6. TEMPERATURE CALIBRATION

Temperature calibration provides a means of quantifying uncertainties in temperature measurement in order to optimise sensor and/or system accuracies.

Uncertainties result from various factors including:

a) Sensor tolerances which are usually specified according to published standards and manufacturers specifications.

b) Instrumentation (measurement) inaccuracies, again specified in manufacturers specifications.

c) Drift in the characteristics of the sensor due to temperature cycling and ageing.

d) Possible thermal effects resulting from the installation, for example thermal voltages created at interconnection junctions.

A combination of such factors will constitute overall system uncertainty. Calibration procedures can be applied to sensors and instruments separately or in combination.

Calibration can be performed to approved recognised standards (National and International) or may simply constitute checking procedures on an "in-house" basis. Temperature calibration has many facets, it can be carried out thermally in the case of probes or electrically (simulated) in the case of instruments and it can be performed directly with certified equipment or indirectly with traceable standards.

Thermal (temperature) calibration is achieved by elevating (or depressing) the temperature sensor to a known, controlled temperature and measuring the corresponding change in its associated electrical parameter (voltage or resistance). The accurately measured parameter is compared with that of a certified reference probe; the absolute difference represents a calibration **error**. This is a **comparison** process. If the sensor is connected to a measuring instrument, the sensor and instrument combination can be effectively calibrated by this technique. Absolute temperatures are provided by **fixed point** apparatus and comparison measurements are not used in that case.

Electrical Calibration is used for measuring and control instruments which are scaled for temperature or other parameters. An electrical signal, precisely generated to match that produced by the appropriate sensor at various temperatures is applied to the instrument which is then calibrated accordingly. The sensor is effectively **simulated** by this means which offers a vary convenient method of checking or calibration. A wide range of calibration "simulators" is available for this purpose; in many cases, the operator simply sets the desired temperature and the equivalent electrical signal is generated automatically without the need for computation. However this approach is not applicable to sensor calibration for which various **thermal** techniques are used.

6.1. CERTIFICATION

Officially recognised (accredited) calibration laboratories are authorised to perform certain types of calibration and to issue the appropriate certificate. Such calibrations are carried out in accordance with appropriate standards, for example UKAS in the U.K. and DKD in Germany. The certificate issued for each sensor will state any calibration error which is measured at the various test temperatures and also the uncertainties which exist in the measurement system used for the calibration.

6.2. THERMAL TEMPERATURE CALIBRATION

Essentially the test probe reading is compared with that of a certified reference probe whilst both are held at a common, stable temperature. Alternatively, if a fixed point cell is used, there is no comparison with a certified thermometer; fixed point cells provide a highly accurate, known reference temperature, that of their phase conversion.

6.2.1. Equipment required for a Calibration System.

The equipment required to achieve thermal calibration of temperature probes is dependent on the desired accuracy and also ease of use. The greater the required accuracy, the more demanding the procedure becomes and of course, the greater the cost.

The required equipment generally falls into one of three groups:

1. **General purpose system** for testing industrial plant temperature sensors will usually provide accuracies between 1.0°C and 0.1°C using comparison techniques.
2. **A secondary standards system** for high quality comparison and fixed point measurements will provide accuracies generally between 0.1°C and 0.01°C.
3. **A primary standards system** uses the most advanced and precise equipment to provide accuracies greater than 0.001°C

A typical general purpose system comprises:
* A thermal reference (stable temperature source)
* A certified Pt100 reference probe complete with its certificate.
* A precision electronic digital thermometer, bridge or DVM (digital voltmeter)

Fig 37: General Purpose Calibration System using a dry block calibrator

A convenient form of **thermal reference** is the dry block calibrator. Such units are available with various ranges spanning from -50°C to +1200°C and have wells to accept various test and reference probe diameters. Alternative temperature sources for comparison techniques include precisely controlled ovens and furnaces and stirred liquid baths.

Dry Block Calibrators

Dry block calibrators provide the most convenient, portable facilities for checking industrial probes and they usually achieve reasonably rapid heating and cooling. The units consist of a specially designed heated block within which is located an insert having wells for the probes. The block temperature is controlled electronically to the desired temperature. The whole assembly is housed in a free-standing case. Although the block temperature is accurately controlled, any indication provided should be used for guidance only. As with any comparison technique, a certified sensor and indicator should be used to measure the block temperature and used as a reference for the test probe.

Two types of unit are available; portable units which can be taken on to plant for on-site calibration and laboratory units to which industrial sensors are brought as required.

Fig 38: Dry Block Calibrator

Alternative "temperature" sources.

Many laboratory furnaces and ovens are available which are specially designed for temperature calibrations. Precisely controlled, they feature isothermal or defined thermal gradient environments for probes.

Stirred liquid baths provide superior thermal environments for probe immersion since no air gaps exist between the probe and medium. Thermal coupling is therefore much better than the alternatives described and stirring results in very even heat distribution throughout the liquid

Alcohols are used for temperatures below 0°C, water from 0°C to 80°C and oils for up to 300°C. Various molten salts and sand baths are used for temperatures in excess of 300°C.

A Reference Standard Platinum Resistance Thermometer is a specially constructed assembly using a close tolerance Pt100 sensing resistor or a specially wound platinum element with a choice of Ro values. Construction is such as to eliminate the possibility of element contamination and various techniques are utilised to this end such as special sheath materials, gas filling and special coil suspension.

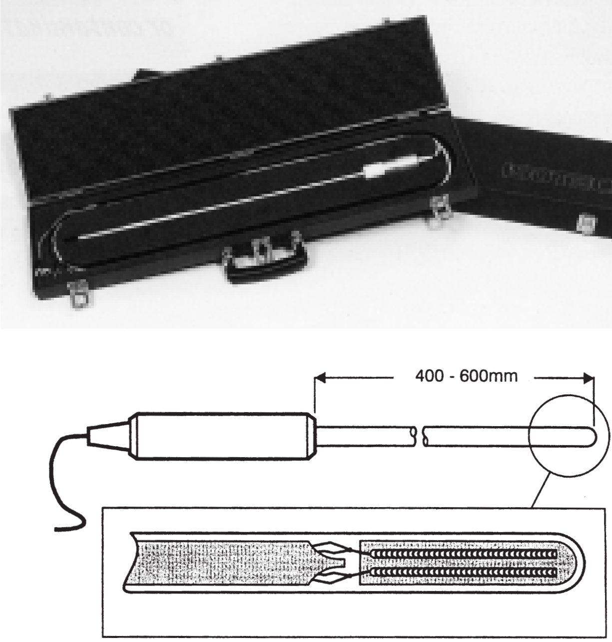


Fig 39: Standard Platinum Resistance Thermometer

Precision Temperature indicators are available in a wide variety of configurations and with alternative accuracy and resolution specifications. By definition, such instruments must be highly accurate and very stable. Normally, the performance of the measuring instrument will be superior to that of the reference sensor to avoid compromising the system performance. As with any measuring system, such factors must be considered when specifying system components.

Developments in high precision digital thermometry have resulted in a high level of “user-friendliness”. Features of such instruments can include built-in automatic cold junction compensation with very high stability which allows direct connection to thermocouples without the need for an ice point reference. Another benefit is that of non-volatile memory facilities for storing correction values of certified probes; when this is done, the test probe readings can be directly compared with the corrected reference probe values without the need for user computations. Such a feature enhances the accuracy on reliability of readings.

Communications for data transfer and/or remote control and PC software are sometimes available to further enhance the versatility of the modern electronic thermometer.

Fig 40: High Precision Digital Thermometer

Thermocouple readings can alternatively be taken using a digital volt-meter; in this case, readings are displayed in microvolt units and calculations must be performed for cold junction temperature and characterisation in order to obtain a true temperature measurement.

PRT resistances can be measured using a precision bridge instead of a temperature indicator; again calculations must be performed to obtain temperature measurements.

6.2.2. Fixed Points

Fixed points are the most accurate devices available for defining a temperature scale. Fixed point devices utilise totally pure materials enclosed in a sealed, inert environment; they are usually fragile and need to be handled with care. They work in conjunction with apparatus which surrounds them and provides the operational conditions required for melting and freezing to obtain the reference plateaux. The housings incorporate isothermal blocks with wells into which the probes are placed. Since fixed point temperatures are defined by physical laws, comparison of the test probe to a reference probe is not required.

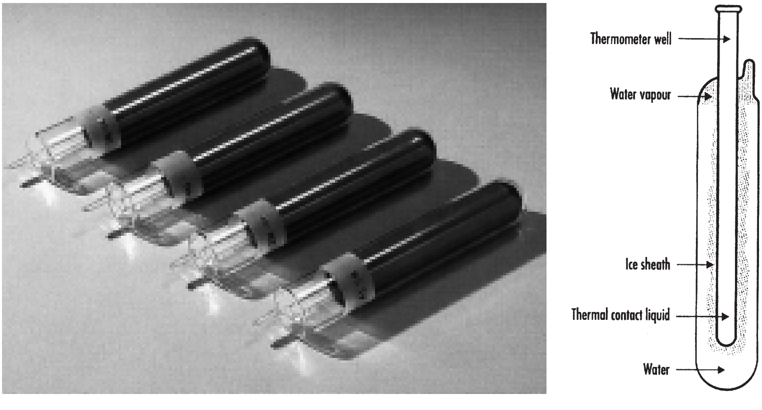


Fig 41: Triple Point of Water Cell

ITS 90 Fixed points include:

Boiling point of Nitrogen	-195.798°C
Mercury triple point	-38.8344°C
Triple point of water	0.01°C
Melting point of Gallium	29.7646°C
Freezing point of Indium	156.5985°C
Freezing point of Tin	231.928°C
Freezing point of Lead	327.462°C
Freezing point of Zinc	419.527°C
Freezing point of Antimony	630.63°C
Freezing point of Aluminium	660.323°C
Freezing point of Silver	961.78°C

All such fixed point apparatus is available commercially.

6.2.3. Electrical Calibration – Simulators and Sources.

Indicators and controllers are calibrated by injecting signals which simulate thermocouples, resistance thermometers or thermistors. A simulator provides a very quick and convenient method for calibrating an instrument at many points. Very sophisticated and highly accurate laboratory instruments are available; conversely, compact and convenient portable units are available to permit on-site checking and calibration with a good level of accuracy.

Calibrator/simulators can be either blind (without indication) or with a built-in indicator. In many cases, such instruments can be used for measuring the temperature sensed by thermocouples and resistance thermometers in addition to providing calibration signals.

Fig 42: Calibration/Simulator

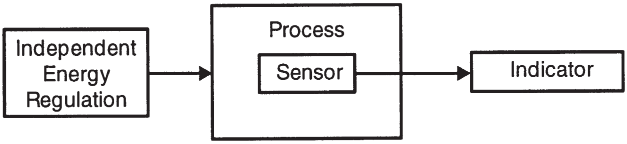
7. TRANSMITTERS AND INSTRUMENTATION

Temperature instrumentation, including temperature transmitters is briefly described in this chapter for purposes of guidance only. It is not intended to be a thorough treatment which would require a volume or volumes to achieve. Reference should be made to appropriate books such as Instrumentation Reference Book published by Butterworth Heinemann for comprehensive guidance. This and other relevant publications are available from the Institute of Measurement and Control.

The sensor, whether thermocouple, Pt100 or thermistor is, in many ways the most important component of a measurement system. Clearly the failure of any item in the system will render it inoperative but, because the sensor will usually be exposed to a harsh environment, compromise may be impossible. For example, a wide range of instruments will almost certainly provide a choice of price and specification but there may be little such choice in the sensor. The overall system accuracy and stability will be no better than that of the sensor.

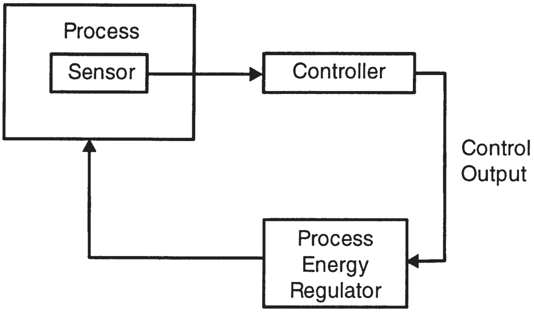
Instrumentation requirements range from a simple display of a single temperature value to multi-sensor data acquisition and logging or from a simple controller to multi-zone communicating control systems. Other requirements may include transmission and signal conditioning, analogue recording, alarm monitoring and communications.

Fundamentally, instrumentation will be in one of two forms, **open loop** or **closed loop**. **Open loop** is where there is no system feedback and therefore no control action; the measuring instruments exerts no influence over the process behaviour other than possible alarm action which may result in “power-down”. **Closed loop** is where there is direct or indirect feedback from the instrument to the process energy regulator resulting in control of the process temperature.



Sensor simply provides temperature information to the indicator.
Process regulation is effected independently.

Fig 43: Open Loop System



Sensor provides temperature feedback thus allowing automatic control.

Fig 44: Closed Loop System

7.1. SENSOR CONSIDERATIONS WITH INSTRUMENTATION.

Since most modern electronic (often microprocessor based) measuring and controlling instruments offer high accuracy and stability, great consideration must be given to the choice of temperature sensor to realise the performance potential. When specifying any system, a desired accuracy must be stated and all components be considered accordingly. For example, the use of a low-cost base metal thermocouple with ±2.5°C short term accuracy is pointless if extra money is spent to procure a 0.1 °C accuracy controller when a 1°C accuracy instrument at lower cost would suffice.

Note however that the theoretical overall accuracy of a system is the sum of the individual accuracies of the system components. If a simple measurement system is structured as follows:

Nominal overall accuracy = accuracy of (thermocouple + transmitter + indicator)

e.g. Overall accuracy = ±2.5°C ±2°C ±1°C say Overall accuracy =±5.5°C ***worst case***.

In practice, this figure may be pessimistic; e.g. If the actual realised accuracies are +2°C -1°C+0.5°C respectively-Actual accuracy at start up would be +1.5°C. However worst case values must be borne in mind when specifying the components. It is clear from this example that is order to obtain good overall accuracy, the main emphasis must be places on optimising the sensor accuracy. For example by means of:

a) Specifying a calibrated sensor if necessary (this will define **actual** accuracy).

b) and/or specifying a higher accuracy sensor such as close tolerance version of either thermocouple or Pt100.

c) and/or specifying a Pt100 instead of a thermocouple if the application permits and if the instrumentation can be specified to suit.

d) Specifying a type of thermocouple with better basic accuracy and stability than say the standard type K. Examples are type T, N, R and S. However, suitability for the working temperature must be observed.

Note: Wiring and instrument input type must be considered when choosing the type of sensor.

7.2. TRANSMITTERS AND SIGNAL CONDITIONING

Temperature transmitters are widely used m measurement systems because their use allows long cable runs back to the associated instrumentation. They also perform a **signal conditioning** function.

A 2 wire temperature transmitter accepts a thermocouple or 3 wire Pt100 input and converts the “temperature” output into a 4-20mA current signal. The transmitter usually requires a 24Vdc supply which is connected in series with the 2 wire interface (or is provided by the host instrument). The amplified temperature signal can be transmitted via a long cable run if required, a considerable advantage with large site installations.

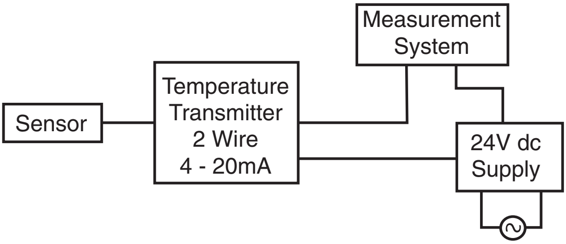


Fig 44a: Temperature Transmitter Circuit

The output can be either linear with temperature (usually the case with Pt100 inputs) or linear with thermocouple voltage (not linear with temperature - usually the case with thermocouple inputs). It is important to ascertain linearity or otherwise since this will have ramifications as far as the indicator is concerned, if the interface is non-linear with temperature, the indicator must display the appropriate transfer characteristic in order to give an accurate temperature readout (e.g. scaled for the Type K curve).

Transmitter scaling must be specified as required e.g. 0 to 400°C = 4 to 20mA. Remember this must correspond to the instrument scaling to avoid measurement errors. ***Input to output isolation is not necessarily incorporated as standard and it is essential to use electrically insulated sensors if isolation is not incorporated.***

Signal conditioning is the process of modifying the raw input signal in one or more ways to facilitate communication and measurement. The transmitter is a simple form of signal conditioner but signal conditioners usually provide linerisation scaling facilities and other functions. The most common form of signal conditioner housing is a DIN rail mounting module.

Signal conditioners are particularly useful when different parameters are measured in a process (e.g. Pt100 and thermocouple outputs, flow rates, pressure and force). The output from all of the appropriate sensors or transducers can be rationalised into a common interface such as 4-20mA or 1-5V. Transfer characteristics can also usually be applied to suit a range of sensors and transducers resulting in a linear function. On this basis, standard process indicators can be utilised thus simplifying the instrumentation.

Programmable and so called “smart” transmitters effectively combine transmission and signal conditioning functions. In addition to manipulating the input-output function, a variety of transmission modes can be selected. Isolation of input to output further enhances their scope of applications; for example a multi-sensor installation with individual transmitters can be used without danger of earth loops establishing spurious potentials. Programming is performed via a PC using software normally supplied or via a plug-in module,

7.3. INSTRUMENTATION & DATA COMMUNICATIONS & EMC

Many microprocessor based indicators and controllers are user configurable for many thermocouple types and, in some cases for Pt100 as well. If the input type is not user selectable, it is essential that this is specified to suit the associated sensor. Ideally the sensor type should define the instrument, not vice versa; this is because the sensor must be chosen to suit the process. In practice, both should be considered to ensure optimum accuracy and cost-effectiveness.

7.3.1. Temperature Measurement & Control

Instrumentation for temperature measurement accept input signals directly or indirectly (via transmitters) from the sensor. The input requirements are different for the alternative signals, Pt100, thermistor, thermocouple or transmitter. Indication can be either analogue (usually a drum scale or recorder chart) or digital and various options are available for the user to extend the functions beyond mere indication. Such options include single or multiple alarms and digital or analogue outputs (communications).

Single or multiple input instruments are available; for multi-channel inputs, selection can be either manual or automatic as with multiplexers and scanners. If isolation is not provided between inputs or between input and output the use of insulated (isolated) probes should be considered.

Scanning, logging and data acquisition Systems are basically electronic measuring instruments with some form of input multiplexing and appropriate storage or re-transmission of the measured temperatures. Alarm functions are usually incorporated. Section 7.3.2. provides more information.

Chart Recorders provide a hard copy record of process temperature often in addition to many other functions such as digital real-time displays and alarms. Such records are a legal requirement in some industries such as food and drug production. Sophisticated recorders have multi-channel capability and various analytical functions.

Temperature Alarms provide for indication of and some form of output switching in the event of the process temperature using above of falling below certain specified limits. They are used for process safety and product quality purposes, often as an adjunct to control systems by way of an independent "policeman".

Where high precision thermometry is required, more expensive **high accuracy instruments** are available. Designed primarily for laboratory use, such indicators provide a high resolution display of temperature and very good stability. The use of such instruments is described in **Chapter 6, Temperature Calibration**.

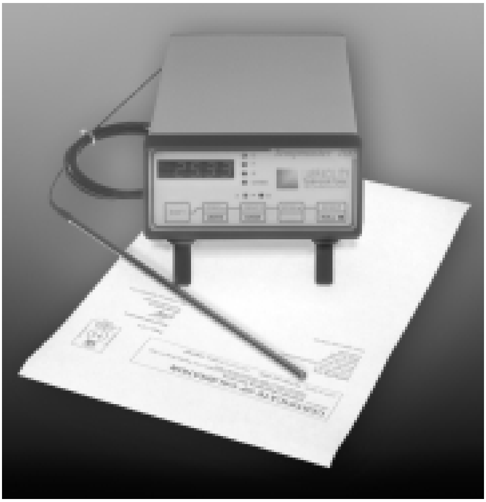


Fig 45: High Accuracy Digital Thermometer

Automatic Cold Junction Compensation

Temperature measurement instrumentation almost invariably incorporates some form of automatic cold junction compensation for thermocouple inputs. As described in Chapter 2, thermocouple measurements must be referred to a 0°C "cold" junction in order to give a true "hot" junction value. This is achieved in practice by incorporating a compensating circuit; this measures the actual ambient temperature (very rarely 0°C) at the thermocouple input terminals of the instrument and effectively adds the equivalent thermal e.m.f. to that of the thermocouple. This occurs continuously to compensate for both the value of ambient temperature and for its variations. The resulting indicated temperature is therefore a true representation of the process temperature.

The quality of this compensation is normally expressed as a **rejection ratio** or **temperature coefficient.** A rejection ratio of say 25:1 specifies that a 25°C change in ambient temperature would result in a 1°C change in indicated (measured) temperature. The higher the rejection ratio, the better the compensation. A figure of 20:1 to 25:1 is typical and usually adequate; higher performance instruments can achieve 75:1 or better. The stability may be expressed as say 0.05°C/°C which is equivalent to 20:1.

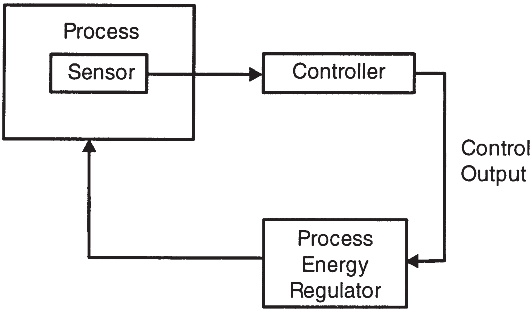
Temperature Control

A temperature controller is effectively a combination of temperature indicator and added control board with some form of output circuit. The preceding **Temperature Measurement** copy is therefore applicable to this **control** explanation as far as indicators and measurement aspects are concerned.

Fig 46: PID Temperature Controller

The principles of temperature control are treated in some depth in chapter 8 which should be referred to for an explanation of P.I. and D terms and more detail.

The addition of a control and output circuit to the measurement instrument permits **closing of the loop** to achieve closed loop automatic control of a process. Process energy can be derived from electricity, gas or oil and it is the function of the output stage to regulate it as appropriate.



Sensor provides temperature feedback thus allowing automatic control.

Fig 47: Closed Loop System

The diagram above illustrates a simple, single loop control system. Loops may be more complex and many installations will use multi-loop configurations; however, the basic concept is the same.

The control circuit applies either on-off or a combination of proportional (P), integral (I) and derivative (D) functions as described in Chapter 8 to achieve the best possible control of process temperature. The output stage is instructed by the control circuit to apply or remove energy to or from the process accordingly by one of the various "switching" modes available.

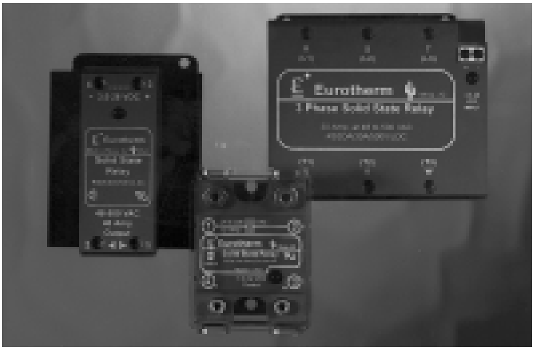


Fig 48: Solid State Power Switches for Electrical Heaters

Electrical energy is ultimately regulated via solid state switches (triacs; thyristors or solid state relays) or via electromechanical relays or contactors. The actual switching device maybe external to the controller in which case control signals are issued by the output circuit (e.g.0-1V, 4-20mA, logic signal or pulses).

Gas or oil are regulated by solenoid valves or proportional motorised valves and the controller issues electrical control signals to suit (voltage or current).

The **process temperature** is normally displayed digitally although some instruments provide some form of analogue indication (drum scale or deviation indication).
The **desired** temperature (**set-point**) is set via analogue or digital adjustment.

7.3.2. Data Acquisition & Logging

Fig 49: Data Logger

Data acquisition is the process of gathering data from a variety of transducers or sensors for monitoring, storage or processing. A data logger is a stand-alone instrument for data gathering and storage. Logging is simply recording the data with a time/date stamp such that the data can be displayed, printed, analysed and archived as required.

In the case of temperature, a typical application would be some form of experiment which involved any number of temperature sensors (e.g. thermocouples, resistance thermometers, thermistors). An event would require “collecting” measurements from any or all of the sensors at a specified sampling rate for subsequent analysis. Data storage is very important in long term projects.

When specifying a data acquisition system, considerations include the number and type of inputs and outputs, communications protocols, sampling speeds and data storage methods. Such a system can be “stand-alone” or a “front-end” for use in conjunction with a personal computer (PC). Digital printer or analogue chart recorders can be used to print-out data either on a real-time basis or from stored data.

The chosen sampling rate (the rate at which signals from the input transducers are scanned and acquired) needs to be consistent with the dynamics of the process, response times of the transducers and the multiplexing capability of the system.

In the case of remote sensing such as on a large site, radio telemetry is often used to transmit the measured data to the data acquisition system. Supervisory Control and Data Acquisition (SCADA) systems monitor and record data in the same way but additionally are programmed for real-time, on-line decision making, process control activity and alarm monitoring.

7.3.3. Data Communications & Analogue Retransmission

Analogue Outputs from measuring and control instruments are not data communications in the strict definition of the term. However, analogue (retransmission) signals are commonly used for outputting the scaled and amplified process variable to chart recorders and data loggers. Such signals are typically 0-1V dc or 4-20mA dc.

Data Communication is used for transferring data and instructions between associated instruments or between instruments and computers, usually PCs.

Data characters are represented by a data code, each element of which consists of a group of binary digits (bits) each being 1 or 0. The group of bits is called a byte or word. The task of data transmission is to send bytes from one point to another (e.g. instrument to PC).

Data communication is performed as either serial or parallel communication depending on the configuration provided by the indicator or controller and/or the requirements of the application. **Parallel communication** refers to data bits transmitted via separate lines for each bit and therefore utilizes several wires (an 8 bit word requires 8 lines).

Serial Communication refers to data bits transmitted serially through a single line and therefore utilizes a single pair of wires. Examples of widely used recommended standard (RS) include RS-232C, RS-422A and RS-485.

a) RS-232C is perhaps the most common standard as specified by EIA (Electronics Industries Association). It is used for interfacing between data terminal equipment and data communications equipment. A maximum line length of 15m is permitted. It is a single, bi-directional serial interface.

b) RS-422A, another EIA standard, specifies a low impedance differential signal permitting a line length of around 1200m. It is a single, bi-directional serial interface.

c) RS-485 is another EIA standard which specifies the interface characteristics but allows the equipment designer to choose the desired protocol. This enables users to configure multi-drop and local area network communications to suit different applications. It is a multi-drop, bi-directional, serial interface with a capacity of up to 32 transmit / receive drops per line. Developments of serial data communications for industrial applications include HART, MODBUS and other examples developed by leading manufacturers.

HART (Highway Addressable Remote Terminal) is used with “smart”, analogue process control instruments for example. MODBUS is an alternative versatile, industrial networking system.

For more information on digital communications, the Institute of Measurement & Control can supply details of a wide range of suitable publications.

7.3.4 Electro-Magnetic Compatibility (EMC)

EMC Requirements for Electrical Equipment for Measurement, Control and Laboratory Use.

Temperature instruments in common with all types of instrumentation must comply with European EMC (Electro-Magnetic Compatibility) regulations in terms of electromagnetic radiation if they are to be available in the European market.
The regulation in question is IEC 1326-1. Accordingly, CE marking which indicates compliance, is mandatory.

The regulation is basically that electrical / electronic equipment must not generate significant amounts of electromagnetic radiation (including r.f.i) nor be sensitive to its effects. Standards published accordingly define the requirements, test procedures and various aspects covering both emission and immunity.

Equipment within the scope of the regulations can be subjected to electromagnetic disturbances (EMI), conducted by measurement or control lines or radiated from the environment. The types and levels of disturbances depend on the prevailing conditions in which the equipment operates. Such equipment can also be a source of electromagnetic disturbance over a wide frequency range; again, such energy can be conducted through signal lines or directly radiated and this can affect other equipment. Emissions must be minimized to ensure that interference with normal operation of other equipment does not occur. EMC defines three basic aspects of interference

a) A **source** which generates an inteference signal
b) A **recipient** which is adversely affected by the signal
c) A **path** which carries the signal

Interference can be INTRASYSTEM where each aspect is in a separate system. Interference sources can be various in form – natural, man-made intentional (e.g. radio waves) and unintentional (e.g. power lines). Similarly recipients can be either intended or unintended.

The path can be conduction or radiation or a combination of both.

The key elements are defined as:

EMC Electro-Magnetic Compatibility. The condition which exists when a piece of electrical equipment neither malfunctions nor causes malfunction in other equipment when operating in surroundings for which it was designed.

EMI Electro-Magnetic Interference. The unintentional interaction between a piece of electrical equipment and its electromagnetic surroundings.

8. TEMPERATURE CONTROL

8.1. CONTROL LOOPS EXPLAINED

Whatever the process or the parameter (temperature, flow, speed for example), the principles of control are similar. Input and output signals are specified as appropriate to the application, usually analogue (e.g. thermocouple signal input, solid state output power control) but these may be digital.

This chapter assumes temperature control with either a thermocouple or platinum resistance thermometer input and a proportional control output.

Control of a process is achieved by means of a closed loop circuit (power fed to the heater is regulated according to feedback obtained via the thermocouple) as opposed to an open loop in the case of measurement only:

Temperature Measurement (Open Loop)

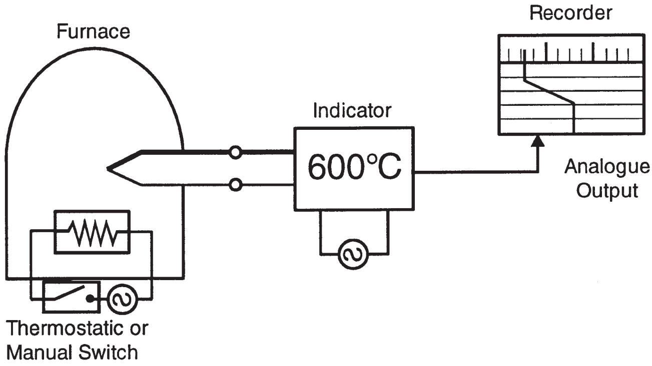


Fig 50: Temperature Measurement (Open Loop)

Temperature Control (Closed Loop)

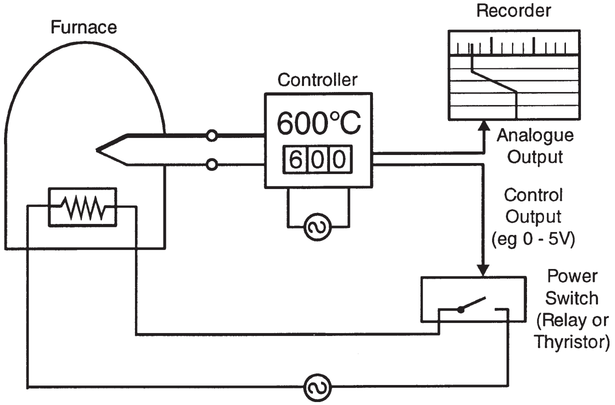


Fig 51: Temperature Control (Closed Loop)

8.2. PID EXPLAINED

With few exceptions, only very crude control of temperature can be achieved by causing heater power to be simply switched on and off according to an under or over temperature condition respectively. Ultimately, the heater power will be regulated to achieve a desired system temperature but refinement can be employed to enhance the control accuracy.

Such refinement is available in the form of **proportional (P), integral (I), and derivative (D)** functions applied to the control loop. These functions, referred to as control "terms" can be used in combination according to system requirements. The desired temperature is usually referred to as the "set-point" (SP) and the measured temperature is usually called the "process variable" (PV).

To achieve optimum temperature control whether using on-off, P,PD or PID techniques, ensure that:

a) Adequate heater power is available (ideally control will be achieved with 50% power applied!)

b) The temperature sensor, be it thermocouple or PRT, is located within reasonable "thermal" distance of the heaters such that it will respond to changes in heater temperature but will be representative of the load temperature (the "thing" being heated).

c) Adequate "thermal mass" in the system to minimise its sensitivity to varying load or ambient conditions.

d) Good thermal transfer between heaters and load.

e) The controller temperature range and sensor type are suitable – try to choose a range that results in a mid-scale set-point.

Control Functions Simply Described

a) **On – Off** – Usually simplest and cheapest but control may be oscillatory. Best confined to alarm functions only or when "thermostatic" type control is all that is required, but this may be the most suitable means of control in some applications.

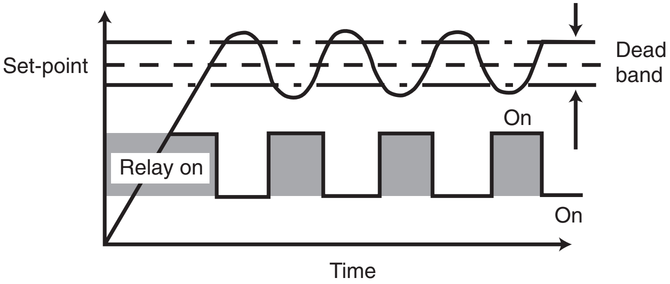


Fig 52: On/Off Control with Dead-Band

b) **Proportional (P)** – A form of anticipatory action which slows the temperature rise when approaching set-point. Variations are more smoothly corrected but an offset will occur (between set and achieved temperatures) as conditions vary.

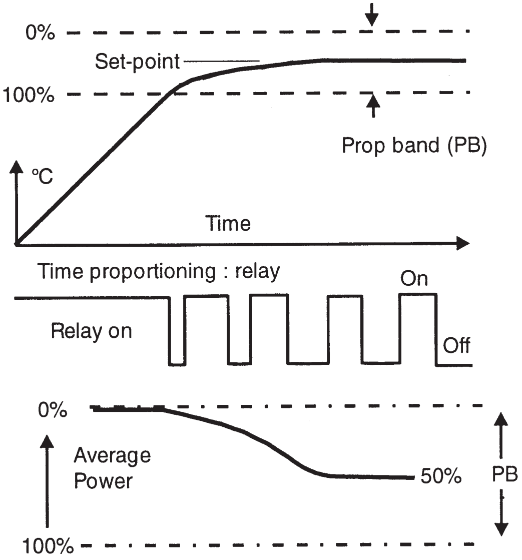
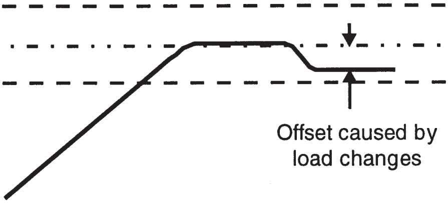


Fig 53: Proportional Control

Average heater power over a period of time is regulated and applied power is proportional to the error between sensor temperature and set-point (usually by time proportioning relay switching). The region over which power is thus varied is called the Proportional Band (PB) it is usually defined as a percentage of full scale.

c) **Integral (Offset)** I is the deviation of the sensor temperature from the desired value (set-point). This can be adjusted out manually by means of a potentiometer adjustment (Manual Reset) or automatically (Integral Action).



Manual Reset Action

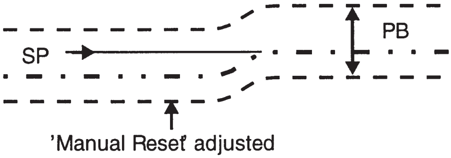


Fig 54: Offset

d) **Proportional + Derivative (PD)** – The Derivative term when combined with proportional action improves control by sensing changes and correcting for them quickly. The proportional action is effectively intensified (its gain is increased) to achieve a quicker response.

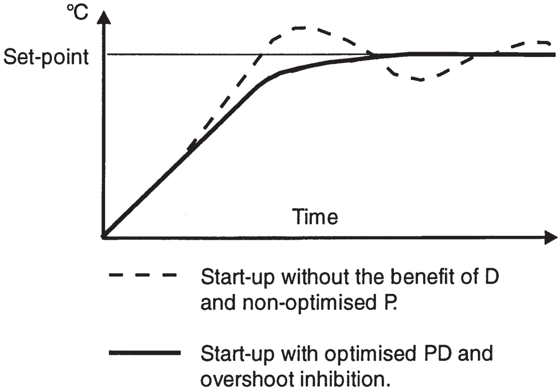


Fig 55: Start-up Performance with PD Control

PD action is commonly employed in general applications. Its use can minimise or even eliminate overshoot on system start up.

e) **Proportional + Integral + Derivative (PID)**
Adding an integral term to PD control can provide automatic and continuous elimination of any offset. Integral action operates in the steady state condition by shifting the Proportional Band upscale or downscale until the system temperature and set-point coincide.

f) **Approach Optimisation**
Under certain conditions, even with PID action, when the process is started, the set-point value can be exceeded prior to the process settling down and this is referred to as “start-up overshoot”. Many controllers employ certain techniques to minimize this situation; this is referred to as “approach optimization”

g) **Choosing P, PD or PID**
Although superior control can be achieved in many cases with PID control action, values of the PID terms inappropriate to the application can cause problems.

If an adequately powered system with good thermal response exists and the best possible control accuracy is required, full PID control is recommended.

If somewhat less critical precision is demanded, the simpler PD action will suffice and will suit a broad range of applications.

If simple control is all that is required, for instance to improve upon thermostatic switching, Proportional (P) or on-off action will suffice.

Adjustable PID Values?

If the controller specified offers adjustable PID values, the opportunity exists to optimise or “tune” the control loop to achieve the best possible accuracy in each case.

Fuzzy Logic

Fuzzy logic is a development of computer intelligence which, when utilized in controllers allows them to handle a diverse range of system demands. Basically, the controller benefits from optimization techniques which learn the process characteristics.

Benefits include a more rapid start up with little or no overshoot, more rapid settling following process disturbances (e.g. opening an oven door) and changes in set-point.

Heating and Cooling

Controllers which are used in processes requiring both heating and cooling use a heat-cool algorithm to achieve a stable temperature in the “cross-over region” (a heating-cooling overlap). Such applications include exothermic conditions where resultant work (process generated) heat could result in excessive temperature (e.g. plastics extruder barrels).

Typically, the heating would be electrical and the cooling achieved by water or fan.

8.3. OPTIMISING CONTROL TERMS (TUNING)

The majority of modern controller and control systems utilize self-tuning circuitry for automatic loop optimization. Where manually adjusted PID values are used the “Fast Tune” guide below is useful.

Fast Tune PID Control

All processes have some finite delays and on-off control will result in start-up temperature overshoot as shown.

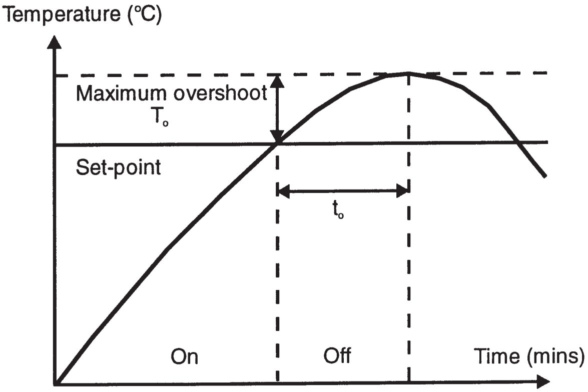


Fig 56: Start-up Temperature Overshoot

Firstly adjust P to minimum, D to off and I to off (or some very large value if not to off).

Full power is applied to the heaters and is switched off when the measured temperature rises to set-point. The resultant overshoot T_o and the time taken to attain the maximum overshoot t_o, allow suitable P, I and D values to be calculated:

$$P = \frac{\text{overshoot °C } (T_o)}{\text{controller span, °C}} \times 100 \qquad \text{percent}$$

$$D = \frac{120t_o}{5} \qquad \text{seconds}$$

$$I = 4\,t_o \qquad \text{minutes}$$

These or similar values should then be set on the controller and good results will be achieved.

For critical processes there are alternative more precise methods for obtaining optimum PID values. Such methods are more time consuming and Auto Tune Techniques described below provide an attractive solution in most applications, simple or complex.

Auto Tune PID Control

Auto tune controllers utilize PID terms and an "approach" feature which are all optimized automatically. During the first process warm-up the controller familiarizes itself with the system dynamics and performs self-optimisation. No user adjustments are required for PID values. Some instruments include an "approach" feature to minimize or eliminate start-up overshoot, also automatically.

8.4. CONTROL OUTPUTS & ALARMS

Accurate and reliable energy regulation are essential for good control loop performance if it is assumed that suitable PID values have been determined and applied.

Depending on the method of applying energy to the process, for example electrical energy to a resistive heating element, a suitable type of controller output arrangement must be specified. In some cases, more than one output may be required (e.g. for multi-zone heaters, heating-cooling applications).

Options most commonly available are:

Electromagnetic Relay, typically rated 2,5 or 10 Ampere contact.

Electronic relay (Solid State Relay or SSR) typically rated up to 3kW.

Thyristor Unit, usually rated from 3kW to 100kW.

Analogue dc control signals, usually 0-1V, 1-5V, 4-20mA and similar to operate external energy regulation devices or converters (e.g. external thyristor units).

Valve Positioner, actuator drive for gas or oil fired burners with or without position feedback function.

Alarms and safety

Whilst built-in alarms provide a convenient method of "policing" the process against over or under temperature occurrence, they should never be relied upon for plant safety. If there is any possibility that component or sensor failure could result in heating power being permanently applied instead of regulated then a completely independent over-temperature alarm should be utilized. In the event of excessive temperature rise, such an alarm would remove energy from the process.

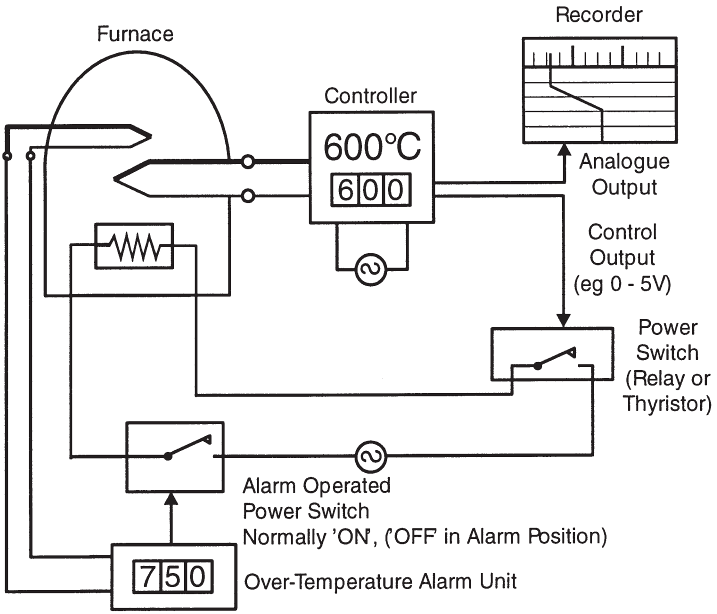


Fig 57: Temperature Control System with Independent Alarm

Alarm Functions

1. High Alarm – this operates if the process temperature exceeds the alarm set value.
2. Low Alarm – this operates if the process temperature falls below the alarm set value
3. High / Low Alarm – this operates if the process temperature exceeds or falls below the alarm set values.
4. Deviation Alarm – this operates if the process temperature reaches a predetermined deviation from the set-point.
5. Process Alarm – this operates if the process temperature reaches the alarm set value, regardless of the process set-point value.

In practice, various features are available with alarm functions to suit process needs. These include dead-band, delay and reset functions and alternative contact modes.