Noncontact Temperature Measurement Theory and Application

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Noncontact temperature measurement is the preferred technique for small, moving, or inaccessible objects; dynamic processes that require fast response; and temperatures <1000°C (1832°F). To select the best noncontact temperature measurement device for a particular application, it is essential to understand the basics of temperature measurement technology, temperature measurement parameters, and the features offered by the various measurement systems currently available.

DEFINING THE TERMS

Temperature. Temperature is one expression for the kinetic energy of the vibrating atoms and molecules of matter. This energy can be measured by various secondary phenomena, e.g., change of volume or pressure, electrical resistance, electromagnetic force, electron surface charge, or emission of electromagnetic radiation. The most frequently used temperature scales are Celsius and Fahrenheit, which divide the difference between the freezing and boiling points of water into 100° and 180°, respectively.

The thermodynamic scale begins at absolute zero, or 0 Kelvin, the point at which all atoms cease vibrating and no kinetic energy is dissipated.

0 K = –273.15°C = –459.67°F

IR Radiation. Infrared is that portion of the electromagnetic spectrum beyond the visible (blue to red, 0.4-0.75 µm) response of the human eye. IR wavelengths extend from 0.75 µm to 1000 µm, where the shortest microwaves (radar) begin. Because IR radiation is predominantly generated by heat, it is called thermal radiation.

For the purpose of radiation thermometry, only portions of the IR spectrum are important. The spectrum is frequently divided into "atmospheric windows" that provide maximum loss-free transmission through water vapor in air:
0.7-1.3 µm; 1.4-1.8 µm; 2.0-2.5 µm; 3.2-4.3 µm; 4.8-5.3 µm; 8-14 µm

Thermometer. Most of the well-known thermometers, e.g., glass bulb mercury or alcohol, thermocouple, or resistance thermometer, must be placed in direct contact with the temperature source. Their useful measurement range is –100°C to 1500°C.

Radiation Thermometer. This noncontact thermometer determines the surface temperature of an object by intercepting and measuring the thermal radiation it emits.

Emissivity. This quality defines the fraction of radiation emitted by an object as compared to that emitted by a perfect radiator (blackbody) at the same temperature. Emissivity is determined in part by the type of material and its surface condition, and may vary from close to zero (for a highly reflective mirror) to almost 1 (for a blackbody simulator). Emissivity is used to calculate the true temperature of an object from the measured brightness or spectral radiance. Because an object's emissivity may also vary with wavelength, a radiation thermometer with spectral response matching regions of high emissivity should be selected for a specific application. Emissivity values are listed in the literature for a variety of materials and spectral bands, or these values can be determined empirically.

Brightness/Single-Color Pyrometer. These devices measure and evaluate the intensity, or brightness, of the intercepted thermal radiation. Intensity, or, more generally, spectral radiance, is measured in a narrow wavelength band of the thermal spectrum. Band selection is dictated by the temperature range and the type of material to be measured.

The oldest brightness pyrometers compared optical brightness in the visible (red) spectrum at 0.65 µm by matching the glowing object to a hot "disappearing" filament. The term "single-color" derives from the single

Table 1: On-Line Temperature Measurement Instruments

LOW TEMPERATURE	HIGH TEMPERATURE
General Purpose 0 to 500°C (30 to 1000°F) 8-14 mm wide band radiation thermometers • thermopile detector • optical resolution: 4 mm target (15:1 D-ratio) • response time: 0.5 sec • emissivity adjustment • analog output (mv/°C, mV/°F)	**General Purpose** 400 to 2000°C (750 to 3600°F) narrow spectral band radiation thermometers (0.7-1.1 µm; 0.9-1.9 µm) • solid-state photoelectric detectors (Si, Ge) • optical resolution 1 mm target (60:1 D-ratio) • response time 3 msec • emissivity adjustment • analog output (mV°C, mV/°F)
Extended Temperature Ranges – 30°C to 800°C (–20°F to 1500°F) high-stability, 8-14 µm thermometers • pyroelectric detector • chopper stabilized to compensate for rapid changes in ambient temperature • optical resolution: 3 mm dia. (30:1 D-ratio) • response time: 50 msec • analog output 4-20 mA	**High-Stability/Complex Applications** 300 to 2500°C (600 to 4500°F) narrow spectral band radiation thermometers • for glass and/or through hot gas (3.9 µm) • for glass surfaces (5.0 µm) • for combustion gases (4.2, 4.5, 5.3 µm) • pyroelectric detector • chopper stabilized • optical resolution: 1 mm target (100:1 D-ratio) • response time: 30 msec • analog output 4-20 mA
High-Precision/Complex Applications 50°C to 800°C (–60°F to 1500°F) narrow spectral band radiation thermometers • for thin plastic films with CH absorption bands (3.4 µm; 6.8 µm) • for polyester/fluorocarbon films (8.0 µm) • for thin glass and ceramics (7.8 µm) • optical resolution: 1.5 mm dia. (100:1 D-ratio)	**High-Speed, Two-Color Ratio** 150 to 2500°C (300 to 4500°F) narrow spectral bands (0.8/0.9 µm; 2.1/2.4 µm) • greatly independent of emissivity fluctuations and/or sight path disturbances • automatic compensation for moving targets • internal calibration check
Programmable/High-Performance –100°C to 2500°C (–150°F to 4500°F) with built-in signal conditioning and digital computing, spectral band choices in wide or narrow bands between 2 µm and 20 µm • digital RS 232 bidirectional interface • max./min./differential/hold functions • programmable ambient temperatures • choice of through-lens-sighting, LED, or laser	

narrow wavelength band of red seen by the user. Instruments sensitized to measure in the IR region are also called spectral radiation pyrometers or spectral radiation thermometers.

Ratio/Two-Color Pyrometer. This radiation thermometer measures temperatures on the basis of two (or more) discrete wavelengths. The ratio of the brightnesses in separate wavelengths corresponds to color in the visible spectrum. The use of two distinct, visible colors – typically red and green – has long been popular to infer color temperatures. More recently, the term has broadened from its initial usage to include wavelengths in the infrared. The advantage of ratio measuring is that temperature readings are greatly independent of emissivity fluctuations and/or sight path obscurations. The technique is generally used for temperatures above incandescence (700°C,1300°F), but measurements down to 200°C (400°F) are also possible.

MEASUREMENT PARAMETERS

Advanced optical and electronic signal processing modules greatly extend the accuracy and performance capabilities of noncontact temperature measuring. For process control, standardized interfaces are available that provide conditioned signal outputs optimized for specific applications.

RADIATION DETECTION

Emissivity Adjustment. Temperature reading accuracy depends on the correct adjustment of the instrument to the target emissivity. Preset emissivity values can be used for on-line sensors to monitor targets of constant emissivity. Measurements on those materials with changing emissivities require an accurate and reproducible emissivity adjustment.

Surrounding Area Temperature. Thermal target radiation always contains stray radiation emitted by the environment surrounding the target area and reflected by the target's surface. In practice, the ambient temperature is frequently presumed to be the same as the temperature of the sensor. If the target is exposed to a different thermal environment, e.g., inside a heated furnace, inside a cooled chamber, or outdoors facing the open sky, adjustments are necessary for accurate measurement. Separate sensors for the area surrounding the target may be used for automatic temperature calculation.

Sight Path Obscuration. Gases, water vapor, dust, and other aerosols in the sight path of a sensor may affect the temperature reading. Using one of the "atmospheric windows" in the IR region greatly reduces measurement errors. Since both optical channels are equally attenuated, ratio pyrometers are generally immune to sight path obscuration, and the signal color ratio remains unaffected.

Ambient Temperature Drift. By the nature of their design, radiation detectors are strongly affected by ambient temperature changes. To maintain high measurement accuracy, precise compensation of this temperature drift is required. Temperature drift is specified in error/°C or error/°F of ambient temperature change.

OPTICAL SYSTEMS

Optics. Reflective (mirror) and refractive (lens) optics are used in noncontact temperature sensors to isolate and define radiation from the measured target.

Field of View. The field of view (FOV) is expressed in degrees solid angle or in radians. The FOV allows easy calculation of the minimum target size for each working distance. A convenient measure is the distance-to-target ratio, e.g., 20:1, indicating a minimum target of 1 in. at a 20 in. measuring distance.

Focusing on Target. Optics in noncontact temperature sensors are generally of the fixed-focus type. Focusing at longer measuring distances is not required if the target area is smaller than the entrance aperture (lens diameter) of the instrument.

Small Targets. For miniature objects, fixed-focus close-up optics are used, and the minimum target size is specified. Targets as small as 0.5 mm can be isolated.

Fiber Optics. Fiber optics permits a physical separation of the lens assembly from the detector and signal processing electronics in restricted spaces or hostile environments. The useful measuring range of fiber optics starts at 400°C (750°F). Minimum target areas are as defined above.

Target Scanning. Reflective surface mirrors are used to change the viewing angle of the measuring sensor if direct viewing is difficult or impractical. An oscillating mirror can be employed to deflect the intercepted radiation and to scan a predetermined temperature profile across a target area.

A sequence of scanned temperature profiles taken at preset spatial intervals over the target can be displayed as a thermal image or in the form of a thermal map.

Aiming on Target. A variety of optical aiming techniques are used with noncontact temperature sensors:
- Simple bead-and-groove gun sights
- Integrated or detachable optical view finders
- Through-the-lens sighting
- Integrated or detachable light beam markers

SIGNAL PROCESSING

Direct Output. Noncontact temperature sensors convert the intercepted thermal radiation into an electrical signal

Table 2: On-Line Temperature Measurement Instruments

LOW TEMPERATURE	
General Purpose 0 to 500°C (30 to 1000°F) 8-14 µm wide band • thermopile detector • optical resolution: 4 mm dia. (15:1 D-ratio) • emissivity adjustment • max./min. value	**Extended Temperature Ranges** –50 to 1400°C (–60 to 2550°F) 8-14µm with built-in signal conditioning • optical resolution: 32 mm target (30:1 D-ratio) • data collection • peak/valley/averaging functions • digital RS-232 output
High Stability – 30 to 800°C (–30 to 1500°F) 8-14 µm • pyroelectric detector • chopper stabilized • choice of optics	**Miniature Probe** –50 to 500°C (–60 to 1000°F) 8-14 µm with interchangeable probes for long distance or small target applications • large LCD information display • max./min./differential/hold signal conditioning • optical resolution: 2.5 mm dia. (7:1 D-ratio) • LED or laser aided target aiming
HIGH TEMPERATURE	
General Purpose 250 to 2500°C (500 to 4500°F) narrow spectral band radiation thermometers (0.65 µm; 0.7-1.1 µm; 0.9-1.9 µm) • solid-state photoelectric detectors (Si, Ge) • optical resolution 0.9 mm dia. (250:1 D-ratio)	**High-Precision, Two-Color Ratio Pyrometer** 650 to 2500°C (1200 to 4500°F) spectral bands 0.8/0.9 µm • greatly independent of emissivity fluctuations and/or sight path disturbances • automatic compensation for moving targets

proportional to the spectral radiance emitted from the target surface.

Linearized Output. An electronic network converts the thermal radiance signal into an electrical current/voltage proportional to temperature.

Sample and Hold. The momentary temperature reading, selected by an external trigger is held (frozen) until replaced by a new value in the next sampling cycle.

Maximum Value or Peak Hold. The highest temperature reading over the specific measuring period is displayed. Reset is triggered by an external signal.

Minimum Value or Valley Hold. The lowest temperature reading during a specific measurement period is displayed. Rest is triggered by an external signal.

Peak to Peak. The difference between the maximum and the minimum temperature readings during a specific measurement period is displayed.

Speed of Response. Short response time is needed to follow rapidly changing dynamic temperature processes. Long response time integrates all signal variations during a specific measurement period and enhances temperature resolution in order to average changing values or to improve measurement precision.

Automatic Trigger (Wave Function). The highest temperature reading is detected and displayed. Reset is triggered automatically when the signal reaches an adjustable threshold, but the last peak value is held on display until it is replaced by the following peak value. This technique is appropriate for rapid sampling and analysis of intermittent target values, without the use of external trigger signals.

Alarms. An output signal (relay) is activated when the signal reaches a preset temperature value. Two independent set points – HI/LO – are generally provided.

ACCESSORIES

Water Coolable Jackets. Water cooling extends the sensor's ambient temperature range up to 400°C (752°F) or beyond.

Air Purge Fittings. Lens barrels or attachments with fittings for compressed air are designed to direct a clean air flow across the lens surface. They keep the optical sight paths free of vapors, fumes, and dust.

BLACKBODY CALIBRATORS

Deep cavities controlled at a homogeneously distributed temperature serve as blackbody simulators for the calibration of radiation thermometers. To accommodate the variety of instruments, they provide an effective aperture of ~ 1 in. (25 mm) and are optimized for their operating temperature range:

- Stirred water bath: 30-100°C (86-212°F)
- Aluminum core: 50-400°C (122-752°F)
- Stainless steel core: 350-1000°C (662-1832°F)
- Portable, battery operated field calibrator: fixed temperature choices from 40°C-100°C (104-212°F)

ON-LINE OR PORTABLE?

On-Line Instruments. These devices are generally used for continuous process monitoring and control. They are available in low- and high-temperature models, each with its own operating specs (see Table 1).

Portable Instruments. Portables are typically favored for process checks, preventive/predictive maintenance, thermal surveys, R&D, and temporary temperature monitoring. The low- and high-temperature versions differ in performance, as shown in Table 2.

APPLICATIONS

Successful applications of both on-line and portable noncontact temperature measurement instruments are summarized in Table 3.

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Table 3: Temperature Measurement in Process Control

SUCCESSFUL APPLICATIONS	ON-LINE			PORTABLES		
	R	H	L	R	H	L
Cement kiln burning zones, preheaters	X	X		X	X	
Energy conservation insulation and heat flow studies, thermal mapping			X			X
Filaments annealing, drawing, heat treating	X			X		
Food baking, candy-chocolate processing, canning, freezing, frying, mixing, packing, roasting			X			X
Furnaces flames, boiler tubes, catalytic crackers	X	X		X	X	
Glass drawing, manufacturing/processing bulbs, containers, TV tubes, fibers	X	X	X	X	X	X
Maintenance appliances, bearings, current overloads, driving shafts, insulation, power lines, thermal leakage detection			X			X
Metals (ferrous and nonferrous) annealing, billet extrusion, brazing, carbonizing, casting, forging, heat treating, inductive heating, rolling/strip mills, sintering, smelting	X	X		X	X	
Quality control printed circuit boards, soldering, universal joints, welding, metrology	X	X	X	X	X	X
Paint curing, drying			X			
Paper coating, ink drying, printing photographic emulsions, web profiles			X			X
Plastic blow-molding, RIM, film extrusion, sheet thermoforming, casting			X			X
Remote sensing (thermal mapping) clouds, earth surfaces, lakes, rivers, roads, volcanic surveys			X	X		X
Rubber calendering, casting, molding, profile extrusion tires, latex gloves			X			X
Silicon crystal growing, strand/fiber, wafer annealing, epitaxial deposition	X		X	X		X
Textile curing, drying, fibers, spinning			X			X
Vacuum chambers refining, processing, deposition	X			X		

R=Ratio/Two-Color H=High-Temperature L=Low Temperature