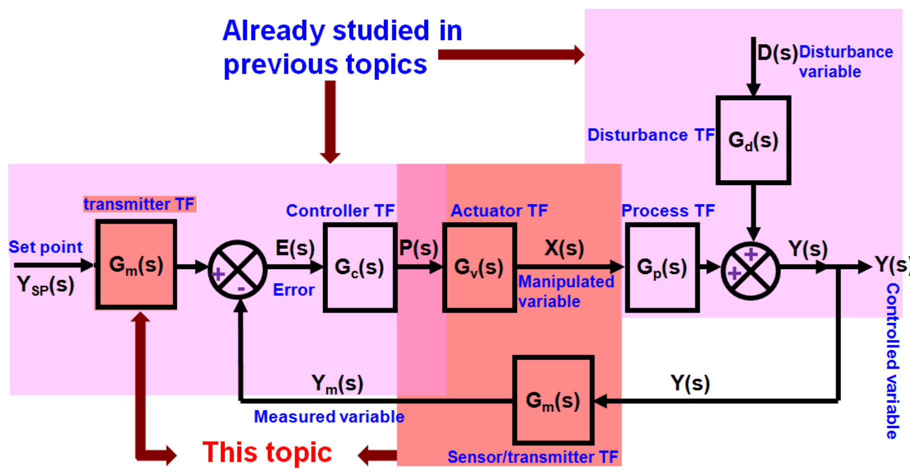
Sensors, Transmitters, Filters, and Actuators



"Standard block diagram of feedback controller with one disturbance"

Sensors, Transmitters, Filters, and Actuators

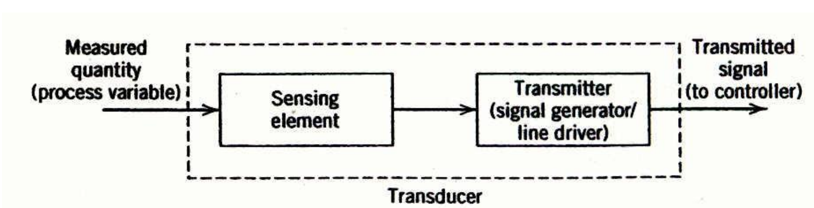
- **Sensors/Transmitters**
  - **What is sensor?** A device which produces physical/chemical phenomenon to measure process variable (T, P, q, L, p, pH,…etc).
  - **There are different types of sensors to measure:**
    - **Temperature:** Thermocouple, Resistance Temperature Detector (RTD), and Thermistor, Infrared(IR), ..etc.
    - **Pressure:** Bourdon gage, . Piezoelectric Pressure Transducer, Strain Gage Pressure Transducer , Magnehelic pressure gage,..etc.
    - **Flow rate:** Orifice, Venturi, magnetic, ultrasonic, Corliolis effect sensors,..etc.
    - **Liquid level:** Float level, differential pressure, ultrasonic
    - **pH:** pH electrode,..etc.
    - **Composition:** GC, IR, NIR, UV spectrophotometer, electrical conductivity,..etc.

Sensors, Transmitters, Filters, and Actuators

- **Sensors/Transmitters**
  - **What is transmitter?** A device that generates an industrial standard signal from the sensor output.
  - **Standard instrumentation signal levels:**
    - Voltage: 0~10 VDC, 0~5VDC, -10~+10VDC, ..etc.
    - Current: 4~20mA
    - Pneumatic: 3-15psig
  - **Signal Transmitter:**
    - I/P or P/I converter: current-to-pressure or vice versa.
    - I/V (I/E) or V/I converter: current-to-voltage or vice versa.
    - P/E or E/P converter: pressure-to-voltage or vice versa.
    - A/D or D/A converter: Analog-to-Digital or vice versa.

Sensors, Transmitters, Filters, and Actuators

- **Sensors/Transmitters**
  - **Transducer**: consists of a sensing element(sensor) combined with a driving element (transmitter):

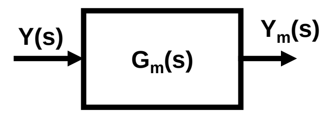


  - Most commercial transducers and transmitters have an adjustable input range (or span). For example, a temperature transmitter might be adjusted so that the input range of a platinum resistance element (the sensor) is 50 to 150 °C.

Sensors, Transmitters, Filters, and Actuators

- **Sensors/Transmitters**
  - Sensor-transmitters **Transfer Function**:
    - Many sensor/transmitters have overdamped dynamic responses to step in the variable being measured. Thus, it is a reasonable to be modeled by **first-order transfer function**:

$$G_m(s) = \frac{Y_m(s)}{Y(s)} = \frac{K_m}{\tau_m s + 1}$$



• **K_m**: transmitter gain. For temperature transmitter to electrical current signal the unit of K_m is mA/°C.
• **τ_m** : the transmitter time constant. It is usually of few seconds and it can be neglected when the process space time is of order of minutes.

Sensors, Transmitters, Filters, and Actuators

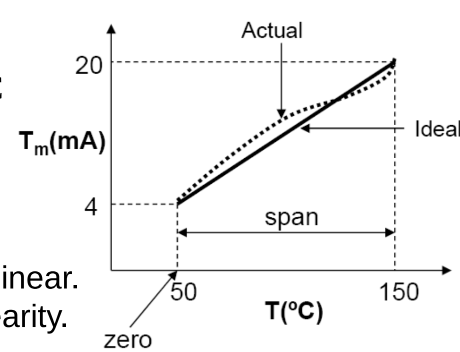
- **Sensors/Transmitters**

Example. Find the temperature transmitter gain in mA/°C if the input range is adjusted to be from 50 to 150 °C. What are zero and span of input?

By assuming linear variation between output and input:

$$\text{Gain} = K_m = \frac{\Delta\text{output}}{\Delta\text{input}}$$

$$= \frac{20-4}{150-50} = 0.16\,\text{mA/}^{\circ}\text{C}$$



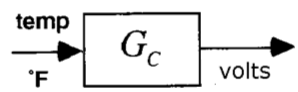
→ The actual variation is NOT linear. However, it is closed to the linearity.

Sensors, Transmitters, Filters, and Actuators

- **Sensors/Transmitters**

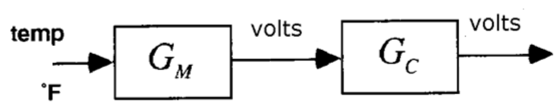
Example. Suppose that a controller output signal has a range of 0-10 volts and it receives a temperature values with a range of 100-200 ^{o}F. Find the controller gain. How can you obtain a dimensionless Kc?

$$\text{Dimensional } K_c = \frac{\Delta \text{output}}{\Delta \text{input}}$$



$$= \frac{10-0}{200-100} = 0.10\,\text{volt}/^{o}\text{F}$$

→To obtain dimensionless gain, transmitter must be installed before controller:

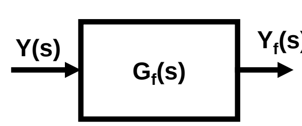


Sensors, Transmitters, Filters, and Actuators

- **Noise filters**

- To reduce/remove noise in the measured signal.
  - **Noise source**: process nature (turbulence, vibration, oscillation…), various noise source from environment, power line, electromagnetic force, etc.
- Noise filter **Transfer Function**:

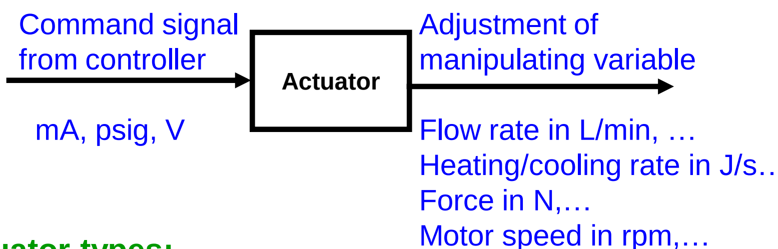
$$G_f(s) = \frac{Y_f(s)}{Y(s)} = \frac{1}{\tau_f s + 1}$$



$\tau_f \equiv$ the noise filter time constant.

Sensors, Transmitters, Filters, and Actuators

- **Actuators**
  - **What is actuator?** Device that converts the controller output signal to action such as valve opening in order to enable some process variable to be manipulated such as flow rate.



- **Actuator types:**

✓ **Control valve**: pneumatic, electric, or hydraulic.
✓ **Electric heater**: Thyristor or SCR(silicon controlled rectifiers)
✓ **Pump/Motor speed**: Inverter
✓ **Displacement**: pneumatic, electric, or hydraulic.

Sensors, Transmitters, Filters, and Actuators

- **Actuators**

- Standard instrumentation signal levels and signal conversion transmitters are used:

  - **Pneumatic**: Simple; Low cost; Fast; Low torque; Hysteresis.
  - **Electric**: Motor and Gear box; High torque; Slow.
  - **Hydraulic**: High torque; Fast; Expensive

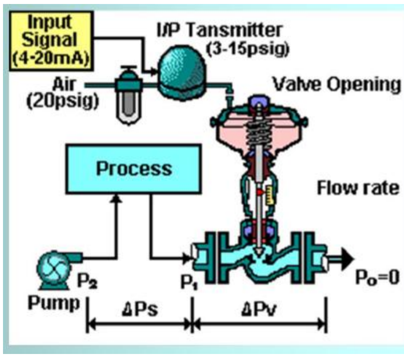
→ **Thus, it is recommended to use pneumatic control valve**:

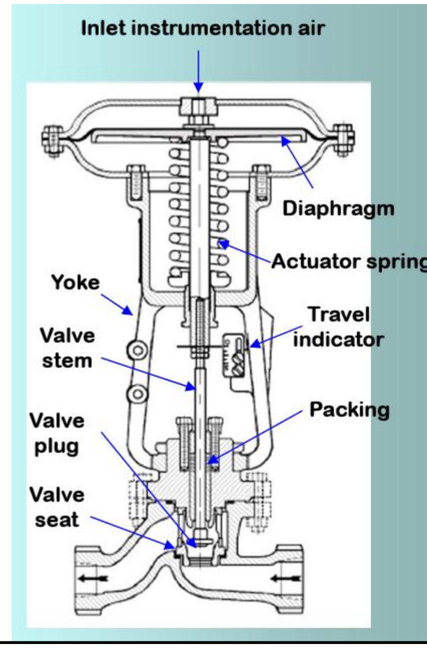
– Usually 3~15psig signal is provided.
– I/P transmitter converts 4~20mA signal to 3~15psig
- pneumatic signal via 20 psig air supply.

Sensors, Transmitters, Filters, and Actuators

- **Actuators**

Pneumatic Control Valve:





Sensors, Transmitters, Filters, and Actuators

- **Actuators**
  - **Hysteresis in pneumatic control valve:**
    - **Hysteresis**: when the command signal (pneumatic signal) is going up and down, the flow rate will not be same even though the command signal is same depending on the direction of signal change.
    - Hysteresis happens due to friction between the stem and packing, loose linkage, stiction, or etc.

    - **Hysteresis remedy**

✓ Change the command signal by lowering or increasing it momentarily.

✓ or use valve positioner: the valve positioner is a controller which can synchronize the command signal and its corresponding valve stem position.

→ **By using valve positioner, hysteresis can be overcome.**

Sensors, Transmitters, Filters, and Actuators

- **Actuators**
  - **Action of pneumatic control valve:**

As air pressure increases, the valve opening can becomes larger or smaller:

1- Air-to-open (A/O) or (A-O) valves; normally closed; fail close): as the air pressure increases, the valve opening gets larger.

2- Air-to-close (A/C) or (A-O) valves; normally opened, fail open): as the air pressure increases, the valve opening gets smaller.

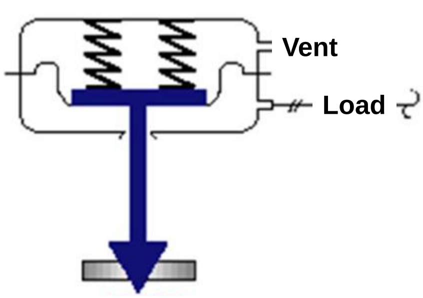
→ The selection of A/O or A/C should be made based on the **safety consideration.**

Sensors, Transmitters, Filters, and Actuators

- **Actuators**

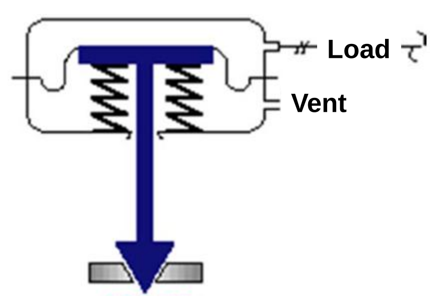
Air-to-open and Air-to-Close valves:

Air-to-Open/Fail Closed



A/O-FC
(Reverse action)
Stem "extends on
Loss of air pressure

Air-to-Closed/Fail Opened



A/C-FO
(Direct action)
Stem "retracts" on
Loss of air pressure

Sensors, Transmitters, Filters, and Actuators

- **Actuators**

Pneumatic Control Valve

Example. Pneumatic control valves are to be specified for the applications listed below. State whether an A/O or A/C valve should be specified for the following manipulated variables:

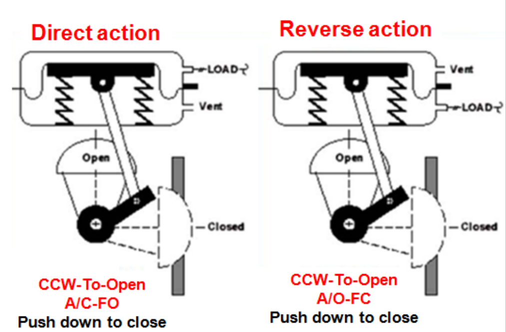
(a) Steam pressure in a reactor heating coil: **A/O**
(b) Flow rate of reactants into a polymerization reactor: **A/O**
(c) Flow of effluent from a wastewater treatment holding tank into a river : **A/O**
(d) Flow of cooling water to a distillation condenser: **A/C**
(e) Furnace fuel valve: **A/O**
(f) Coolant valve in exothermic reactor: **A/C**

Sensors, Transmitters, Filters, and Actuators

- **Actuators**

→ Control valves classification:

- Control Valve
  - Linear motion
    - Globe
    - Diaphragm
    - Pinch or clamp
    - Gate
  - Rotary motion
    - Eccentric plug
    - Butterfly
    - Ball

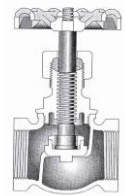


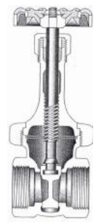
CCW: counterclockwise

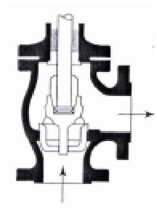
Sensors, Transmitters, Filters, and Actuators

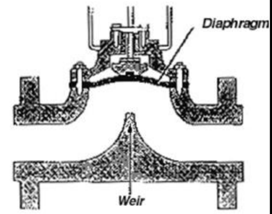
- **Actuators**

Control valves classifications:


"Globe valve"

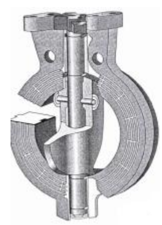

"Gate valve"

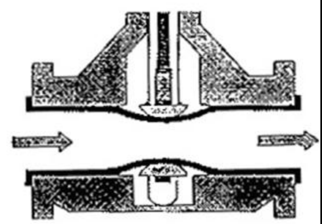

"Angle valve"



"Diaphragm valve"


"Ball valve"


"Butterfly valve"


"Pinch valve"

Sensors, Transmitters, Filters, and Actuators

- **Actuators**

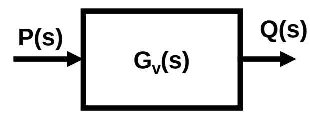
Characteristics of some control valves:

- Globe valve: rugged, usually the most expensive, particularly in the larger sizes, accurate and repeatable control, high pressure drop.
- Gate Valve: sliding disc (gate), ideal for high pressure and high temperature applications where operation is infrequent, multi-turn or long stroke pneumatic and electro-hydraulic actuators are needed, poor control.
- Ball Valve: tight shutoff, high capacity with just a quarter-turn to operate.
- Butterfly Valve: damper valve , most economical valves, high torque required
- Diaphragm Valve: simplest, tight shutoff, isolated, ideal for corrosive, slurry and sanitary services.

Sensors, Transmitters, Filters, and Actuators

- **Actuators**
  - Actuator **Transfer Function**:
    - Actuator transfer function can be modeled by **first-order transfer function:**

$$G_v(s) = \frac{Q(s)}{P(s)} = \frac{K_v}{\tau_v s + 1}$$



• **K_v**: actuator gain. If the actuator is pneumatic control valve K_v has the unit of volumetric flow rate divided by psig.
• **τ_v**: actuator time constant. It is usually of few seconds and it can be neglected when the process space time is of order of minutes.
• **Q(s):** manipulated variable, If the actuator is pneumatic control valve , it is volumetric flow rate.

Sensors, Transmitters, Filters, and Actuators

- **Actuators**
  - **Determination of the actuator gain (K_v)**
    - **Consider control valve actuator:**

$\rightarrow$ The flow rate q(t) is the manipulated variable. It has the following discharge equation:

$$q(l) = C_v f(l) \sqrt{\frac{\Delta P_v}{SG}}$$

• ***l***: valve opening(dimensionless) with the range $0 \leq l \leq 1$
$l = 0$: The valve is completely closed.
$l = 1$: The valve is fully opened.
• **C_v** : Valve loss coefficient. It is decided by valve size and type.
• **SG**: Specific gravity of the fluid at flowing conditions.
• **ΔP_v** : Pressure drop across the valve in psi,

Sensors, Transmitters, Filters, and Actuators

- **Actuators**
  - **Determination of the actuator gain (K_v)**

• ***f* (*l*) :** some function of valve opening which depends on the type of valve trim:

- **Linear valve trim:**

$$f(l) = l$$

- **Quick-opening (Square root) valve trim:**

$$f(l) = \sqrt{l}$$

- **Equal-percentage valve trim:**

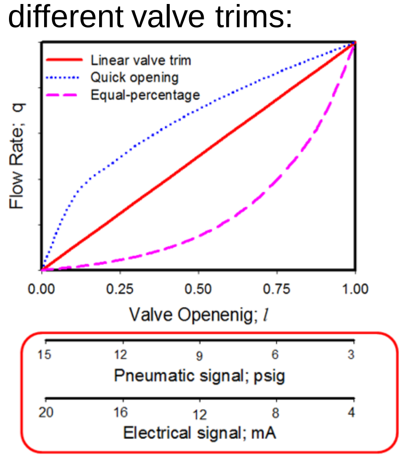
$$f(l) = R^{l-1} \quad ; \quad 20 \le R \le 50$$

R: Valve design parameter

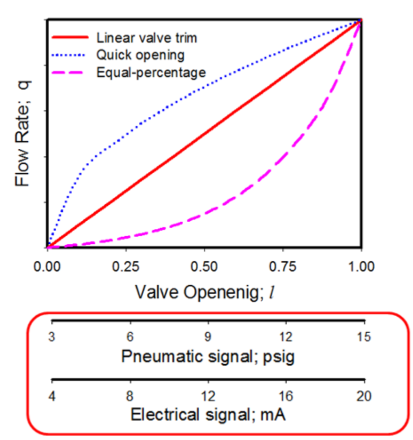
Sensors, Transmitters, Filters, and Actuators

- **Actuators**
  - **Determination of the actuator gain (K_v)**

▪ Effect of valve opening *l* on the flow rate *q* for different valve trims:



Air-to-Close/Fail Opened



Air-to-Open/Fail Closed

Sensors, Transmitters, Filters, and Actuators

- **Actuators**
  - **Determination of the actuator gain (K_v)**
    - If certain flow rate is known at some valve opening, for example, the flow rate, q_{FO} , at full opening valve (l =1), the flow rate equation can be expressed as below:
    - **For linear trim:** $q_{FO} = C_v(1)\sqrt{\frac{\Delta p_v}{SG}} \Rightarrow C_v\sqrt{\frac{\Delta p_v}{SG}} = q_{FO}$

$$\Rightarrow q = C_v l\sqrt{\frac{\Delta p_v}{SG}} = q_{FO} l \quad and \quad \frac{dq}{dl} = q_{FO}$$

Thus, for linear trim, the steady gain between Q and L is:

$$\frac{\Delta Q}{\Delta L} = \frac{dQ}{dL} = \frac{dq}{dl} = q_{FO}$$

Sensors, Transmitters, Filters, and Actuators

- **Actuators**
  - **Determination of the actuator gain (K_v)**
    - **For quick-opening valve trim:**

$$q_{FO} = C_v\sqrt{1}\sqrt{\frac{\Delta p_v}{SG}} \Rightarrow C_v\sqrt{\frac{\Delta p_v}{SG}} = q_{FO}$$

$$\Rightarrow q = C_v\sqrt{l}\sqrt{\frac{\Delta p_v}{SG}} = q_{FO}\sqrt{l} \quad and \quad \frac{dq}{dl} = q_{FO}\frac{1}{2\sqrt{l}}$$

Now, the steady gain between Q and L is:

$$\frac{\Delta Q}{\Delta L} = \left.\frac{dq}{dl}\right|_{l=\bar{l}} = q_{FO}\frac{1}{2\sqrt{\bar{l}}}$$

Where $\bar{l}$ is the nominal (original steady state) valve opening.

Sensors, Transmitters, Filters, and Actuators

- **Actuators**
  - **Determination of the actuator gain (K_v)**
    - **For equal-percentage valve trim:**

$$q_{FO} = C_v R^{1-1}\sqrt{\frac{\Delta p_v}{SG}} \Rightarrow C_v\sqrt{\frac{\Delta p_v}{SG}} = q_{FO}$$

$$\Rightarrow q = C_v R^{l-1}\sqrt{\frac{\Delta p_v}{SG}} = q_{FO} R^{l-1} \; and \; \frac{dq}{dl} = q_{FO}(\ln R) R^{l-1}$$

Then, the steady gain between Q and L is:

$$\frac{\Delta Q}{\Delta L} = q_{FO}\left.\frac{dq}{dl}\right|_{l=\bar{l}} = q_{FO}(\ln R) R^{\bar{l}-1}$$

Sensors, Transmitters, Filters, and Actuators

- **Actuators**
  - **Determination of the actuator gain (K_v)**
  - Effect of controller signal, p, on the opening, l of A/O valve :

✓ For electrical signal:

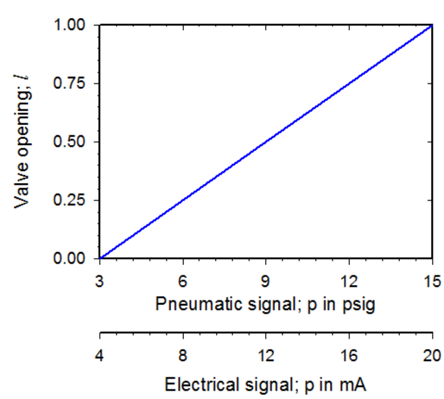
$$\frac{dl}{dp} = \frac{dL}{dP} = \frac{\Delta l}{\Delta p} = \frac{1-0}{20-4}$$

$$= 0.0625 \; mA^{-1}$$

✓ For pneumatic signal:

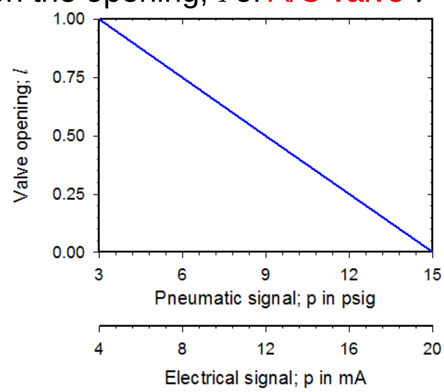
$$\frac{dl}{dp} = \frac{dL}{dP} = \frac{\Delta L}{\Delta P} = \frac{1-0}{15-3}$$

$$= 0.0833 \; psig^{-1}$$



Sensors, Transmitters, Filters, and Actuators

- **Actuators**
  - **Determination of the actuator gain (K_v)**
  - Effect of controller signal, p, on the opening, l of A/C valve :



✓ For electrical signal:

$$\frac{dl}{dp}=\frac{dL}{dP}=\frac{\Delta l}{\Delta p}=\frac{0-1}{20-4}$$
$$=-0.0625\ mA^{-1}$$

✓ For pneumatic signal:

$$\frac{dl}{dp}=\frac{dL}{dP}=\frac{\Delta L}{\Delta P}=\frac{0-1}{15-3}$$
$$=-0.0833\ psig^{-1}$$

- Finally, the pneumatic control gain is:

$$K_v=\frac{\Delta Q}{\Delta P}=\frac{\Delta Q}{\Delta L}\frac{\Delta L}{\Delta P}$$

- **$K_v > 0$ For A/O control valve" Reverse action"**
- **$K_v < 0$ For A/C control valve" Direct action"**

Sensors, Transmitters, Filters, and Actuators

- **Actuators**
  - **Determination of the actuator gain (K_v)**

Example. Pneumatic A/O control valve is used in a closed loop control system. When the valve was fully opened (l = 1) the flow rate through the valve was 0.2 m^3/min. The steady nominal valve opening is 0.5. Find the valve gain if the valve has: a) linear trim; b) quick- opening trim; and c) equal-percentage trim with R=30.

$$q_{FO}=0.2m^3/\min;\quad \bar{l}=0.5;\ \frac{\Delta L}{\Delta P}=\frac{1-0}{15-3}=\frac{1}{12}$$

a) Valve with linear trim :

$$\frac{\Delta Q}{\Delta L}=q_{FO}=0.2$$

$$K_v=\frac{\Delta Q}{\Delta L}\frac{\Delta L}{\Delta P}=0.2\frac{1}{12}=0.017\frac{m^3/\min}{psig}$$

Sensors, Transmitters, Filters, and Actuators

- **Actuators**
  - **Determination of the actuator gain (K_v)**

b) Valve with quick-opening trim :

$$\frac{\Delta Q}{\Delta L} = q_{FO}\frac{1}{2\sqrt{\bar{l}}} = 0.2\frac{1}{2\sqrt{0.5}} = 0.1414\ m^3/\min$$

$$K_v = \frac{\Delta Q}{\Delta L}\frac{\Delta L}{\Delta P} = 0.1414\frac{1}{12} = 0.012\frac{m^3/\min}{psig}$$

c) Valve with equal-percentage trim of R=30 :

$$\frac{\Delta Q}{\Delta L} = q_{FO}(\ln R)R^{\bar{l}-1} = 0.2(\ln 30)R^{0.5-1} = 0.1242\ m^3/\min$$

$$K_v = \frac{\Delta Q}{\Delta L}\frac{\Delta L}{\Delta P} = 0.1242\frac{1}{12} = 0.010\ \frac{m^3/\min}{psig}$$