ATMOSPHERIC FURNACES – PRODUCT TEMPERATURE IS CRITICAL

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Heat-treating of metal parts in an atmospheric furnace is a very common practice. One such furnace is called a Mesh Belt Furnace, in which the parts are heated in an atmosphere and then eventually quenched. The type of parts heat-treated includes fasteners, stampings, hand tools, bearings, automotive parts and machined components. The processes include; clean hardening, light case carburizing and carbon nitriding, as well as austempering and martempering. The control of the furnace is usually fully automatic and the control of the temperature during the entire process is very critical. In addition to temperature control, a record of the part temperature is usually an absolute necessity for the end-customer.

Why is temperature control so critical?
If the part is over heated, it will have an undesirable grain structure.
If the part is not heated to the right temperature, the material will not be at the required austenitizing temperature and will not have the proper microstructure.

HOW IS THE TEMPERATURE MEASURED AND CONTROLLED?
In metals applications, the most common sensor is a thermocouple, with infrared thermometers used to measure the final temperature. Which is the best type of sensor, thermocouple or infrared? They both have advantages and disadvantages, but when used in the correct manner, they both do a very good job of temperature measurement.

When a thermocouple is installed in a furnace, what is the sensor measuring? It is really indicating the temperature of the tip of the thermocouple. If the line speed changes or if the amount of material is increased or decreased, the thermocouple cannot detect the temperature change in the material because of the furnace loading or line speed. When installed properly, infrared thermometers will not see the environment, and will measure the real temperature of the product. Since they do not touch the product, they are an ideal instrument for moving targets because they do not interfere with the actual process and there is no contamination of the product. (See Figure 1)
Because of these advantages, we will concentrate on the use of infrared thermometers to measure the part temperature in the mesh belt furnace. To understand how an infrared thermometer works and how to measure temperature accurately, we need to review the theory of infrared and how the instruments operate.

Infrared energy was discovered by accident. A German physicist aimed a beam of white light at a prism and he saw the rainbow. He wanted to see if there was a different level of energy in each of the colors. He discovered that while he could see the red, green and blue color, his energy collectors showed that there was some energy on either side of the rainbow and in fact on one side, beyond the red color, the amount of energy emitted was very substantial. As an example, if you were to look at a piece of steel at 1500°F, you would see a lot of visual light, but what you cannot see is in the infrared spectrum, where there is 100,000 times more energy being emitted.

He determined some basic rules about infrared energy:

1. Every object in the world emits infrared energy at all wavelengths.
2. As an object gets hotter, it emits more and more infrared energy.
3. Infrared energy travels at the speed of light.
4. Infrared energy can be reflected with mirrors and concentrated with lens, just like light energy.
When we discuss infrared thermometers, we talk about instruments that operate at different wavelengths. To denote the wavelength, we use one micron as a unit of measure. One micron is $10^{-6}$ meters in length. This is hard to visualize, so it is helpful to think of a human hair, which is 65 microns thick. Our eye can see wavelengths of 0.3 to 0.7 microns. Infrared thermometers operate in the range of 0.65 to 14 microns, with the infrared spectrum extending to about 1000 microns, not all of which are used to measure temperature.

To build an infrared thermometer, a temperature standard is required and this standard is called a Black Body. What is a Black Body?

1. It is a perfect emitter; nothing can emit more energy at any wavelength or temperature than a Black Body.
2. It is a perfect absorber; all infrared energy that strikes a black body is absorbed.
3. It is the standard for all infrared thermometers.

What do they look like? (See Figure 2) A Black Body is basically a furnace with a special cavity inside of it. The Black Body is heated to specific temperatures. The cavity temperature is measured with a thermocouple. The infrared thermometer is sighted into the cavity and its temperature must match the temperature of the cavity or it is considered out of calibration.

The engineer who designed the first Black Body, Max Planck, developed a family of curves called Black Body curves. (See Figure 3) These curves show that as the temperature of the Black Body increases, the amount of energy emitted also increases. Using these curves, you can develop an infrared thermometer that will work at any wavelength because you can calculate the signal from the detector based on the temperature of the hot product.
What happens when you measure the temperature of a hot target, and it indicates a low temperature? Is it out of calibration? No – this is a characteristic called emissivity. It is a known fact that everything in the world emits infrared energy less efficiently than a perfect Blackbody, so we assign emissivity numbers to compensate for this. For example, a piece of steel that has an emissivity of 0.8, emits 80% of what a real black body emits at the same wavelength and temperature. What effect does this have on the temperature indication?

Let’s compare three hot targets that have the same temperature of 816°C/1500°F. The first is a Black Body with an emissivity of 1.00 or 100%. The second is a piece of steel with an emissivity of 0.8 and the third is molten aluminum with an emissivity of 0.05. They are all operating at the same temperature of 816°C/1500°F, but when you visually look at the three targets, the Black Body appears the hottest. The steel appears to be the next hottest and the molten aluminum does not appear to be hot at all (it does not even glow red because it only has a 5% emissivity or 95% less than perfect). If you were to measure these same targets with an infrared thermometer without adjusting for emissivity, you would again read too low with the worst case being the molten aluminum.

How do we compensate for this emissivity factor? On every infrared thermometer, there is a control or menu item labeled Emittance. When you set this value at 0.8, the instrument automatically increases the energy signal 20% to make the thermometer indicate a true Black Body. This means in order to indicate the correct temperature with an infrared thermometer, you must know the correct emissivity and it must be set on the thermometer.
There are some basic rules about the value of emissivity for a hot target:

1. The emissivity of a Black Body = 1.0
2. The emissivity of everything else is < 1.0
3. The emissivity changes with wavelength, except for a gray body
4. The emissivity usually does not change with temperature unless you change the surface condition, for example Example – solid to liquid or unoxidized to oxidized.

Rules # 1 and #2 need no explanation, but #3 and #4 require further comment. There are many types of infrared thermometers on the market and there are twelve basic wavelengths that everyone produces. This means that in order to measure the true temperature, you must know the emissivity for the wavelength instrument you are using and the material you are measuring. The exception is a material called a Gray Body. This is a material that has a uniform emissivity at all wavelengths. The most reliable example of a Gray Body is oxidized steel. It has an emissivity of 0.82 for all wavelength instruments. This is about the only material that has a repeatable emissivity at all wavelengths.

Rule #4 is a little more difficult. Since we are dealing with metals, we will only consider these factors. When the metal changes from solid to molten or from unoxidized to oxidized, the emissivity value changes for all wavelengths. Therefore, to measure the correct temperature, the state of the surface, spectral response (wavelength) of the instrument and the kind of material must be known in order to determine the correct emissivity.

Why does emissivity change?

Figure 4 shows what is known as the RAT theory. In this figure, we have a block of material, such as a piece of glass. When you aim a beam of infrared energy at the glass, some of the energy reflects off the surface. Everything except a Black Body has reflection (R). The rest of the energy goes into the glass and some of it is absorbed (A), which heats up the glass. The rest of the energy goes through the glass and this is transmitted (T) energy. If you add up the reflected energy, absorbed energy and transmitted energy, you have accounted for all the energy. This is expressed as

\[ R + A + T = 1.0 \]

The same engineer who came up with the RAT theory also discovered that the rate of absorption is equal to the rate that the material will emit at the same wavelength. Using this formula, we can calculate the following:

\[ R + A + T = 1.0 \text{ and } E = A \]

Therefore, \[ R + E + T = 1.0 \text{ and the final formula is } E = 1 - R - T. \]
This shows that the emissivity of a product varies by how transparent and how reflective the material is. For metals, the transmission is zero, so the only reason the emissivity varies is how reflective the material is at the wavelength the instrument is operating. As an example, aluminum is very reflective, so it can have a low emissivity of 0.15. Oxidized steel is a dull gray with minimal reflection, so the emissivity is quite high (-0.82). These numbers will become more important as we discuss the right instrument to use and how to install the thermometer.

![Fig. 4. R+A+T=1.0](image)

What is the right wavelength instrument to use for metals applications? The basic rule is to use the shortest wavelength instrument that will measure the target temperature. Why? Because, as you work with shorter wavelengths, the emissivity of the metal is higher. The problem is that as you work with shorter wavelength instruments, the lowest temperature that can be measured is limited. For example, a 1 micron instrument can measure to about 482ºC/900ºF, a 1.6 micron instrument can measure 260ºC/500ºF minimum and a instrument that operates at 2-2.6 microns can only measure to 66ºC/150ºF. To go lower in temperature requires using a longer wavelength instrument.

The second reason for using the shortest wavelength is that a change in emissivity has the least effect on measurement accuracy for short wavelength instruments. Figure 5 shows four instruments viewing a target at 1000ºC/1832ºF. If the emissivity changed 10%, the error for a 1 micron instrument is only 10ºC/50ºF. If you used an instrument that operated at 8-14 micron wavelength, the error would be 80ºC/176ºF. These errors are dictated by the laws of physics and affect all infrared thermometers the same way.
Because the temperatures of the parts are 927-982°C/1700-1800°F at the exit of the furnace, the ideal wavelength is a 1 micron thermometer. These thermometers can measure a range of 482-1371°C/900-2500°F.

![Temperature Error](image)

**Fig. 5**

**INSTALLATION**

Now that an instrument has been selected, it must be installed correctly. The first parameter to be considered is optical resolution. Figure 6 shows the optics of a typical instrument that has through-the-lens focusable optics. To determine the spot size of the instrument, the formula is \( d = \frac{D}{F} \). "d" is the spot size of the instrument at the focal point. D is the distance from the sensor to the focal point and F is the focal factor that is a characteristic of each instrument. This value is always provided in the instrument specifications or user manual. How does this work? Suppose the distance from the sensor to the center of the mesh belt (Figure 7) is 60 inches. If the focal factor was 100, then the smallest spot the instrument can measure would be \( d = \frac{60}{100} = 0.6 \) inches. This means the target must be larger than 0.6 inches or it will not fill the spot the instrument is measuring and an error will be created. If the target is smaller than this, then an instrument with a higher resolution factor will be needed. The most typical instrument used for this application has \( F = 150 \). So for the above example \( d = \frac{60}{150} = 0.4 \) inches.
The best way to install the sensor is to aim it across the mesh belt and just above the belt (Figure 7). We also suggest focusing the instrument at the center of the belt. This will provide the best cone of vision across the entire belt. Note that the target does not have to be at the focal point. It can be anywhere along the cone of vision and as long as it is big enough to fill the cone of vision, the instrument will measure the correct part temperature.
Figure 8 shows the typical installation of a sensor on the oven. The sensor system consists of a water-cooling assembly, an air purge and the sensor. We do not suggest using a window because they are very hard to keep clean and if the window gets dirty, the instrument will measure the wrong temperature value. The purge gas for the air purge can be the gas used in the furnace, thus preventing air from being introduced into the furnace.

The instrument is installed so that it measures the parts just as they are about to fall off the mesh belt into the quench. Why not in the furnace? Inside the furnace, the heaters are hotter than the parts. Since a typical part could have an emissivity of 0.8, this means it is a 20% reflector. The infrared thermometer will see infrared energy from the hot part, but will also see 20% of the energy from the heaters reflecting off the surface of the material and add this to the signal. This would cause the instrument to measure too high of a target temperature. With some of the newest infrared thermometers, it is possible to correct for any errors caused by reflected background radiation. This can be done by measuring the furnace walls or heater temperature with a thermocouple sensor or another infrared thermometer. Using this temperature as a signal input to the primary sensor, measurement error caused by the background radiation can be eliminated. In some cases, it may still be difficult to eliminate this reflection error inside of the furnace. In these cases, thermocouples can still be used in the main part of the furnace.

At the exit of the furnace and just before the quench, there is a short space where the parts are in an enclosure, but they are not heated. This means the hottest items in the area are the heated parts and the infrared thermometer only sees radiant energy from the hot parts - not the oven walls or any heating element. As a result, an accurate part temperature is achieved at this point. This is the final temperature of the part just before it is quenched, which determines the microstructure of the part. It is also the temperature that the end-user wants to have recorded for his customer.

End-users often inquire about the use a two-color thermometer, which does not require that the cone of vision be filled with the hot target. This makes it easy to work with small parts. However, the two-color instrument is not ideal if there is any reflected energy around. This reflected energy has a greater effect on the two-color instrument than it will on a single wavelength instrument. So, for this reason, it is usually not suggested that a two-color instrument be used for this application.
CONCLUSION
An infrared thermometer with active background compensation or thermocouples are the best sensors to use inside a furnace to eliminate possible errors caused by reflected energy in the furnace. At the exit of the furnace, the infrared thermometer is by far the best instrument because it truly indicates the actual part temperature and is not affected by the air temperature in the oven. If the line speed or loading of the oven changes, the temperatures changes will be quickly detected and these values can be used as a final control input to the heating process, further guaranteeing high quality parts for the final customer.

Additionally, installation of an infrared thermometer is simple - the instrument must be focused, the lens must be kept clean and the right wavelength has to be selected. Infrared thermometers are rugged and last for many years without repair.

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