MODULE TITLE : CONTROL SYSTEMS AND AUTOMATION

TOPIC TITLE : CONTROL DEVICES AND SYSTEMS

LESSON 1 : VALVE CHARACTERISTICS

CSA - 4 - 1

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INTRODUCTION

In this lesson we examine control valves and the flow characteristics of linear, equal percentage and quick opening valve plugs. The flow characteristics of a control valve are normally represented graphically by plotting percentage flow through the valve against the percentage opening of the valve, assuming that the pressure drop across the valve is constant irrespective of the flow passing through it. In practice, the pressure drop is not constant which explains the need for a set of modified characteristics which we term the "installed characteristics".

YOUR AIMS

On completion of this lesson you should be able to:

- sketch different types of valve plug and their flow characteristics
- select suitable types of valve plug for particular applications according to appropriate criteria.

LINEAR FLOW CHARACTERISTICS

To produce a linear characteristic, the valve plug must be shaped so that equal increments of valve opening result in equal increments of increased flow when a constant pressure difference is maintained across the valve. A typical graph associated with this characteristic, shown in FIGURE 1, indicates an almost constant gradient.

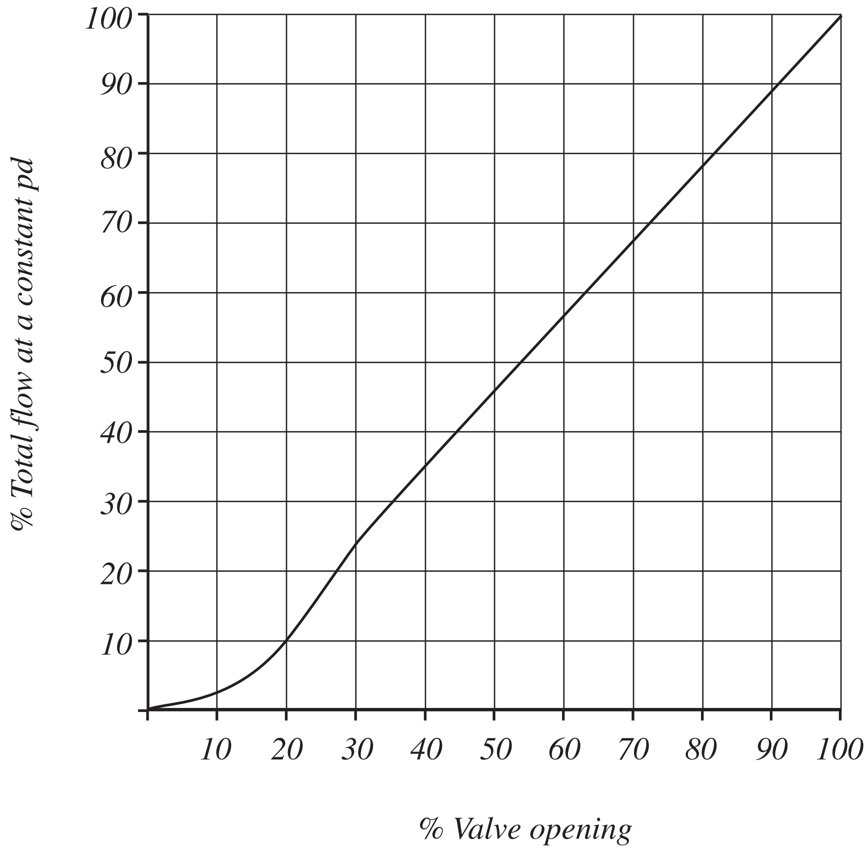

FIG. 1 Linear characteristic

The ratio between changing flow rate and valve opening is known as the valve gain. For a linear valve, the gain is constant apart from a slight deviation at the start, caused by the extra movement required to ensure tight shut off (no leakage). The degree of this deviation is dependent upon valve size, its configuration and the system operating conditions. The relationship between % total flow and % valve opening (often known as valve lift) for a linear valve may be expressed mathematically in the following form:

$$Q = Kl$$

where, Q = flow rate
l = valve lift
K = constant of proportionality.

THE USE OF LINEAR VALVE PLUGS IN CONTROL SYSTEMS

It is important to select the correct plug for any particular application if stable control is to be achieved. Selection of an incorrect plug can cause under-damping or over-damping of the control of a process and can also cause extreme wear on the valve.

The criteria for selecting a linear valve plug are listed below. It should be emphasised that it is unlikely that a system will satisfy all of these requirements and a compromise often has to be made.

CRITERIA FOR SELECTION OF A CONTROL VALVE WITH LINEAR CHARACTERISTIC

(a) If a control valve with linear characteristic (known as linear valve trim) is fitted, the overall relationship between the output and input of the control system should be linear.

(b) The control valve should provide the main source of pressure drop within the system, so that the effect of other pressure drops is comparatively small.

(c) There should be a stable pressure drop across the control valve. This implies that the supply demand, subject to the process variables upstream of the valve, and the load demand, subject to the process variables downstream of the valve, remain fairly constant. FIGURE 2 shows a process which satisfies these criteria.

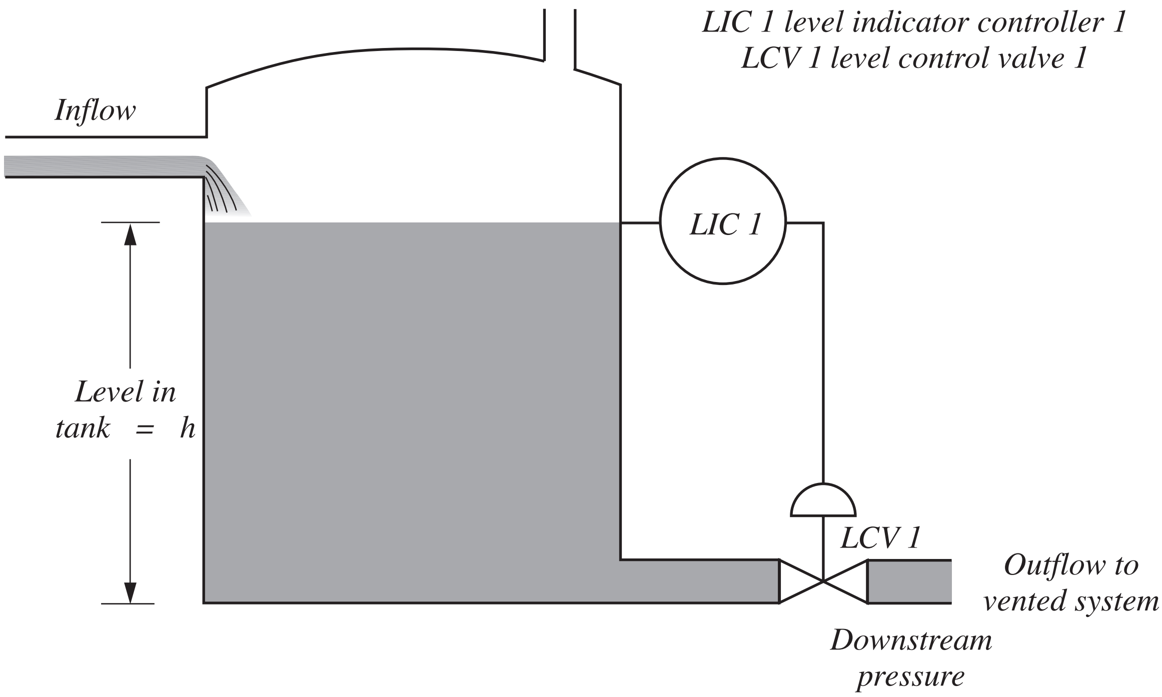

FIG. 2

In this process it is necessary to maintain a predetermined level of fluid in the tank. Let's see how the listed criteria are met:

(a) At any position of the liquid level there is a corresponding valve position where the outflow equals the inflow. The pressure drop across the valve will equal '$h\rho g$' minus the downstream pressure. If the valve moves 10% and the change in level is, say, 'x', then when the valve moves by 20% the change in level will be $2x$. The relationship between the valve movement and the change in level will be fairly linear for any particular set value of h because the variations in pressure drop across the valve should be relatively small.

(b) In this system the only pressure drop is that which occurs across the valve.

(c) The supply demand to this valve is constant, because if the level falls the controller detects the change and closes the valve to maintain the level 'h'. Changes in downstream pressure or load do not affect the valve pressure drop because the outflow goes to another vented system.

Later in this lesson a section on 'Installed Characteristics' will provide further insight into the selection of control valve plugs.

EXAMPLES OF LINEAR VALVE TRIMS

The examples shown in FIGURE 3 are examples of the types of linear valve trim commonly found in industry. The contoured port valve shown in FIGURE 3(a) can also be supplied as a double seated valve.

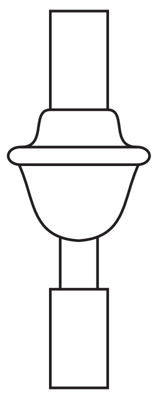

FIG. 3(a) Contoured Plug

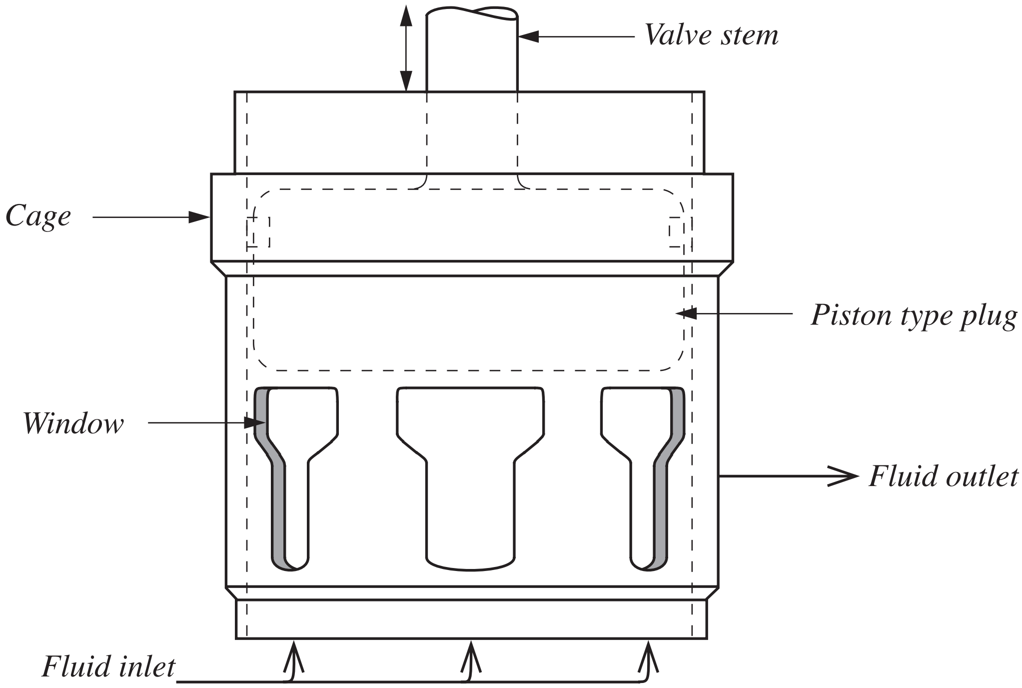

FIG. 3(b) Linear Windows

EQUAL PERCENTAGE CHARACTERISTICS

A valve plug with equal percentage characteristics is shaped so that equal increments of valve lift produce equal percentage changes in flow for a constant pressure drop across the valve. This type of relationship is exponential, though in instrumentation it is often called "semi-logarithmic". The graph has a continuously increasing slope as illustrated in FIGURE 4.

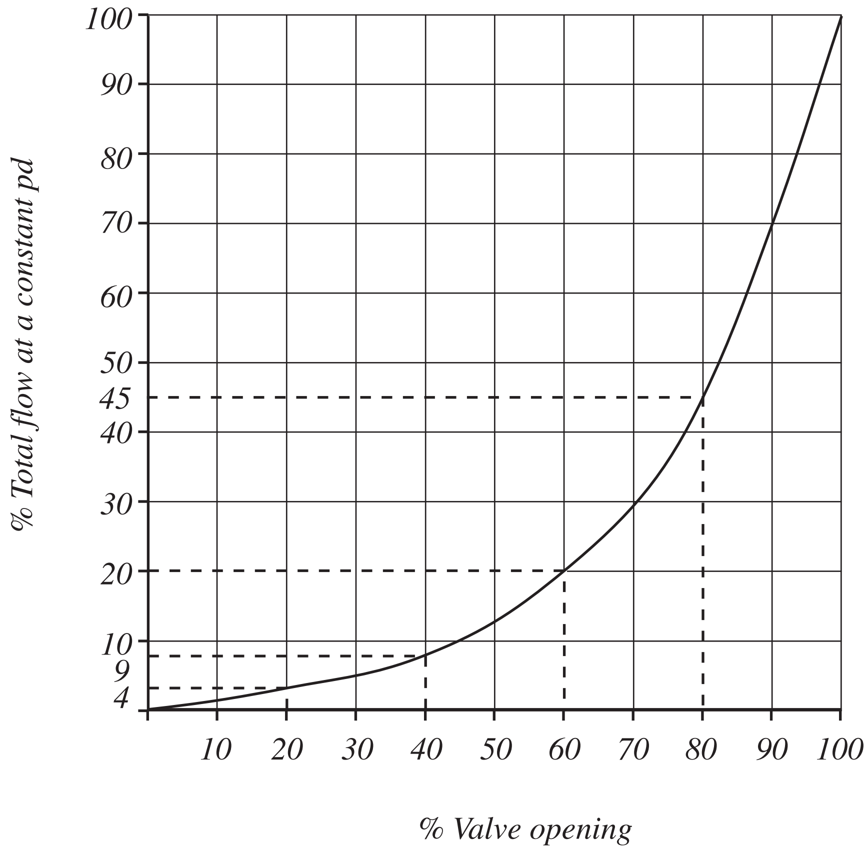

FIG. 4 Equal Percentage Characteristic

Any small change in flow rate from F_1 to F_2 is proportional to the flow rate F_1. Thus, when the valve-plug is close to the seat, the flow rate is small, and any *change* in flow rate will also be small. On the other hand, when the valve-plug opening is wide, allowing a large flow rate, any *change* in flow rate will also be large. The equal percentage characteristic may be expressed mathematically in the form:

$$Q = Q_o e^{nl}$$

where Q = flow rate $(m^3\ h^{-1})$
Q_o = minimum controllable flow $(m^3\ h^{-1})$
e = the natural logarithmic base
n = constant of proportionality which partly depends on the valve gain
l = valve travel (cm).

See if you can use the above flow rate equation to determine the flow through an equal percentage control valve which is 2.0 cm open. The valve plug has a minimum controllable flow of 0.1 $m^3\ h^{-1}$ and a constant of proportionality (n) of 2.0.

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Flow rate through control valve $Q = Q_o e^{nl}$

When the valve is 2 cm open: $Q = Q_o e^{n \times 2}$

$= 0.1 e^{2 \times 2}$

$= 0.1 e^{4}$

$= 0.1 \times 54.6$

Flow through the control valve when 2 cm open $= 5.46 \text{ m}^3 \text{ h}^{-1}$

We can illustrate the equal percentage relationship using the graph shown in FIGURE 4.

Assume we make **two** 20% changes in valve lift. We should expect the percentage increase in flow rate to be the same for both cases.

Case 1

20% – 40% increase in valve lift.

From the graph we see that at 20% valve opening the flow rate is 4% of the total available. At the new position of 40% valve opening the flow rate is 9% of the total.

This shows an increase in total flow rate of 9% – 4% = 5%. The percentage increase in flow with respect to the original flow is:

$$\frac{\text{increase in flow rate}}{\text{original flow rate}} \times \frac{100\%}{1} = \frac{5}{4} \times \frac{100\%}{1}$$

$$= 125\%$$

For a 20% increase in valve lift there is a 125% increase in flow rate.

Case 2

60% – 80% increase in valve lift.

Again from the graph in FIGURE 4 we see that at 60% valve opening the flow rate is 20% of the total. At the new position of 80% valve opening the flow rate is 45% of the total.

This shows an increase in total flow rate of 45% – 20% = 25%.

∴ the percentage increase in flow with the respect to the original flow is:

$$\frac{\text{increase in flow rate}}{\text{original flow rate}} \times \frac{100\%}{1} = \frac{25}{20} \times \frac{100\%}{1}$$

$$= 125\%$$

Again, for a 20% increase in valve lift, there is a 125% increase in flow rate.

Thus for equal increments in valve lift, there are equal percentage increases in flow rate.

THE USE OF EQUAL PERCENTAGE VALVE PLUGS IN CONTROL SYSTEMS

The criteria used for selecting an equal percentage valve plug are listed below, though it is unlikely the control system will satisfy all of them. When the control system fails to satisfy the criteria for either an equal percentage or a linear valve plug, or when there is insufficient information on which to base a decision, best results are normally achieved using the equal percentage type.

CRITERIA USED FOR SELECTION OF AN EQUAL PERCENTAGE VALVE PLUG

(a) The pressure changes within the system should be mainly absorbed by other components of the system rather than the control valve.

(b) The pressure changes within the system will be variable, and interacting.

(c) The non-linear flow/lift characteristic of the equal percentage valve trim should counteract other system non-linearities to produce an overall linear output to input relationship for the system.

The following example illustrates the selection of an equal percentage valve in the system shown in FIGURE 5.

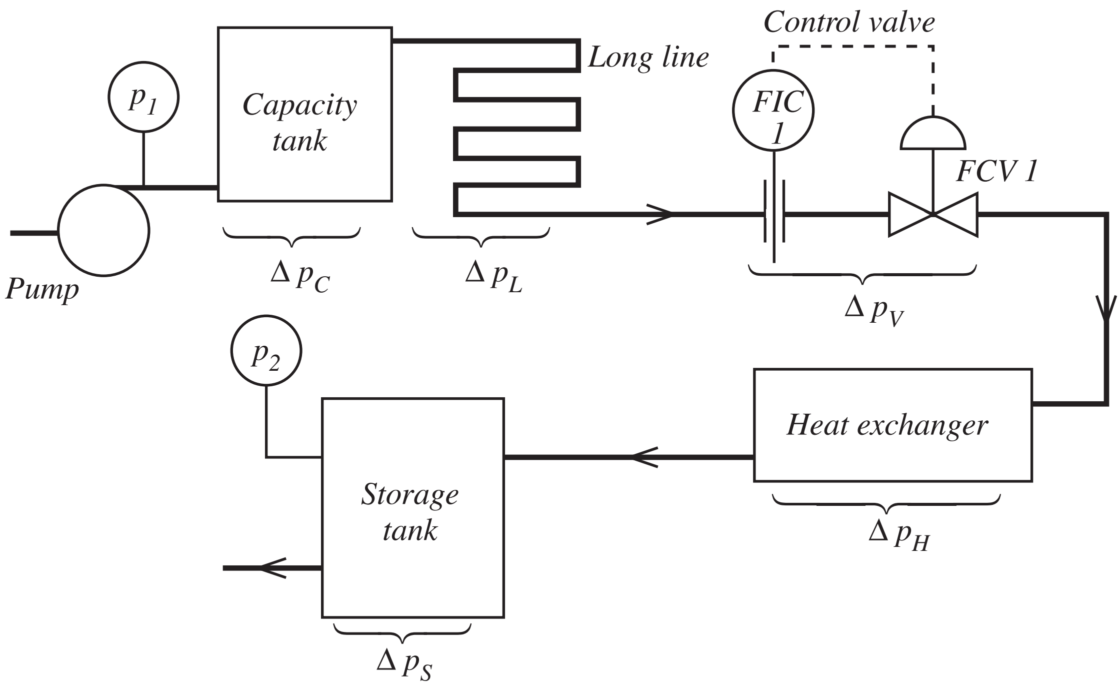

FIG. 5

A pump delivers a fluid to a storage tank, the flow from the pump to the tank being controlled by a control valve. The flow through the system is governed by the overall pressure drop (pd) across the system, $p_1 - p_2$, which is the sum of the following individual pressure drops:

- pd across the capacity tank Δp_C
- pd across the long line Δp_L
- pd across the valve Δp_V
- pd across the heat exchanger Δp_H
- pd across the storage tank Δp_S

So, $$p_1 - p_2 = \Delta p_C + \Delta p_L + \Delta p_V + \Delta p_H + \Delta p_S$$

The selection of an equal percentage valve is justified by the following factors.

(a) The flow through the system is dependent upon the pressure drop $p_1 - p_2$. If this pressure drop changes, the flow rate through the system will change. However, changes in p_1 and p_2 are not absorbed entirely by the valve. The part of the change absorbed by the valve is dependent on the position of the valve, and the flow through it.

(b) Changes in p_1 or p_2 will not induce equal changes in the individual component pressure drops within the system since individual pressure drops will be different for different circuit components.

(c) Because of the non-linear relationship between flow and pd, equal incremental changes in valve movement do not produce equal incremental changes in flow rate.

The use of an equal percentage valve may reduce the effects of the variable pressure drops and linearize the relationship between control valve position and the fluid flow rate.

EXAMPLES OF EQUAL PERCENTAGE VALVE TRIMS

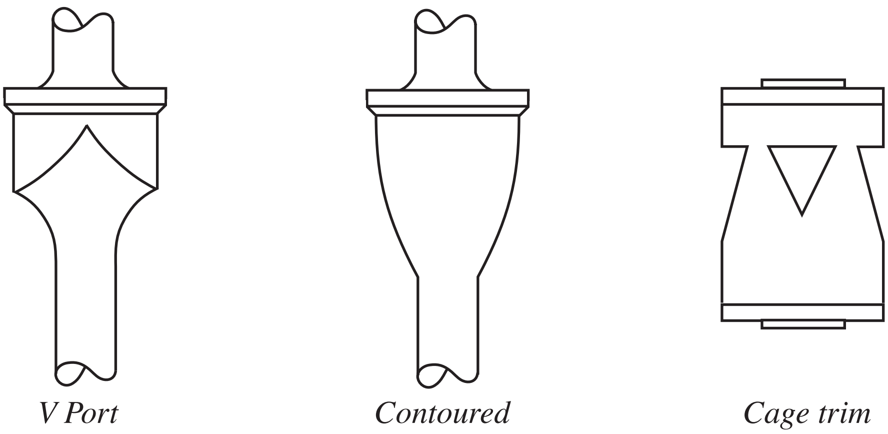

FIG. 6   Typical examples of equal percentage valve trims

The examples shown in FIGURE 6 illustrate that linear movement of the plug in an equal percentage valve does not give a linear increase in area between plug and seat. The area enlarges at an increasing rate as the valve opens, producing corresponding increases in flow rate.

These trims are commonly found in industry, though others are available to meet specific demands. The 'V Port' and 'Contoured' types can be supplied as double seated valves.

QUICK-OPENING CHARACTERISTICS

Valve trims designed to have "quick opening" characteristics are shaped to allow maximum flow rate with minimum valve opening. The characteristic exhibits a linear relationship up to 60% of total flow for only 10% of valve opening. Further increases in valve travel produce reduced flow changes. When the valve plug nears the wide open position, the flow rate increase is very small. This type of characteristic is illustrated graphically in FIGURE 7.

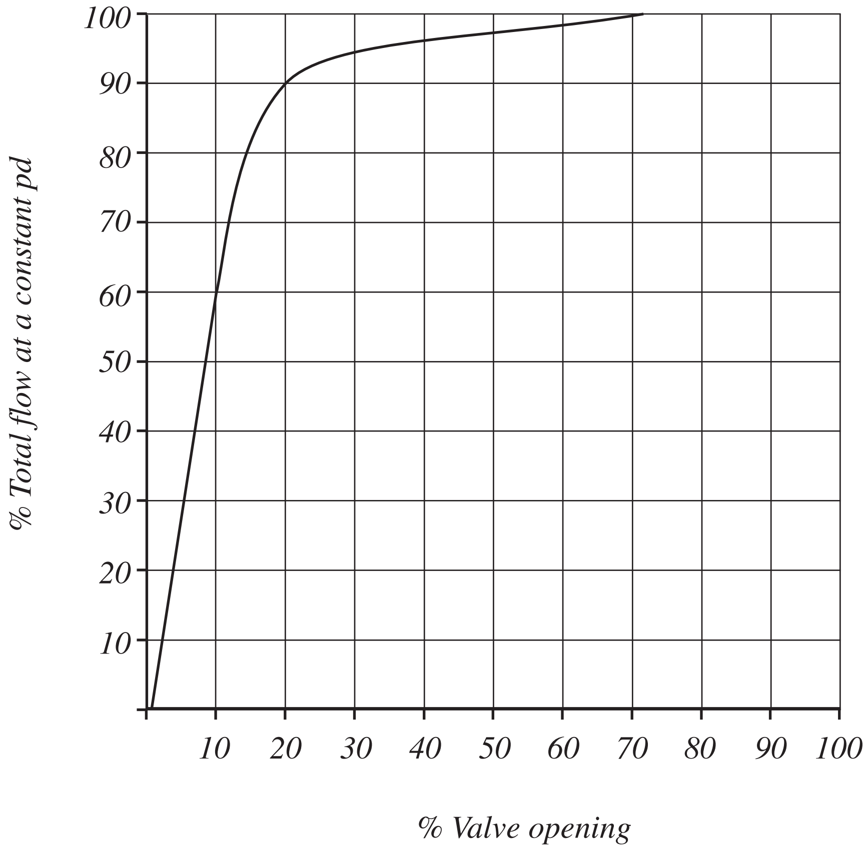

FIG. 7 Quick-opening valve characteristic

The mathematical expression for this type of valve is complex and is beyond the scope of this lesson.

THE USE OF QUICK-OPENING VALVE TRIMS IN CONTROL SYSTEMS

Valves which possess quick-opening characteristics are used when a rapid change in fluid flow is required in response to small valve movements. They are employed in ON/OFF applications, where rapid interchange between minimum and maximum flow rates is required, and for processes which may need to be vented in order to prevent dangerous build up of pressure. A simple example of the latter application is shown in FIGURE 8.

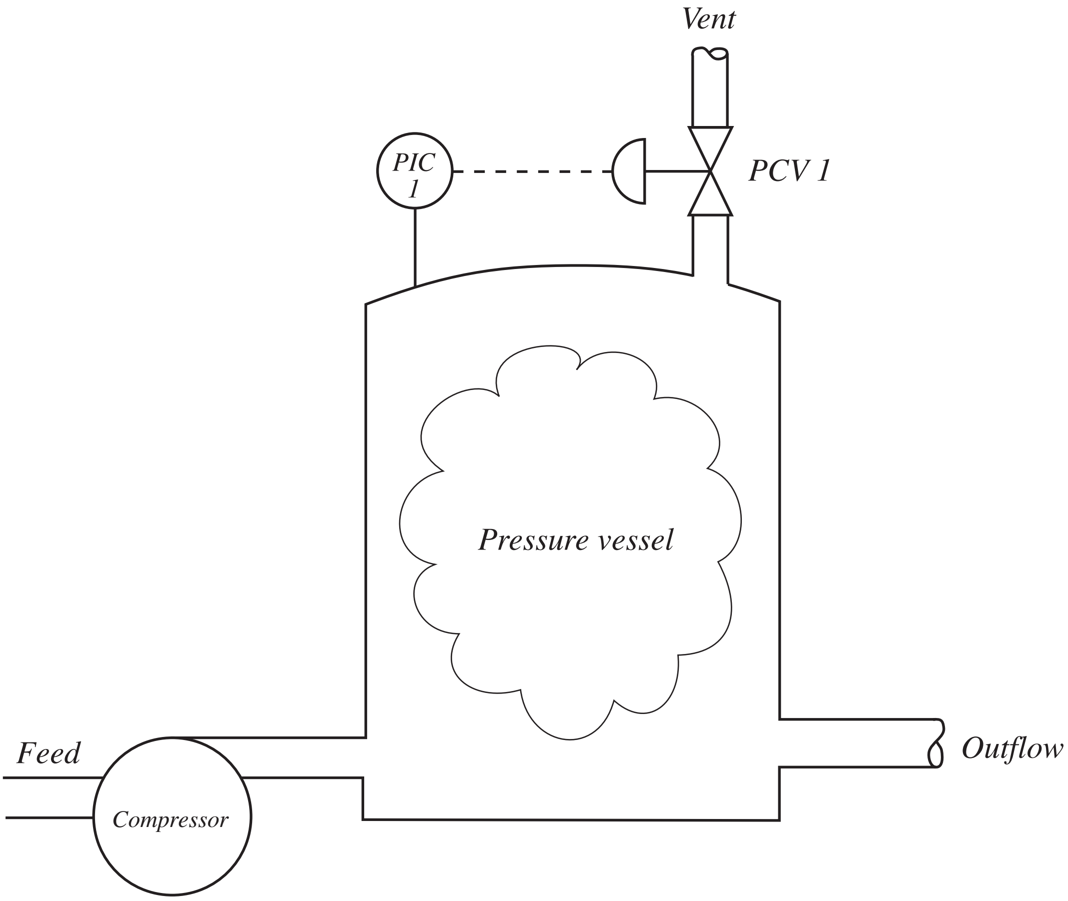

FIG. 8 Typical application of a quick opening valve

PCV is a pressure relief valve. If the pressure in the vessel reaches a dangerous level the valve will open quickly, reduce the pressure to a safe level and reseal. With this system we are not concerned with the control of the pressure, but simply preventing it from exceeding a specified level.

Two examples of quick-opening valve trims are shown in FIGURE 9.

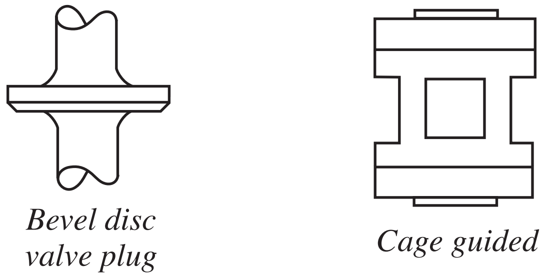

FIG. 9 Typical quick-opening valve trims

Both designs allow the maximum flow to occur quickly after valve lift commences.

INSTALLED FLOW CHARACTERISTICS OF CONTROL VALVES

The valve characteristics which we have discussed so far assume that the pressure drop across the valve remains constant as the valve is opened or closed.

In practice, this is unlikely to occur and the pressure drop will vary according to the degree of opening of the valve. When the valve is closed there is no flow and the pressure drop across the valve is at its maximum. As the valve opens to allow the passage of fluid, the pressure drop reduces, reaching its minimum value at the fully open position.

This variable pressure drop can have a significant effect on the flow characteristics of a control valve when it is installed in a control system. An example of this effect is illustrated in FIGURE 10.

The straight line plot represents the constant pressure drop characteristics of a linear valve trim. Consider the valve to be installed in series with another plant item, such as piping or process plant, which offers a constant flow resistance.

As the valve opens, the increased flow through the system produces a greater pressure drop across the flow restriction, leaving a reduced pressure drop across the valve. Hence, the installed characteristic curve deviates from the constant pressure line and the maximum flow rate is reduced.

In practice, the valve would be sized according to the maximum predicted pressure drop across the system and a larger control valve trim would be fitted.

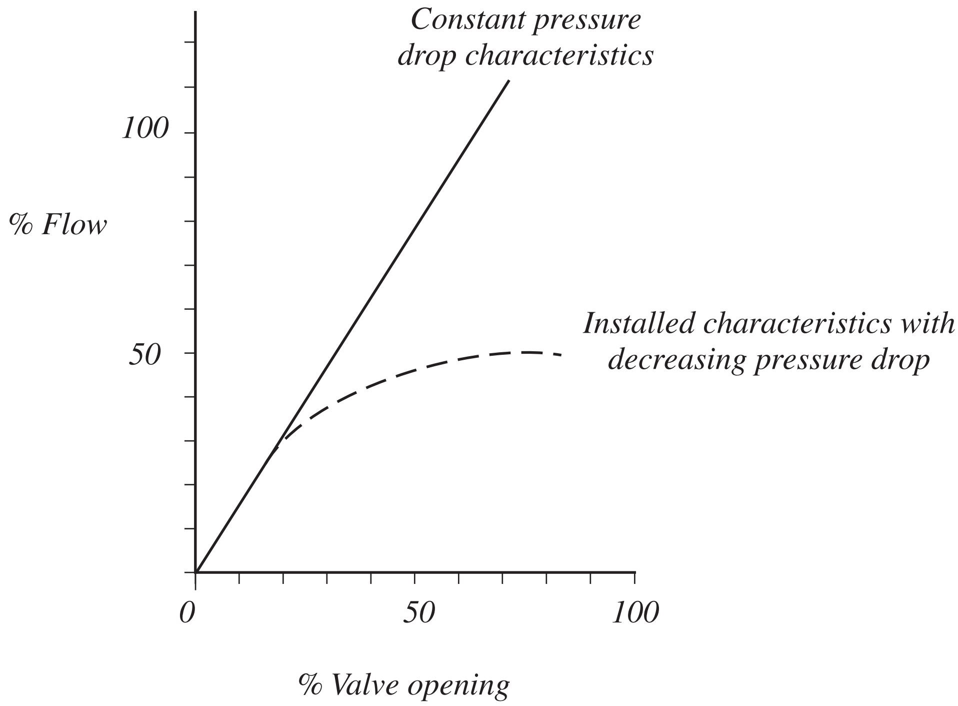

FIG. 10

Which other type of valve characteristic does the linear trim installed characteristic resemble?

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The "quick-opening" characteristic.

FIGURE 11 illustrates that as the percentage of the total pressure drop absorbed by the plant restriction increases, the valve characteristic takes on an increasing resemblance to the "quick-opening" type. Note that the vertical axis in FIGURE 11 represents percentage maximum flow rate and the absolute maximum flow rate figure will be different for each curve.

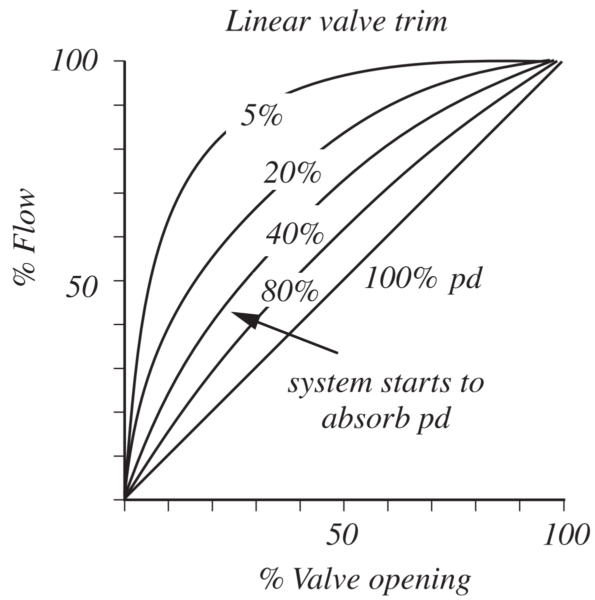

FIG. 11

This 'family' of curves illustrates how the installed characteristics of a linear trim may sometimes resemble those of a quick opening device.

Similarly, an equal percentage valve trim also produces a lower flow rate than anticipated and the characteristic curve will "flatten out" because of the non-linear relationship between flow and differential pressure. FIGURE 12 illustrates this effect.

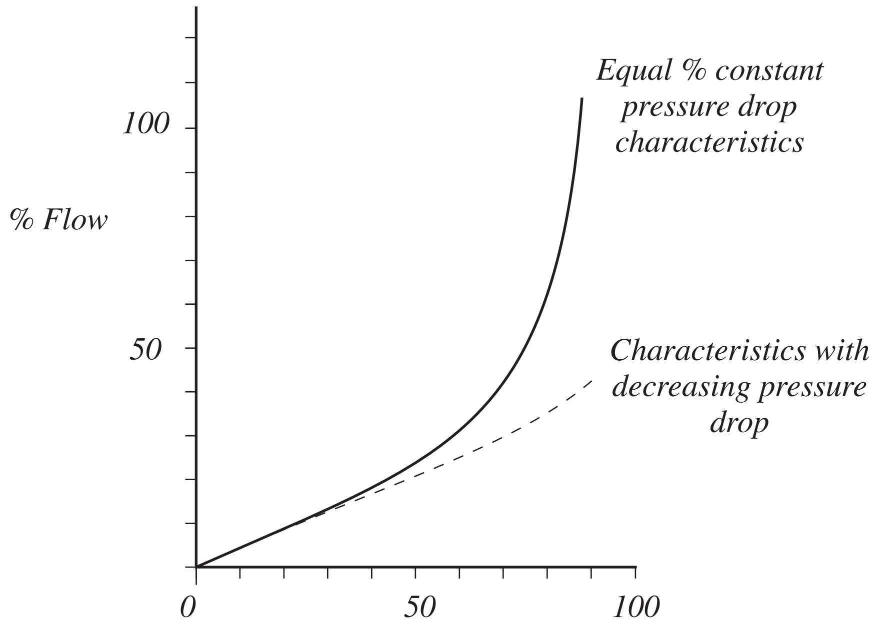

FIG. 12

FIGURE 13 illustrates the effect of reduced differential pressures on equal percentage valve characteristics. Again the curves have been "normalised" so that the vertical axis represents the percentage of maximum flow rate for a particular set of circumstances, and not the actual flow rate through the valve.

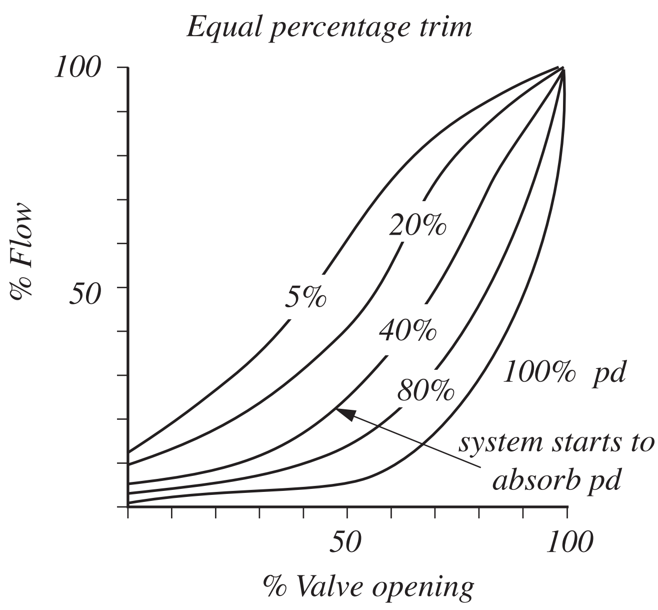

FIG. 13

The curves shown in FIGURE 13 illustrate an important point made previously in the lesson. You see now how the equal percentage characteristic valve can produce almost a linear characteristic when installed as part of a system. This explains the choice of an equal percentage valve in a system where the main pressure drops are across the associated plant, and not across the control valve. The overall control system can thus be linearised.

Now attempt the following Self-Assessment Questions.

NOTES

SELF-ASSESSMENT QUESTIONS

1. On the same axes sketch graphs which illustrate linear, equal percentage and quick opening valve characteristics.

2. You are working on a modification to a chemical plant which requires the installation of the pressure vessel shown in FIGURE 14. Select a suitable valve plug for each of the two control valves shown, and explain the reasons for your selection.

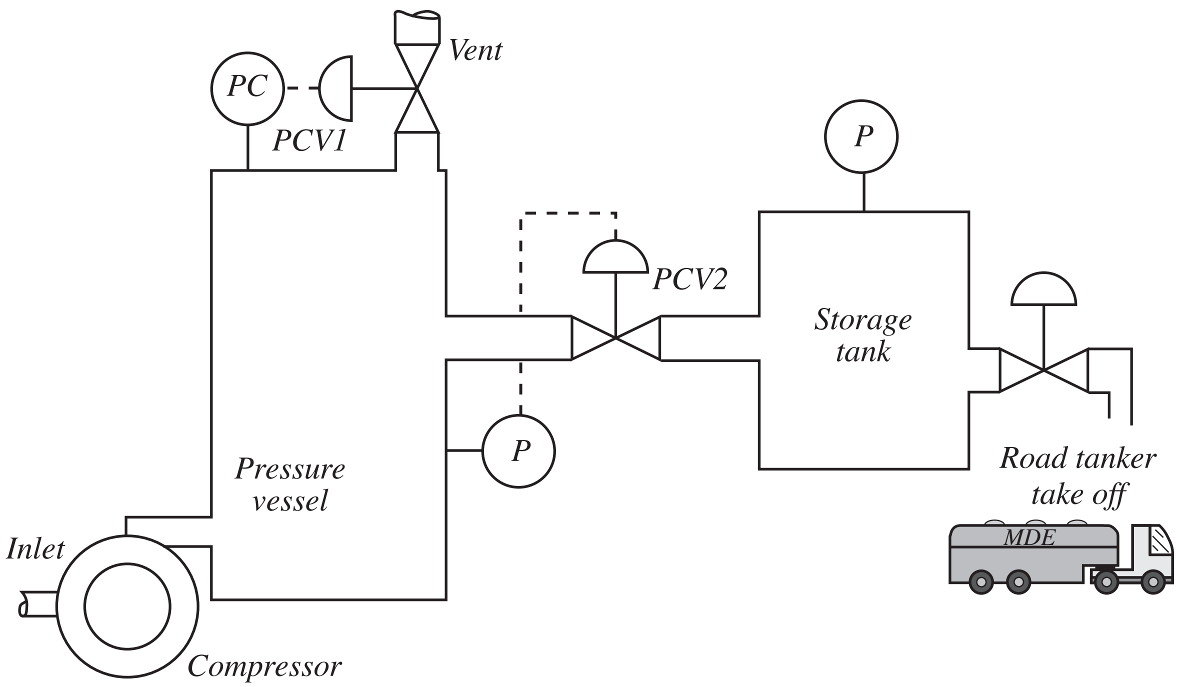

FIG. 14

3. An equal percentage control valve has a minimum controllable flow of $0.2\ m^3\ s^{-1}$, and the constant of proportionality for the valve is 1.0. Determine the flow through the valve at its maximum valve opening of 3 cm.

NOTES

ANSWERS TO SELF-ASSESSMENT QUESTIONS

1. Your graph should look like this:

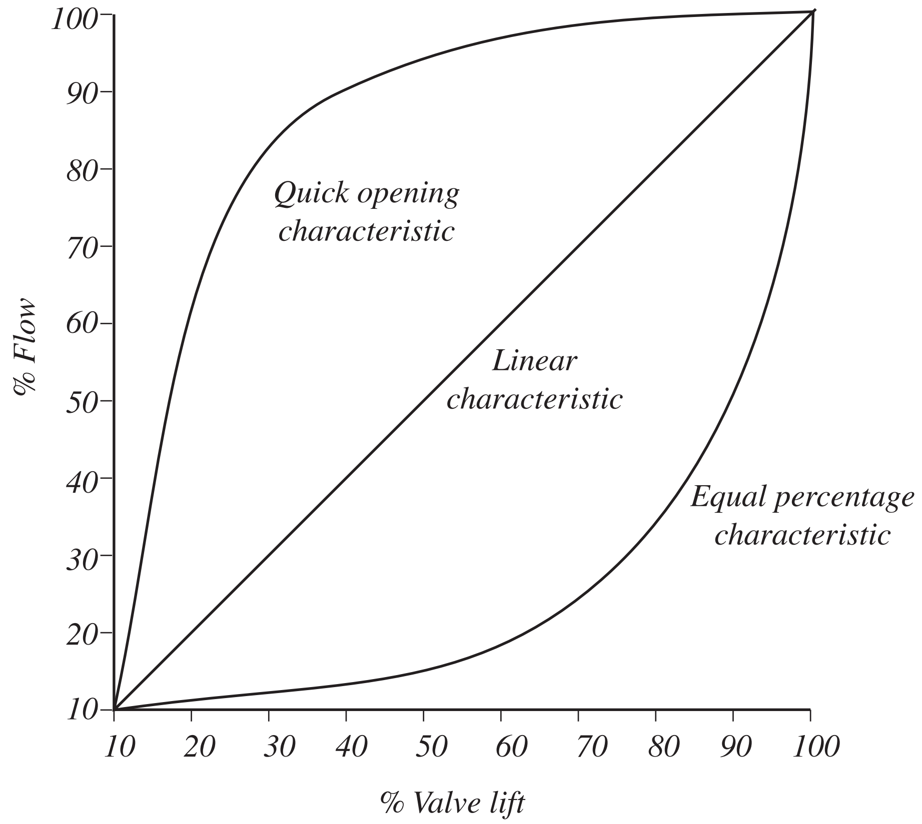

FIG. 15

2. PCV1. Since this valve links the vessel to atmosphere, it is reasonable to assume that it is a relief valve required to reduce the pressure within the tank as quickly as possible. The type of valve which meets this requirement is one with a *quick-opening* characteristic. (See FIGURE 9 for diagram.)

   PCV2. This valve is controlling the pressure within the pressure vessel. It is unlikely that the upstream and downstream pressures are constant. The upstream, or supply side pressure, is dependent on the compressor's output and the downstream pressure is affected by the storage vessel.

The flow through the valve is not only dependent on the valve position but also on the difference in pressures between the pressure vessel and the storage tank. It will, therefore, be non-linear.

Any change in pressure within the system will largely be absorbed by the two tanks, but the pressure drop across the control valve is dependent on its position.

Under these conditions an equal percentage characteristic valve would be specified. (See FIGURE 6 for diagram)

3. Using the formula from page 8 and solving for Q:

$$Q = Q_o e^{nl}$$

where, Q = total flow rate $(m^3\ s^{-1})$
Q_o = minimum controllable flow $(m^3\ s^{-1})$
n = constant of proportionality
l = valve travel (cm)
e = the natural logarithmic base

and, $Q_o = 0.2\ m^3\ s^{-1}$
$n = 1.0$
$l = 3$ cm

$$
\begin{aligned}
Q &= Q_o e^{nl} \\
&= 0.2e^{1.0 \times 3} \\
&= 0.2e^{3} \\
&= 0.2 \times 20.08 \\
\text{Flow through valve} &= 4.02 \text{ m}^3 \text{ s}^{-1}
\end{aligned}
$$

SUMMARY

- Linear control valves give flow characteristics for which increasing flow is directly proportional to valve opening. They find most use in linear process applications such as level control, or where flow conditions can be accurately specified.

- The semi-logarithmic characteristic of the equal percentage valve plug is very adaptable, finding use in many process applications such as pressure and flow control, or where the flow conditions are variable or have not been accurately specified.

- The disc shape of the quick-opening valve achieves a high percentage of the total flow for small valve opening. This makes it ideal for "fast response" applications such as pressure relief.

- Control valves installed in process lines exhibit installed flow characteristics which can differ greatly from the inherent characteristics. Where possible, a valve plug is selected to linearise the process response, thus the installed characteristics must be considered at the selection stage.

- Supply demand is determined by all the process variables prior to the valve. Load demand is determined by all the process variables downstream of the valve.