

# CHE660

## Process Instrumentations



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## 1.0 Introduction to process control

### 1.1 Applications of automation

- Chemical processing plants
- Manufacturing industries
- Building
- Aircraft, ship, automobile

#### Significants of automation in chemical processing and manufacturing industries

- reduce defective products
- capable of operating at hazard area such as nuclear power plant, smelting ind., etc.
- high-speed measurement and control
- precise and accurate measurement and control
- continuous and non-stop operation

#### Disadvantage of automation

- high cost of instruments, hardwares and softwares.
- require highly trained workers in automation

- 1.2 Control systems have three main configurations; namely,  
 a) feedback control  
 b) cascade control  
 c) and feedforward control.

1.2 a) Feedback control – e.g. Level control and flow control

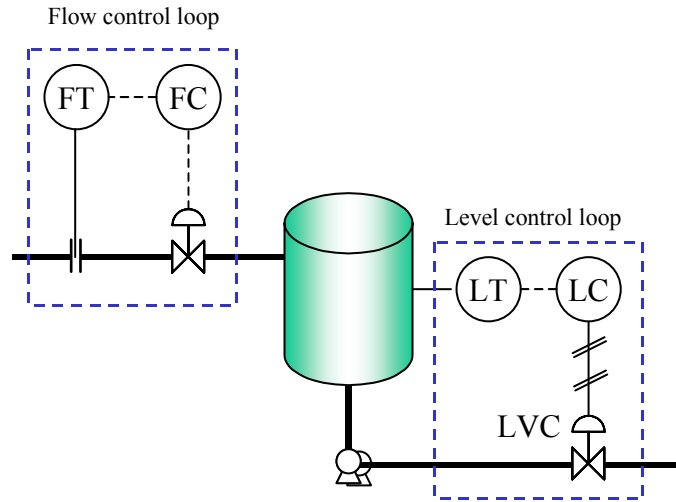


Figure 1.21 – P&ID for flow and level SISO feedback control system.

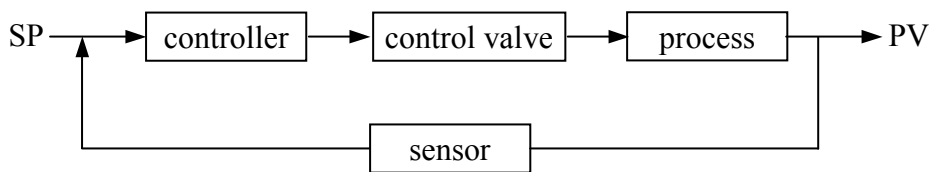


Figure 1.22 – Block diagram for SISO level feedback control.

1.2 b) Cascade control – e.g. level/flow cascade control

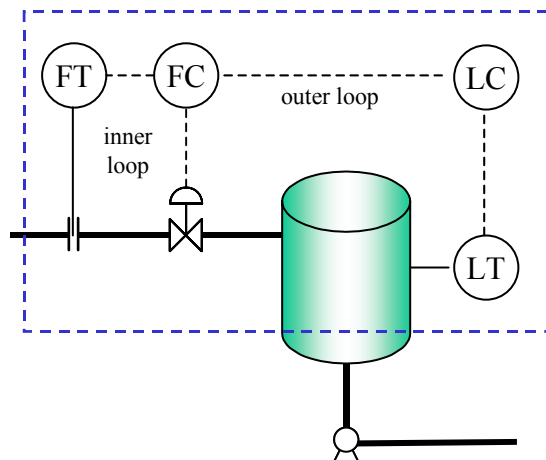


Figure 1.23 – Example of P&ID for level/flow cascade control system.

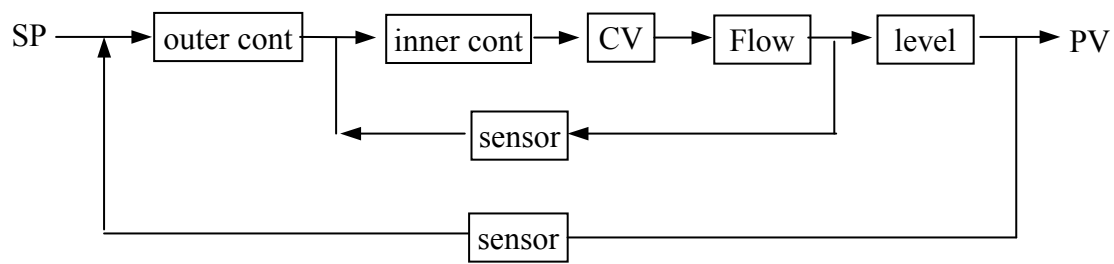


Figure 1.24 – Block diagram for cascade control system.

1.2 c) Feedforward control – e.g. level feedforward control

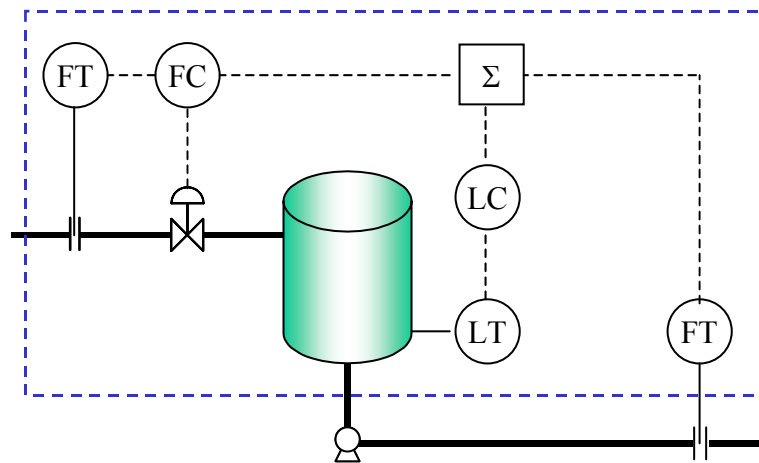


Figure 1.25 – Example of P&ID for feedforward level control system  
(source: Syntek Engineering's Lab Manual).

### 1.3 Terminologies:

#### Feedback control

- A method of control at which the action is based on past result.

#### Cascade control

- A method of control at which the set point of the inner loop controller is from the outer loop's controller.

#### Feedforward control

- A method of control at which the action is based on changes in load variables.

#### Controller

- A device used to compute the amount of change needs to be made at the final control element.

#### Final control element

- A device used to perform the change instructed by the controller.

#### Process

- A mass that change its characteristics due to chemical reaction or quantity such as volume expansion. Examples of processes are liquid flow, liquid level, etc.

#### Transmitter

- A device used to amplify the signal from a sensor and relay it to the controller.

#### Sensor

- A device used to measure the changes in process.

#### Set point

- The targeted stabilization value.

#### Manipulated variable

- The variable that being changed by the final control element.

#### Controlled variable

- The variable that being controlled.

#### Load variable

- The variable (i.e. other than manipulated variable) that may affect a change in the process.

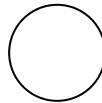
#### Measured variable

- The variable that being measured by the sensor.

### 1.4 Process & Instrumentation Diagram (P&ID)

#### Instrument and computing device

Instrument – rounded circle, e.g.



Computing device – square box, e.g.



#### Signals transmission

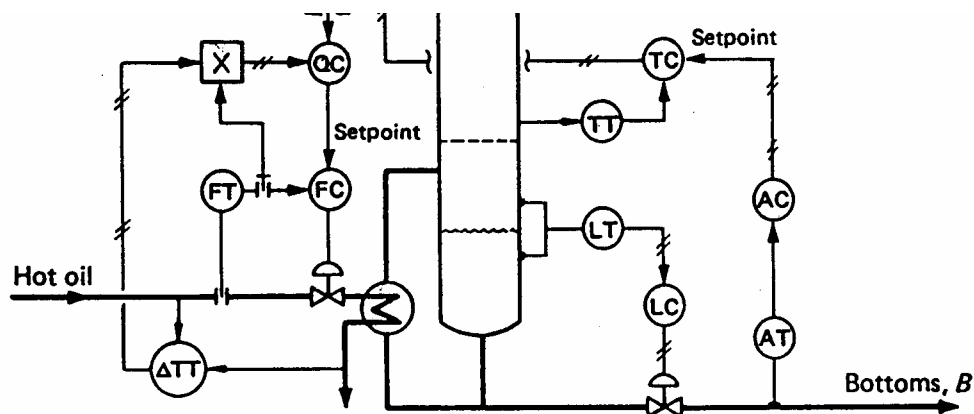
- ----- electrical line
- // // // pneumatic line

#### Instrument labeling

First letter – measured variable  
 Second letter – device  
 Third letter – device or condition.

e.g. PC – Pressure Controller, PT – Pressure Transmitter  
 LC – Level Controller, LR – Level Recorder

Common devices: I = indicator, R = recorder, C = Controller, T = transmitter, A = alarm  
 Common measured var.: L = level, P = pressure, F = flow, T = temperature  
 Common notations: PRV = pressure relief valve, FCV = flow control valve,  
 LAL = level alarm low,



Excerpt from T. Senbon & F. Hanabuchi, *Instrumentation Systems: Fundamentals and Applications*, Springer-Verlag, 1991, p.138

The following description on pressure, level, flow and temperature devices had been taken from T. Senbon & F. Hanabuchi, Instrumentation Systems: Fundamentals and Applications, Springer-Verlag, 1991, pp 141-144

### Differential Pressure Transmitters

Electronic pressure transmitters are also grouped into the same three types as are pneumatic transmitters. The operating principle of electronic pressure transmitters is shown in Fig. 1. Pressure is applied to the two diaphragms of the twin diaphragm capsule. This pressure is transmitted from the twin diaphragms to the sensing diaphragm through the sealing liquid. Two fixed electrodes are placed symmetrically on the left and right side of the insulator and an electrical capacitance is formed between these electrodes and the sensing diaphragm. If there is a pressure differential between the high pressure side and the low pressure side, the position of the sensing diaphragm will change in proportion to that differential, and an electrical capacitance differential will be produced. This capacitance differential is converted an electrical current and output as a signal of 4 mA to 20 mA DC, corresponding to the measured pressure differential range. Zero setting and span adjustment are done in the transmitter.

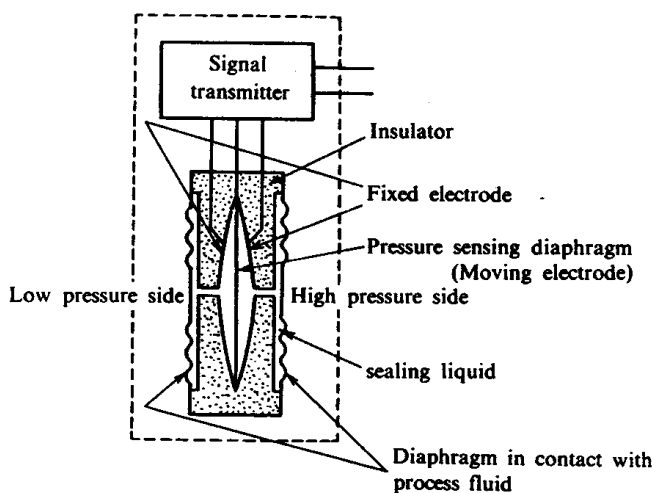


Figure 1 – Differential pressure sensor.

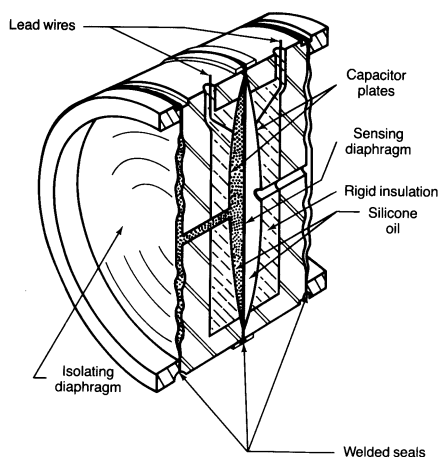


Figure 2 – 3-D view of a differential pressure transmitter (excerpt from D.R. Gillum, Industrial pressure measurement, ISA, 1982, p.43)

## DP Level Transmitters

The principle of differential pressure (DP) liquid-level meters is that the static pressure at any point in a liquid is equal to the product of the distance from that point to the surface of the liquid, the density of the liquid, and the acceleration due to gravity. Thus, if the liquid density and the acceleration due to gravity are known, the distance to the surface (that is to say, the liquid level) can be determined from the pressure. The method of tapping the pressure is different for open tanks and closed tanks.

### (a) Open tanks

A pressure differential transmitter or pressure transmitter is connected to the tank by a pressure tapping tube, as shown in Fig. 3.9. When a pressure differential transmitter is used, the liquid is tapped for the high pressure side, and the open air is tapped for the low pressure side.

The following relationship exists among the pressure (gage pressure), the density of the liquid, and the acceleration due to gravity.

$$P = \rho g (H+h)$$

Here,  $P$  is the pressure (gage pressure, Pa),  $\rho$ , is the density of the liquid ( $\text{kg/m}^3$ ),  $g$  is the acceleration due to gravity ( $\text{m/s}^2$ ),  $H$  is the plumb distance between the minimum liquid level and the surface (m), and  $h$ , is the plumb distance between the minimum liquid level and the pressure detector (m).

The relationship between the input and output of the transmitter is linear, so the output of the transmitter changes in direct proportion to changes in the liquid level.

### (b) Closed tanks

When measuring the liquid level in a closed tank, the pressure differential transmitter is used. The low pressure tap is the pressure of the gas above the liquid in the upper part of the tank (Fig. 3.80). The pressure of the gas is also applied to the high pressure tap at the same time, so when taking the pressure differential, it cancels out and so does not affect the output of the transmitter. Thus, the level of the liquid can be known from the pressure differential.

High pressure tap pressure	$P_H = \rho_1 g (H+h_1) + P_G$
Low pressure tap pressure	$P_L = P_G$
Pressure differential	$P_H - P_L = \rho_1 g (H+h_1)$

Here,  $P_G$  is the pressure of the gas in the upper part of the tank.

If condensation from the gas in the upper part of the tank collects inside the tapping tube, the low pressure tap pressure in the tube will change and the output of the pressure transmitter will be affected. To avoid this problem, the condensation is collected in a drain pot.

Another method involves using a relatively heavy liquid that does not easily evaporate to fill the tube, as shown in Fig. 3.81. The pressure of the gas in the tank is then applied to the pressure detector through this liquid. This method is called the wet leg method, as opposed to the dry leg method described above. In the wet leg method, the pressure is calculated in the following way.



$$\begin{aligned} \text{High pressure tap pressure} \quad P_H &= \rho_1 g (H+h_1) + P_1 \\ \text{Low pressure tap pressure} \quad P_L &= \rho_2 g h_2 + P_G \\ \text{Pressure differential} \quad P_H - P_L &= \rho_1 g (H+h_1) - \rho_2 g h_2 \end{aligned}$$

Here,  $\rho_2$  is the density of the liquid in the wet leg ( $\text{kg/m}^3$ ), and  $h_2$  is the height of the liquid in the wet leg (m).

When using pressure differential liquid-level meters, care must be taken regarding the following points.

- (1) The pressure differential transmitter must be positioned below the minimum liquid level.
- (2) Corrections must be made for changes in the density of the liquid.
- (3) If there is a pulsating motion in the liquid, the output of the transmitter will be unstable.
- (4) The tapping tubes should be as straight as possible so as not to trap air. Also, use of points that might leak should be minimal.

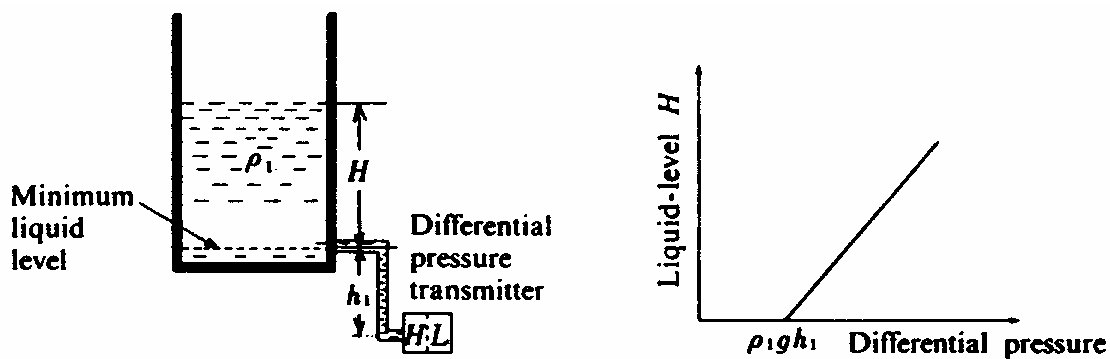


Figure 3.79 – Open tank differential pressure transmitter system.

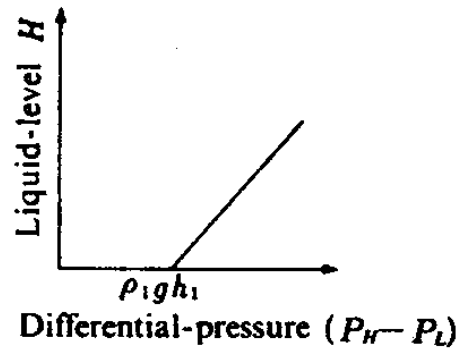
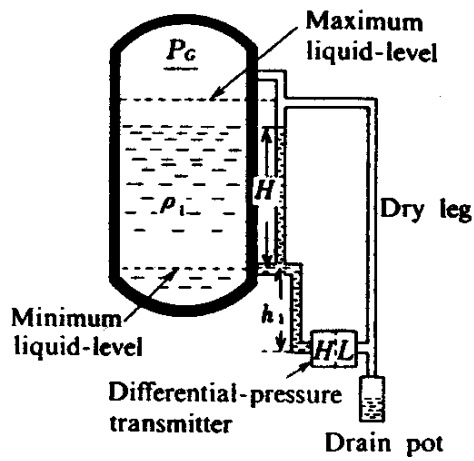


Figure 3.80 – Liquid measurement using dry leg system of closed tank.

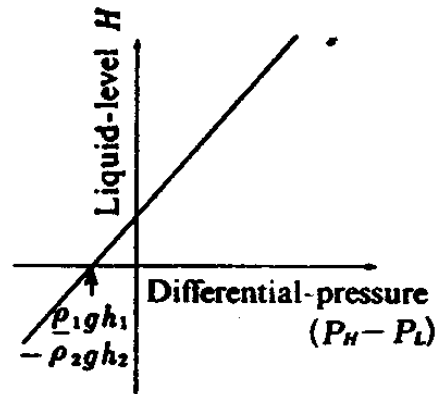
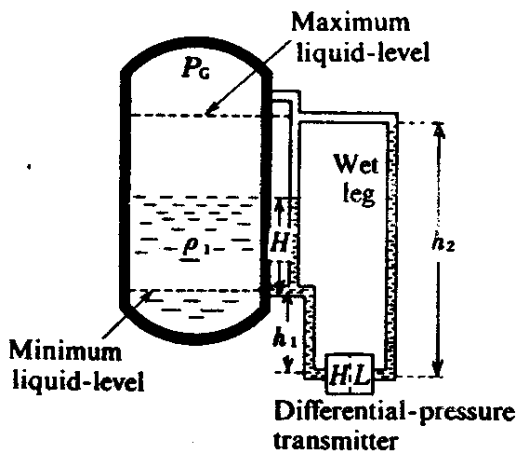


Figure 3.81 – Liquid measurement using wet leg system of closed tank.

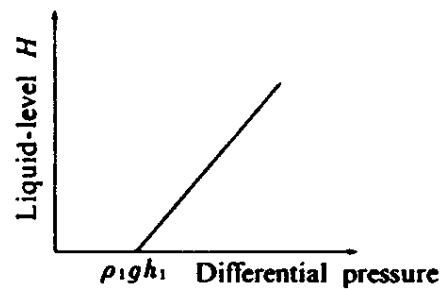
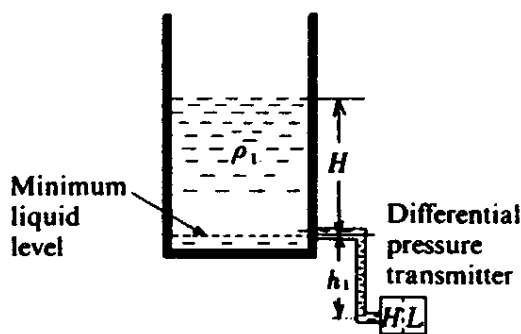


Figure 3.79 – Liquid measurement for open tank.

### Ultrasonic Liquid Level Transmitter

As shown in Fig. 3.84, an ultrasonic liquid-level meter measures the time required for an ultrasonic wave emitted by a transducer and reflected off the surface of the liquid to return to the transducer, thus determining the liquid level. The relationship between the liquid level, speed of the ultrasonic wave, and time is given by the following equation.

$$2(L - H) = t u$$

Here,  $L$  is the distance from the minimum liquid level to the ultrasonic transducer (m),  $H$  is the liquid level (m),  $t$  is time between the emission of the signal and its subsequent reception at the transducer (s), and  $u$  is the propagation velocity of the ultrasonic wave (m/s).

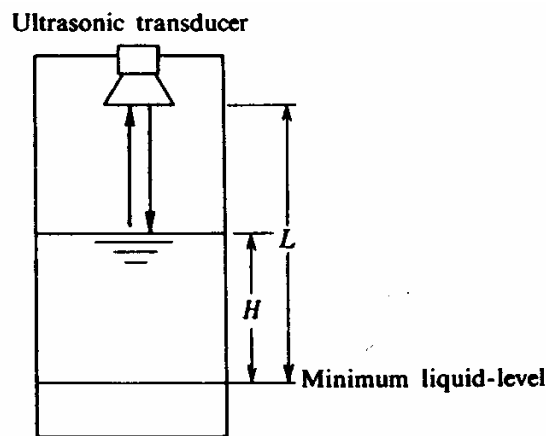


Figure 3.84 – Ultrasonic level transmitter

The velocity of the ultrasonic wave  $u$  varies with the type of gas it travels through and the temperature, so the temperature of the gas must be measured and corrections applied according to the results.

Ultrasonic liquid-level meters have the following special features.

- (1) Measurement can be accomplished without touching the liquid.
- (2) There are no moving parts, so inspection and maintenance are easy.
- (3) They are small and light, so installation and operation are easy.

### Capacitance Liquid Level Transmitter

The electrostatic capacitance of two facing electrodes varies with the dielectric constant of the material separating them. As shown in Fig. 3.85, if the space between two concentric tubular electrodes contains a liquid, a change in the level of that liquid will change the capacitance between the electrodes as described by the following equation.

$$C = \frac{2\pi \{(e_2 - e_1)H + e_1 L\}}{\ln(D/d)}$$

Here,  $C$  is the electrostatic capacitance between the electrodes (F),  $e_1$  is the dielectric constant of gas (F/m),  $e_2$  is the dielectric constant of the liquid (F/m),  $H$  is the liquid level (m),  $L$  is the height of the electrodes (m),  $D$  is the diameter of the outer tubular electrode (m), and  $d$  is the diameter of the inner tubular electrode (m).

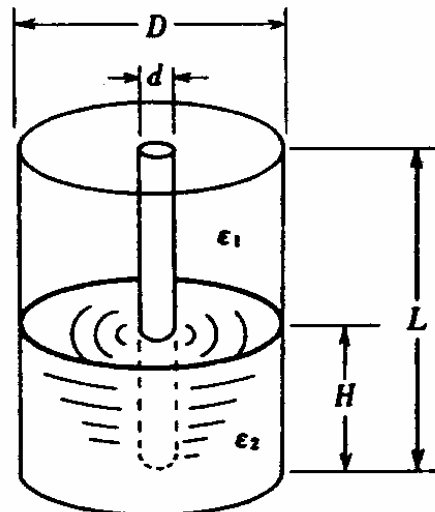


Figure 3.85 – Capacitance level transmitter

The terms  $L$ ,  $D$ ,  $d$ ,  $\epsilon_1$  and  $\epsilon_2$  are constants, so by measuring the capacitance  $C$ , the liquid level  $H$  can be determined. The surfaces of the electrodes are coated with an insulating material that must be selected considering the nature of the liquid being measured.

Capacitance liquid-level meters have the following special features.

- (1) The detector has a simple construction.
- (2) They have no moving parts, and thus a long service life.
- (3) Changes in the dielectric constant that are caused by changes in the temperature and density of the liquid being measured produce errors in measurement.

### Magnetic Flowmeter

Flow signal is detected with electrodes installed on outside of ceramic tube through capacitance of tube wall. As the electrodes are not exposed to process fluid they are free from slurry noise and sticking problem of insulating substance.

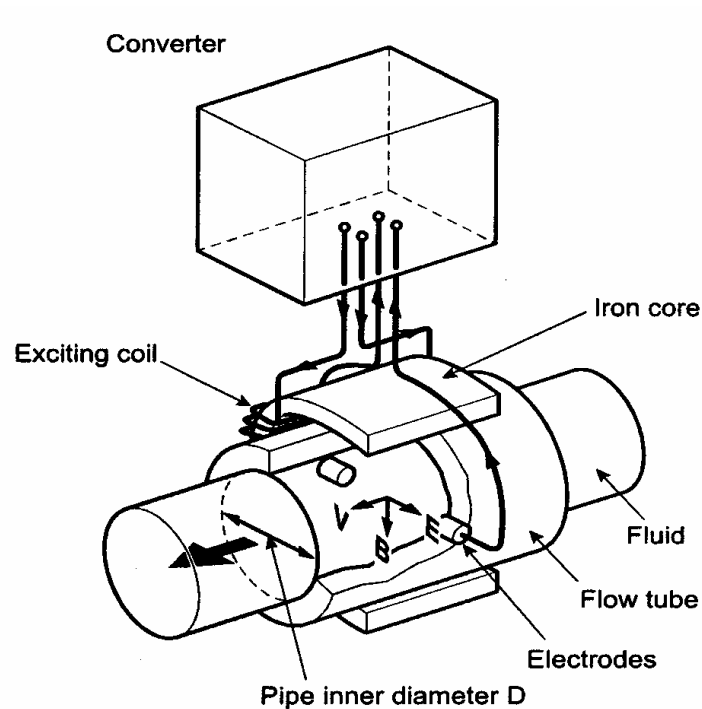
### Operating principle

The principle employs Faraday's law of electromagnetic induction that states an electromotive force (EMF) is induced when a conductor moves through a magnetic field. The value of EMF is proportional to the conductor (fluid) velocity, magnetic flux density, and the conductor width (pipe inner diameter).

The excitation coils generate the magnetic field. The electrodes sense EMF induced when the conductive fluid moves through the magnetic field. As the EMF is proportional to fluid velocity, a magnetic flowmeter outputs linear signal.

$$E = D V B$$

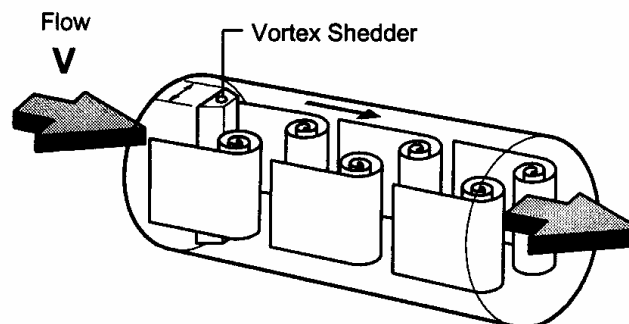
Where,  $E$  is the Electromotive Force (V),  $D$  is the Pipe Inner Diameter (m),  $V$  is the Flow Velocity (m/s) and  $B$  is the Magnetic Flux Density ( $T/m^2$ )



## Vortex Flowmeter

### Working principle

Vortex flowmeters utilize the vortex-shedding phenomenon known as the von Karman effect. When a vortex shedder is installed in a process flow line, Karman vortices appear downstream of the shedder. The vortex generation frequency is directly proportional to fluid velocity - so by measuring this frequency, fluid velocity can be determined.



von Karman effect of vortex flowmeter

The relationship between vortex frequency ( $f$ ), width of the vortex shedder ( $d$ ), and flow velocity ( $V$ ) is given by,

$$f = \frac{St V}{d} \quad (3.29)$$

Here,  $St$  is a non-dimensional constant called the Strouhal number determined by the shape and dimensions of the vortex shedder. With an appropriately chosen vortex shedder, the Strouhal number is constant over a wide range of Reynolds numbers. This means that within this range of Reynolds numbers where  $St$  is constant, the vortex frequency  $f$  is proportional to the flow velocity  $V$ , and is not affected by factors such as the fluid density and viscosity. Further, the Reynolds number  $Re$  for a typical value of  $d$  can be expressed as  $Re = V d / \nu$ , where  $\nu$  is the kinematic viscosity.

The relationship in Eq.(3.29) is also established for the flow in a measuring pipe of inner diameter  $D$ , so for flow rate  $Q$  and flow velocity in the constricted part  $V = \frac{Q}{(\pi/4)D^2 - dD}$

$$f = \frac{St}{((\pi/4)D^2 - dD)d} Q = KQ \quad (3.30)$$

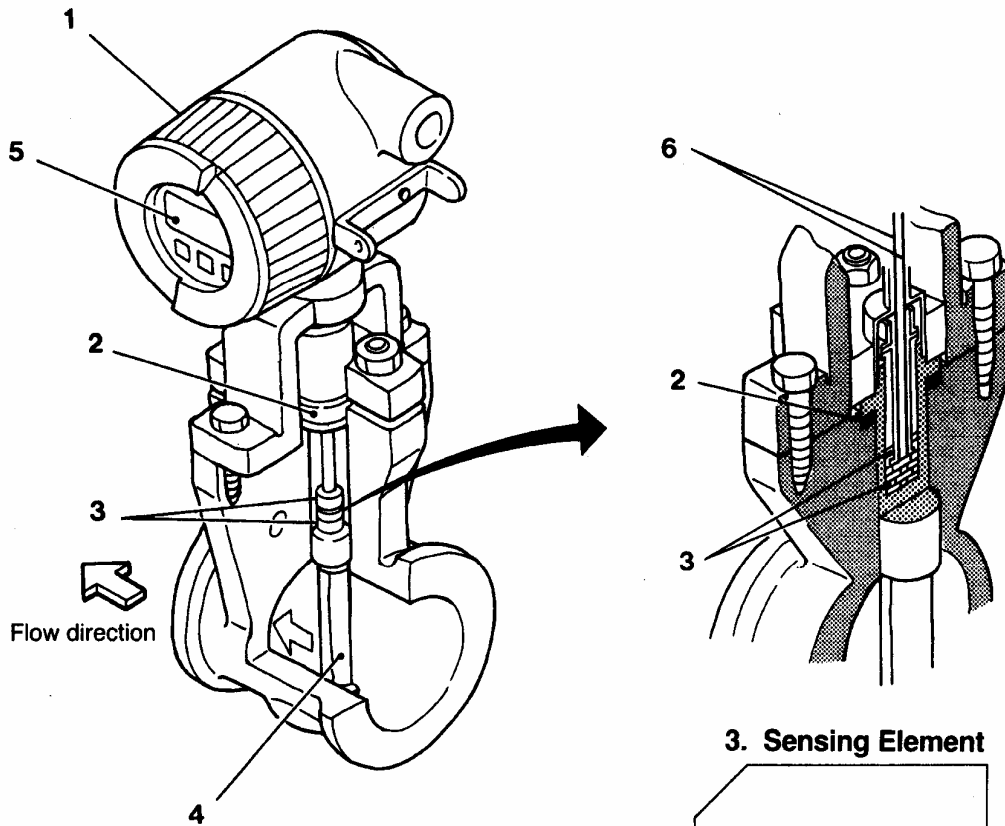
Accordingly, if  $St$  is known in advance, the flow rate  $Q$  can be measured by measuring  $f$ .

The vortex shedder is a dominant constituent of the flowmeter. It must produce strong, stable vortices, and at the same time, the proportional relationship between  $Q$  and  $f$  shown in Eq. (3.30) must hold over a wide range of flow rates. For this reason, much effort is concentrated on experimentally determining the most appropriate shape for the vortex shedder.

### General characteristics of vortex flowmeters

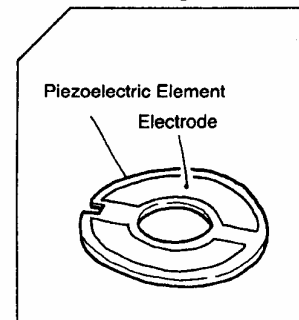
- (1) The output signal of a vortex flowmeters is directly proportional to the flow rate, and a pulse signal can be obtained.
- (2) The output signal indicates the volumetric flow rate, and is not influenced by temperature, pressure or the type of fluid.
- (3) The applicable Reynolds number range is wide, and accuracy is high.
- (4) The pressure loss is relatively low, but is affected by flow velocity distribution, so a straight section of pipe is required upstream,  $15D$  to  $40D$ , depending on pipe conditions ( $D$ : nominal bore of the flowmeter), and downstream,  $5D$ .

Cross-sectional view of a vortex flowmeter



- 1. Transmitter
- 2. Gasket
- 3. Sensing Element
- 4. Vortex Shedder
- 5. Output Signal Indicator or Totalizer (Option)
- 6. Sensor Signal Wire

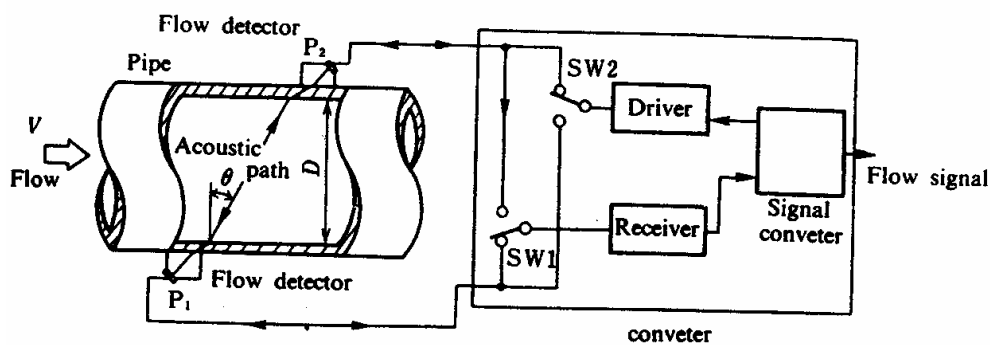
**3. Sensing Element**



## Ultrasonic flowmeters

### Working principle

With ultrasonic flowmeters, ultrasonic waves are generated in the fluid from outside the pipeline, and the flow rate is determined by detecting externally the change in the transmitted waves or the reflected waves caused by the flow velocity. At this time, they are mainly used to measure the flow of water. There are two typical methods in practical use, classified broadly by the principle of measurement they employ. One, called the transit time differential method, obtains the flow rate by measuring the difference in arrival times of ultrasonic pulses between detectors set facing each other obliquely to the pipe axis on the outside pipe walls. The other method uses the Doppler effect. By measuring the difference in frequencies of the transmitted waves and those reflected back from foreign objects in the fluid, the velocity of those objects, and thus the velocity of the fluid, can be determined.



Ultrasonic flowmeter utilizes TTD method.

### Characteristics of ultrasonic flowmeters

- (1) The detectors are attached to the outside walls of the pipe, requiring no alterations of the existing piping. Furthermore, they allow measurement of the flow rate without stopping the flow.
- (2) The detectors do not come in contact with the fluid, so there is no concern for corrosion or material adhering to them. Also, there is nothing to obstruct the flow, so no pressure loss results from their use.
- (3) Disturbances in the flow velocity distribution affects measurement accuracy, so an appropriate length of straight pipe is required upstream and downstream of the place where the detectors are installed.
- (4) In process industries, flowmeters for use with liquids mainly measure water flows. Based on the particular characteristics of their respective measurement principles, use of the two types of ultrasonic flowmeters is differentiated according to the characteristics of the fluid measured in the following way.
  - a. *Transit time differential flowmeters*: Mainly clean water, water for industrial use, raw water for water purifying plants, water for agricultural use, and other types of clean water.
  - b. *Doppler flowmeters*: Mainly drain water, factory effluent, and other such dirty water which contains foreign particles.



## (2) Comparison in Accordance with Measuring Objects.

Table 2-2 shows applicability of various flowmeters to flow objectives.

Table 2.2 Comparison of Flowmeters According to Various Flow Objects.

Type of flowmeter		Measuring objects												
		Fresh water	Sewage	Corrosive fluid	Abrasive slurry	Fibrous slurry	Viscous fluid	Low flow speed fluid	High temperature fluid	Low temperature fluid	High pressure fluid	Oil	Steam	Gases
Vortex flowmeter		⊙	△	○	△	△	△	△	⊙	⊙	⊙	△	⊙	⊙
Electromagnetic flowmeter ADMAG	Teflon lining	⊙	⊙	⊙	○	⊙	⊙	⊙	○	×	△	×	×	×
	Rubber lining	⊙	⊙	△	⊙	⊙	⊙	⊙	×	×	△	×	×	×
	Ceramic lining	⊙	⊙	⊙	⊙	⊙	⊙	⊙	○	×	○	×	×	×
Differential pressure type flowmeter UNI Δ	Orifice plate	⊙	△	○	△	×	△	×	⊙	⊙	○	○	⊙	⊙
	Venturi tube	⊙	○	△	△	△	△	△	△	△	○	△	⊙	⊙
Ultrasonic flowmeter YEWSONIC	Transit time difference	⊙	△	△	×	×	△	△	×	△	○	△	△	△
	Doppler effect	×	⊙	△	△	△	△	△	×	×	○	△	×	×
Variable area flowmeter		⊙	○	○	×	×	△	△	○	×	△	○	○	⊙
Positive displacement flowmeter		⊙	×	△	×	×	⊙	△	△	○	△	⊙	△	△
Mass flowmeter	Thermal type	×	×	×	×	×	×	△	×	×	△	×	×	⊙
	Coriolis' force type	⊙	○	×	○	○	○	△	△	○	△	○	△	△
Turbine flowmeter		⊙	×	△	×	×	△	△	△	○	△	○	△	○

(⊙ : Suitable, ○ : Normally applicable, △ : Applicable under a certain condition, × : Not applicable)

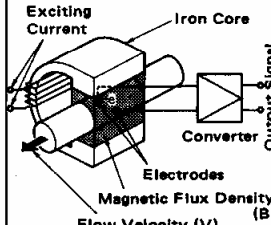
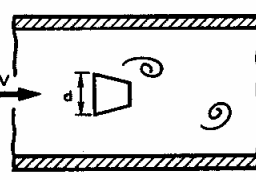
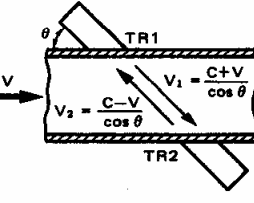
2. SELECTING CONDITIONS

(1) Comparison of Measuring Principles

Table 2.1 compares the fundamental features of various flow measurement principles.

2.1 Comparisons between Several Flowmeter Types

Table 2-1. Comparison of Flowmeters According to Measuring Principles.

Type of flowmeters		Electromagnetic flowmeter	Vortex flowmeter	Ultrasonic flowmeter
Principle or measuring method		 <p>The e.m.f (e) is proportional to (<math>\propto</math>) the flow velocity due to Faraday's law of electromagnetic induction.</p> $Q \propto e = B \cdot V \cdot D$ <p>(D: Diameter of Pipe)</p>	 <p>Vortices are generated, whose generation frequency (f) is proportional to (<math>\propto</math>) the flow velocity on the downstream side of the vortex shedder.</p> $Q \propto f = K \cdot V/d$	 <p>Difference of ultrasonic wave propagation times is utilized.</p> $Q \propto V = \frac{C \cos \theta}{2} \left( \frac{1}{T_1} - \frac{1}{T_2} \right)$ <p>C: Sound Velocity</p>
Corresponding YOKOGAWA product		ADMAG	YEWFLOW	YEWSONIC
Process conditions	Measurable fluid	Conductive liquids	Gases, liquids and steam	Liquids (Gases are measurable in principle)
	Fluid pressure	40 kg/cm <sup>2</sup> Max. (Flange rating) 570 PSIG Max. (Flange rating)	300kg/cm <sup>2</sup> Max. (Flange rating) 4270PSIG Max. (Flange rating)	Same as in user's piping
	Fluid temperature	- 10 to 160°C 14 to 320°F	- 200 to 400°C - 328 to 752°F	0 to 60°C 32 to 140°F
	Rangeability	$\infty$	1:20	$\infty$
Performance	Required straight run of pipe	Upstream run 5D Downstream run 2D	Upstream run 10D Downstream run 5D	Upstream run 10D Downstream run 5D
	Accuracy	$\pm 0.5\%$ (of Rate)	$\pm 1\%$ (of Rate)	$\pm 1\%$ (of Span)
	Moving parts	None	None	None
	Pressure loss	Negligible	Low	Negligible
	Change of measuring span	Simple	Simple	Simple
Features	Available diameter	2.5 to 2800mm 0.1 to 106 inch	15 to 300 mm 0.5 to 12 inch	150 to 3000mm 6 to 120 inch (Outer diameter of piping)
	Effect of Viscosity	None	Rangeability varies	Slight effects on accuracy
	Reverse flow measurement	Yes	Not recommended	Yes
Wetted part material		Pipe lining: Fluorocarbon resin, Polyurethane rubber, Ceramic Electrode: 316L Stainless steel, Hastelloy C, Tantalum, Titanium, Platinum	Stainless steel (1/2"-8") Hastelloy C (1"-2") Carbon steel (6"-8")	Not wetted

TI 1E6A0-07E

## Thermocouple Temperature Measurement

Thermocouple: The junction of two dissimilar metals which has a voltage output proportional to the difference in temperature between the hot junction and the lead wires (cold junction).

### Measurement principle

As shown in Fig. 3.12, if two dissimilar metals, A and B, are joined at point n, and are left free at the other end, point m, the difference in temperature at the two points ( $T_2 - T_1$ ) generates the electromotive force  $E_{AB}(T_2, T_1)$ . The metals A and B are called a thermocouple, point m is called a cold junction, point n is called a hot junction, and the electromotive force  $E_{AB}(T_2, T_1)$  is called the thermoelectromotive force. Because there is a fixed relationship between the thermocouple materials, the cold junction temperature, the hot junction temperature, and the thermoelectromotive force, for a given thermocouple and a fixed cold junction temperature, the hot junction temperature can be determined by measuring the thermoelectromotive force.

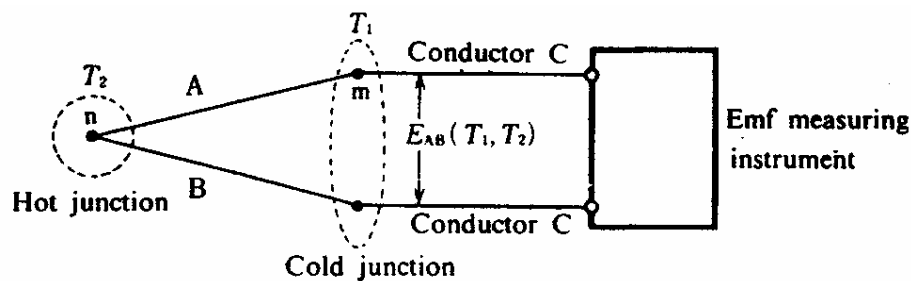


Figure 3.12

To measure the thermoelectromotive force with almost no current flow, it is necessary to use a measuring instrument with a high input resistance.

### Types of thermocouples

There are many kinds of thermocouples suited for various uses. JIS C1602 defines seven types. Thermocouples are broadly classified into noble metal thermocouples (type codes B, R, and S), and base metal thermocouples (type codes K, E, J, and T). The noble metal thermocouples generally have excellent resistance to corrosion, but produce small thermoelectromotive forces compared with the base metal types.

Practical use in thermocouples requires the following qualities.

- (1) Good corrosion resistance, robustness against gases, etc.
- (2) Large thermoelectromotive force.
- (3) Good heat resistance and ability to maintain mechanical strength at high temperatures.
- (4) Stable thermoelectromotive force even over long periods of use, with small thermocouple loss.

- (5) Interchangeability: thermocouples of the same type normally have the same characteristics.

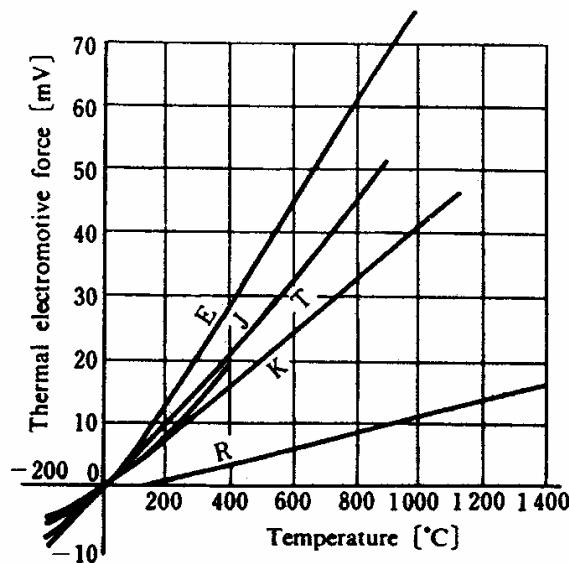


Figure 3.15 shows the thermoelectromotive force for each type of thermocouple.

**Thermocouples with protective tube**

The ends of two thermocouple element wires are joined by gas welding, arc welding, resistance welding and so on, to form the hot junction. In this state it is called a bare thermocouple. To insulate the two element wires electrically, they are led into an insulating tube as shown in Fig. 3.16.

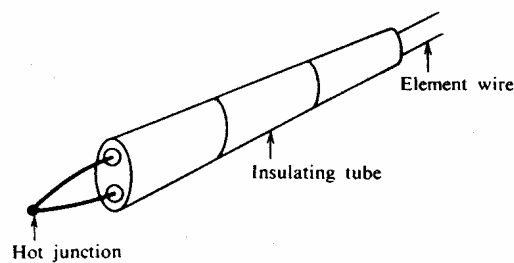


Figure 3.16 – Structure of thermocouple with insulating tube

At this stage it is called a thermocouple with insulating tube. Because it is susceptible to corrosion and mechanical damage, it is put into a protective metal or non-metal tube, and the two element wires are connected to a terminal at the head of the tube. Fig. 3.17 shows how the thermocouple with protective tube is constructed.

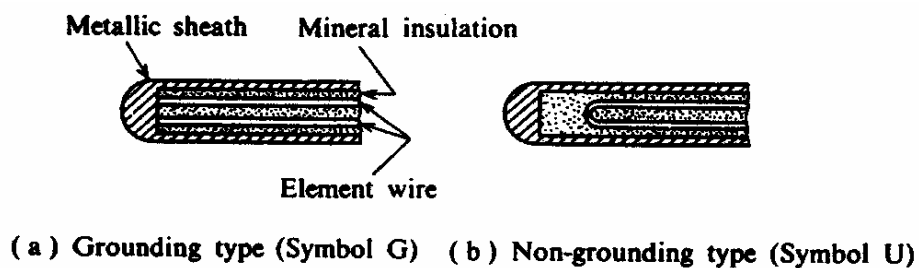


Figure 3.18 – Hot junction structure

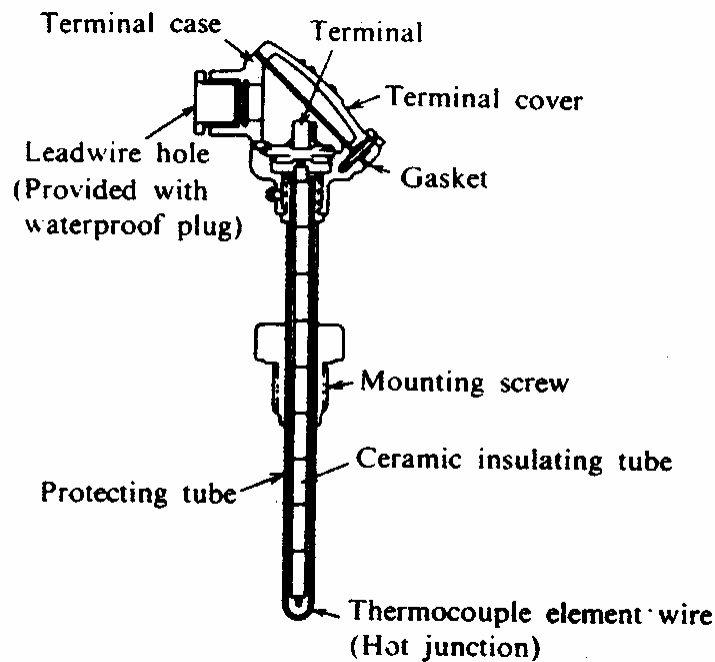


Figure 3.17 – Structure of thermocouple with protecting tube

### Sheathed thermocouples

In a sheathed thermocouple, the space between the element wires and the metal sheath is filled with a powdered inorganic insulator and sealed. It is then processed to produce a single-unit construction. JIS C1605 defines four types of sheathed thermocouples (type symbols SK, SE, SJ, and ST). The element wire materials of these thermocouples are the same as the corresponding K, E, J, and T thermocouples.

The metal sheath is made of either austenite stainless steel (symbol A), or Ni-Chrome heat resistant alloy (symbol B). The hot junction can be either the grounded type (symbol G) or the ungrounded type (symbol U) (Fig. 3.18). The overall unit can either have a terminal plate or not (Fig. 3.19). Table 3.3 lists the symbol, measured temperature range, accuracy class, tolerance, and normal operating temperature limits for each type of sheathed thermocouple.

Sheathed thermocouples have the following characteristics:

- (1) Fast response. The metal sheath has a small diameter and the wire elements are fine, so the heat capacity is small. Also, since the sheath is bonded to the insulating material, which is in turn bonded to the element wires, heat resistance is low. Thus the response to heat is exceptionally good, and the temperature of objects having low heat capacity can be measured.
- (2) Flexible: Because of the small outside diameter of the sheath, (1 mm to 8 mm) it can be curved to fit into small places.
- (3) Low mechanical strength: For measurement of fast flowing liquids, or when the sheath is installed horizontally, reinforcement such as a protective tube is needed.

- (4) Insulator deterioration: The insulating material (MgO) is highly hydrophilic. If it is not completely sealed, it will absorb moisture, causing deterioration of its insulating properties.

Features of base metal thermocouples (K, E, J, and T)

(a) *K-type (chromel-alumel)*

- (1) Can be used in an oxidizing environment
- (2) Deteriorates slowly in a reducing environment
- (3) Strong against metal vapors
- (4) Good linearity of thermoelectromotive force

(b) *E-type (chromel-constantan)*

- (1) Good resistance to corrosion and oxidation
- (2) Deteriorates slowly in a reducing environment
- (3) Large thermoelectromotive force
- (4) High electrical resistance
- (5) Little measurement lag

(c) *J-type (iron-constantan)*

- (1) Can be used in an reducing environment
- (2) Relatively large thermoelectromotive force; good linearity
- (3) Rusts easily
- (4) Quality is not consistent
- (5) Exhibits hysteresis thermoelectromotive force at high temperatures (800°C)

(d) *T-type (copper-constantan)*

- (1) Suited for use at low and extremely low temperatures
- (2) Suited for use in reducing environments
- (3) Large heat transfer error

## Resistance Temperature Detector (RTD)

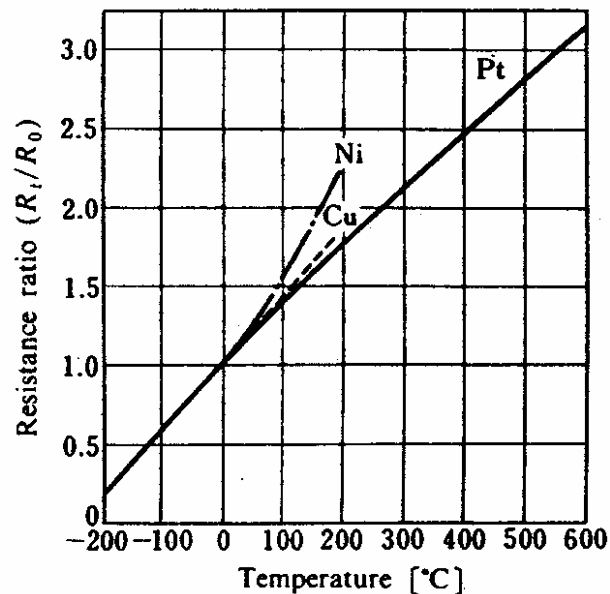
### Measurement principle and characteristics

Because there is a fixed relationship between the electrical resistance of a metal and temperature, it is possible to determine a temperature by measuring electrical resistance. Platinum (Pt), nickel (Ni), and copper (Cu) are used in this type of thermometer. The temperature and electrical resistance characteristics of these metals are shown in Fig. 3.20.

Thermometer materials must satisfy the following conditions.

- (1) The relationship between temperature and electrical resistance must be continuous and have unique values within the working temperature range.
- (2) There is no change in the resistance over time or according to other factors.
- (3) There is no hysteresis effect in the relationship between resistance and temperature.
- (4) The material is resistant to corrosion, thus stable.

- (5) The material has a high intrinsic resistance and resistance temperature coefficient.
- (6) Interchangeable.
- (7) Easily worked.



**Fig. 3 - 20 Temperature-resistance characteristics**

Platinum has the best combination of the above properties, and the platinum resistance temperature detector is the JIS standard. Its measuring range is from -200°C to 650°C (Pt100) or -200°C to 500°C (JPt100).

The resistance temperature measurement method has the following characteristics compared with the thermocouple method.

- (1) High sensitivity.
- (2) Stable over a long period of time when used in a low-vibration environment.
- (3) Response is slow because of its large size.
- (4) Has a low maximum working temperature.
- (5) Susceptible to shock and vibration because a fine resistance wire element is used.

When a current flows in a resistor, the voltage between the ends of the resistor is given by the following relationship, according to Ohm's law.

$$V = I R$$

In this equation,  $V$  represents voltage (V),  $I$  is current (A), and  $R$  is resistance ( $\Omega$ ). If  $I$  is fixed and  $V$  is measured, we can determine  $R$ , and thus measure the temperature of the resistance temperature detector.

### Resistance temperature detector with protective tube

A mica-insulated element inserted into a protective tube, with internal wires connected, is called a resistance temperature detector with protective tube. An internal wire material is

used which does not generate a thermoelectromotive force, and which does not oxidize or degenerate at the maximum working temperature. For low to medium temperature use, silver wire covered with fluorocarbon resin or a glass tube or for high temperature use, nickel wire covered with a porcelain tube, is use. For the external wiring, the 3-wire configuration is mostly used. Moisture entering the protective tube degrades the insulation, so for low temperature use, the protective tube is packed with paraffin or filled with dry air and tightly sealed.

Figure 3.25 shows the construction of a resistance temperature detector with protective tube. JIS C1604 specifies protective tubes with outside diameters between 3.2 mm and 15 mm, and lengths between 250 and 1000 mm.

### Other resistance temperature detectors

Other than platinum, other metals such as nickle or copper are used for the resistance material. Nickel is less expensive than platinum, and its temperature coefficient is 0.6% at room temperature. However, because the thermal characteristics vary with the element material, the temperature coefficient is adjusted to the standard value by combining the material with constantan wire or other such material. The working temperature range is -50°C to 300°C.

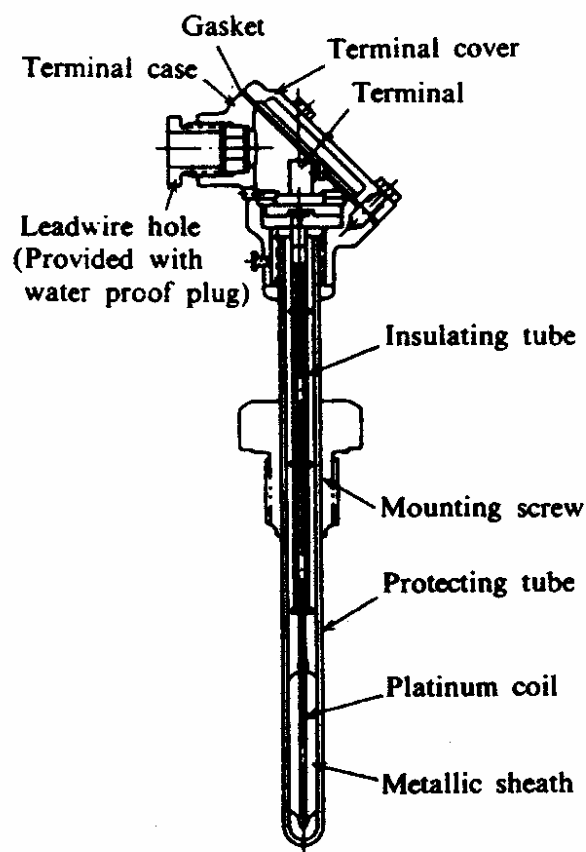


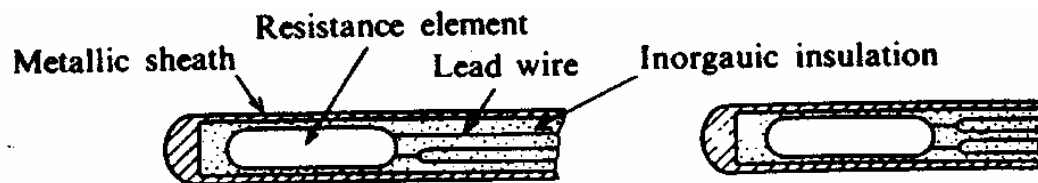
Figure 3.25 – RTD with protecting tube.

Copper wire of high purity can be obtained, and its temperature characteristics are uniform. Furthermore, it has better accuracy, linearity and interchangeability than nickel. However, because its intrinsic, resistance is low, a long coil is needed. In addition, at around 250°C oxidation begins to change its resistance. Thus the working temperature range is 4°C to 120°C.



### Sheathed resistance bulbs

Sheathed resistance bulbs are specified in JIS C1606. The space inside the sheath and between the resistance element wires is filled with a powdered inorganic insulator and processed to produce a single-unit construction, and platinum is used in the resistance temperature detector. Ordinary stainless steel having sufficient heat resistance and durability to prevent penetration by environmental elements is used for the metal sheath. The inorganic insulation protects the resistance element, the internal wires and the metal sheath. This material must be stable in the appropriate temperature range, and must not affect electrical characteristics. Magnesium oxide (MgO) is often used. The internal wire must not generate a thermoelectromotive force, and must not be susceptible to problems arising from evaporation or oxidation. Thus nickel is largely used. The 3-wire and 4-wire configurations of internal wires are illustrated in Fig. 3.26.



**Fig. 3 • 26 Internal wires**

The resistance element either a ceramic sealed element or a glass sealed element. These elements are themselves hermetically sealed, and buried in the inorganic insulation inside the sheath. Thus they are not affected by the environment. They also have fast response and are strong against mechanical vibration.

### Thermistor Temperature Measurement

*Thermistor:* A temperature-sensing element composed of sintered semiconductor material which exhibits a large change in resistance proportional to a small change in temperature coefficients.

Thermistors are sintered bodies of the oxides of metals such as manganese, nickel, and cobalt, whose resistance varies with temperature. The resistance-temperature coefficient of thermistors is negative; an increase in temperature lowers the electrical resistance.

Compared with platinum resistance temperature detectors, thermistors, have the following characteristics:

- (1) Large electrical resistance
- (2) High sensitivity
- (3) Poor linearity of resistance
- (4) Fast response due to small size

### Measurement principle

The resistance  $R_T$ , of a thermistor at temperature  $T$  is represented theoretically as

$$R_T = R_a e^{B(1/T - 1/T_a)} \quad (3.3)$$

Where  $R_a$  is the resistance ( $\Omega$ ) at temperature  $T_a$ , and  $B$  is the thermistor constant (K).

If  $\alpha$  is taken as the thermistor temperature coefficient, then because  $\alpha = (1/R_T)(dR_T/dT)$ , and from Eq.(3.3),

$$\alpha = \frac{1}{R_T} \frac{dR_T}{dT} = -\frac{B}{T^2} \quad (K^{-1}) \quad (3.4)$$

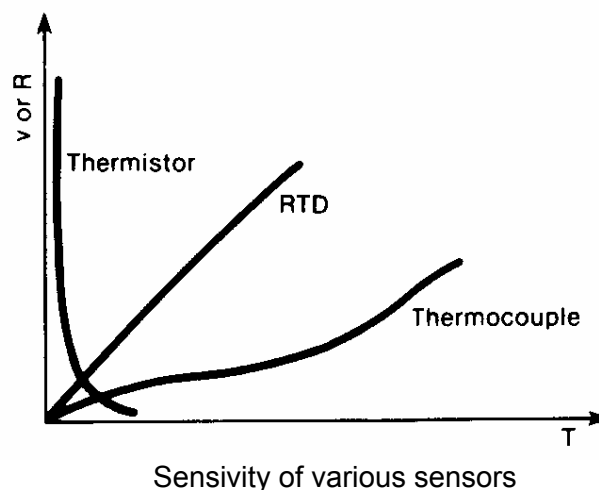
From Eq.(3.4), we see that thermistor sensitivity varies greatly with the temperature. The value of B is usually 3000 K to 5000 K, but actually depends on temperature. The value of  $\alpha$  is as large as  $-3\%/^{\circ}\text{C}$  to  $-6\%/^{\circ}\text{C}$  at room temperature.

### Excerpt from OMEGA's Temperature Handbook Vol. 29

Like the RTD, the thermistor is also a temperature sensitive resistor. While the thermocouple is the most versatile temperature transducer and the RTD is the most stable, the word that best describes the thermistor is sensitive. Of the three major categories of sensors, the thermistor exhibits by far the largest parameter change with temperature.

Thermistors are generally composed of semiconductor materials. Although positive temperature coefficient units are available, most thermistors have a negative temperature coefficient (TC); that is, their resistance decreases with increasing temperature. The negative temperature coefficient can be as large as several percent per degree Celsius, allowing the thermistor circuit to detect minute changes in temperature which could not be observed with an RTD or thermocouple circuit.

The price we pay for this increased sensitivity is loss of linearity. The thermistor is an extremely non-linear device which is highly dependent upon process parameters. Consequently, manufacturers have not standardized thermistor curves to the extent that RTD and thermocouple curves have been standardized.



An individual thermistor curve can be very closely approximated through use of the Steinhart-Hart equation's

$$1/T = A + B (\ln R) + C (\ln R)^3$$

where,  $T$  = Degrees Kelvin,  $R$  = Resistance of the thermistor , and  $A,B,C$  = curve-fitting constants.

$A$ ,  $B$ , and  $C$  are found by selecting three data points on the published data curve and solving the three simultaneous equations. When the data points are chosen to span no more than  $100^{\circ}\text{C}$  within the nominal center of the thermistor's temperature range, this equation approaches a rather remarkable  $\pm 0.02^{\circ}\text{C}$  curve fit. Somewhat faster computer execution time is achieved through a simpler equation:

$$T = \frac{B}{\ln R - A} - C$$

where  $A$ ,  $B$ , and  $C$  are again found by selecting three  $(R,T)$  data points and solving the three resultant simultaneous equations. This equation must be applied over a narrower temperature range in order to approach the accuracy of the Steinhart-Hart equation.

### Disadvantages of thermistors

Because they are semiconductors, thermistors are more susceptible to permanent decalibration at high temperatures than are RTD's or thermocouples. The use of thermistors is generally limited to a few hundred degrees Celsius and manufacturers warn that extended exposures even well below maximum operating limits will cause the thermistor to drift out of its specified tolerance.

Thermistors can be made very small which means they will respond quickly to temperature changes. It also means that their small thermal mass makes them especially susceptible to self-heating errors. Thermistors are a good deal more fragile than RTD's or thermocouples and they must be carefully mounted to avoid crushing or bond separation.

*Special Acknowledgement to Tn. Hj. Safarudin Kamaruddin for giving this book.*