield height on the temperature error for the first three shield heights.

An example of the temperatures logged when using the refractory ceramic lined shield is given in Figure 8 when the furnace was cooling. The radiation shield is hotter than the target steel strip, and it causes the surface thermocouple temperature to increase when the shield approaches the steel surface (8 mm height), while the pyrometer temperature decreases. Even one of the thermocouples under the steel strip registers a temperature increase (plate bottom right side), so heat input from the hot shield is occurring. Raising the radiation shield and lowering it again gave a pyrometer temperature less than the surface thermocouple. This test shows how the large thermal mass of a heavy refractory radiation shield can interfere with the temperature measurements, so the use of a thin metallic radiation shield is preferable.

Figure 8: Temperatures logged for a trial with the refractory ceramic shield.
5. CONCLUSIONS
These trials with a Williamson ratio pyrometer and radiation shields illustrate how interference from stray furnace radiation can be minimized to improve the accuracy of surface temperature measurements in hot furnaces. A shield with a large diameter close to the surface is recommended to reduce the effect of furnace radiation. Additional accuracy can be possible by making a series of temperature measurements and extrapolating the temperature data to a height of zero, that is, the equivalent of having the radiation shield in contact with the surface, if the radiation shield does not affect the temperature of the target. The temperature of the target can be affected by interference from the purge gas flow which is used to keep the lens clean and the thermal mass of the shield. In these trials, the refractory lined shield had a larger thermal mass than the stainless steel shield, which could affect the target temperature and contribute to temperature measurement errors. This technique using a radiation shield to avoid furnace radiation is suitable for moving targets, as in annealing furnaces, when there is little time for the presence of the shield to influence the target temperature.

6. REFERENCES

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