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Introduction

The movement of atoms and molecules causes every body with a temperature T above absolute zero temperature $T_0 = -273° C$ to emit because of electromagnetic radiation. Measuring equipment that determines the temperature produced by this infrared radiation is designated as infrared thermometer or radiation pyrometer (or simply pyrometer).

Features of contactless temperature measurement

Some features that differ from contact temperature measuring procedures must be considered for pyrometry. Because an optical measuring procedure is involved, the surface of the measured object must be in line-of-sight from the measuring equipment. The measuring set-up, the characteristics of the surface and the measuring distance, as well as the effect of interfering radiation are also critical for correct measurement.

The wavelength range significant for the contactless temperature measurement covers approximately $0.7 \mu m - 1 \, mm$. Within this range, the radiation is designated as heat radiation or infrared radiation, as appropriate.

Grundbegriffe und Gesetze der Temperaturstrahlung

The heat radiation that a body emits depends on the temperature, the wavelength and the emissivity coefficient. The Planckian radiation law describes the relationship between the spectral specific radiation, the temperature $T$ and the wavelength $\lambda$ of a “blackbody radiator”.

$$M_{\lambda\lambda}(\lambda; T) = \frac{C_1}{\lambda^4} \left[ \exp \left( \frac{C_2}{\lambda T} \right) - 1 \right]$$
**Stefan Boltzmann law**

The integration over all wavelengths provides the total specific radiation of a blackbody.

\[
M_{S}(T) = \sigma * T^{4}
\]

\[
\sigma = \text{Stefan - Boltzmann constant} = 5.67 \times 10^{-8} \text{W/m}^2\text{K}^4
\]

Therefore, the radiation intensity increases with the 4th power of the temperature. This means that higher temperatures can be acquired easier with regard to the associated energy. Consequently, smaller measuring surfaces or larger measuring distances are possible for higher temperatures.

**Wien's displacement law**

The radiation intensity has a distinctive maximum for a specific wavelength \( \lambda_{\text{max}} \) that can be calculated with Wien's displacement law:

\[
\lambda_{\text{max}} = \frac{2897.8 \mu m}{T[K]}
\]

The law states that the wavelength maximum changes inversely proportional to the temperature. This means, low object temperatures should be acquired with long-wave measuring pyrometers, whereas high object temperatures should be acquired with short-wave measuring sensors.

**Atmospheric windows**

Our atmosphere is not permeable to all electromagnetic radiation wavelengths. Consequently, a contactless temperature measurement is possible only in specific wavelength ranges because the air constituents make the absorption or emission very small in such cases. These wavelength ranges are called the atmospheric windows.

The atmospheric windows at:

\[
\begin{align*}
0.7 \mu m & - 1.3 \mu m \\
1.4 \mu m & - 1.8 \mu m \\
2 \mu m & - 2.5 \mu m \\
3.2 \mu m & - 4.3 \mu m \\
4.5 \mu m & - 5.3 \mu m \\
8.0 \mu m & - 14 \mu m 
\end{align*}
\]

This results in typical wavelength ranges for various temperature measuring ranges.
Sensors for different temperature ranges

Depending on the design, sensor and filter of the pyrometer, the radiation of only a small wavelength range is received and converted into a temperature-proportional measured quantity. The choice of the wavelength for a pyrometer depends primarily on the temperature range to be measured. The following table describes the relationship between the wavelength ranges deployed most frequently in pyrometry and the associated measuring ranges.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Sensor</th>
<th>Temperature range</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 μm – 14 μm</td>
<td>Thermopile</td>
<td>-30 °C – 1000 °C</td>
</tr>
<tr>
<td>1,1 μm – 1,7 μm</td>
<td>InGaAs-photodiode</td>
<td>250 °C – 2500 °C</td>
</tr>
<tr>
<td>0,8 μm – 1,1 μm</td>
<td>Si-photodiode</td>
<td>500 °C – 3000 °C</td>
</tr>
<tr>
<td>4,8 μm – 5,2 μm</td>
<td>Thermopile (for glass)</td>
<td>300 °C – 2500 °C</td>
</tr>
</tbody>
</table>
Non-contact temperature measurement in aluminum manufacturing

Task:
Fast, accurate and non-destructive temperature measurement of aluminum during heating of slabs, billets, ingots and at the extrusion.
Description:

Prior to forging, rolling or extrusion, aluminum is preheated to the required process temperature. In forging operations, precise temperature control is crucial because the work piece is heated close to the melting point of aluminum. To achieve high material throughput rates and short cycle times at the automated press forging line, quick and highly accurate temperature detection is essential to maintaining exact process temperatures.

Temperature is a critical parameter affecting press speed and product quality. Both the billet and the die are preheated and additional heat is generated by friction during the forming process. The aluminum profile at the press exit should not be too hot because this could lead to hot cracks or hot tear formation. In addition, excess temperatures will wear out the die. Nondestructive, fast and reliable temperature monitoring is crucial to achieving and maintaining strict quality control standards.

Solution:

Aluminum does not radiate thermal energy well. Oxidation can cause the aluminum surface to vary between shiny and matt. Given such circumstances, a standard pyrometer will not able to produce accurate temperature data. The ARDOMETER MPA 29 was designed especially for temperature measurement of aluminum. Its spectral sensitivity enables the pyrometer to ignore light from other sources which might be reflected off of the aluminum. The changing surface characteristics typical of aluminum will not affect the measurement at this particular wavelength. That is why ARDOMETER MPA 29 is able to accurately detect the infrared radiation of shiny, reflective metals with low emissivity at low temperatures.

Two variants are available; the one most suitable depends on the size of the target, the measuring distance and required temperature range. To facilitate focusing, the ARDOMETER MPA 29 comes equipped with either through the- lens sighting or a laser spot light. The pyrometer is infinitely adjustable to ensure superior precision across a wide focusing range starting at 300 mm. The brightly lit display panel indicates the temperature reading and is easy to read from a distance of several meters.

Application example:

- Heat treatment system
- Aluminium Extrusion
Task:

In asphalt production, process temperature is a crucial factor in plant performance and the properties of the hot mix. To ensure long-term quality of the road surface, temperatures must be precisely monitored during the production process and as the hot mix is loaded onto trucks.
Description:

In asphalt production, a crucial process parameter is the temperature of the mineral aggregate and the reclaimed asphalt pavement (RAP). As these materials enter the dryer drum, their temperatures can vary depending on weather conditions. To ensure that temperatures remain within specified limits as the material is fed to the mixer, temperatures are monitored at the point where the material exits the drum. Burners are controlled based on this data.

The hot asphalt mix is discharged directly from the mixer or from the hot mix storage silo onto trucks that deliver the asphalt to the road construction site. In order to achieve uniform quality and long-term performance of the road surface, it is essential that the hot mix exhibits a specific temperature as it arrives at the job site and when road paving operations begin. Asphalt temperatures are thus monitored and documented as the hot mix is loaded onto delivery vehicles. Common to all asphalt plants are the severe environmental conditions. A temperature detection device will be exposed to hot and aggressive vapors and dust.

Solution:

Pyrometers are ideal for monitoring temperatures of a hot liquid material. A pyrometer detects the infrared radiation emitted from an object at a safe distance, without surface contact, and produces an accurate temperature reading. Most commercially available pyrometers will not hold up to the aggressive fumes and dust present at asphalt mixing plants. Lenses are especially sensitive to such harsh industrial environments. The ARDOCELL PK 18 AF 1 pyrometer was specifically designed for use at asphalt and concrete plants and features stainless steel housing as well as a special lens whose surface is highly resistant to impurities. When combined with certain fittings and accessories such as an air purge and sighting tube, the PK 18 AF 1 provides many years of reliability and precision. At proper operation the measuring system works maintenance and wear-free.

The integrated digital display is very convenient during commissioning and plant maintenance procedures. During overhead load out onto trucks, a temperature reading is recorded for each load and saved in the plant's data acquisition system as a matter of quality control and verification.

Application example:
Non-contact temperature measurement at concrete mixing plants

Task:

At concrete mixing plants temperatures are measured just as the concrete flows through the mixer exit chute and is poured onto the truck. The working temperature of concrete, especially for public works structures such as tunnels and bridges, must remain within a prescribed range. For the purpose of verification management the temperature readings must be documented.
Description:

Temperature measurement at a concrete mixing plant requires a system that is able to withstand harsh environmental conditions. The objective is to obtain a reliable temperature reading of the ready-mixed concrete during loading using an accurate, maintenance-free temperature measurement system. These readings are documented and serve as evidence of quality control during the production process.

Solution:

The pyrometer ARDOCELL PK 18 AF 1 was developed specifically for measuring temperatures at concrete mixing plants. This pyrometer has a special, highly resistive lens. Augmented by the PS 01/A air purge and the ZA 01/Q protective tube, this system provides high performance even when used under severe ambient conditions. The mounting accessories prevent aggressive particles in the air from contaminating the optics. The PS 01/K insulation tube ensures electrical and thermal decoupling of the measuring system from the rest of the facility. The measurement data is then transmitted as a 0 (4) -20 mA output signal to the PLC.

Application example:

Measurement at the drum outlet

Mounting accessories PS 01-048
Range of application:

Pyrometers are used in numerous glass making stages and processes: melt furnace, regenerator, float lines, gob, cooling and coating processes, annealing lehr, molds.
Melt Furnace:

To prevent unexpected melt furnace shut-down, it is imperative to perform regular maintenance checks of the refractory material. Pyrometers measurements help to ensure maximum efficiency.

Float Glass:

The float glass cooling rate in the annealing lehr is crucial to the resulting product quality. Improper cooling can lead to breakage during downstream processes. Correct temperatures are also critical across the width of the tin bath.

Containers and Bottles:

Pyrometers are installed at various zones to monitor glass temperature at various processes. These include the molten gob, the fore hearth, annealing lehr and surface treating.

Benefits of real-time temperature monitoring:

- Increased productivity
- Minimized down-times
- Enhanced process control
- Uniform product quality
Task:

The use of appropriate temperature sensors is a prerequisite for optimal temperature control in induction heating systems. Pyrometers, because they detect temperatures in milliseconds without contact, are ideally suited for such applications.
Description:

The quality expectations of metal materials such as steel, aluminum, copper and various alloys used for modern machinery and motors are constantly on the rise. Material properties must be improved to satisfy the industries' exacting and ever-increasing requirements. Post process heat treatment plays a most significant role in enhancing performance characteristics of a metal material. Furthermore, production facilities must comply with stringent environmental regulations while increasing production quantities and improving process reliability. What this means is that modern facilities must produce greater outputs and meet demanding quality standards in regard to process and material.

Heating by means of induction has gained significance in the last few decades. This heating method's versatility and speed make it suitable for a multitude of applications. The application range covers various heat treatment processes, from hardening, annealing and tempering to melting, soldering, welding and shrink fitting up to powder coating systems and special-purpose machines.

Induction technology, when paired with state-of-the-art control systems, enables manufacturers to achieve the desired objectives. This, however, requires strict adherence to production parameters, especially with fully automatic and semiautomatic production lines. Industrial consumers such as the automotive industry as well as their suppliers have increasingly come to demand that crucial parameters be monitored and documented as a quality Principle of Induction Heating.

The operating principle of high-frequency induction heating consists of placing an electrically conductive material in a fluctuating electromagnetic field. The induction heating power supply sends alternating current through a single or multiple induction coils, thus generating a magnetic field. When a work piece is placed within the induction coil and enters the magnetic field, eddy currents are induced within the work piece, generating precise and localized heat. An induction heater works according to the same principle as a transformer: the inductor functions as the primary winding and the work piece as the secondary winding.

Solution:

Siemens ARDOCELL PK 2x Pyrometer Series were specially designed for induction heating applications. Because these instruments can measure temperatures between 250 °C and 1600 °C, they cover the entire temperature range of induction heating processes.

Since heating is only required at selected, localized points, it is all the more important that the instrument provide a high resolution and thus precise targeting to a very small spot. Due to the pyrometers' broadband, antireflection-coated high-precision optical system, targets with a diameter as small as Ø 0,8 mm can be achieved.
Temperature measurement at soldering and brazing facilities

Task:

The use of appropriate temperature sensors is a prerequisite for optimal temperature control in induction heating systems. Pyrometers, because they detect temperatures in milliseconds without contact, are ideally suited for such applications. Inductive heating is a well-proven method for soldering diamond composite segments to stone saw blades. This holds true for both high-volume production as well as for repair work. Pyrometry is the only temperature measurement technique able to meet the high measurement standards and thus the high product quality the industry demands.
Description:

Induction heat soldering or brazing is not as well-known as other soldering methods. The operating principle of high-frequency induction heating consists of placing an electrically conductive material in a fluctuating electromagnetic field. The induction heating power supply sends alternating current through a single or multiple induction coils, thus generating a magnetic field. When a work piece is placed within the induction coil and enters the magnetic field, eddy currents are induced within the work piece, generating precise and localized heat.

An induction heater works according to the same principle as a transformer: the inductor functions as the primary winding and the work piece as the secondary winding.

Due to the highly efficient heating process - virtually heating from the inside out - induction soldering and brazing is an ideal technique. Unlike lasers, induction heating is still efficient when the position of the brazed or soldered joint varies.

Electromagnetic induction provides more rapid and uniform heating than a soldering iron. Whereas soldering tips will wear out and need to be replaced oft-en, an induction loop is virtually wear-free because it is a non-contact method. Induction soldering and brazing is ideal when it is necessary to define or limit the heat to a specific region on a work piece. Induction equipment requires less capital investment and the simplified maintenance means reduced operating costs, thus providing additional advantages over other soldering and brazing methods.

In the past, induction heating was primarily used for creating heavy or wide joints. Today, by using finer induction loops, through non-contact temperature measurement technology as well as more precise feeding and shaping of the filler metal it has become increasingly possible to employ induction heating for extremely small parts such as printed circuit boards and substrates.

Because of the highly localized heat, the solder joint rapidly reaches the required temperature for fusion without risking damage to the work piece. Induction brazing is economical as well, and due to its high repeatability, this method is perfectly suited for automated, high-volume processes.

Solution:

Siemens ARDOCELL PKL 28 was specially designed for those applications which place high demands on temperature measurement such as induction brazing and soldering operations. Because the ARDOCELL PKL 28 can measure temperatures between 300 °C and 1400 °C, this pyrometer covers the entire temperature range for soldering and brazing processes.

Since heating is only required at selected, localized points, it is all the more important that the instrument provide a high resolution and thus precise targeting. Due to the ARDOCELL PKL 28 high-precision optical system, targets with a diameter as small as 1.5 mm can be achieved.

The use of spot light illumination is essential in order to accurately aim the pyrometer at the target spot. The ARDOCELL PKL 28 has an integrated LED spot light based on most recent LED technology. Compared to a laser beam spot light, an LED has the advantage that it not only shows the precise location of the target but the actual target spot size is defined as well. In addition, the LED does not pose a health hazard and will radiate light continuously. The service life of an LED is several times longer than that of a laser.

For precise temperature control of the heating process, a pyrometer must be able to instantly detect temperature changes. The ARDOCELL PKL 28 offer a response time of 2 ms and is therefore ideally suited for immediate process control.
Because installation space at a brazing machine is often limited, the importance of compact instrument size is not to be underestimated. With a diameter of 30 mm and a length of 190 mm, the ARDOCELL PKL 28 – thanks to the screw thread mounting - can easily be installed in cramped locations.

In modern induction brazing and soldering facilities, temperature measurement using ARDOCELL PKL 28 combined with a programmed control system will ensure an efficient, highly repetitive and non-wearing production process with better product yield to satisfy today’s high industry demands.

Application example:
Non-contact temperature measurement in tunnel kilns

Task:

Intensified competition and the constant downward pressure on prices have had their effect on industrial manufacturing including the heavy clay industry. Manufacturers who don’t strive to reduce production costs will eventually fall out of the running. It only makes sense to influence such cost-intensive operating parameters which have the greatest savings potential: reducing energy consumption and minimizing the reject rate.

The kiln temperature profile has a significant influence on the amount of fuel required and the quality of the yield. In this respect, it is of utmost importance to precisely monitor the temperature of the clay product during the firing cycle using accurate measuring instruments.
Description:

Today we see a trend toward equipping new kilns (and retrofitting older ones) with so-called pyrometers, which—as opposed to thermocouples—measure the temperature directly at the surface of the ceramic product, and thus give the most accurate representation of the real heating process taking place within the kiln to enable optimal process control. Thermocouples merely measure the air temperature within the kiln. Their measurement reading will deviate up to 50° C from the actual temperature of the fired ware, and will furthermore depend on variables such as air flow and kiln setting. Thermocouples react sluggishly to thermal fluctuations whereas pyrometers instantly indicate temperature changes. A pyrometer immediately detects the lower temperature of a new batch entering the kiln so that the firing process can be adjusted accordingly. Tighter control of the optimal kiln temperature profile will result in a significant reduction of fuel consumption. Since effective process control depends on reliable temperature measurement, the sensor drift that all thermocouples experience while in service is a major drawback of thermocouple use. Sensor drift will creep up noticeably and measurement errors will not be recognized until defects are discovered on the products exiting the kiln. Process intervention is only possible at a very late stage in the firing process. Pyrometers have the advantage of not being subject to drift. Process control based on reliable pyrometer readings results in a considerably lower reject rate. Furthermore, pyrometer measurement is a nonbearing system meaning that no follow-up costs will be incurred. Today the purchase price of a pyrometer system hardly exceeds the initial cost of a thermocouple. With a view toward operating cost reduction it is wise to switch to pyrometer measurement.

Solution:

The pyrometers of the PK Series have proven successful for stationary measurements at the kilns of countless ceramic works. The entire optics and electronics are housed in a stainless steel enclosure with a 30 mm diameter and a length of 180 mm. The output signal of the instrument is a 4-20 mA linear current signal, thus the pyrometer can be directly connected to standard, commercially available displays, controllers and PLCs. A comprehensive range of accessories—designed especially for tunnel kiln applications—round off the system. This set consists of an insulation tube, a quartz window, an air purge, a sighting tube and a mounting flange.

Mounting example for tunnel kilns
Temperature detection at rolling mill stands

Task:

Today’s demand for product quality poses an ever increasing challenge to producers of iron and steel goods. To satisfy requirements, manufacturers must strictly comply with those production parameters so crucial to quality control. In addition, sheet metal manufacturers have in recent years further reduced rolling mill process temperatures.
Description:

To monitor these temperatures in compliance with current industrial requirements, it is imperative that the latest temperature measuring instruments be employed. These instruments must be particularly suitable for this specific application. The lower threshold of the rolling temperature has been reduced to such an extent that instruments today must be able to reliably detect temperatures as low as 600 °C. Pyrometers are used to accurately detect the slab temperature. The relevant measuring points are subjected to steam and smoke in the atmosphere. To obtain reliable temperature data, two-color pyrometers must be used. However, not every two-color pyrometer is appropriate for this task. It is essential that a pyrometer be selected which features a suitable sensor – one that will not be affected by atmospheric disturbances such as steam or smoke.

Solution:

A two-color pyrometer detects the intensity of the infrared radiation emitted by an object's surface at two distinct wavelengths. A temperature reading is calculated from the ratio of the two intensities. When the path of radiation between the target and the pyrometer is impaired due to atmospheric smoke, dust or water vapor, the sensor cannot detect the total amount of emitted energy, thus resulting in a weakened signal. A ratio (or two-color) pyrometer compensates for this interference. The accuracy of the temperature reading will remain unaffected, even when signal attenuation is as high as 50%.

By integrating state-of-the-art sensors, modern signal processing and special optics, Siemens has developed a pyrometer which can reliably detect temperatures as low as 500 °C at rolling mill stands. Due to the spectral sensitivity of its sensor, ARDOCOL MPA 40 AF 20 yields accurate temperature readings despite the presence of atmospheric influences such as water vapor. This pyrometer dynamically adapts to the atmospheric conditions so that even when the infrared radiation is obstructed to 90%, it will still be possible to detect temperatures as low as 580 °C. ARDOCOL MPA 40 AF 20 yields highly reliable temperature readings for today's reduced processing temperatures at steel rolling mills and is thus in step with the latest industrial requirements.

Mounting example:

M264-A27