1 Measuring elements and Sensors

The objective is to obtain values for the current conditions within the process and to make this information available in a form usable by the control system, process operators, or management information systems. A measuring element is the first element or group of elements which responds quantitatively to the variable in question to produce a signal suitable for transmission to indicating, or control devices [1, 2].

- Number of measurable quantities increases

  Process 1970 year - 300; 1980 year - 3000; 2000 year - 30000

  Control - ≈ 6000 is needed

- Some important parameters is hard to measure
  - hue,
  - taste, etc.

1.1 Measurement performance terms

There are two major process measurement categories:

Continuous measurements: level measurement device that determines the liquid level in a tank.

Discrete measurements: level switch that indicates the presence or absence of liquid at the location at which the level switch is installed.

In most applications, continuous measurements provide more information than discrete measurements.

A typical components for continuous measurement device are:

Sensor This component produces a signal that is related in a known manner to the process variable of interest.

The sensors in use today are primarily of the electrical analog variety, and the signal is in the form of a voltage, a resistance, a capacitance, or some other directly measurable electrical quantity.

Signal processing linearization

Transmitter The measurement device output must be a signal that can be transmitted over some distance.

A measuring transmitter which usually develops an electrical signal for an electronic controller or a pneumatic signal for a pneumatic controller [3].

Criteria:

Accuracy - amount of error that may occur when measurements are taken.

Range of operation - defines the high and low operating limits between which the device will operate correctly.

The difference between the upper range and the lower range is the span of the measurement device.

Cost - This is generally determined by the budget allocated for the application.

More critical control applications may be affected by different response characteristics [4].

Hysteresis - difference in the output for the given input.

Linearity - expresses the deviation of the actual reading from a straight line. If all outputs are in the same proportion to corresponding inputs over a span of values, then input-output plot is a straight line else it will be non linear.

Repeatability - defines how close a second measurement is to the first under the same operating conditions, and for the same input.

Response - The time taken to respond of the output can provide critical information about the suitability of the device.

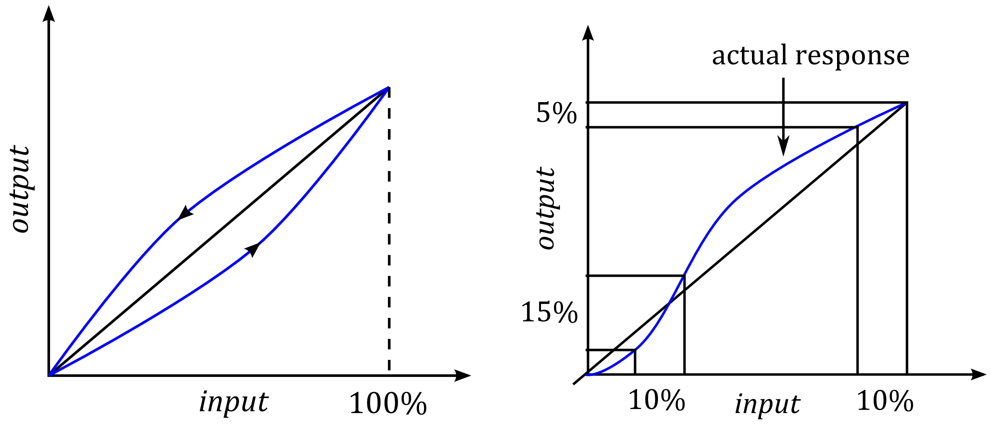


Figure 1: Response characteristics: Hysteresis and Non-linearity

Table 1: Major types of measurement devices

Temperature	Flow	Pressure	Level	Composition
Thermocouple	Orifice	Liquid column	Float-activated	Gas-liquid chromatoraphy (GLC)
Resistance temperature detector (RTD)	Venturi	Elastic element	- chain gauge	Mass spectometry (MS)
Filled-system thermometer	Rotameter	-bourdon tube	- lever	Magnetic resonance analysis (MRA)
Pirometer	Turbine	-bellow	-magnetically coupled	IR, raman, UV spectroscopy
Laser	Vortex-shedding	-diaphragm	Head devices	Thermal conductivity
Surface acoustic wave	Ultrasonic	Strain gauges	-bubble tube	Refractive index (RI)
Semiconductor	Magnetic	Piezoresistive transducers	Electrical (conductivity)	Capacitance probe
	Thermal mass	Piezoelectric transducers	Sonic	Surface acoustic wave
	Coriolis	Optical fiber	Laser	Electrochemical

1.1.1 Calibration

Calibration of some measurement devices involves comparing the measured value with the value from the working standard. The specific calibration procedures depend on the type of measurement device.

2 Temperature sensors

Present temperature scales have been in use for about 200 years.

All materials are affected by temperature, and thus there are so many means available for inferring temperature from some physical effect. Early thermometers depended on volumetric changes of gases and liquids with temperature change. Advantages of electrical systems include higher accuracy and sensitivity, practicality of switching or scanning several measurement points, larger distances possible between measuring elements and controllers, replacement of components in the event of failure, fast response, and ability to measure higher temperatures [3, 5].

2.1 Principles of Temperature Measurement

There are several methods of measuring temperature that can be categorized as follows [6]

1. Expansion of a material to give visual indication, pressure, or dimensional change;
2. Electrical resistance change;
3. Semiconductor characteristic change;
4. Voltage generated by dissimilar metals;
5. Radiated energy.

Temperature measurement relies on the transfer of heat energy from the process material to the measuring device.

There are two main industrial types of temperature sensors [4]:

Contact Contact is the more common and widely used form of temperature measurement

- Thermocouples;
- RTD's;
- Thermistors.

Non-contact

- Infrared;
- Acoustic.

2.2 Thermocouples

Thermocouples are formed when two dissimilar metals are joined together to form a junction. An electrical circuit is completed by joining the other ends of the dissimilar metals together to form a second junction.

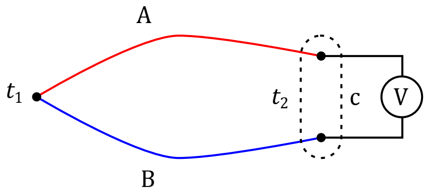


Figure 2: Thermocouple

In practice, the voltage difference between the two junctions is measured Fig. 2; the difference in the voltage is proportional to the temperature difference between the two junctions.

A thermocouple requires a reference junction, placed in series with the sensing junction. As the two junctions are at different temperatures a thermal emf (electro-motive force) is generated. The reference junction is used to correct the sensing junction measurement. The reference, or cold junction is normally connected to the measuring instrument and held at $0°C$.

The relationship between mill-volts and temperature is not linear. In microprocessor based equipment, the conversion is done based on the data stored in the device [4].

Table 2 lists some thermocouple materials.

Table 2: Operating Ranges for Thermocouples

Type	≈ Range ($°C$)	Features
Copper – Constantan (T)	-200 to 370 $\pm 1°C$	✓ for oxidising or reducing atmospheres, ✓ high resistance to corrosion ✓ relatively linear output ✓ very stable thermocouple ✓ used in extremely low T applications.
Chromel – Constantan (E)	-100 to 1260 $\pm 1.7°C$	✓ the most sensitive thermocouple ✓ highest change in EMF E per ΔT, ✓ tend to drift more
Iron – Constantan (J)	-190 to 760 $\pm 2.2°C$	✓ used in reducing atmospheres ✓ good near-linear output ✓ least expensive
Chromel–Alumel (K)	-190 to 1260 $\pm 2.2°C$	✓ used in oxidising atmospheres ✓ most linear thermocouple ✓ general use
Nicrosil–Nisil (N)	-279 to 1260 $\pm 1.7°C$	✓ same T limits as K-type ✓ better repeatability from $300°C$ to $500°C$ than K-type
Platinum (rhodium 10%)–Platinum (S)	0 to 1450 $\pm 1.5°C$	✓ used in very high T applications ✓ high accuracy ✓ high stability
Platinum (rhodium 13%)–Platinum (R)	0 to 1450 $\pm 1.5°C$	✓ suitable for oxidising atmospheres ✓ improved stability than S-type ✓ more expensive

For operation over the full temperature range the accuracy is about ±10% without linearization.

To increase the sensitivity and accuracy by increasing the output voltage when measuring low temperature differences a number of thermocouples connected in series. That is called thermopile.

Pyrometers are devices that measure temperature by sensing the heat radiated from a hot body through a fixed lens that focuses the heat energy on to a thermopile; this is a non-contact device [6].

Advantages

- Low cost
- Small size
- Robust
- Wide range of operation
- Accurate for large temperature changes
- Provide fast response
- Do not depend on the wire length and diameter

Disadvantages

- Very weak output, millivolts
- Limited accuracy for small variations in temperature
- Sensitive to electrical noise
- Nonlinear
- Complicated conversion from EMF to temperature

For critical temperature measurement, an accurate reference junction temperature needs to measured and compensated for. This may require the use of an RTD [4].

2.2.1 Interpolation

The thermocouple tables give the voltage that corresponds to the temperature, then the reference junctions are at a particular reference temperature. Refering to the tables (see Appendix, Practical work No. 2), we see what reference junction temperature is $T = 0\ ^\circ C$.

In many cases measured voltage is not equal to table value. When it happens, we need to interpolate between table values.

In general, value of temperature can be found using

$$T_m = T_l + \left[\frac{T_h - T_l}{V_h - V_l}\right](V_m - V_l), \tag{1}$$

where m is measured value, l and h are lower and higher values, which are in the table. The measures value V_m should lie between higher voltage V_h and lower voltage V_l [7].

2.3 Resistance Temperature Detectors

RTDs (see Fig. 3) operate on the principle of changes in electrical resistance of pure metals and are characterized by a linear positive change in resistance with temperature. The transducer is the temperature sensitive resistor itself, with the sensor being a combination of the transducer and electronics that measure the resistance of the device.

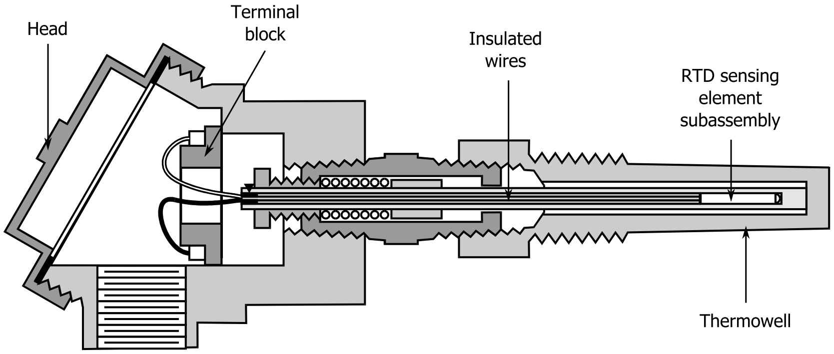


Figure 3: Industrial RTD construction

Industrial resistance thermometers are usually constructed of platinum, copper, or nickel, and more recently semiconducting materials such as thermistors are being used. Basically, a resistance thermometer is an instrument for measuring electrical resistance that is calibrated in units of temperature instead of in units of resistance (typically ohms Ω).

Several common forms of bridge circuits are employed in industrial resistance thermometry, the most common being the Wheatstone bridge. A resistance thermometer detector (RTD) consists of a resistance conductor (metal) which generally shows an increase in resistance with temperature [2].

In a resistance thermometer the variation of resistance with temperature is given by

$$R_t = R_0(1 + \alpha_1 \cdot \Delta T + \alpha_2 \cdot \Delta T^2 + \ldots + \alpha_n \cdot \Delta T^n), \tag{2}$$

where R_0 resistance at 0 $^\circ C$. The temperature coefficient of resistance, α_t is expressed as

$$\alpha_t = \frac{1}{R_t}\frac{\mathrm{d}R_t}{\mathrm{d}T} \tag{3}$$

and has units of $\Omega/°C$. The greater the temperature coefficient, the more the resistance will change for a given change in temperature. This ultimately defines how sensitive the device is.

Linear approximation

Linear approximation means that there is straight line, that approximates the resistance versus temperature ($R - T$) curve over some specified span.

The equation for this line typically written as

$$R(T) = R(T_0)\left[1 + \alpha_0 \Delta T\right], \tag{4}$$

where

$$\alpha_0 = \frac{1}{R(T_0)}\left(\frac{R_2 - R_1}{T_2 - T_1}\right). \tag{5}$$

Parameter α_0 is a fractional change in resistance per degree of temparature at T_0 and has units $[1/°C]$.

Table 3: Temperature coefficients of resistance

Material	α_t	Material	α_t
Iron	0.006	Tungsten	0.0045
Nickel	0.005	Platinum	0.00385

Table 4: Operating Ranges of RTDs

Type	≈ Range ($°C$)	Features
Pt100	-200 to 850	✓ high accuracy, excellent repeatability ✓ small size, good long term stability
Pt1000	-200 to 550	✓ high accuracy, excellent repeatability ✓ small to large size, good long term stability
Nickel 1000	-210 to 320	✓ medium accuracy, good repeatability ✓ large size, fair long term stability
Balco 2000	-75 to 200	✓ low accuracy, fair repeatability ✓ large size, fair long term stability

RTDs are generally quite linear, however the temperature coefficient does vary over the range for about 2% (for Platinum).

Platinum is most popular for RTD's, it has good calibrated accuracy, is quite stable and has good repeatability, but is quite expensive.

There are two basic type:

Pt100 Platinum with resistance of 100 Ω at 0 $°C$. These are wire wound.

Pt1000 Platinum with resistance of 1000 Ω at 0 $°C$. These are thin film devices and more expensive.

Advantages

- Good sensitivity
- Uses standard copper wire

Disadvantages

- Massive
- Fragile at temperatures above 320 $°C$ if there is any vibration present
- Slow thermal response time
- More sensible to electrical noise
- More expensive to test and diagnose
- Self-overheating

2.4 Thermistors

Thermistors are a class of metal oxide (semiconductor material) which typically have a high negative temperature coefficient of resistance, but can also be positive. Thermistors have high sensitivity which can be up to 10% change per $°C$, making them the most sensitive temperature elements available, but with very nonlinear characteristics [6].

When a thermistor is used as a temperature sensing element, the relationship between resistance and temperature is of primary concern. The approximate relationship applying to most thermistors is [5].

$$R_t = R_0 \cdot \mathrm{e}^{B\left(\frac{1}{T} - \frac{1}{T_0}\right)}, \tag{6}$$

where

R_0– resistance value at reference temperatureT_0 K, Ω

R_t–resistance at temperature T K, Ω

B–constant over temperature range, dependent on manufacturing process and construction characteristics.

$$B \cong \frac{E}{K}, \tag{7}$$

E–electronvolt energy level,
$K = 1.380\ 6488(13) \cdot 10^{23}\ J/K$–Boltzmann's constant.

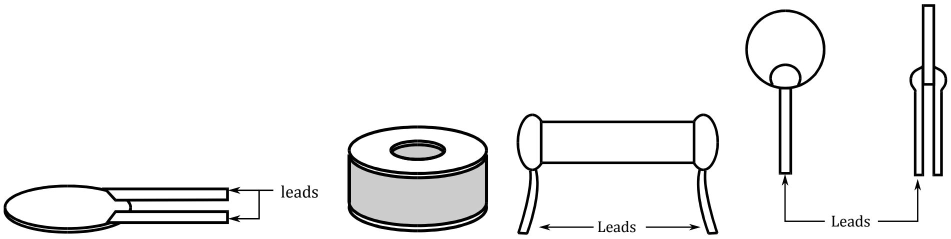
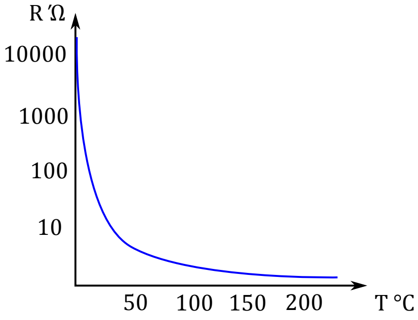


Figure 4: Bead, washer, rod and disc type thermistors

Thermistors have a much higher temperature coefficient than RTDs, so a small temperature change is easier to detect. However, thermistors do not have the accuracy of RTDs and this probably accounts for thermistors being limited in process instrumentation.



The evaluation of thermistor performance characteristics is in many cases similar to that of resistance thermometers, but problems lie in obtaining conversion units that fit the desired characteristic curve and meet the required accuracy.

Thermistors are not linear, and their response curves vary for the different types.

Thermistors have a much higher temperature coefficient than RTDs, so a small temperature change is easier to detect. However, thermistors do not have the accuracy of RTDs and this probably accounts for thermistors being limited in process instrumentation.

Due to their low cost, thermistors are used in many applications requiring information about process equipment for alarming and indication purposes [4].

Advantages

- Small size
- Fast response

- Hight sensitivity (range)
- No cold junction compensation
- Cheap
- Wide selection

Disadvantages

- Unstable due to drift
- Not easy interchangeable
- Nonlinear
- Narrow span
- Fragile
- Hight resistance, noise problems

2.5 Filled, Bimetallic Thermal Systems

Filled thermal systems, which traditionally have been used most in the food, paper, and textile industries, consist of sensors (bulbs) connected through capillary tubing to pressure or volume sensitive elements. These systems are simple and inexpensive and generally have fast dynamic responses. Their use with pneumatic and electronic transmitters has removed inherent distance limitations of filled systems and has minimized the danger of capillary damage.

Liquid-expansion systems are characterized by narrow spans, small sensors, uniform scales, high accuracy, and capability for differential measurements.

Advantages

- Low cost
- Simplicity
- No recalibration required

Disadvantages

- Interpretation of measurement
- Localized measurement only

- Isolated from other control and recording equipment
- Fragile

Vapor-pressure systems are reliable, inherently accurate, and require no compensation for ambient temperature effects. Instruments follow the vapor-pressure curves of the filled fluid, and associated dials and charts are thus nonuniform, featuring more widely spaced increments at high temperatures. Measurements occur at the interface between liquid and vapor phases of the filling medium. If the temperature in the sensor exceeds that in the capillary and indicating element, the sensor is filled with vapor while the capillary and indicator contain liquid such as methyl chloride, ethyl alcohol, ether, toluene, and so on.

Gas-pressure systems, which rank second to the vapor-pressure devices in simplicity and cost, offer the widest range of all filled systems. Conventional designs use large-volume sensors, which mar be shaped to suit particular applications. For example, in duct-temperature averaging, the sensor mar be constructed of a long length of tubing of small cross section.

Advantages

- Low cost
- Simplicity
- No power source required
- Easily maintained
- Reasonably accurate

Disadvantages

- Bulky
- Slow response time
- Wide spans only
- Subject to gauge pressure problems
- Nonlinear

Mercury-expansion systems are classified separately from other liquid-filled systems because of the unique properties of the fluid. For example, mercury is toxic and harmful to some industrial processes and products, and high-liquid density places limitations on sensor-to-instrument elevation differences. Sensors used in mercury-expansion systems are generally larger in diameter and more expensive than those used in either liquid or vapor systems. For these reasons, mercury is frequently bypassed in favor of other filling media.

Bimetallic temperature sensors work on the basis that different metals expand by different amounts. A bimetallic device consists of two metals bonded together which have different coefficients of expansion. Bending occurs as one metal expands more than the other.

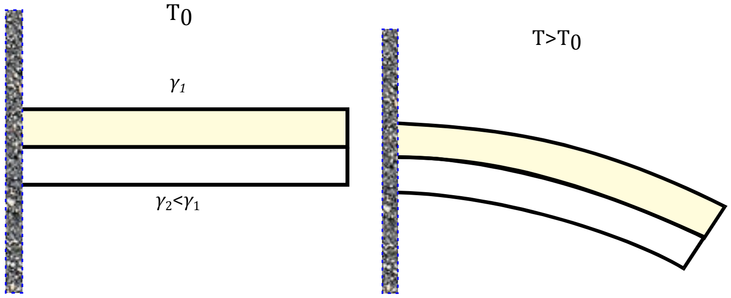


Figure 5: Bimetallic sensor

Advantages

- Low cost
- Simplicity

Disadvantages

- Limited accuracy
- Localized measurement only
- Indication or simple switching only
- Easily decalibrated due to mechanical shock
- Hysteresis

Bimetallic thermometers can be used in a thermowell. Vibration and heat transfer can be a problem with some applications. Primarily used for simple switching or indication on a dial [3, 4].

2.6 Non-contact Pyrometers

Radiation thermometry represents a practical application of the Planck law and Planck radiation formula and makes it possible to measure the temperature of an object without making physical contact with the object. Another important advantage is the wide useful temperature range—from subzero temperatures to extremely high, virtually unlimited values. Representative industrial designs generally have a precision of ±0.5 to ±1%.

Pyrometric methods of temperature measurement use the electromagnetic radiation that is emitted from a material. The emitted radiation is proportional to the temperature.

Thus early applications generally involved monitoring such operations as glass, metal, chemical, cement, lime, and refractory materials. During the past few decades, radiation thermometry has extended into lower temperature regions, including subzero measurements, as encountered in the foods, electronics, paper, pharmaceutical, plastics, rubber, and textile industries, among others.

2.6.1 Infrared Pyrometers

Originally called radiation pyrometers, then radiation thermometers, and, more recently, infrared (IR) thermometers. See Introduction to Infrared Pyroelectric detectors.

Any object with a temperature above absolute zero will radiate electromagnetic energy. Infrared thermometers measure the amount of energy radiated from an object in order to determine its temperature.

Radiation pyrometers use an optical system to focus the radiated energy onto a sensing device.

Planck's law predicts very accurately the radiant power emitted by a blackbody per unit area per unit wavelength, or complete radiation. It is written

$$M^b(\lambda, T) = \frac{C_1}{\lambda^5}\frac{1}{\mathrm{e}^{C_2/\lambda T}-1} \ \left[W \cdot m^{-3}\right], \tag{8}$$

where

$C_1 = 2\pi h C^2 = 3.7415 \cdot 10^{16}$ $\left[W \cdot m^2\right]$- the first radiation constant;

$C_2 = Ch/k = 1.43879 \cdot 10^{-2}$ $[m \cdot k]$- the second radiation constant.

A graphic representation of the radiant exitance as predicted by Planck's law, for several temperatures, is given in Fig. 6. Note that for each temperature there is a peak value of emission and that the peak value shifts to shorter wavelengths as the temperature is increased.

Measuring Temperatures of Non-blackbodies can be complicated by:

1. Non-blackbodies emit less radiation than blackbodies, and often this difference is wavelength dependent.
2. Extra radiation from other radiant sources may be reflected from the object's surface, thus adding to the measured radiation and thereby increasing the apparent temperature.

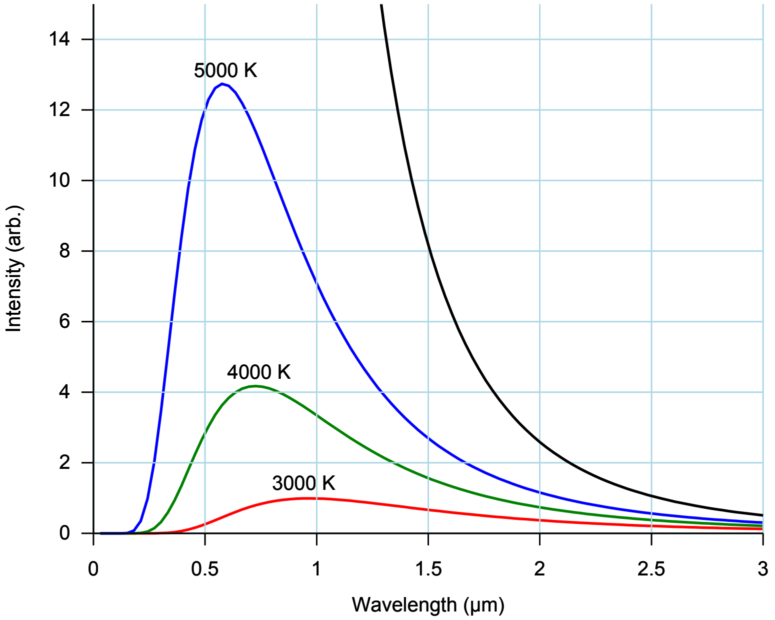


Figure 6: Radiant emission of thermal radiation from a blackbody at various temperatures

3. The intensity of the emitted radiation may be modified in passing through media between the object and the instrument, thus resulting in a change in the apparent temperature.

Classes of IR Thermometers

Total radiation This type of radiation thermometer measures all the energy, over a broad spectrum, emitted by the object. Because of the broad spectrum of sensing, this type of measurement is easily affected by any impurities or inconsistencies between the sensor and the object. Greater errors occur for materials with lower emissivity.

Single wavelength Unlike the broad spectrum, this type of radiation thermometer measures the magnitude of radiation at one wavelength. This optimizes the accuracy of the device by selecting the wavelength best suited to the object being measured. This type of measurement provides good accuracy provided the emissivity is known.

Dual wavelength When the emissivity is low and hard to measure, or even variable, accuracy and reliability can be improved with a dual wavelength sensor. This type measures the magnitude of two wavelengths at the same time. The temperature is calculated from the two readings.

Advantages

- Non contact measurement
- High temperature sensing
- Remote sensing
- Fast response and can sense objects in motion
- Sense small or area targets

Disadvantages

- Expensive
- Non linear response
- Subject to emissivity of material
- Require wide range of operation

The accuracy is affected by reflections, presence of gases in the radiation path and the surface emissivity of the object [5, 4].

2.6.2 Acoustic pyrometers

Acoustic pyrometers work on the principle that the speed of sound in a gas is dependant on the nature of the gas and its temperature. The time of flight is used, and since the distance between points is known it is possible to measure any change in conditions. This principle is adapted for liquid and solid temperature measurement also.

Acoustic pyrometers are used when requiring an average temperature or the temperature over a large area or volume of gas.

Acoustic pyrometers are useful for measuring gas temperatures inside kilns and furnaces. They work over a very large temperature range and are useful for mapping thermal contours. Very expensive [4].

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