KMM4631

PROCESS DYNAMICS AND CONTROL

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CONTROL INSTRUMENTS
&
CONTROLLERS

History of Process Control

__Up to 1930s__:

Everything was mechanical or pneumatic.

__Up to 1980s__:

Control rooms with controllers, recorders, signals recorded on paper.

Analog signal systems.

__Today__:

Digital signal systems → Bytes

Computer-aided control.

Today

- ✓Computers are used to monitor the condition of the process. Signals and the status of the process are monitored on the computer screen.
- ✓Many signals are still transmitted in analog electronic form, but the use of digital buses and networks is increasing day by day. These systems provide much more calculation capability and enable on-line operation (while the process is running) based on the mathematical model of the process.
- ✓Despite all these changes, the basis of control system structures and control algorithms is the same as 30 years ago.

Signals:

Analog: Air pressure signal (3-15 psig)

Current signal (4-20 mA)

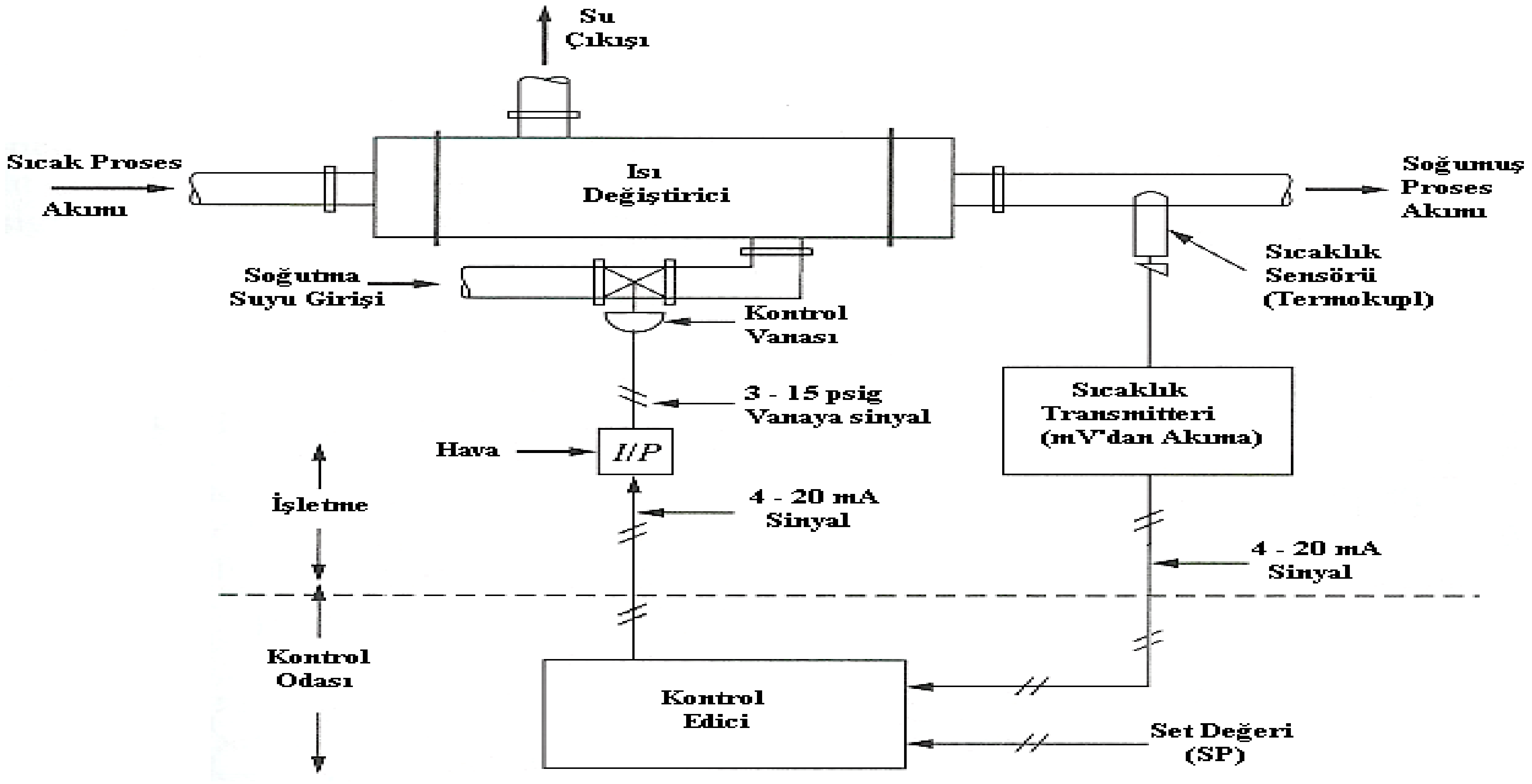
Voltage signal (0-10 V)

For instance, pneumatic valves convert signals between 4-20 mA to signals between 3-15 psig.

Digital: Bytes

As discussed earlier, the feedback control loop includes:

- A **sensor** to detect process variables;
- A **transmitter** to convert the measurement signal to an equivalent signal (an air pressure signal in pneumatic systems or a current signal in analog electronic systems),
- A **controller** that compares the process signal with a desired set point and generates a suitable controller output signal, and
- Adjusting according to the signal generated by the controller, It consists of a **final control element** that modifies the variable. Usually the last control element is an air operated control **valve** that opens and closes to change the flow rate of the set current.



The figure shows a diagram of a process controlled by feedback control.

- Sensor, transmitter and control valve are physically located on the process (in operation).
- The controller is usually in a remote control room, on a panel or on a computer.
- The current signal transfer from the transmitter to the controller and from the controller to the final control element or the connection between the units is provided by cables.

- Control parts used in chemical and petroleum plants are analog or digital.
- Analog signals use an air pressure signal (3 to 15 psig) or a current / voltage signal (4-20 mA or 0-10 V DC).
- The parts are powered by 1.4 bar air pressure or 24 V DC electricity.
- Pneumatic systems send air pressure through small pipes. Analog electronic systems use cables. Because many valves still operate with air pressure, flow signals are often converted into air pressure.
- An "I / P" (current to pressure) converter is used to convert signals between 4-20 mA into signals of 3-15 psig.

- There is a manual / automatic on-off assembly (or software) in the control room. When starting up or in abnormal situations, the plant operator or engineer may want to adjust the control valve instead of the controller. The power button is usually on the control panel or computer. In the "manual" position, the operator or engineer can adjust the valve as desired. In the automatic position, the valve is adjusted directly by controlling correction commands.

Each controller must do the following:

a) It should determine the value of the control variable, (the signal from the transmitter) (CV or PV)

b) Determine the set value signal, (SP or SV)

c) Determine the value of the signal to be sent to the valve, (Controller output) (CO)

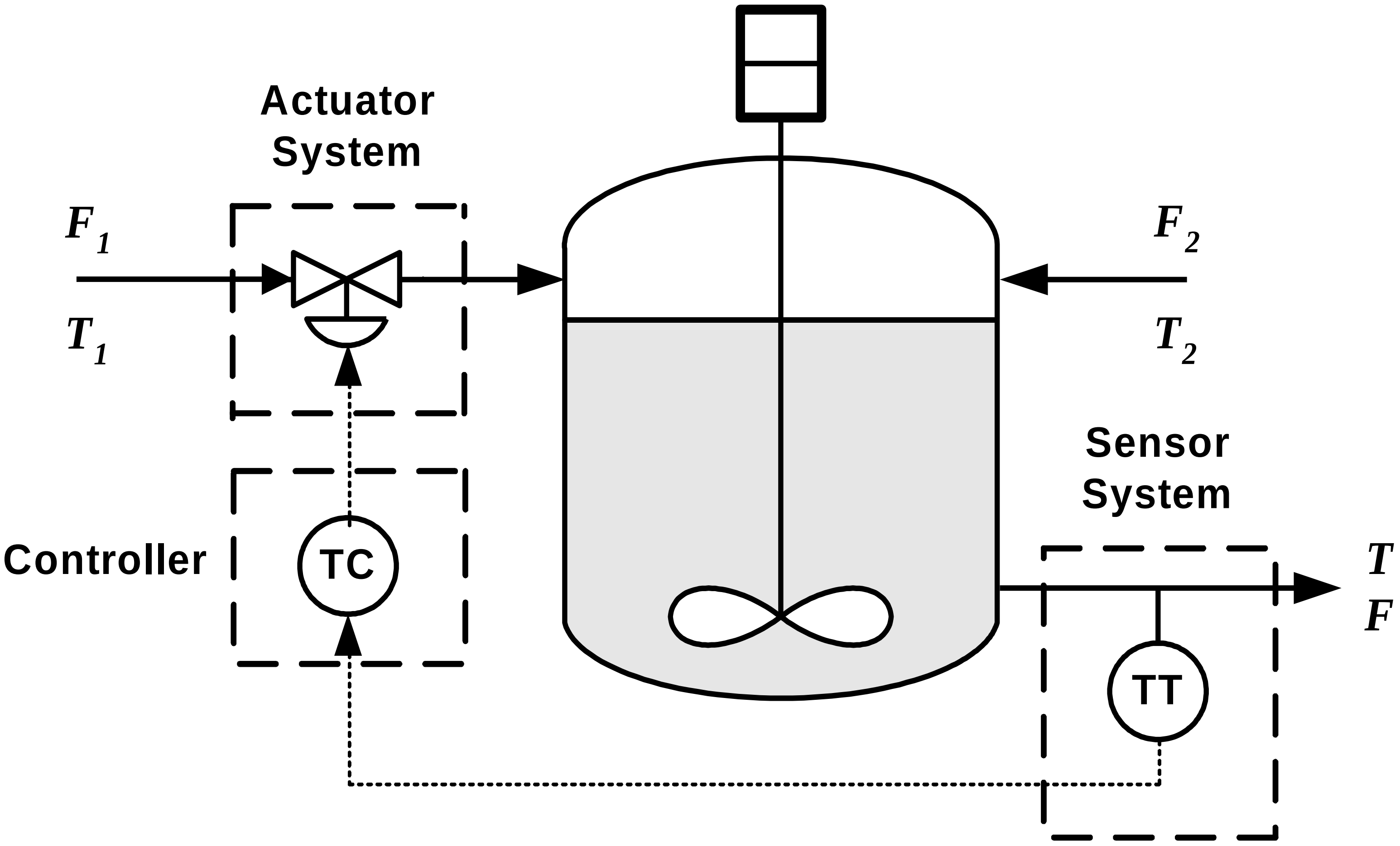
d) Have Manual / Automatic buttons,

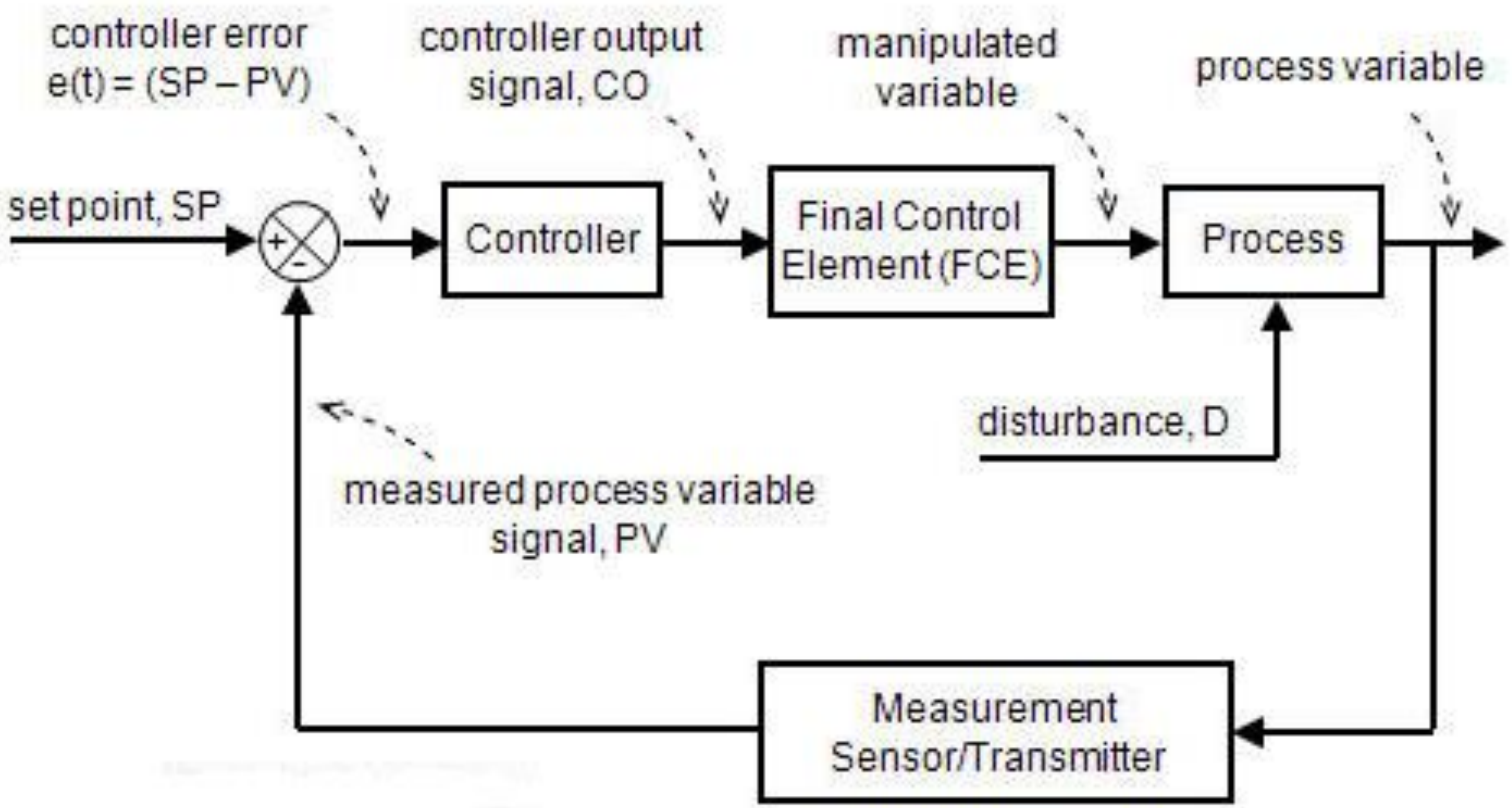
e) It should have a button to enter the set value while the controller is automatic,

f) When the controller is in manual, there should be a button to send a signal to the valve.

Control Instruments

Control Diagram of a Typical Control Loop




controller error
e(t) = (SP – PV)
controller output
signal, CO
manipulated
variable
process variable
set point, SP
+
-
Controller
Final Control
Element (FCE)
Process
disturbance, D
measured process variable
signal, PV
Measurement
Sensor/Transmitter

In simple words:

- **Measure (PV)**
- **Evaluate (SP-PV)**
- **Decision (by controller)**
- **Action (by FCE)**

The Structure of Control Systems

1. **A SENSOR** (the measurement device, to determine the process variables)
2. **A TRANSMITTER** (to convert the measurement signal to an equivalent signal)
3. **A CONTROLLER** (to compare the process signal with the set point, and accordingly to produce a controller output signal)
4. **A FINAL CONTROL ELEMENT** (-usually a control valve- to change the manipulated variable with respect to the signal generated by the controller)

Controller

The controller is a device, which monitors and affects the operational condition of a dynamic system. In a process control system the controller is not necessarily limited to one variable, but can measure and control many variables.

Measuring element

In order to make the controlled variable accessible to the controller, it must be measured by a measuring element or primary sensing element (sensor, transducer) and converted from a physical variable to an electrical signal that can be processed by the controller as an input.

The control loop starts with the measurement. An assembly has been developed to measure many variables online. The most important variables in chemical engineering processes; **flow rate, temperature, pressure and level**. There are also measurement tools to measure variables such as pH, density, viscosity, infrared and ultraviolet absorption, and refractive index.

If the measuring instrument used measures the change in the variable with a delay, the dynamic model of that measuring instrument or the transfer function must be removed. If measurement is taking place without delay, the transfer function of the meter will only equal the gain value.

Sensors:

It is a device that can detect physical variables, such as temperature, light intensity, or motion, and have the ability to give a measurable output that varies in relation to the amplitude of the physical variable.

- Temperature sensors
- Flow rate sensors
- Level sensors
- Pressure sensors
- Composition analyzers

Temperature

Thermocouples consist of two wire legs made from different metals. The wires legs are welded together at one end, creating a junction. This junction is where the temperature is measured.

There are many types of thermocouples, each with its own unique characteristics in terms of temperature range, durability, vibration resistance, chemical resistance, and application compatibility.

Type J, K, T, & E are “Base Metal” thermocouples, the most common types of thermocouples.

Type R, S, and B thermocouples are “Noble Metal” thermocouples, which are used in high temperature applications

In the table, thermocouples made of various metal and metal alloys, the measuring range and the μV electrical signal generated per unit °C are given. The control engineer should choose a thermocouple according to the temperature range to be measured.

ELEMAN TELİ	DIN 43710 ve IEC 584	SICAKLIK ARALIĞI		İÇERDİĞİ ELEMANLAR	DUYARLILIK
Cu-Const	T	-200° C	+300° C	Bakır-Konstantan	~43 μV/°C
Fe-Konst	J	-200° C	+800° C	Demir-Konsantan	~52 μV/°C
Cr-Al	K	-200° C	+1200° C	Kromel-Alümel	41 μV/°C
NiCr-Ni	K	-200° C	+1200° C	NikelKrom-Nikel	41 μV/°C
Cr-Const	E	-200° C	+1200° C	Kromel-Konstantan	68 μV/°C
Nikrosil-Nisil	N	0° C	+1200° C	NikelKrom-Silikon-Nikelsilikon Magnezyum	39 μV/°C
Pt%10Rh-Pt	S	0° C	+1500° C	Platin Rodyum-Platin (%10)	10 μV/°C
Pt%13Rh-Pt	R	0° C	+1600° C	Platin Rodyum-Platin (%13)	10 μV/°C
Pt%18Rh-Pt	B	0° C	+1800° C	Platin Rodyum-Platin (%13)	
Tn-Tn%26Re	W	0° C	+2000° C	Tungten-Tungsten%26Renyum	

The dynamic response of many sensors is generally much faster than the dynamic behavior of the process itself. The time constant of a temperature gauge and a thick thermocouple housing can be 30 seconds or more.

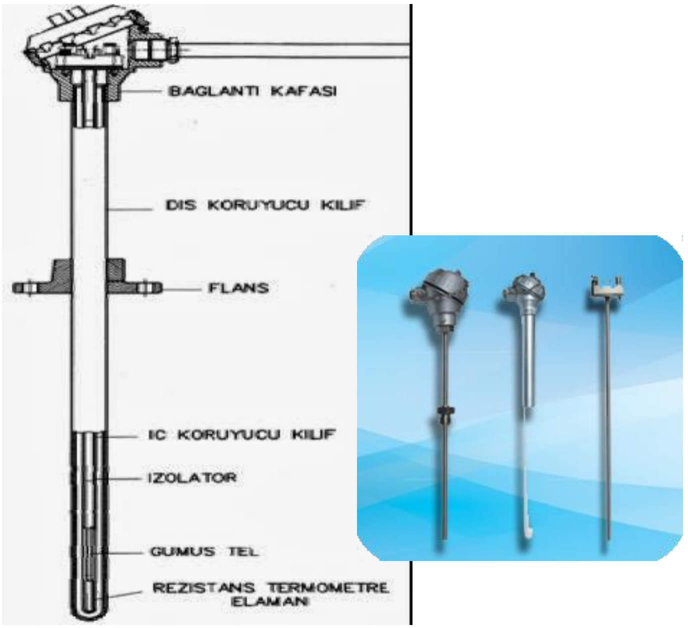
Thermocouples are produced with metal sheaths made of various alloys according to the corrosive conditions, mechanical wear, chemical and physical abrasive properties of the process in which they will be used. Thermocouples to be used at extremely high temperatures are covered with porous or non-porous ceramic sheaths against thermal shocks. If the thermocouple is covered with polymer or other material, the response time may take several minutes. Since this situation affects the control performance, the dynamic model of the thermocouple should be created and included in the control loop dynamics.

$$\boxed{G_s(s) = \frac{K_s}{\tau_s s + 1} = \frac{16/90 \ mA/°C}{\tau_s s + 1}}$$

Full-bulb temperature meters are also widely used. An inert gas is present in a constant volume system. A change in process temperature causes a pressure increase on the gas side. Where sensitive temperature measurement is required, resistance thermometers are used. The principle of use is that the electrical resistance of the wires changes as the temperature changes.

Full-bulb temperature meter

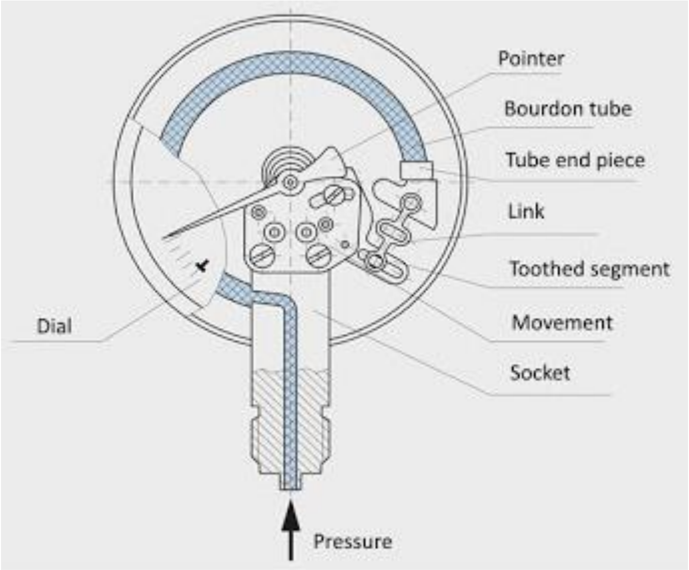
Infrared thermometer



Resistance thermometer

Pressure

In the past, mechanically operated **Bourdon tubes, bellows and diaphragms** were used to detect pressure and pressure differences. The pressure force in the process would be balanced by the action of a spring, and the position of the spring would correspond to the process pressure.



Bourdon tubes

Diaphragm pressure meter

New generation pressure meters are manufactured with diaphragm and can produce instantaneous signal. It is easy to use and is sufficient to be installed where the measurement will be taken.

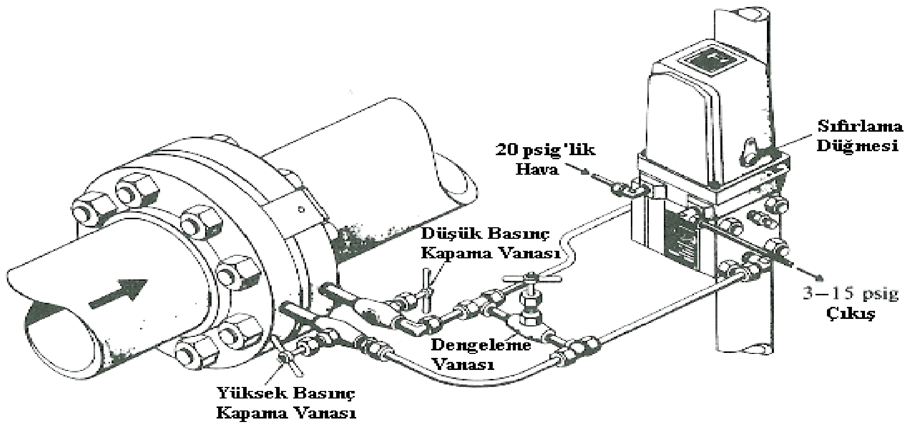
Pressure Transmitters

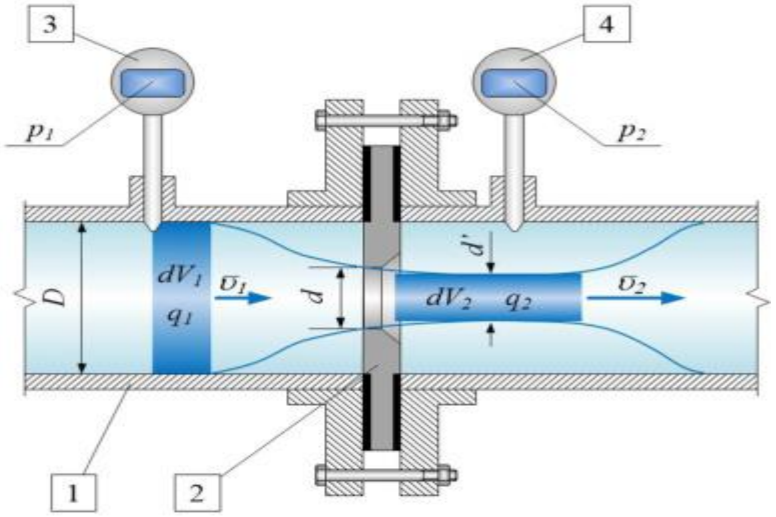
Flow Rate

The most commonly used type of flow rate sensor is **orifice plates**.

In order to be measured correctly, the pipe must be straight before the orifice is installed. For control purposes, it is not necessary to know the exact value of the flow, but the changes in the flow rate should be known.

Signals from flow rate measurements are often noisy due to oscillations around the actual value caused by turbulent flow. Such signals must be passed through the filter (an electronic device) before being sent to the controller.



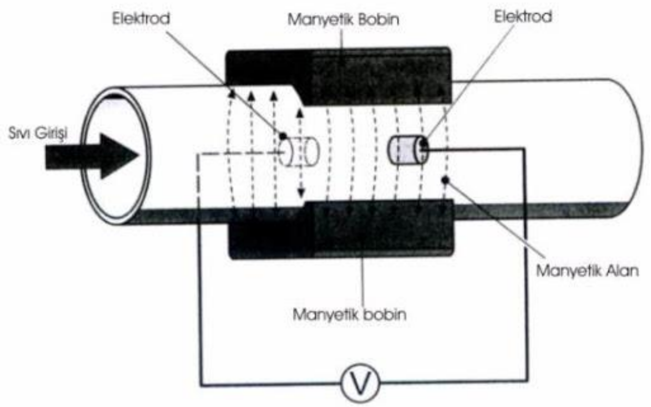


Turbine meters are also widely used. They are very expensive, but provide a more accurate flow measurement.

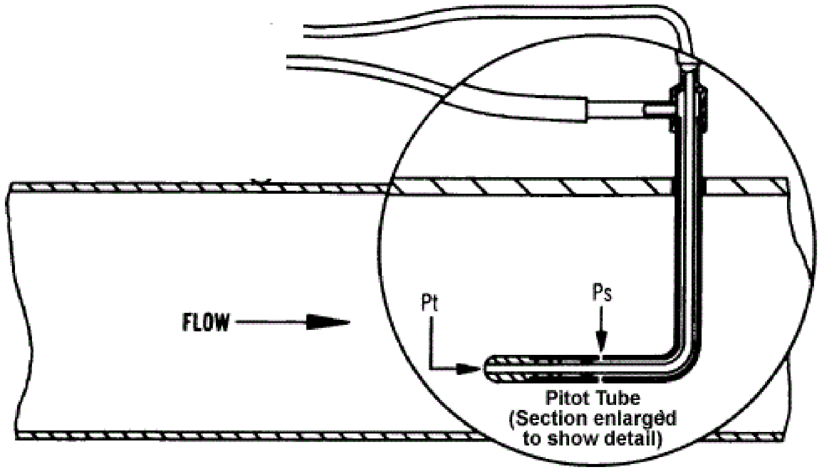
Other types of flowmeters include **sonic flowmeters, magnetic flowmeters, rotameters, and pitot tubes**.

Sonic flowmeters

Magnetic flowmeters



Rotameter



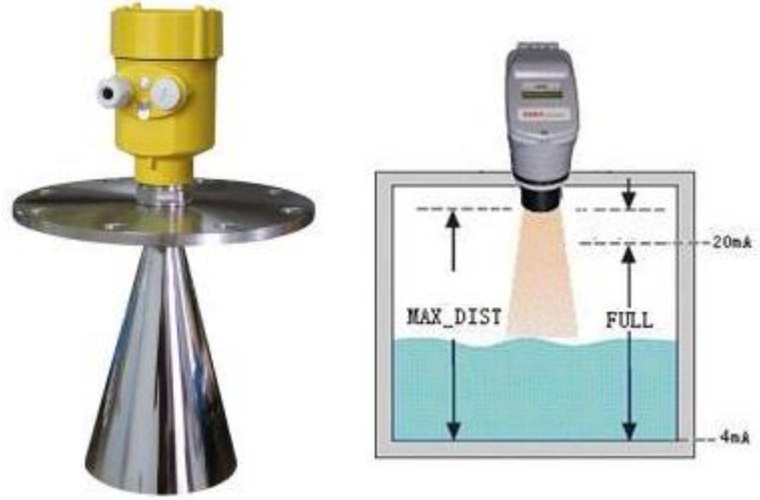
Pitot tubes

Fluid Level

It is possible to measure the fluid level in many ways. In principle, it is possible to measure the liquid level in three different ways:

1. Tracking the swimming position of an object lighter than the fluid (Buoy/Float),
2. Measuring the apparent weight of a heavy cylinder,
3. Measuring instruments based on the measurement of the hydrostatic pressure of the liquid level have been developed.

Float level meter



Ultrasonic level meter

Hydrostatic
level meter

Composition Measurement

Some components can be detected at low concentrations using sensors that have been designed to pick up that component.

- Examples: O_2, CO, H_2S, H_2
- Component sensors are often sensitive to other components, so check carefully with vendor to make sure the device is rated for the application.

More detailed composition can be measured by on-line GC methods.

- TCD: thermal conductivity detector
- FID: flame ionization detector
- Response can be slow (5 to 30 minutes), particularly if a long column is used.

Online NIR can be used in some cases.

Composition is often inferred from other properties.

- Boiling point
- Conductivity

pH and Conductivity Meter

Density and Viscosity Meter

Portable Gas Chromatograph for gas composition measurement

Temperature	Flow	Pressure	Level	Composition
Thermocouple	Orifice	Liquid column	Float-activated	Gas-liquid chromatography (GLC)
Resistance temperature detector (RTD)	Venturi	Elastic element	—chain gauge, lever	Mass spectrometry (MS)
Filled-system thermometer	Rotameter	—bourdon tube	—magnetically coupled	Magnetic resonance analysis (MRA)
Bimetal thermometer	Turbine	—bellows	Head devices	Infrared (IR) spectroscopy
Pyrometer	Vortex-shedding	—diaphragm	—bubble tube	Raman spectroscopy
—total radiation	Ultrasonic	Strain gauges	Electrical (conductivity)	Ultraviolet (UV) spectroscopy
—photoelectric	Magnetic	Piezoresistive transducers	Radiation	Thermal conductivity
—ratio	Thermal mass	Piezoelectric transducers	Radar	Refractive index (RI)
Laser	Coriolis	Optical fiber		Capacitance probe
Surface acoustic wave	Target			Surface acoustic wave
Semiconductor				Electrophoresis
				Electrochemical
				Paramagnetic
				Chemi/bioluminescence
				Tunable diode laser absorption

Language problem

Synchronization between sensor and controller, controller and FCE etc.

FCE should understand what Controller speaks

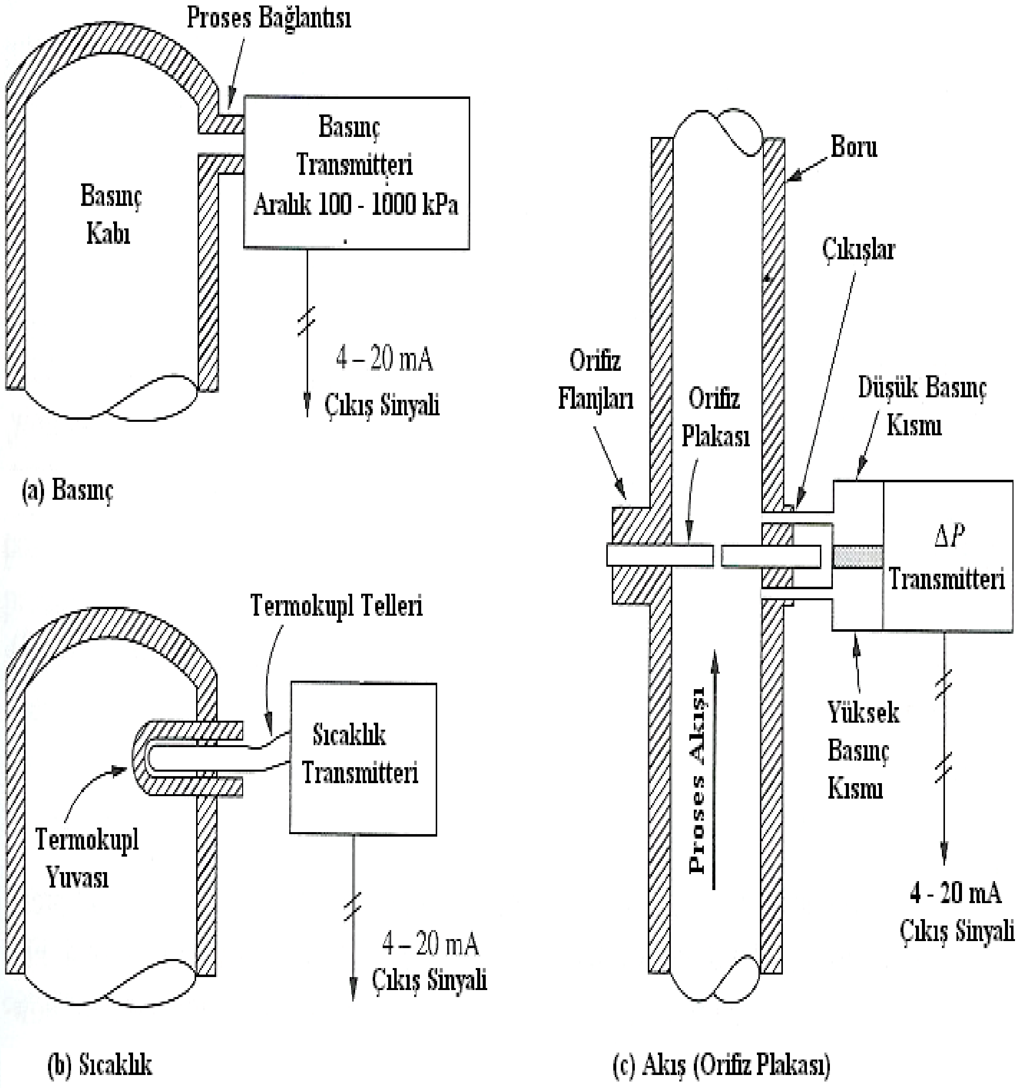
We need a translator (I/P, I/V, P/I)

Transmitters:

- Transmitters provide the link between the process and the control system. The goal of the transmitter is to convert the sensor signal (such as millivolt, mechanical motion, pressure difference) into a control signal (4-20 mA current).

- Consider a pressure transmitter like in Figure a. Suppose this special transmitter converts the process pressure in the vessel ranging from 100-1000 kPa to an output current signal varying between 4-20 mA.

- This is called the range of the transmitter. The span of the transmitter is 900 kPa. 0 value in the transmitter corresponds to 100 kPa. The transmitter has two adjustment knobs to alter the aperture or zero value to adjust. Therefore, if we change the value corresponding to zero to 200, the transmitter span will remain at 900 kPa while the transmitter range will be between 200-1100 kPa.



The dynamic response of many transmitters is generally faster than that of process and control valves. As a result, we can think that the transfer function of the transmitter is only equal to the gain value (a step change entering the transmitter suddenly comes out as a step function at the output). The gain of such a pressure transmitter would be as follows;

$$G_T(s) = K_T = \frac{20\text{ mA} - 4\text{ mA}}{1000\text{ kPa} - 100\text{ kPa}} = \frac{16\text{ mA}}{900\text{ kPa}}$$

Hence, the transmitter is simply a converter that converts process variables into an equivalent signal.

Figure b shows a temperature transmitter that receives the thermocouple input signal and converts the process temperature ranging from 10-100°C to a current signal of 4-20 mA.

The temperature transmitter has a range of 10-100°C, a span of 90°C and a zero value of 10°C. The temperature transmitter gain is as follows;

$$G_s(s) = K_s = \frac{20\text{ mA} - 4\text{ mA}}{100°\text{C} - 10°\text{C}} = \frac{16\text{ mA}}{90°\text{C}}$$

$$G_s(s) = \frac{K_s}{\tau_s s + 1} = \frac{16/90\ mA/°C}{\tau_s s + 1}$$

Instrument Selection Criteria

- Solid/gas/liquid, corrosive fluid
- Nature of signal, speed of response
- Accuracy, measurement range
- Costs
- Previous plant practice
- Available space
- Maintenance, reliability
- Materials of construction
- Invasive/non-invasive
- Environmental/safety (enclosures, fugitive emissions)

Final Control Element:

At the end of the control loop, **the connection with the process is provided by the last control element**. In almost all chemical engineering processes, the final control element is an **automatic control valve** that throttles or opens the flow adjustment variable. As seen in the schematic representation in the figure, many control valves have a plug mounted on a metal rod end.

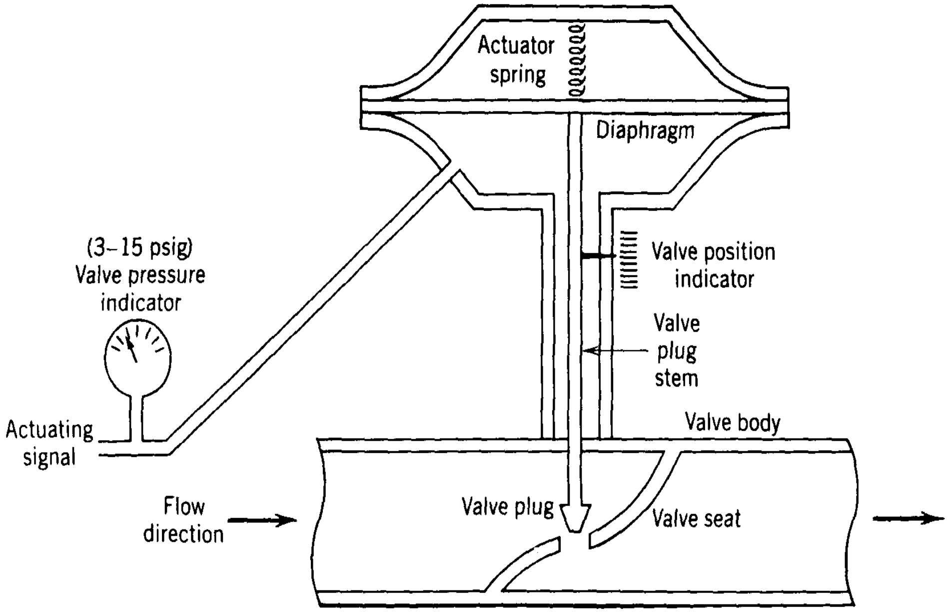


Figure 9.8. A pneumatic control valve.

When the metal rod moves up and down, the plug opens and closes the orifice opening. It is mounted on a diaphragm that moves with the change of air pressure acting on the plug.

Air pressure (pneumatic signal) is provided by the IP converter that converts the mA current from the controller into a pneumatic signal (3-15 psig). These converters function with an external supply of 20 psig (1.4 bar). Air pressure force is countered by a spring. Valves are designed not to be in a fully open or fully closed position. The action for process safety corresponds to the influence of the setting variable. For example, if the valve is adjusting steam or fuel, we want the flow to be cut off completely. If the valve adjusts the cooling water to a reactor, we want the flow to be maximized immediately.

Actuator or solenoid valves are used when the flow rate is low.

Actuators are electric or air pressure operated and sliding. They open or close the valve to the desired extent according to the incoming air pressure or analog signal (current).

Solenoid valves operate directly with 220 V electricity, and the way they work is completely magnetic. They are used in conjunction with an electrical relay to which the cables from the controller are connected. They usually work with a contact (on-off) output signal, and the valve is completely open when the signal arrives, completely closed when the signal is disconnected. Control or setting change is achieved by setting the stay times on or off. They are generally preferred in systems where a simple control will be performed.

Actuator

Solenoid valve

Current-pneumatic
(IP) converter

Controllers

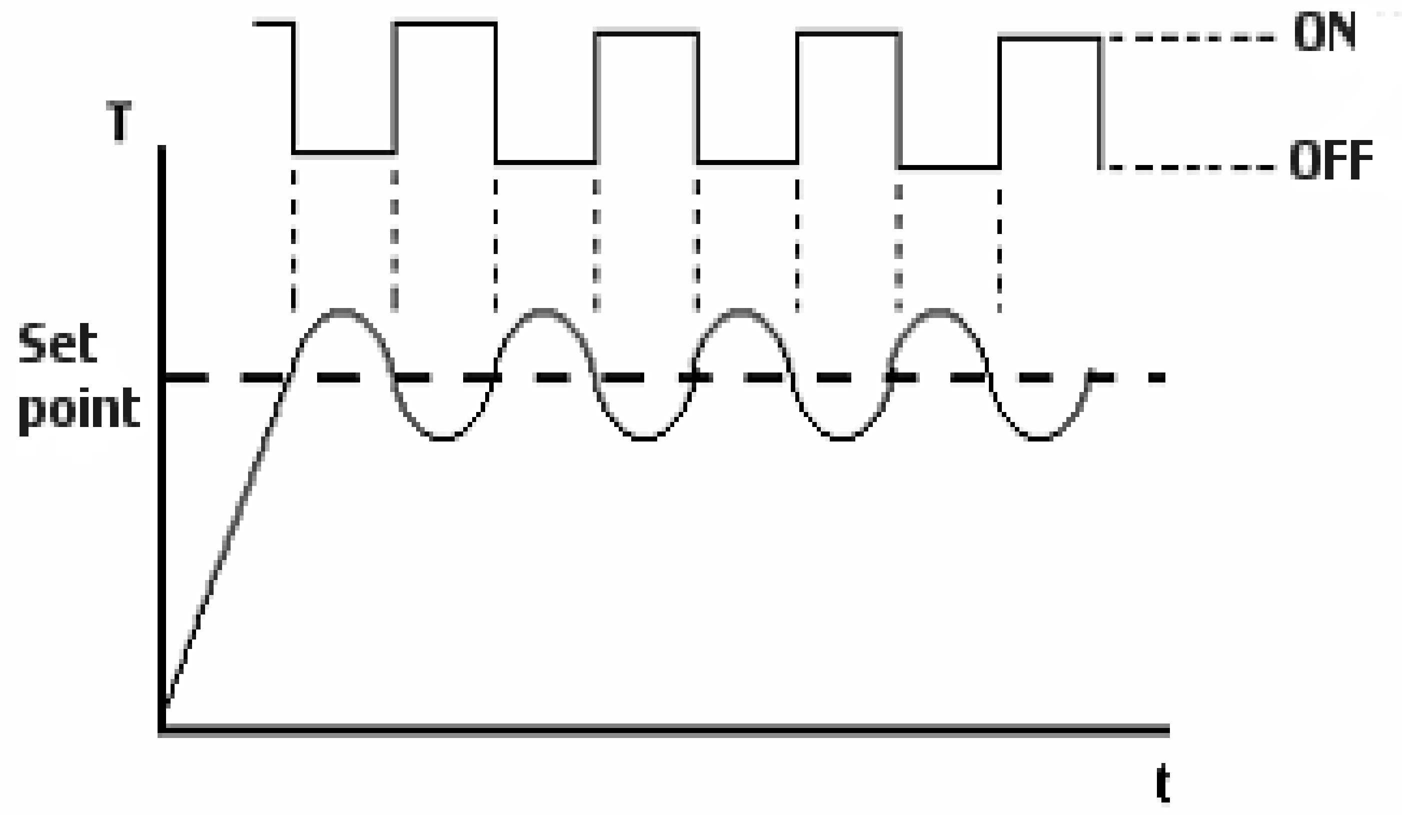
1. On Off Controllers
2. Proportional Controllers (P)
3. Proportional Integral Controllers (PI)
4. Proportional Derivative Controllers (PD)
5. Proportional Integral Derivative Controllers (PID)

On Off Controllers:

The manipulated variable is **completely shut down or completely opened** when the value of the controlled variable is higher or smaller than the set point value, respectively.

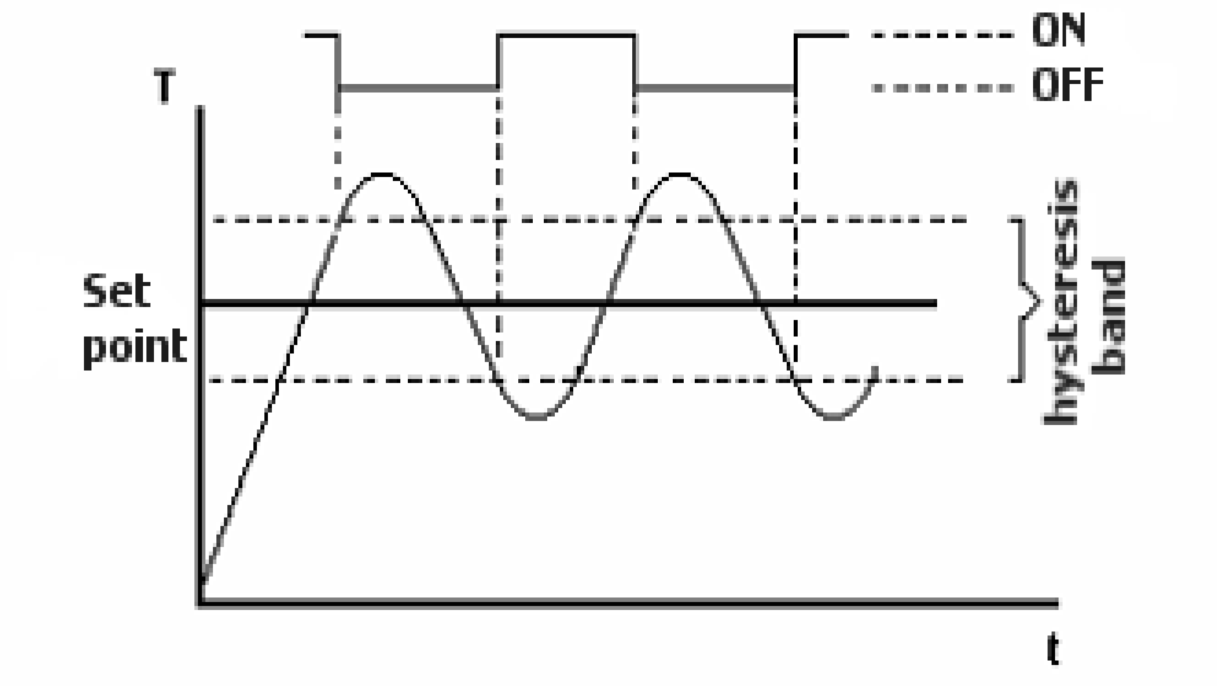
It operates completely mechanically and is preferred in simple systems, where precise control is not required.

Household irons, water heaters, electric ovens, aquarium heaters, old-style refrigerators, air compressors, hydrophores are controlled in this way.



System never reaches steady-state.
A hysteresis band occurs during this oscillation.

The manipulated variable is closed when the controlled variable reaches the top level and the manipulated variable is opened when the control variable is at the bottom level.



<u>Proportional Control (P Control):</u>

It is the type of controller where the **controller output is directly proportional to the error**. Its mathematical expression and Laplace form are given by the following expression;

$$Output = Bias \pm K_c \varepsilon$$

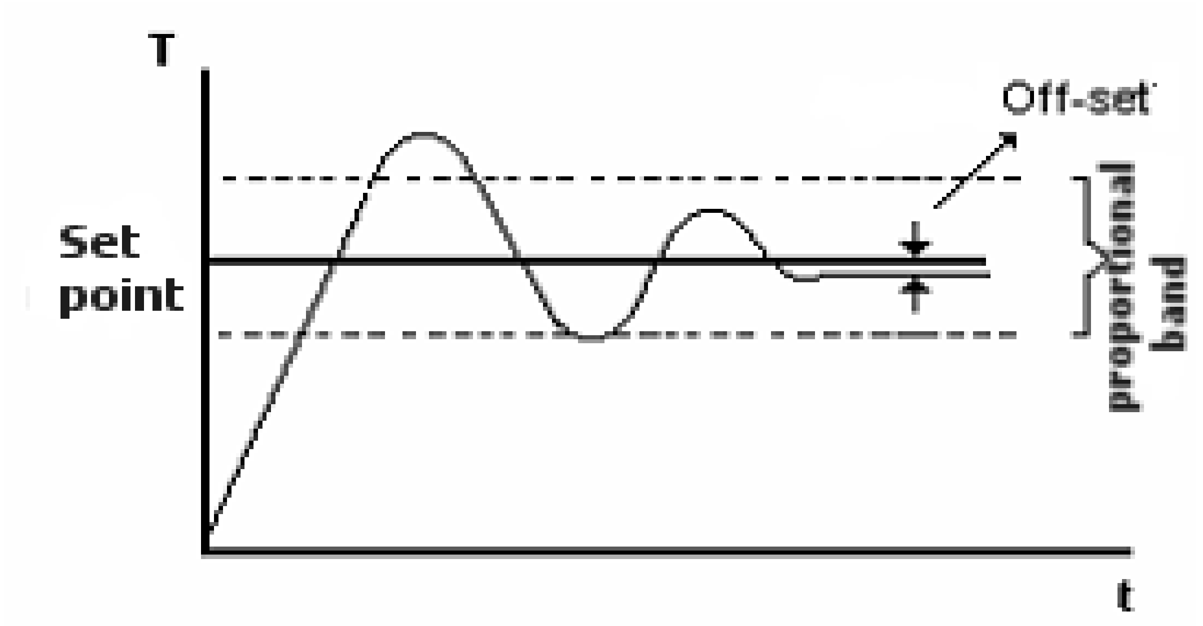
$$\Rightarrow \quad G_c(s) = K_c$$

The bias signal is a constant and the <u>controller output value in the absence of any deviation</u>. Kc is called the controller gain. **When the gain is large, the controller output will be larger for a given deviation**. For example, if the gain is 1, for a deviation of 10% of the full scale, the controller output will change by 10% of the scale. Often times the term proportional band (PB) is used instead of gain. The relationship between the two terms is as follows.

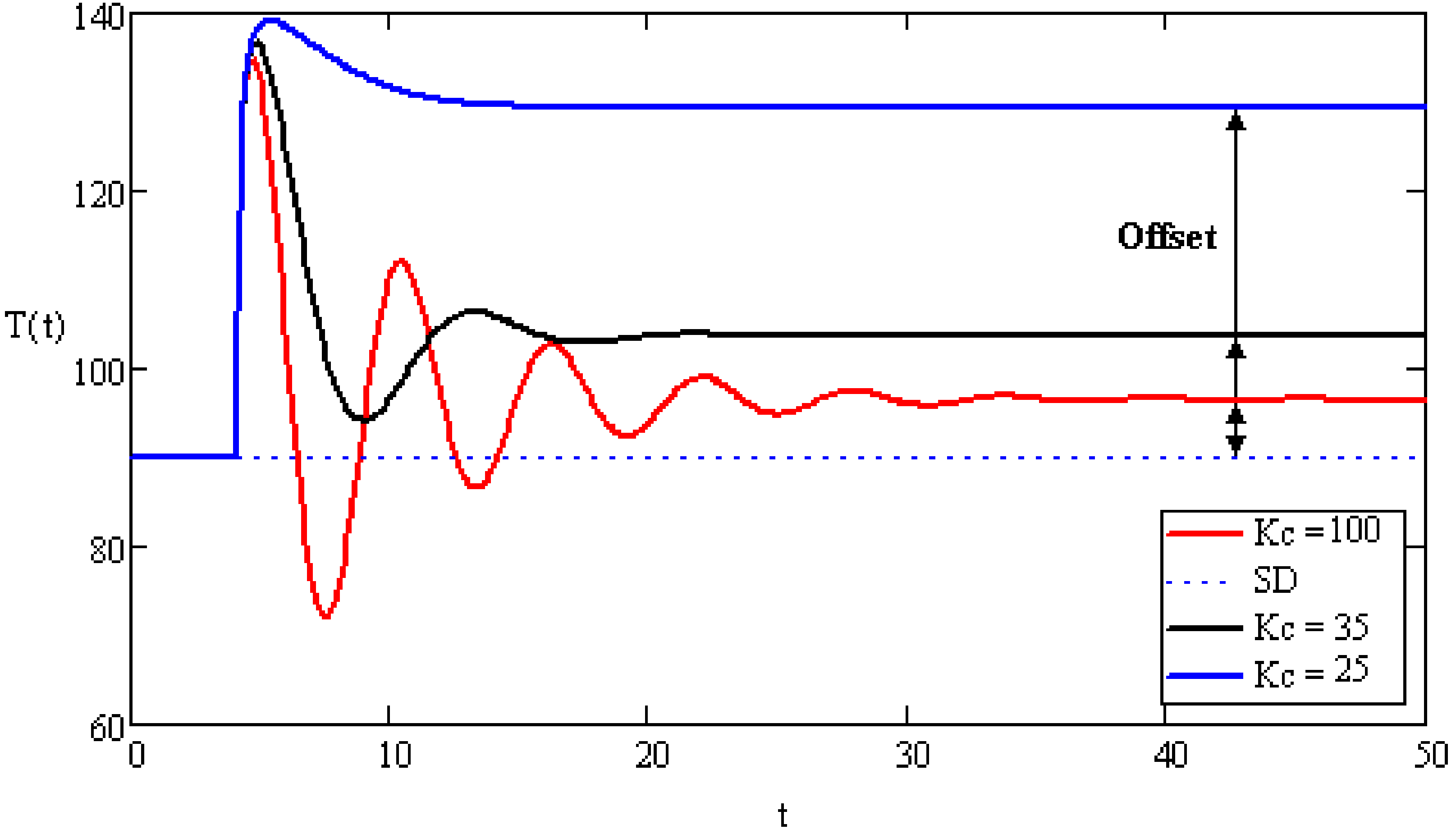
$$PB = 100/K_c$$

The higher or wider proportional band corresponds to lower gain. The term <u>**proportional band is the range of correction above the full scale that the controller will apply to correct any deviation**</u>.

In general, the proportional band is defined as a percentage of the full scale (span) value of the control variable and is spread evenly around the desired value. Hence, a wide PB means a low gain and a narrow bandwidth means a high gain.



- The value of the controlled variable **oscillates** and then approaches to equilibrium.
- Low or high losses may cause differences between equilibrium value and set point. This difference is called as **offset**.
- **Increasing the proportional band increases the offset**.
- **Decreasing the proportional band decreases the offset; however the control approximates to on/off control and oscillation increases**.


140
120
100
80
60
T(t)
0
10
20
30
40
50
t
Offset
Kc =100
SD
Kc = 35
Kc = 25

Proportional Integral Control (PI Control):

- In addition to proportional control, the output is corrected by the integral of deviations.
- Difference signal between measurement value and set point is integrated according to time. This integral value is added up with the difference value and the proportional band is shifted. In this way, the energy supplied to the system is automatically increased or decreased and the process temperature is set to the desired value. The function of the integrator circuit continues until there is no difference (error) between the desired value and the measured value. As soon as the difference signal is zero, there is no longer a signal for the integrator circuit to integrate.

The correction command and transfer function produced by the Proportional-Integral controller are defined by the following mathematical expressions;

$$Output = Bias \pm K_c\left(\varepsilon + \frac{1}{\tau_I}\int \varepsilon dt\right)$$

$$\Rightarrow \qquad G_c(s) = K_c\left(1 + \frac{1}{\tau_I}\frac{1}{s}\right)$$

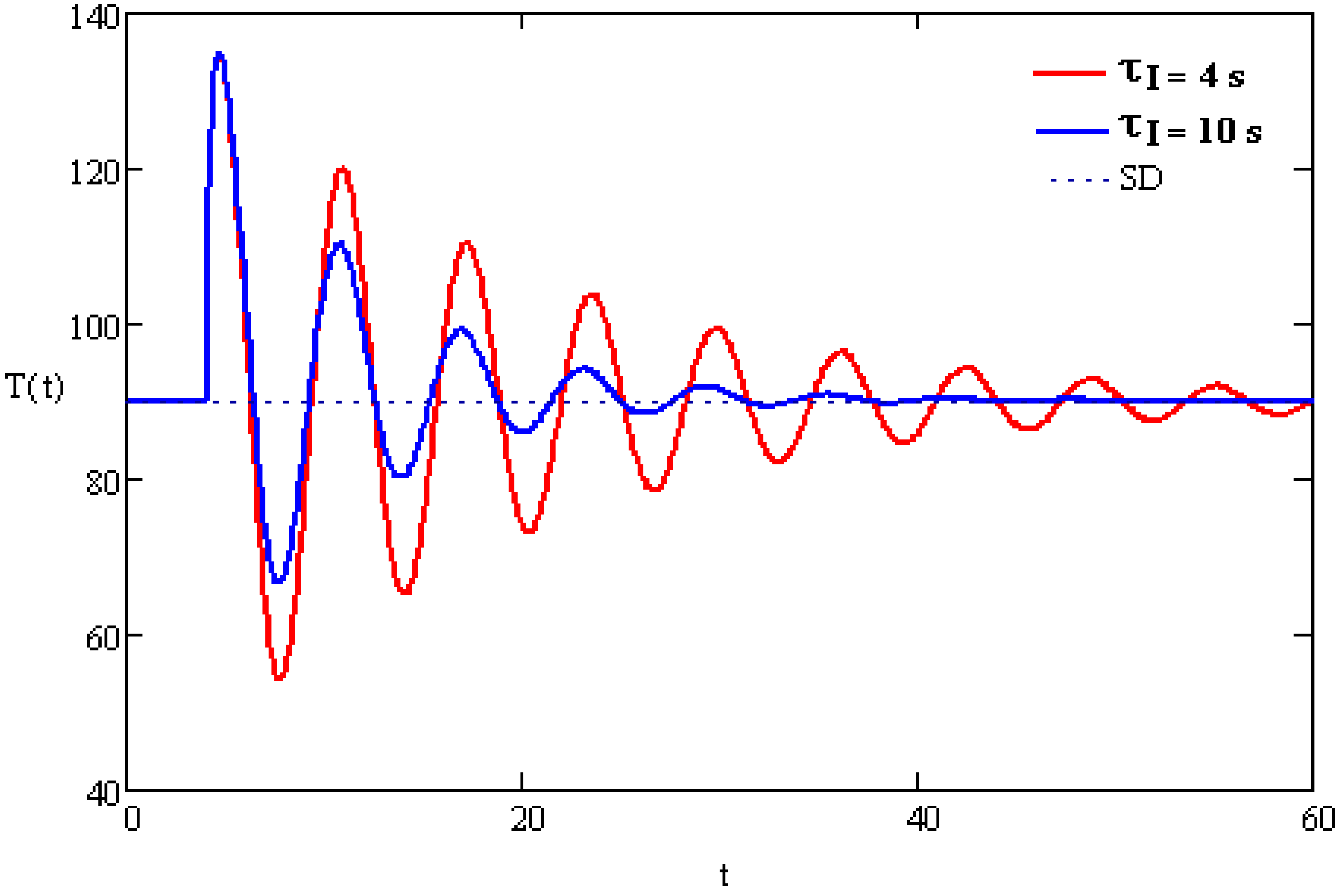
In any load variable, if the value of the control variable moves away from the desired value, a difference signal is generated again and the integrator circuit shows the corrective effect. **The most prominent feature of the PI controller is that the value of the process control variable first increases (overshoot) by exceeding the set value and then decreases again to the undershoot and becomes stable at the set value after a few oscillations**.

The effect of the integrator circuit is determined by the integral time constant (reset time) defined as τ_I.

The unit of the integral time constant is time, and by integrating the errors in the duration as much as the entered value, the correction of the errors occurring over time is performed.

When the integral time constant is a large value, its contribution to the correction of errors may be insufficient. However, when lower values are entered, oscillations in the control variable may increase or even lead to instability in the process. A suitable gain (Kc) and integral time constant τ_I must be entered for the process.

Since the effect of the PI controller on the process control variable is generally **oscillating**, it is not preferred in systems with slow dynamic behavior. Because of the large number of oscillations, the time to stabilize is prolonged. In systems with fast dynamic behavior, the oscillatory motion that should be will still appear. However, as the period of the oscillations will be very small, oscillations occur in a short time and will become steady at the entered set value.



140
120
100
80
60
40
T(t)
0
20
40
60
t
$\tau_I = 4$ s
$\tau_I = 10$ s
SD

Proportional Derivative Control (PD Control):

The main function of the derivative effect is to **decrease the overshoot-undershoots**. The PD controller is generally preferred in processes that show an oscillating dynamic behavior, in order to both keep the control variable under control and to reduce the oscillations caused by the dynamic behavior as much as possible.

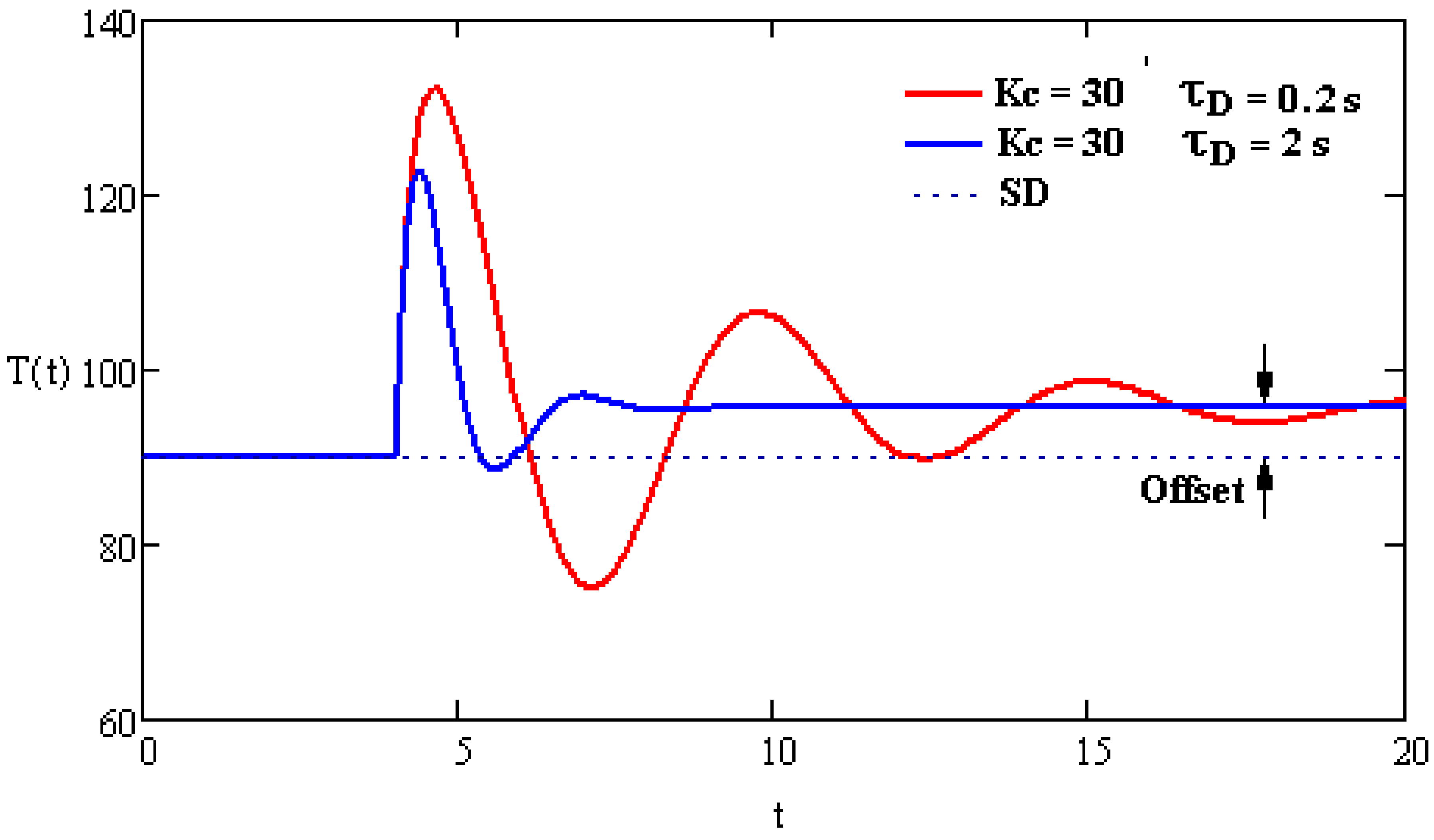
However, in the case of using a PD controller, some deviations (**off-set**) may occur in the value of the process variable, as in the P controller. The PD controller cannot eliminate the offset.

The correction command and the transfer function generated by the PD controller are defined by the following mathematical expressions;

$$Output = Bias \pm K_c\left(\varepsilon + \tau_D\frac{d\varepsilon}{dt}\right)$$

$$\Rightarrow \qquad G_c(s) = K_c(1 + \tau_D s)$$

The effect of the derivative circuit is determined by the derivative time constant defined as τ_D. The unit of the derivative time constant is time and by taking the derivative of the errors in the duration as much as the entered value, the correction of the errors that occur over time is performed. **When the derivative time constant is a small value, its contribution to the correction of errors may be insufficient.**



140
120
100
80
60
T(t)
0
5
10
15
20
t
Kc = 30 τD = 0.2 s
Kc = 30 τD = 2 s
SD
Offset

Proportional Integral Derivative Control (PID Control):

In systems with slow control, complex or dynamic behavior, and in processes where P, PI, PD controllers are insufficient, the PID controller is preferred.

It is the most ideal of feedback controllers, but its price is higher than others.

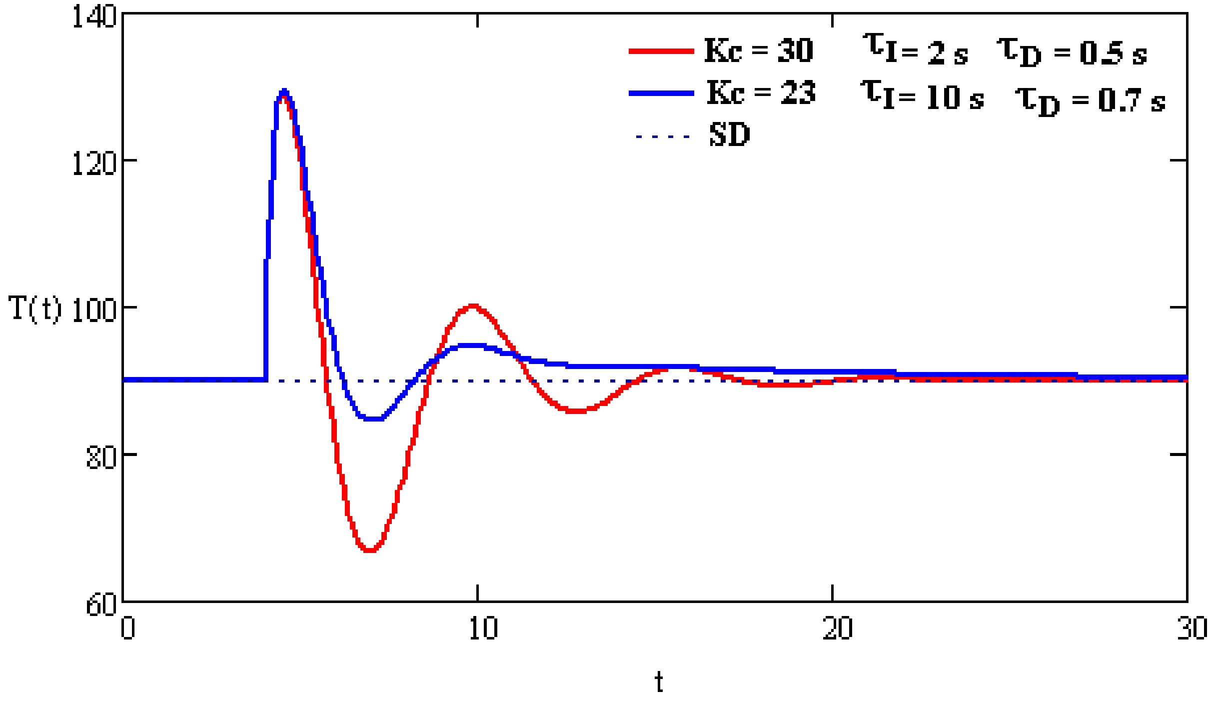
The off-set seen in the P and PD controller are not seen in the PID controller, and the number of oscillations is small compared to the PI controller.

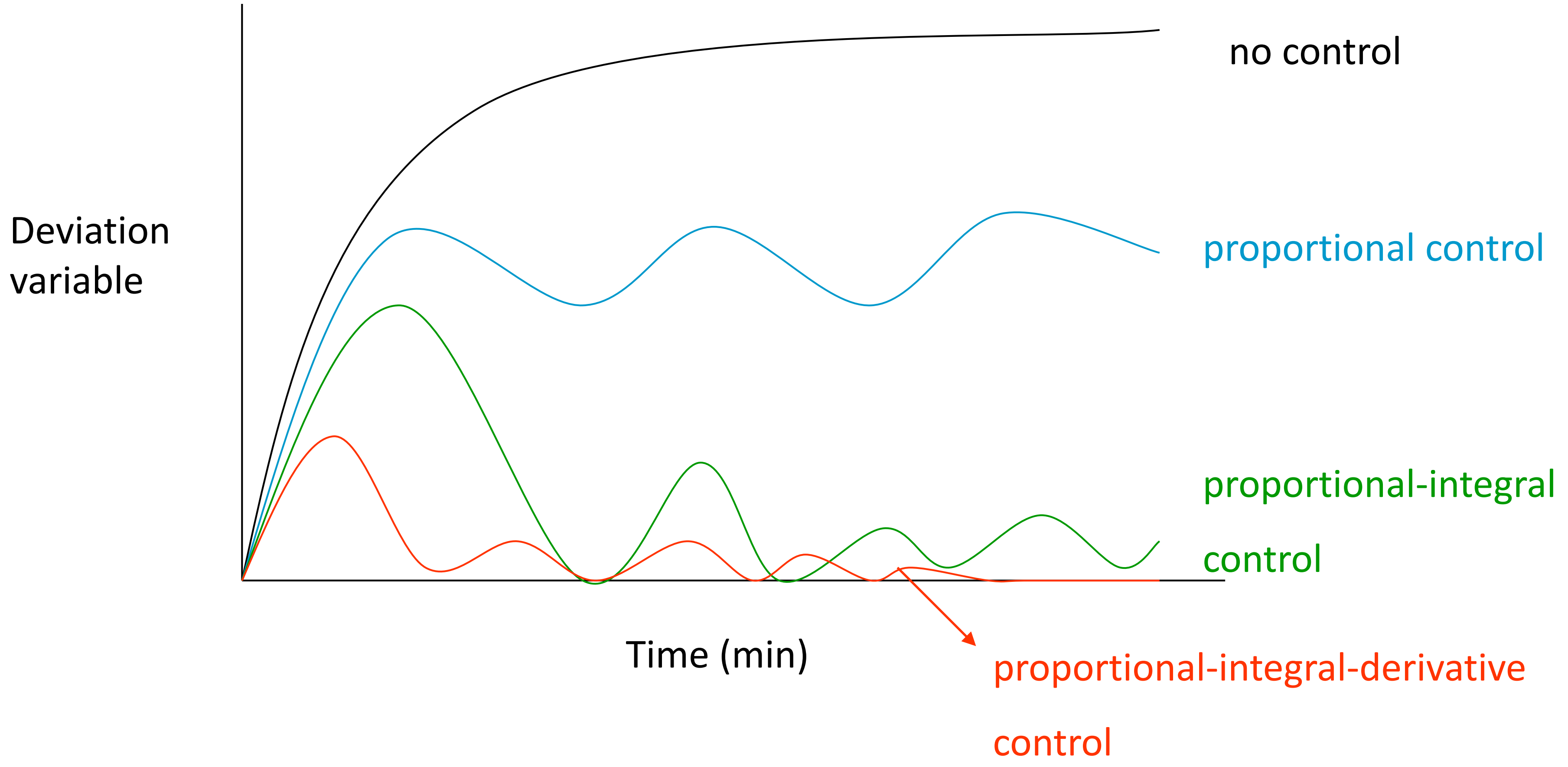
The correction command and transfer function generated by the PID controller are defined by the following mathematical expressions;

$$Output = Bias \pm K_c\left(\varepsilon + \frac{1}{\tau_I}\int \varepsilon dt + \tau_D \frac{d\varepsilon}{dt}\right)$$

$$\Rightarrow \quad G_c(s) = K_c\left(1 + \frac{1}{\tau_I}\frac{1}{s} + \tau_D s\right)$$

The figure shows the effect of the PID controller on the control variable. As can be seen from the figure, the value taken by the controller parameters has a great role in correcting the errors in the control variable. They cannot take random values, control parameters that best suit that process must be determined or calculated. Otherwise, even when the control loop has a stable structure, it will go towards an unstable structure if incorrect controller parameters are entered.





Deviation variable
Time (min)
no control
proportional control
proportional-integral control
proportional-integral-derivative control

Table 8.2 Key Characteristics of Commercial PID Controllers

Controller Feature	Controller Parameter	Symbol	Units	Typical Range*
Proportional mode	*Controller gain*	K_c	Dimensionless [%/%, mA/mA]	0.1–100
	Proportional band	$PB = 100\%/K_c$	%	1–1000%
Integral mode	*Integral time* (or *reset time*)	τ_I	Time [min, s]	0.02–20 min 1–1000 s
	Reset rate	$1/\tau_I$	Repeats/time [min^{-1}, s^{-1}]	0.001–1 repeats/s 0.06–60 repeats/min
	Integral mode "gain"	K_I	Time^{-1} [min^{-1}, s^{-1}]	0.1–100
Derivative mode	*Derivative time*	τ_D	Time [min, s]	0.1–10 min. 5–500 s
	Derivative mode "gain"	K_D	Time [min, s]	0.1–100
	Derivative filter parameter	α	Dimensionless	0.05–0.2
Control interval (Digital controllers)		Δt	Time [s, min]	0.1 s–10 min

*Based on McMillan (1994).

Control Room

Most plant control rooms now use shared display devices that show the outputs of multiple instruments on a VDU screen.

Operator can see a flow diagram that identifies where the instrument is and can enter set points.

Software also allows data to be plotted as trends.

Data can be accessed remotely.

Data is collected and logged for process records.


NY 21